Research-Based Display Design Guidelines for Vehicle Crewman and Ground Warrior Interfaces, Which Enhance Situational Understanding and Decision Cycle Performance

by Elizabeth S. Redden and Linda R. Elliott
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This document is written primarily for designers of the information displays for Future Force Warrior and the Future Combat Systems and was sponsored by Situational Understanding as an Enabler for the Unit of Action Maneuver Team Army Technology Objective (ATO). It provides guidelines pertaining to the design of displays to increase the efficiencies of warfighters in echelons of platoon and below. These guidelines address interventions and strategies that avoid information overload and incompatibility between display designs and warfighter primary tasks. This document includes guidelines based upon ATO-sponsored research experiments and meta-analyses regarding the optimization of different types of displays (e.g., visual, auditory, tactile); designing displays for different types of tasks; and designing for individual differences that can affect performance with different types of displays. For each guideline, a commentary, examples, and sources are provided. The guiding principles that are contained in the appendix of this document were developed from a review of available literature on experiments that were performed outside the ATO.

display design guidelines; meta analysis; multimodal tactile
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1. Introduction

Future Army networked systems will generate an extremely large amount of information that was previously unavailable to Soldiers operating in echelons of platoon and below. This creates a great potential for information overload, which could decrease the Soldiers’ abilities to use the information effectively and could adversely affect their performance and their actual ability to survive on the battlefield. The U.S. Army Research Laboratory (ARL) initiated an advanced technology objective (ATO) entitled “Situation Understanding (SU) as an Enabler for the Unit of Action Maneuver Team” to address this issue of information overload. The purpose of the ATO was to perform systematic investigations regarding information display designs to identify principles to ameliorate task workload and enhance Soldier performance. Experimental approaches were developed, based on the identification of critical information requirements (Redden, 2002), predictions of task workload (Mitchell, Samms, Glumm, Krausman, Brelsford, & Garrett, 2004) and theory-based predictions, drawn from the Multiple Resource Theory (MRT) (Wickens, 2002; Wickens & Hollands, 2000). These experiments investigated multimodal and alternate modal display designs and their impact on task situations predicted to have high and conflicting workload. Concurrently, the University of South Florida (USF) performed a comprehensive literature search to identify appropriate research performed by other organizations, which could contribute to the effort (Coovert, Gray, Elliott, & Redden, in review; Coovert, Gray, Elliott, & Redden, 2007).

The quantitative metric for the SU ATO was to identify the display interventions to reduce decision cycle time and increase effectiveness at least 25% over the baseline systems. The objective improvement goal was a 50% improvement over the baseline systems. The research performed under the ATO demonstrated display interventions that met these requirements for dismounted and mounted Soldiers. Some examples of interventions that met or exceeded the metrics are

- An auditory cue that information was available on a visual display freed Soldiers to concentrate on the primary task of shooting and reduced friendly fire decision error 66% over no cue. A forearm-mounted display (FMD) reduced overall shooting decision error by 42% as compared to an occluding helmet-mounted display (HMD).
- The hit percentage of dismounted Soldiers against enemy targets was increased by 47% when secondary task information was presented auditorily rather than on an HMD, which provided an auditory alert cue that new secondary task information was being presented on the display (43% versus 29%).
- Research indicated that a C-2 tactor (a plunger type tactor) increased the ability of Soldiers to localize tactile signals when they were traversing a demanding obstacle course 63% more accurately than with the more commonly used inertial shaker tactors (a vibratory tactor commonly found in cell phones).
• In an experiment of unimodal alerts, response time for a vehicle commander was reduced by 54% when an auditory alert (beep) was used rather than a red flashing light visual alert. It was reduced by 41% over the visual alert when a tactile alert was provided. In an experiment of uni- and multimodal alerts, response time was reduced by 63% over the visual cue when multimodal cues were used (visual + auditory and visual + tactile alerts).

• Targets that were relatively visible to a gunner in a simulated closed hatch position were acquired faster (19%), workload was rated lower (7%), and more information (24%) was recalled from concurrent auditory communications when unimodal cues about the location of targets were provided in any modality. When targets were well camouflaged and target location cues were provided, differences in target acquisition time and workload between baseline and unimodal cue conditions increased even more. Target acquisition time decreased by 31% (3.3 seconds) over baseline, the percentage of hits increased by 53%, overall ratings of workload decreased by 15%, and 30% more information was recalled from concurrent auditory and visual communications.

The research-based guidelines presented in this report were compiled to address the design of the information systems for two of the Army’s most visible programs: the Future Combat Systems (FCS) and the Future Force Warrior (FFW) science and technology program. They are based upon the research performed by ARL and universities under contract to the SU ATO and several meta-analyses of 64 published experiments performed by USF to identify generalizable effects of interest (Burke et al., in review).

This document attempts to follow the tradition of knowledgeable practitioners who have distilled their knowledge into compact, generalizable aphorisms or rules of thumb. Compilations of guidelines offer a roadmap to follow that avoids the potholes and side roads that others have unknowingly taken. Guidelines also assist the experienced by causing them to look at problems from a larger point of view and to identify the important issues. Most importantly, they can provoke discussion about which guidelines are applicable in the specific circumstances encountered and what principles should be added from new lessons learned. Guidelines are more than one person’s lightly considered opinion, but they are not rigid standards. They are not comprehensive academic theory that has strong predictive value, but they can be prescriptive. Many of these guidelines are based on Soldier context and tend to expand the sometimes limited content of laboratory theory. They are presented with justifications and examples so that designers can understand the basis for including the guidelines.

No set of guidelines is complete, especially guidelines that address the fast-paced technology of information systems. They should be used in conjunction with knowledge of the ever-changing research in this field and should be updated periodically. These guidelines are suggestions and do not have the authority of requirements nor are they as complete as a handbook. They are primarily focused on the use of alternate modalities to present information to the Soldier in an attempt to offload work and thus, do not attempt to cover all aspects of information design. The reader
should therefore use them in conjunction with MIL-STD-1472 and MIL-HDBK-759 (DoD, 1999, 1995). A report on guiding principles, which was prepared by USF, is shown in appendix A. This report was based upon a comprehensive literature search of field and laboratory studies to identify appropriate research performed by other organizations (Coovert, Gray, Elliott, & Redden, in review; Coovert, Gray, Elliott, & Redden, 2007). It contains detailed information covering a broader range of topics than those covered in the SU ATO and has been included for further elucidation.

2. Display Design General

2.1 Guideline 1.1

Visual displays should be used rather than auditory displays if the visual information can be processed with a single glance.

2.1.1 Comment

Visual and auditory information presentation both have benefits and drawbacks, but in some cases, visual displays are preferred because of the inherent speed of visual processing. Processing visual information can be faster than auditory information because Soldiers do not have to wait for the auditory stream to complete (which also taxes working memory), and they can time share between two visual tasks (e.g., target identification and math problems) more efficiently than when the information is presented aurally.

2.1.2 Examples and Sources

An ACT-R (Adaptive Control of Thought-Rational) cognitive architecture model revealed that the number of shooting decision errors (friend versus foe) that Soldiers were likely to make in a dual task paradigm (target identification while solving math problems) was about the same for a visual input modality versus an auditory input modality. However, the model also revealed that time to respond to cues was different for the visual and auditory displays that were modeled because the cost of eye movements between displays was not as significant as waiting for auditory information to complete (Kelley & Scribner, 2003).

The multimodal meta-analysis project (Burke et al., in review) found that when single modality comparisons were performed in the meta-analysis (visual versus auditory, visual versus tactile, and auditory versus tactile), performance with visual feedback usually exceeded the auditory and tactile forms of feedback, and performance with tactile forms exceeded auditory forms for a variety of task types. Although point effect sizes ranged from -.18 (small) in favor of visual compared to auditory, to -.38 in favor of visual over tactile, to 0.53 (medium) in favor of tactile
compared to auditory, statistical tests of significance were not achieved, but the results leaned toward the visual modality.

2.2 Guideline 1.2
Multimodal display of task information has distinct advantages over unimodal display of task information across task types.

2.2.1 Comment
Visual-tactile task feedback appears to enhance performance and reaction times, much more so than visual alone. Visual-tactile feedback shows even stronger improvements when a user is performing multiple tasks and experiencing a high amount of workload. This supports Wicken’s MRT theory, which states that adding additional modalities will improve performance in high workload situations by reducing the cognitive workload of the user.

Visual-audio is also better than the single visual modality in terms of the user’s reaction time and performance and better than audio alone for error rates as well as reaction time and performance. This suggests that visual task information presentation has a strong link to the user’s error rate. The multimodal visual-audio benefit is best in low workload conditions and weaker in high workload conditions, which suggests that those modalities do not reduce workload as much as the visual-tactile combination. The multimodal (audio-tactile) display also has been shown to enhance user effectiveness more than either modality alone.

2.2.2 Example and Source
The multimodal meta-analysis project (Burke et al., in review) found that when comparisons of multimodalities to single modalities were performed in the meta-analysis, five of the six comparisons were significant point estimates, and the sixth (tactile versus auditory/tactile) was marginally significant, with a large effect size (Hedge’s $g = .75$). The effect size point estimates ranged from .38 to .87, indicating moderate to large effects for incorporating more than one modality into feedback mechanisms. It is interesting that the largest effects reported were from the combination of auditory and tactile feedback compared to auditory alone ($g = .87, p < .01$) and compared to tactile alone ($g = .75, p = .07$). These effects are based upon a small number of studies; however, it is a notable effect and points to this multimodal combination as worthy of further study.

2.3 Guideline 1.3
An effective visual-tactile multimodal display offers more benefits across task levels, types, and workload conditions than does an effective visual-auditory display.
2.3.1 Comment
Visual-tactile displays are most effective when users are performing multiple tasks under high workloads and are still effective for single task or normal workload conditions. In addition, tactile cues can support the visual channel when visual conditions are degraded and when auditory channels are not effective (e.g., during conditions of high noise or need for stealth). Soldiers have also expressed a preference for tactile cues when radio communications must be maintained.

2.3.2 Example and Sources
The multimodal meta-analysis project (Burke et al., in review) found that visual-tactile feedback enhanced performance in single and multiple task paradigms but was particularly effective when participants had to execute multiple tasks. Visual-auditory feedback was most effective when a single task was being performed ($g = .87$) and in normal workload conditions ($g = .71$). Visual-tactile feedback was more effective when multiple tasks were being performed ($g = .77$) and workload conditions were high ($g = .84$).

A study was conducted to assess the utility of adding tactile and 3-D auditory systems to a visual display to reduce the time for assimilation of information during high-workload target acquisition and robot navigation tasks. Adding a tactile directional display to a visual display in a navigation task resulted in lower response times than with the visual display alone or than with the visual display plus a 3-D auditory alert (Savick, Zubal, Elliott, & Stachowiak, in review).

2.4 Guideline 1.4
The addition of a tactile display to a visual display can decrease response times.

2.4.1 Comment
Visual-tactile displays show promise across task types for decreasing reaction times.

2.4.2 Example and Source
A study was conducted by Savick, Zubal, Elliott, and Stachowiak (in review) to assess the utility of adding tactile and 3-D auditory systems to a visual display to reduce the time for assimilation of information during high-workload target acquisition and robot navigation tasks. Adding a tactile directional display to a visual display in a navigation task was found to result in lower response times than with the visual display alone or than with the visual display plus a 3-D auditory alert.

The multimodal meta-analysis project (Burke et al., in review) found that visual-tactile feedback decreased response times over visual alone ($g = .81, p = .00$).

2.5 Guideline 1.5
The addition of a tactile display to a visual display can result in lower perceived workload.
2.5.1 Comment
Tactile displays can offload some of the effort involved in visual search and visual attention.

2.5.2 Example and Source
A study was conducted to assess the utility of adding tactile and 3-D auditory systems to a visual display to reduce the workload associated with assimilation of information during high-workload target acquisition and robot navigation tasks (Savick, Zubal, Elliott, & Stachowiak, in review). Adding a tactile display to a visual display resulted in lower ratings of workload (i.e., lower mental demand, lower temporal demand, lower frustration and lower effort) than with the visual display alone or than with the visual display plus a 3-D auditory alert.

A study was conducted to compare the use of a visual “arrow” global positioning system (GPS) display and a tactile belt display of GPS data, singly and together, for various land navigation tasks. The use of both devices together was rated by Soldiers as less difficult than the visual display alone, for finding waypoints, re-routing around large obstacles, knowing the terrain directly around you, knowing your location relative to landmarks, and being simple to use. Also, having both devices was rated significantly lower ($p = .01$) in overall workload (Rating Scale of Mental Effort; mean = 19.58) than having just the visual display (mean = 27.96) (Elliott, Redden, Duistermaat, & van Erp, in review).

2.6 Guideline 1.6
Non-occluding visual displays for wearable information systems for infantry Soldiers should be used when possible.

2.6.1 Comment
Occluding HMDs can degrade Soldier task performance over other display types.

2.6.2 Example and Source
Soldiers who had to multi-task between target scanning and shooting performed significantly more poorly in the shooting tasks when wearing an HMD that is not see-through versus using an FMD that can be seen with a small eye movement. Auditory and visual FMD presentation (combined with an tonal auditory alert of incoming information) of secondary task information allowed faster shot reaction times for the primary task of shooting than helmet-mounted visual presentation of secondary task information (with or without an auditory alert). Display of secondary task information on an FMD reduced overall shooting decision error (6.6% versus 3.82%) as compared to an occluding HMD. Shot reaction time was significantly higher with an HMD and no cue (2.76 seconds) as compared to the auditory condition in which secondary task information was provided via voice (2.63 seconds) (Scribner, Wiley, & Harper, 2005).
Soldiers who had to multi-task between walking, scanning for targets, and performing land navigation tasks performed more poorly when an occluding HMD was worn, compared to a hand-held display and compared to a torso-mounted tactile display. When traveling cross-country and performing land navigation during night operations, Soldiers navigated slower while searching for targets and found fewer targets when they used a map displayed on the HMD than they did when they used a tactile display (Duistermaat, 2005; Elliott, Redden, Duistermaat, & van Erp, in review).

3. Visual Display Design

3.1 General

3.1.1 Guideline 2.1
Trade-offs between knowledge of the enemy or surrounding area, level of information fusion, and degradations in mission task times should be understood before visual displays are provided to warfighters.

3.1.2 Comment
Providing visual displays at the team leader level can enhance situational awareness (SA) and provide some performance gains but at an increase in mission time.

3.1.3 Example and Source
A study was conducted to evaluate team leader mission performance and determine the impact on SA, lethality, and survivability when visual, auditory, and combined displays are used. Results showed that providing visual displays (digital maps and unmanned aerial vehicle displays) to the team leader enhanced SA and provided some performance gains but at an increase in mission time. Incorporating “information manager” presentation of information to the team leader enhanced SA, survivability, and lethality, with a reduction in workload, and with no time penalty. Having an “information manager” to interpret, integrate, and verbally relay information and guidance provided the best operational impact, but this currently requires a human operator. The optimal system would incorporate a smart information display that allows the team leader to keep his attention on his immediate surroundings and not on his display system (Wiley, Scribner, & Harper, 2006).
3.2 Labels

3.2.1 Guideline 2.2
Use military terminology for menu options and instructions.

3.2.2 Comment
Sometimes engineers and designers use words that are not understood or that have alternate meanings to military users.

3.2.3 Example and Source
Night vision engineers often use the word “IR” to refer to devices that convert radiated or reflected heat into images (thermal devices). Soldiers most commonly think of “IR” as the infrared light source that is located on their night vision goggles. A designer of a fused system combining thermal and image intensification can cause confusion by labeling the thermal device “IR” (Redden, 2006).

3.3 Icons and Fonts

3.3.1 Guideline 2.3
A 16-point True Type font is the minimum symbol size that can be discriminated and identified on a 3.5-inch simulated wrist map display.

3.3.1.1 Comment
When small displays are used, there is a trade-off between font size and screen space.

3.3.1.2 Example and Source
A study was conducted to evaluate the effects of symbol (icon) size on symbol identification when a small map display is used. The purpose was to determine the minimum resolvable symbol size for a group of selected warfighting symbols that could be discriminated and identified on a 3.5-inch simulated wrist map display (Myles, 2006).

3.3.2 Guideline 2.4
For an urban map display, six symbols (icons) or fewer should be used when a symbol size of 16 points is used. For a rural map, 12 symbols or fewer should be used.

3.3.2.1 Comment
When small displays are used, there is a limit to the number of symbols or icons that can be effectively displayed before clutter inhibits search times.
3.3.2.2 Example and Source

A study was conducted to determine the number of symbols (defined as clutter) that could be displayed on a 3.5-inch display when a rural and urban map display is used, without significant decreases in performance. For an urban map display (a display with background clutter), mean scan times begin to increase after a clutter level of six symbols when a symbol size of 16 points is used. If the map background did not perceptibly contribute to display clutter (e.g., rural map), superimposing as many as 12 symbols over the map yielded no change in scan times for a target symbol (Myles, 2006).

3.3.3 Guideline 2.5

When the color of a critical indicator icon is being selected, a color with the same luminance and shade as objects that the observer is searching for in the scene should be chosen, if possible. However, the color should not contradict current doctrine.

3.3.3.1 Comment

Variations in color may be a factor in the ability to attend to something. For example, if a person is attending to a number of objects that are one color shade (e.g., dark green), it may be possible that this person might not see an additional object that appears in his or her field of view (FOV) if it is a different color and shade.

3.3.3.2 Example and Source

Savick (2006) showed that trained participants found significantly more vehicles when they were the same color as the tanks for which they were already looking.

4. Auditory Display Design

4.1 Guideline 3.1

Bone conduction communication can be used as the communication interface for mounted Soldiers. However, it is extremely important that there is a proper fit of the communication system to the listener’s head for successful communication to be achieved.

4.2 Comment

Some people have hypothesized that the use of bone conduction communication systems may be limited by body vibration caused by a moving vehicle. However, bone conduction communication has been found to work in moving vehicles if the system is properly fitted.
4.3 Example and Source
A study was conducted to determine the effects of vehicle noise and body vibration on the effectiveness of bone conduction communication and to compare it with the effectiveness of the standard communication system used by crew members of military vehicles. Although listeners performed best when they wore the combat vehicle crewman’s (CVC) helmet, the two bone conduction systems achieved or nearly achieved the MIL-STD-1472D speech intelligibility standard (Henry & Mermagen, 2004).

5. Tactile Display Design

5.1 Guideline 4.1
Vibrotactile stimulation, rather than other tactile signal types such as embossed letters, pressure, electricity charges, chemicals, and thermal stimulation appears to be the most effective tactile signal type and to be compatible with Soldiers’ clothing and missions.

5.1.1 Comment
Vibrotactile sensations can be well controlled and are well tolerated. Clothing items such as the Interceptor Body Armor (IBA) have no effect on tactile pattern recognition when they are worn over this type of tactile display. IBA does not vibrate with the motors in a tactile display, does not impede their vibration on the skin, and so has no effect on tactile pattern recognition. Vehicle vibration appears to have no adverse effect on tactile pattern recognition.

5.1.2 Example and Source
In his chapter titled “Touch Systems in Perspective” (Gilson, Redden, & Elliott, 2007), Gilson states that other attempts at tactile stimulation have failed (i.e., pressure fades, electricity hurts, chemicals spread, thermal stimulation neutralizes).

A study was conducted in which subjects wearing their IBA were required to identify which of eight tactile patterns presented with a 4 by 4 tactile display worn on the lower back was being presented. The IBA was found to have no effect on performance with 100% accurate identification of the patterns presented (Jones, Kunkel, & Piateski, in review; Lam, 2006).

A study was conducted to determine how performing combat assault maneuvers would affect the detection and recognition of tactile patterns presented with two types of tactile displays: a belt display and a back display. Six tactile navigation patterns were presented to participants as they moved through obstacles that simulated combat assault maneuvers. Participants wore a fighting
load or fighting load and IBA. The IBA did not have an adverse effect on pattern recognition (Krausman & White, 2006).

A study by Krausman, White, and Haas (in press) was conducted to determine if tactile signaling could be perceived by participants experiencing whole-body vibration produced by a vehicle simulator that was replicating movement of a tracked or wheeled vehicle in extreme conditions. Participants detected well over 90% of the signals sent when the plunger tactors were used. Of those signals detected, 97% of the signals were correctly localized.

5.2 Guideline 4.2

Maximum tactile signal strength should be strong enough to be felt in vibration environments and during rigorous physical events.

5.2.1 Comment

Even though it is infrequent, rigorous activity can sometimes interfere with the perception of vibrotactile signals. Display designers should ensure that vibrotactile signals can be felt by the operator during realistic mission context.

5.2.2 Examples and Sources

A study was conducted that assessed the abilities of Soldiers to localize tactors on a belt worn around the waist. Soldiers achieved high proportions of correct localizations for the static trials (from 86.1% to 91.8% with the different tactor types). However, during the dynamic trials, correct localizations fell, and the percentages were 48.8% to 78.7% for the different tactor types. Soldiers suggested that the intensity of the tactors be raised so that they could be more easily localized during rigorous events (Redden, Carstens, Turner, & Elliott, 2006).

5.3 Guideline 4.3

The user should have the capability to adjust the level of intensity of a tactile display.

5.3.1 Comment

Variation in pain thresholds between individuals and variations in task rigor affect “felt intensity” of the tactors.

5.3.2 Examples and Sources

Van Erp (2002) suggested that differences between threshold sensations and pain between individuals drive the need to adjust tactor intensity.

The ability of Soldiers to localize tactors that were individually actuated on a belt of eight tactors worn around the waist was addressed by having Soldiers complete different types of obstacles and
events. Differences among the percentages of correct localizations were noted for the different event types. Some Soldiers suggested that they should be able to increase the tactor intensity during more rigorous events so that they could be more easily localized (Redden, Carstens, Turner, & Elliott (2006)).

5.4 Guideline 4.4

A plunger tactor actuated within a stationary housing that constrains the vibratory wave propagation and localizes the perceptual signature (i.e., C-2 tactor) appears to work better for precise signaling than an inertial shaker motor.

5.4.1 Comments

The entire housing of the shaker motor vibrates, allowing unconstrained physical wave propagation along the skin. The net effect is interference with point-to-point specificity and degradation of two-point vibratory discrimination. The housing around a plunger tactor can localize the perceptual signature.

Firm pressure is needed to keep the shaker motor in contact with the skin and to constrain erratic shaking. However, pressure changes the overall impedance, thus loading the tiny motor and reducing intensity. Varying pressure such as produced under body armor, particularly during movement, alters the loading and changes attenuation unpredictably.

Pager vibrators normally operate at about 60 Hz rather than in the 200- to 250-Hz range where plunger tactors can operate and to which the Pacinian corpuscles are most sensitive.

Imprecise onset or rise times result with shaker motors. A plunger tactor is capable of precise timing (see Chapters 3.1 and 3.3 of Gilson, Redden, & Elliott, 2007).

5.4.2 Example and Source

On an individual movement techniques course (IMT), Soldiers were able to localize tactile signals better with the two C-2 plunger tactors operating at two different gain levels (78.7% and 70.2% correct localization) than with inertial shakers that operated at a gain level similar to one of the C-2 plunger tactors (48.8% correct localization) (Redden, Carstens, Turner, & Elliott, 2006).

A study was conducted to determine how vibration from a simulated Bradley and high mobility multipurpose wheeled vehicle (HMMWV) moving over gravel and a cross-country course affects detection and localization of tactile signals. Tactile signals were generated by two tactile systems, one employing a C-2 plunger tactor, the other an inertial shaker motor. Localization of tactile signals was superior with the C-2 plunger tactor (3% more correct localizations; Krausman, White, & Haas, in press).
5.5 Guideline 4.5
A plunger tactor allows greater intensity and appears to perform better than inertial shaker motors in demanding environments.

5.5.1 Comment
A plunger tactor allows greater intensity and the ability to adjust the intensity.

5.5.2 Example and Source
In a study in which Soldiers received tactile signals during their negotiation of an IMT obstacle course, response was best with the higher intensity C-2 plunger tactor (78.7%) and worst with a lower intensity inertial shaker tactor (48.8%) (Redden, Carstens, Turner, & Elliott, 2006).

A study was conducted to determine how vibration from a simulated Bradley and HMMWV moving over gravel and a cross-country course affects detection and localization of tactile signals. Tactile signals were generated by two tactile systems, one employing a plunger motor, the other an inertial shaker motor. Detection and localization of tactile signals and time to respond were affected by the type of tactile system and terrain with the higher intensity plunger tactor generating 6% more correct detections than the inertial shaker tactor (Krausman, White, & Haas, in press).

5.6 Guideline 4.6
Stimulating various loci in different combinations can create a large number of possible patterns for cutaneous communication. However, constraints limit the usable patterns.

5.6.1 Comment
Tactile patterns should be short and distinct. If pulsing patterns are used, each pattern should initiate in a different way, since Soldiers will often guess what the pattern is as soon as it begins. Other errors that subjects often make usually relate to confusing the spatial similarity between the two patterns.

5.6.2 Example and Source
In a study of tactile patterns, Soldiers identified patterns while undergoing strenuous IMT activity and wearing full battle load. In many instances, Soldiers initially provided a wrong identification but immediately corrected themselves. Certain patterns were more likely to be confused than others (Pettitt, Redden, & Carstens, 2006).

5.7 Guideline 4.7
The waist appears to be an effective location to place a tactor display.
5.7.1 Comment
Several researchers have established that the waist is an effective torso area for tactors (van Erp & Werkhoven, 1999; Lindeman, Yangida, Lavine, 2003).

5.7.2 Example and Source
Soldiers performing combat maneuvers on IMT obstacle courses and Soldiers riding in combat vehicle simulators did not experience any problems in terms of discomfort or interference with tasks when a tactor array was worn around the waist (Pettitt, Redden, & Carstens, 2006; Redden, Carstens, Turner, & Elliott, 2006; Krausman & White, 2006).

5.8 Guideline 4.8
Use a ring of eight tactors on a belt for an accurate and informative tactor display.

5.8.1 Comment
A ring of eight can be accurately resolved and is sufficient to communicate basic signals.

5.8.2 Example and Source
A ring of eight tactors is the most that could be resolved with accuracy exceeding 90% in a study by Cholewiak, Brill, and Schwab (2004). The use of more tactors to create 12 azimuth sectors presented no apparent advantage over eight sectors (Cholewiak, Brill, & Schwab, 2004).

In a study to compare subjects’ performance in identifying tactile patterns, a tactile display configured as a belt (eight vibrating motors in a row) was found to be as effective as 16 tactors displayed as a 4 by 4 array of motors mounted on the lower back. Excellent performance was achieved with both, with an average of 99% correct responses (Jones, Kunkel & Piateski, in review).

5.9 Guideline 4.9
Use a tactile torso belt in order to communicate direction information.

5.9.1 Comment
The belt can communicate the cardinal directions and is an intuitive way to present directional information.

5.9.2 Example and Source
Several experiments have shown effectiveness of tactile belt displays in supporting tasks involving directional information. Chapter 4.1 of Gilson, Redden, and Elliott (2007) found significant and substantial improvements in perceiving the actual direction of the target using tactile cues to alert
the presence of an unseen target. Elliott, Redden, Duistermaat, and van Erp (in review) and Elliott, et al. (2006) found that the use of tactile belt displays for providing GPS land navigation information were simple to learn and to use. (See sections on target detection and land navigation for additional information.)

6. Designing for Task Type

6.1 Alert Cues

6.1.1 Guideline 5.1

Periodic alerts and warnings may be useful for reminding Soldiers of potential ground hazards and to encourage a more appropriate distribution of attentional resources.

6.1.1.1 Comment

Soldiers can become overloaded with multiple tasks when traversing through rough terrain. When their workload increases and attention is divided, alerts or warnings may support their performance. As the attentional demands of a concurrent cognitive task increase, some individuals may allocate less attention to the performance of a seemingly automatic task of avoiding hazards while walking, attending less to the cognitive aspects of the physical task (i.e., detecting and identifying hazards). They may become less attentive to declines in performance and thus the need to take corrective actions. They may also become less sensitive to cues that can lead to injury, including the physical stresses and strains that the physical task might impose.

6.1.1.2 Example and Source

In a recent experiment by Glumm (2005), Soldiers walked on a treadmill that had marked areas to be avoided. At the same time, their attention was diverted through presentation of arithmetic problems. The more time it took to solve the arithmetic problems at the “moderate” level of mental load, the lower the variability in step length when the Soldiers were avoiding hazards. Subjective ratings of physical demand decreased significantly at the “high” level of mental workload. Also, differences in ratings of performance and overall workload scores between “hazards” and “no hazards” terrain conditions decreased with each increase in mental workload. Findings indicated that periodic alerts were needed to remind Soldiers of potential ground hazards.

6.1.2 Guideline 5.2

Add tactile or auditory alert cues regarding incoming information on a visual display to increase performance, especially when under high, multi-tasking workload (see previous section on multimodal cue guidelines).
6.1.2.1 Comment

When Soldiers are using their visual resources to attend to their environment rather than to their displays, an alternate modality alert cue notifies them when something new and important is being added to the display.

6.1.2.2 Example and Source

An auditory alert cue for visual displays reduced friendly fire decision error from 3.12% to 1.04% over no cue (Scribner, Wiley, & Harper, 2005).

When a platoon leader was engaged in visually demanding tasks, visual alerts led to longer response times and were not as effective or helpful as auditory or tactile alerts. The mean of the response times for the visual alert was 12.32 seconds, the mean for the auditory alert was 5.67 seconds, and the response time mean for the tactile alert was 7.33 seconds. Eighty-two percent of the subjects ranked the visual alert as the worst choice for getting their attention (Krausman, Pettitt, Elliott, & Redden, 2006).

6.1.3 Guideline 5.3

When Soldiers are performing concurrent tasks, multimodal alert cues (preferably visual/tactile) should be used to get the user’s attention.

6.1.3.1 Comment

One potential advantage to designing redundancy into alerts is that in case environmental noise or vibration masks the auditory or tactile portion of the alert or demanding visual tasks interfere with the operator’s ability to see a visual alert, the operator could still rely on an alternate alert modality.

6.1.3.2 Example and Source

A study was conducted to examine the effects of alerts on platoon leader performance and decision making. Tactical information was presented to a platoon leader on a visual display. One uni- and two multimodal alerts (visual, visual + auditory, visual + tactile) were used. Response times for the visual alert alone were 63% slower when compared to both the visual + auditory and visual + tactile alerts (Krausman, Pettitt, & Elliott, 2007).

The multimodal meta-analysis project (Burke et al., in review) found that visual/tactile feedback produced favorable performance for alert-type tasks, but visual/audio feedback was not effective in the studies that were analyzed. Possible explanations for these findings included the use of high noise-level environments in some of the studies and several different types of audio cues were used in the studies.
**6.1.4 Guideline 5.4**

When alerts are used, adding levels of urgency can inform the user of the criticality of information s/he is receiving or the task s/he needs to perform.

6.1.4.1 Comment

Urgency helps the user prioritize his or her responses to alerts.

6.1.4.2 Example and Source

A study was conducted to examine the effects of alert urgency on the performance and decision making of a platoon leader during a simulated mission. Visual, auditory, and tactile alerts, each with three levels of urgency, were presented to the platoon leader. Some differences in response time were observed, which led to the conclusion that adding levels of urgency to alerts results in a combination of efficient task allocation and information management (Krausman, Pettitt, Elliott, & Haas, in press).

**6.2 Target Cuing**

**6.2.1 Guideline 5.5**

Cues about target location should be provided when feasible.

6.2.1.1 Comment

Cues provided to the gunner about the location of known targets can significantly reduce target acquisition time and workload. As the signature of the target is reduced (i.e., when the target is more difficult to be seen), even greater reductions in target acquisition time and workload can be achieved if more information cues about target location are added.

6.2.1.2 Examples and Sources

Targets that were relatively visible to a gunner in a simulated closed hatch position were acquired faster and workload was rated lower when cues about the location of targets were provided (Glumm, Kehring, & White, 2005):

- Target acquisition time decreased by 19% (1.4 seconds) over baseline (i.e., no cues) and the percentage of hits increased by 6%.
- Overall ratings of workload decreased by 7%.
- More information (24%) was recalled from concurrent auditory communications.

When targets were well camouflaged, differences increased significantly for target acquisition time and workload between baseline and conditions in which target location cues were provided (Glumm, Kehring, & White, 2006):

- Target acquisition time decreased by 31% (3.3 seconds) over baseline.
• The percentage of hits increased by 53%.
• Overall ratings of workload decreased by 15%.
• More information (30%) was recalled from concurrent auditory and visual communications.

6.2.2 Guideline 5.6

When the gunner is isolated from the environment (e.g., closed hatch position) and s/he is looking at only one display with low to moderate workload, visual or verbal cues about target location that are intuitively consistent with the operator display allow Soldiers to localize targets more accurately and acquire targets faster than with current 3-D audio or tactile cueing techniques.

6.2.2.1 Comment

Verbal and visual cues can provide a clear indication of a target’s location, thus resulting in less uncertainty and faster rates of slew and localization of the target. Tactile cues result in faster times to begin to slew, but in a closed hatch environment, the intuitiveness of a tactile or 3-D audio cue is lost. The gunner in the Glumm et al. (2006) study had to localize the actuated tactor or 3-D tone, determine the corresponding “o’clock position,” look at the turret indicator icon, and then slew so that the icon corresponded to the position indicated by the tactor or tone. The cognitive requirements for use of a tactile and 3-D target cueing displays were not required for the visual or verbal display. The visual display in this study was identical to the turret position icon and the verbal display used words to tell the “o’clock position” of the target. The modality in which the cue is provided can certainly affect target acquisition time, depending on the conditions. Note that the most effective modality also depends on the amount of work and other tasks that are being performed by the gunner.

6.2.2.2 Example and Source

Target acquisition time for a gunner in a simulated closed hatch position was 13% faster (1 second) with visual and verbal cues than with tactile cues and 26% (2.3 seconds) faster than with 3-D audio cues (Glumm et al., 2006).

6.2.3 Guideline 5.7

Integrating intuitive visual target cues into the sight picture can result in faster acquisition times (e.g., a clock display that corresponds with display controls) during low to moderate visual workload conditions.

6.2.3.1 Comment

Wickens’ MRT indicates that the visual channel is a powerful channel for spatial information.
6.2.3.2 Example and Source

When targets were well camouflaged, greater reductions in target acquisition and workload times by gunners in a simulated closed hatch condition were found when cues were provided via an image of a clock integrated into the sight picture that corresponded with the operator targeting control (Glumm et al., 2006):

- Target acquisition time in the visual mode was 13% faster (1 second) than in the tactile mode and 26% (2.3 seconds) faster than in the 3-D audio condition.
- More information (10%) was recalled from auditory and visual communications in the visual mode than in the verbal, 3-D audio, and tactile conditions.

6.2.4 Guideline 5.8

If a verbal cue is provided, it should be structured to minimize the delay in the transmission of target location information.

6.2.4.1 Comment

The structure of a verbal cue can affect target acquisition time. Delays in the receipt of target location information can result in a similar delay in time to acquire the target. It is important, however, that the structure does not violate standard/approved commands for engaging targets.

6.2.4.2 Example and Source

Target acquisition time was 1 second slower in the verbal mode than in the visual mode when the location of the target was preceded by other information (e.g., “target – 3 o’clock”; Glumm et al., 2005). No differences were found between the visual and the verbal modes in target acquisition times when the verbal cue was restructured (e.g., “3 o’clock – 3 o’clock; Glumm et al., 2006).

6.2.5 Guideline 5.9

During covert dismounted conditions or conditions in which a visual display is not present and the gunner is not isolated from his environment (encapsulated in a vehicle), a tactile cue should be used to provide target cues.

6.2.5.1 Comment

In military settings, the advantage of advanced sensors that can warn Soldiers of a threat is lost if the enemy is also alerted (e.g., by a call-out of the position). It is important for the Soldier to be accurately and discreetly cued about the direction of threat. The signal should be covert and easily understood. Tactile cues are not handicapped by the cone of confusion (front-back reversals) experienced from 3-D auditory cues.
6.2.5.2 Example and Source

Chapter 4.1 of Gilson, Redden, and Elliott (2007) found significant and substantial improvements in perceiving the actual direction of the target using tactile cues to alert the presence of an unseen target. Target detection was approximately three times more accurate for tactile presentations versus 3-D auditory presentations (tactile mean was 11.53 degrees; auditory mean was 34.28 degrees). Moreover, front-back reversals observed in the 3-D auditory condition were not found in the tactile display condition.

Chapter 4.2 of Gilson, Redden, and Elliott (2007) found that spatial tactile display outperforms or equals spatial auditory localization, regardless of body position and orientation.

The multimodal meta-analysis project (Burke et al., in review) found that the addition of a tactile cue to a visual cue increased target acquisition effectiveness over the unimodal visual cue ($g = .68$, $p = .00$).

6.2.6 Guideline 5.10

During periods of high workload or sustained operations, when Soldiers are multitasking or overloaded, target location cues should be provided in pairs (multimodal cues).

6.2.6.1 Comment

The Burke et al. meta-analyses revealed significant effect sizes for multimodal cues over unimodal cues for target acquisition tasks (visual plus audio and visual plus tactile cues). From an operational perspective, it is important that an additional means (beyond a unimodal visual cue) of cueing target location be available when more demanding work is required.

6.2.6.2 Example and Source

When unimodal visual cues and visual plus auditory target cues were compared, a large significant effect size ($g = .61$, $p < .05$) was found for visual compared to visual plus auditory, and a large significant effect size was found for auditory compared to visual plus auditory ($g = .166$, $p < .05$) (Burke et al., in press).

The addition of a tactile cue to a visual cue enhanced performance in single and multiple task paradigms as well as in high and low workload situations but was particularly effective when participants had to execute multiple tasks or were in high workload situations. An overall significant effect size was found for target acquisition in the unimodal/multimodal comparison ($g = .75$, $p < .01$).
6.3 Land Navigation

6.3.1 Guideline 5.11

Tactile displays are recommended, in combination with visual GPS, for land navigation operations in general and particularly for night operations, combat operations requiring visual and/or audio stealth (e.g., no light emissions, no audio), and other high-workload mission situations.

6.3.1.1 Comment

Tactile land navigation displays show advantages because they allow hands-free and eyes-free operation during movement while providing directional feedback. The visual display provides additional information such as location references and distance to waypoints and can be accessed during halts.

6.3.1.2 Example and Source

Three experiment-based evaluations showed tactile displays to be effective for waypoint navigation and avoidance of prohibited areas and terrain obstacles. Tactile displays were found to be associated with more effective navigation, compared to compass and alphanumeric display systems and as effective as helmet-mounted map systems and hand-held visual “arrow” displays with regard to waypoint navigation. During night operations, the tactile system was associated with faster navigation times while Soldiers were searching for silhouette targets and with finding more targets overall, compared to the Land Warrior helmet-mounted map display and the precision lightweight GPS receiver (PLGR) alphanumeric display. Soldiers gave significantly higher ratings for the tactile system over both the hand-held Army GPS (alphanumeric display) system and the Army helmet-mounted map system for (a) watching for terrain obstacles, (b) allowing hands-free operation, (c) ease of staying on route, (d) being simple to learn, (e) being simple to use, (f) effectiveness for night operations, (g) effectiveness for urban operations, (h) effectiveness for wooded terrain, and (i) effectiveness in enemy territory (Elliott et al., in review; Elliott et al., 2006).

6.3.2 Guideline 5.12

Visual GPS-based displays, such as the helmet-mounted Land Warrior (LW) map system or hand-held GPS devices, should be used instead of paper maps for location assessment during land navigation operations. Soldiers should have this GPS-based capability at all times for location assessment. Soldiers particularly appreciated the LW capability to add/send icons or mark areas representing operational information such as enemy territory or prohibited areas, in relation to the icon that represented themselves on the map.

6.3.2.1 Comment

Tactile displays do not quickly or intuitively relate location information for the Soldier or for other target locations. Therefore, a digital display is needed to augment the tactile display for land navigation.
6.3.2.2 Example and Source

Experimental evaluation of a hand-held commercial GPS showed that location can be assessed within 10 seconds, compared to several minutes with a paper map system (Elliott et al., in review).

6.3.3 Guideline 5.13

Navigation information should be presented in a way that minimizes mental calculation.

6.3.3.1 Comment

At times, more complex and detailed information may be necessary for understanding in a larger context. Displays should present this information in a manner to be easily obtained and intuitively understood.

6.3.3.2 Example and Source

In a laboratory study, an icon representing the location for the driver to proceed was overlaid on the driver’s visual display, augmenting the indirect vision camera. Results demonstrated that this improved navigation performance and decreased mental workload with no adverse effect on SA (Davis, 2007).

In another experiment where Soldiers navigated with different devices, they performed less well with a compass, and this is probably attributable (as reported by the Soldiers) to the need to keep track of their pace count in order to calculate distance (Elliott et al., 2006).

6.4 Battle Damage Assessment (BDA)

6.4.1 Guideline 5.14

Displays should include a tool to quickly extract BDA.

6.4.1.1 Comment

The network could already have information about all enemy systems identified in the battle space. When a target is engaged, some sensor might be observing the target to assist the Soldier in targeting and BDA assessment. After this BDA is entered into the network, a tool should be available so that a user can “bound” an area on the map, enter the type of system(s) for which information is needed, and get a report about the number of these systems in various conditions (undamaged, mobility kill, firepower kill, catastrophic kill, etc.).

6.4.1.2 Example and Source

In an FCS experiment, the attack guidance matrix in the maneuver command and control (MC2) was rigid. When commanders did not receive requested fires, they tried to circumvent the system by requesting fires from the white cell. After a call for fire (network fires) was initiated in MC2, all visibility for that call was lost. There was no indication of whether it was approved, where it
was in the queue, what delivery system it went to, or if shot was actually made. Moreover, there was no systematic plan for BDA. If a sensor saw a target after it had been shot, it updated the status of the target. BDA is more a function of unit tactics, techniques, and procedures than an interface capability, since automatic BDA is probably unrealistic. However, tools to help track enemy BDA (assuming sensor coverage) were found to be critical. Players were reduced to using paper and pencil charts of enemy assets that were destroyed (Sterling & Burns, 2004b).

6.5 Communication

6.5.1 Guideline 5.15
Providing dismounted Soldiers with a covert tactile communication system is one way to improve communication and Soldier SA within small units.

6.5.1.1 Comment
Platoon and squad dismounted units use hand and arm signals to communicate simple commands during tactical situations when stealth and noise discipline are required. Using hand and arm signals as a means to communicate requires Soldiers to maintain visual contact with their leaders and often detracts from other tasks such as scanning or becomes impossible at night. Gaining a Soldier’s attention in order to give him a command such as “halt” or “freeze” in a timely manner, especially at night, could mean the difference between mission failure or mission success, depending on the circumstance.

6.5.1.2 Example and Source
A study was conducted to investigate the efficacy of translating infantry hand and arm signals into a vocabulary of tactile commands. The results of the study demonstrated that Soldiers performing IMT were able to receive, interpret, and accurately respond to tactile commands faster than with conventional hand and arm signals. This was found when the information was passed by a leader in the front or the back of a wedge formation. Soldiers also commented they were better able to focus attention on negotiating obstacles and on local SA when they were receiving tactile commands than when maintaining visual contact with their leaders in order to receive standard hand and arm signals (Pettitt, Redden, & Carstens, 2006).

In a study of subjects’ performance in identifying tactile patterns, excellent performance was achieved, with an average of 98% correct responses (Jones, Kunkel, & Torres, 2007).

6.5.2 Guideline 5.16
Information cues for secondary tasks should complement rather than compete with the information channel used for the primary task. For the primary task of shooting, which is visual, it is better to provide information for secondary tasks through another channel.
6.5.2.1 Comment
Soldiers hit more enemy targets when auditory displays were used for secondary tasks as compared to a visual HMD with an auditory alert cue.

6.5.2.2 Example and Source
Enemy hit percentage was lower with an HMD with an auditory alert cue (29.2%), as compared to an auditory presentation condition (43.1%)—a 13.9% difference (Scribner et al., 2005).

6.5.3 Guideline 5.17
Tactile patterns should be used which can be identified when one is performing tasks that require rigorous body movements.

6.5.3.1 Comment
Tactile displays may be an effective means of relaying information in the form of patterns. However, interpretation can be degraded when the Soldier is performing rigorous physical tasks.

6.5.3.2 Example and Source
A study was conducted to determine how performing combat assault maneuvers would affect the detection and recognition of tactile patterns presented via two types of tactile displays: a belt display and a back display. Six tactile navigation patterns were presented to participants as they moved through obstacles that simulated combat assault maneuvers. Participants wore a fighting load or fighting load and IBA. Detection and recognition of some of the tactile patterns were degraded on obstacles that required rigorous body movements (Krausman & White, 2006).

6.6 Decision Making During Uncertainty

6.6.1 Guideline 5.18
When possible, information should be displayed regarding the degree of reliability (e.g., accuracy, degree of certainty, probability of certainty; how old the information is, etc.) of any data that are displayed.

6.6.1.1 Comment
Soldiers and decision makers in general make better judgments if they “know what they don’t know”. The less reliable information is, the more important it becomes to communicate this fact to Soldiers in order for effective information assimilation and valid judgment execution to occur.

6.6.1.2 Example and Source
A recent experiment crossed three levels of information reliability and four types of iconic displays of reliability (no information, graphic, numeric and animated) to present information related to judging time to navigate (terrain, need for stealth, concealment, and visibility). The high reliability
condition used four information cues with high reliability (sampled from $r = 0.7$ to 1.0; $\text{Rsq} = 0.88$). The medium reliability condition used three information cues with high reliability and one cue that was sampled from $r = 0.3$ to 1.0; $\text{Rsq} = 0.77$). The low reliability condition used two information cues with high reliability and two that were sampled from $r = 0.3$ to 1.0; $\text{Rsq} = 0.62$). Results demonstrated that any type of information about reliability is better than no information at all. When the information is uncertain, the Soldier needs to know how uncertain it is (Mahan, Wang, Yanchu, Elliott, Redden, & Shattuch, 2006).

6.6.2 Guideline 5.19

When information reliability is changing (uncertain), graphic and/or animated visual icons should be used to represent degraded information, whenever possible.

6.6.2.1 Comment

Soldiers and decision makers, in general, can more rapidly assimilate graphic and animated information representations that intuitively communicate the value and the level of reliability in the information. Graphic and animated graphic visual representations of reliability produced faster and more accurate judgment outcomes as compared to standard numerical representations of information reliability.

6.6.2.2 Example and Source

In an experiment crossing levels of reliability information with types of iconic displays, the display format of reliability information did not impact performance when the reliability of the information was high. In contrast, iconic display format appeared to be important during performance in medium and low reliability conditions, wherein the graphic and animated iconic formats were associated with superior judgment achievement scores. Graphic icons representing four types of information (terrain, need for stealth, concealment, and visibility) were constructed in which shape indicated the type of information (square, circle, triangle, ellipse) and size indicated magnitude. The baseline condition did not provide any information regarding reliability. The numerical type of icon simply provided the reliability information as a number (e.g., 0.67). The graphic display provided a gray background surrounding and conforming to the dark icon shape, and the thickness of this background represented degree of reliability. The animated icon used pulsing to indicate reliability so that no pulse represented high reliability and fast pulse represented low reliability. The finding that the graphic and animated representations were more effective when information was less reliable was presumably because these formats successfully mapped reliability properties of the task through a spatial representation that participants were able to easily understand and use. The reduced response time for the graphic iconic display conditions suggests that participants used a more intuitively anchored organizing principle during judgment task performance, as opposed to a more deliberative and labor-intensive analytical process when judgments were made on the basis of high-reliability information. Furthermore, when the information became very unreliable, the animated iconic display format appeared to generate the greatest accuracy (Mahan et al., 2006).
7. Designing for Individual Differences

7.1 Guideline 6.1
If possible, displays should be designed so that individuals can tailor them.

7.1.1 Comment
Individuals work better with displays that are tailored to their individual differences.

7.1.2 Example and Source
In a recent study in which the utility of adding tactile and 3-D auditory systems to a visual display to reduce the time for assimilation of information during high-workload target acquisition and robot navigation tasks was addressed, a significant interaction was found with individuals, indicating that display effects can be different, depending on individual differences (Savick et al., in press).

7.2 Guideline 6.2
The type of information processing (e.g., mental arithmetic) that a Soldier is required to perform while moving over hazardous terrain must not be challenging to his/her skill level.

7.2.1 Comment
The amount of resources allocated to a task will vary, based on past experience and other individual differences and may be influenced by the difficulty of the task, the criteria for performance, and the motivation of the individual (Yeh & Wickens, 1988). The less skilled an individual is in performing a task, the more difficult the task is and the higher the level of workload imposed. During experimental conditions, if a task becomes too difficult, an individual may allocate more resources to the task that s/he has a better chance of performing successfully.

7.2.2 Example and Source
In this study, when Soldiers were required to solve the more difficult arithmetic problems at the “high” level of mental load, some of those who were less skilled at mental arithmetic may have chosen to reallocate more of their attention to the task of avoiding hazards. Therefore, at the “high” level of mental load, the number of errors in solving the arithmetic problems increased but not the number of hazards contacted (Glumm, 2005):

- Perceived workload increased with each increase in mental workload.
• The number of hazards contacted did not increase significantly with increases in mental workload.

• Performance of the mental arithmetic task (i.e., correct responses) declined during hazard avoidance.

• The more correct responses to the arithmetic problems at the “moderate” level of workload, the lower the ratings of effort and overall workload scores, and the fewer hazards contacted.

• Lower ratings of workload and times and errors in performing the mental arithmetic task were related to higher scores on the Armed Forces Qualification Test (AFQT) and subtests of the Armed Services Vocational Aptitude Battery (ASVAB) related to arithmetic skills.

• Increases in times and errors in solving the more difficult problems at the “high” level of workload were related to lower scores on the Arithmetic Reasoning subtest of the ASVAB in both the “hazards” and “no hazards” terrain conditions.

7.3 Guideline 6.3
Displays should be tailored to meet the mission and the critical tasks of the individual Soldier as well as his/her capabilities and limitations. Displays that adapt to differences and changes in the cognitive state of the Soldier should be explored.

7.3.1 Comment
Differences among individuals in arithmetic skills and arousal levels may have influenced changes in attentional capacity at the three levels of mental load and changes in the allocation of resources between the mental arithmetic and the hazard avoidance task. If the arousal level is too low (underload) or too high (overload), attentional capacity can be reduced (Kahneman, 1973; Yerkes & Dodson, 1908). Drifts in attention in states of underload or inappropriate allocation of resources in states of overload can be equally dangerous.

7.3.2 Example and Source
Subjects who scored higher on the AFQT and on subtests related to arithmetic skills contacted more hazards when they did not perform the mental arithmetic task at the “no load” level of mental load. Also, the higher the test scores, the higher the ratings of frustration at the “no load” and “moderate” levels of mental load in the “no hazards” terrain condition (Glumm, 2005).
8. **Designing for Personnel Skills**

8.1 **Guideline 7.1**

The Soldier-machine interface in future manned ground systems should be designed to facilitate communication (e.g., voice recognition); vision (e.g., good resolution), conceptual skills (e.g., decision aids to help predict future enemy actions) and speed-loaded skills (e.g., decision aids to enable quick pattern identification). Re-supply vehicle (RSV) commanders and drivers of FCS vehicles need to develop these specific mental skills to maintain SA.

8.1.1 **Comment**

The skill clusters perceived to be needed to maintain SA include “communication,” “conceptual,” “vision,” and “speed-loaded” skills on Fleishman’s skills taxonomy (Fleishman & Quaintance, 1984).

8.1.2 **Example and Source**

Specific skills under “communication” include the ability to give and receive instructions (oral communication). Specific mental skills perceived to be needed under “conceptual” include the ability to detect a known pattern (flexibility of closure); the ability to predict how a pattern will appear after changes are made (visualization); the ability to tell when something is likely to go wrong (problem sensitivity); the ability to know where you are in relation to another object (spatial orientation); the ability to concentrate on a task and ignore distracting stimuli (selective attention); and the ability to retain information (memorization). Specific skills under “vision” were ability to see near, far, and at night and to discriminate colors. Specific mental skills perceived to be needed under “speed loaded” were combining pieces of information into a pattern quickly (speed of closure); comparing patterns quickly (perceptual speed and accuracy); and shifting quickly between different sources of information (time sharing) (Sterling & Burns 2003; Sterling & Burns 2004a).

8.2 **Guideline 7.2**

An interface feature should be included in displays for echelons above squad, which provides the ability to quickly produce and disseminate orders.

8.2.1 **Comment**

Collaborative planning, a critical aspect of SA and FCS doctrine, means that operations orders with maps and graphics must be made rapidly available to leaders and all levels.
8.2.2 Example and Source
During FCS experimentation, it was found that tools were needed to quickly develop and share orders. These types of tools include a variety of items such as an easy-to-navigate template of graphic control measures, drawing tools, terrain analysis tools, the ability to easily edit and save overlays, and an easy-to-use collaborative planning tool (Sterling & Burns 2004b).

9. Summary
A recapitulation of the display design guidelines that appear in this document follows.

9.1 Display Design General
- **Guideline 1.1**: Visual displays should be used rather than auditory displays if the visual information can be processed with a single glance.
- **Guideline 1.2**: Multimodal display of task information has distinct advantages over unimodal display of task information across task types.
- **Guideline 1.3**: An effective visual-tactile multimodal display offers more benefits across task levels, types, and workload conditions than does an effective visual-auditory display.
- **Guideline 1.4**: The addition of a tactile display to a visual display can decrease response times.
- **Guideline 1.5**: The addition of a tactile display to a visual display can result in lower perceived workload.
- **Guideline 1.6**: Non-occluding visual displays for wearable information systems for infantry Soldiers should be used when possible.

9.2 Visual Display Design
- **Guideline 2.1**: Trade-offs between knowledge of the enemy or surrounding area, level of information fusion, and degradations in mission task times should be understood before visual displays are provided to warfighters.
- **Guideline 2.2**: Use military terminology for menu options and instructions.
- **Guideline 2.3**: A 16-point True Type font is the minimum symbol size that can be discriminated and identified on a 3.5-inch simulated wrist map display.
- **Guideline 2.4**: For an urban map display, six symbols (icons) or fewer should be used when a symbol size of 16 points is used. For a rural map, 12 symbols or fewer should be used.
• **Guideline 2.5**: When the color of a critical indicator icon is being selected, a color with the same luminance and shade as objects that the observer is searching for in the scene should be chosen, if possible. However, the color should not contradict current doctrine.

### 9.3 Auditory Display Design

• **Guideline 3.1**: Bone conduction communication can be used as the communication interface for mounted Soldiers. However, it is extremely important that there is a proper fit of the communication system to the listener’s head for successful communication to be achieved.

### 9.4 Tactile Display Design

• **Guideline 4.1**: Vibrotactile stimulation rather than other tactile signal types such as embossed letters, pressure, electricity charges, chemicals, and thermal stimulation appears to be the most effective tactile signal type and to be compatible with Soldiers’ clothing and missions.

• **Guideline 4.2**: Maximum tactile signal strength should be strong enough to be felt in vibration environments and during rigorous physical events.

• **Guideline 4.3**: The user should have the capability to adjust the level of intensity of a tactile display.

• **Guideline 4.4**: A plunger tactor actuated within a stationary housing that constrains the vibratory wave propagation and localizes the perceptual signature (i.e., C-2 tactor) appears to work better for precise signaling than an inertial shaker motor.

• **Guideline 4.5**: A plunger tactor allows greater intensity and appears to perform better than inertial shaker motors in demanding environments.

• **Guideline 4.6**: Stimulating various loci in different combinations can create a large number of possible patterns for cutaneous communication. However, constraints limit the usable patterns.

• **Guideline 4.7**: The waist appears to be an effective location to place a tactor display.

• **Guideline 4.8**: Use a ring of eight tactors on a belt for an accurate and informative tactor display.

• **Guideline 4.9**: Use a torso belt in order to communicate direction information.
9.5 Designing for Task Type

- **Guideline 5.1**: Periodic alerts and warnings may be useful for reminding Soldiers of potential ground hazards and to encourage a more appropriate distribution of attentional resources.

- **Guideline 5.2**: Add tactile or auditory alert cues regarding incoming information on a visual display to increase performance, especially when under high, multi-tasking workload.

- **Guideline 5.3**: When Soldiers are performing concurrent tasks, multimodal alert cues (preferably visual/tactile) should be used to get the user’s attention.

- **Guideline 5.4**: When alerts are used, adding levels of urgency can inform the user of the criticality of information that s/he is receiving or the task s/he needs to perform.

- **Guideline 5.5**: Cues about target location should be provided when feasible.

- **Guideline 5.6**: When the gunner is isolated from the environment (e.g., closed hatch position) and s/he is looking at only one display with low to moderate workload, visual or verbal cues about target location that are intuitively consistent with the operator display allow Soldiers to localize targets more accurately and acquire targets faster than with current 3-D audio or tactile cueing techniques.

- **Guideline 5.7**: Integrating intuitive visual target cues into the sight picture can result in faster acquisition times (e.g., a clock display that corresponds with display controls) during low to moderate visual workload conditions.

- **Guideline 5.8**: If a verbal cue is provided, it should be structured to minimize the delay in the transmission of target location information.

- **Guideline 5.9**: During covert dismounted conditions or conditions in which a visual display is not present and the gunner is not isolated from his environment (encapsulated in a vehicle), a tactile cue should be used to provide target cues.

- **Guideline 5.10**: During periods of high workload or sustained operations, when Soldiers are multitasking or overloaded, target location cues should be provided in pairs (multimodal cues).

- **Guideline 5.11**: Tactile displays are recommended, in combination with visual GPS, for land navigation operations in general and particularly for night operations, combat operations requiring visual and/or audio stealth (e.g., no light emissions, no audio), and other high-workload mission situations.

- **Guideline 5.12**: Visual GPS-based displays, such as the helmet-mounted LW map system, or hand-held GPS devices, should be used instead of paper maps for location assessment during land navigation operations. Soldiers should have this GPS-based capability at all
times for location assessment. Soldiers particularly appreciated the LW capability to add/send icons or mark areas representing operational information such as enemy territory or prohibited areas, in relation to the icon that represented themselves on the map.

- **Guideline 5.13**: Navigation information should be presented in a way that minimizes mental calculation.

- **Guideline 5.14**: Displays should include a tool to quickly extract BDA.

- **Guideline 5.15**: Providing dismounted Soldiers with a covert tactile communication system is one way to improve communication and Soldier SA within small units.

- **Guideline 5.16**: Information cues for secondary tasks should complement rather than compete with the information channel used for the primary task. For the primary task of shooting, which is visual, it is better to provide information for secondary tasks through another channel.

- **Guideline 5.17**: Tactile patterns should be used which can be identified when one is performing tasks that require rigorous body movements.

- **Guideline 5.18**: When possible, information should be displayed regarding the degree of reliability (e.g., accuracy, degree of certainty, probability of certainty; how old the information is, etc.) of any data that are displayed.

- **Guideline 5.19**: When information reliability is changing (uncertain), graphic and/or animated visual icons should be used to represent degraded information, whenever possible.

### 9.6 Designing for Individual Differences

- **Guideline 6.1**: If possible, displays should be designed so that individuals can tailor them.

- **Guideline 6.2**: The type of information processing (e.g., mental arithmetic) that a Soldier is required to perform while moving over hazardous terrain must not be challenging to his/her skill level.

- **Guideline 6.3**: Displays should be tailored to meet the mission and the critical tasks of the individual Soldier as well as his/her capabilities and limitations. Displays that adapt to differences and changes in the cognitive state of the Soldier should be explored.

- **Guideline 6.4**: RSV commanders and drivers of FCS vehicles need to develop high levels of mental skills to maintain SA.

### 9.7 Designing for Personnel Skills

- **Guideline 7.1**: The Soldier-machine interface in future manned ground systems should be designed to facilitate communication (e.g., voice recognition); vision (e.g., good resolution),
conceptual skills (e.g., decision aids to help predict future enemy actions) and speed-loaded skills (e.g., decision aids to enable quick pattern identification). Re-supply vehicle (RSV) commanders and drivers of FCS vehicles need to develop these specific mental skills to maintain SA.

- **Guideline 7.2**: An interface feature should be included in displays for echelons above squad, which provides the ability to quickly produce and disseminate orders.

### 10. Conclusions

This document was written primarily for designers of the information displays for FFW and the FCS. It provides guidelines pertaining to the design of information displays to increase the efficiencies of warfighters operating in echelons of platoon and below by avoiding information overload and incompatibilities between the display design and warfighter primary tasks.

These guidelines are based on a series of ATO-sponsored experiments that were systematically identified through task/workload analyses and theory-based principles of attention resource management (Wickens, 2002), to result in improved performance and ease of use. The guidelines are not rigid; instead, the researchers tried to identify and distill insights gained through consideration of each and all studies. We hope these guidelines offer a roadmap to follow that avoids the stumbling blocks that others have encountered. We provide the context and justification for each principle so that designers can more fully consider which guidelines are applicable in the specific circumstances encountered.

The guiding principles that are presented in appendix A were developed from a review of available literature on experiments that were performed outside the ATO. They provide detailed information covering a broader range of topics than those covered in the SU ATO and have been included for further elucidation. The USF research team designed an index of variables (e.g., describing study purpose, study type, study measures, etc.) for the guiding principles report in order to create a searchable database and identify published experiments to be included in meta-analyses that are discussed in the body of this report.

No set of guidelines is complete, especially guidelines that address the fast-paced technology of information systems. They should be used in conjunction with knowledge of the ever-changing research in this field and should be revised periodically. These guidelines are suggestions and do not have the authority of requirements nor are they as complete as a handbook. They are primarily focused on the use of alternate modalities to present information to the Soldier in an attempt to offload work and thus do not attempt to cover all aspects of information design. Thus, the reader should use them in conjunction with MIL-STD-1472 and MIL-HDBK-759.
11. References


Yerkes; Dodson. The Relation of Strength of Stimulus to Rapidity of Habit Formation. Journal of Comparative Neurology and Psychology 1908, 18, 459-482.
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Appendix A. Guiding Principles Developed for a Multimodal Project

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ARL (HRED)
Elizabeth S. Redden
Linda R. Elliott
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1. Individual Differences

Different types of representations work better for different people, with differences occurring across left and right lateralization users and by information display preferences (e.g., a user may prefer to receive information visually or aurally) (Chewar & McCrickard, 2002).

Also in: 5.5.5

GP#:1123

This table provides guidelines for system design after prioritizing usage goals of navigation. It summarizes the findings/conclusions relevant to making a device best for certain kind of users (it addresses some individual differences). (Chewar & McCrickard, 2002)

<table>
<thead>
<tr>
<th>Usage Goal</th>
<th>User Characteristic</th>
<th>Best Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal Navigation Time</td>
<td>General Population</td>
<td>1. audio, 2. graphic</td>
</tr>
<tr>
<td>Left Dominance</td>
<td>+ text list</td>
<td></td>
</tr>
<tr>
<td>Right Dominance</td>
<td>+ text</td>
<td></td>
</tr>
<tr>
<td>Visual Preference</td>
<td>- audio</td>
<td></td>
</tr>
<tr>
<td>Auditory Preference</td>
<td>- graphic</td>
<td></td>
</tr>
<tr>
<td>Minimal Navigation Errors</td>
<td>General Population</td>
<td>1. graphic, 2. audio, 3. text list</td>
</tr>
<tr>
<td>Left Dominance</td>
<td>(2. text list, 3. audio)</td>
<td></td>
</tr>
<tr>
<td>Right Dominance</td>
<td>- text list, + text</td>
<td></td>
</tr>
<tr>
<td>Visual Preference</td>
<td>- audio, - text list</td>
<td></td>
</tr>
<tr>
<td>Auditory Preference</td>
<td>(No change)</td>
<td></td>
</tr>
<tr>
<td>Minimal Distraction to Focal View</td>
<td>General Population</td>
<td>1. text list, 2. audio</td>
</tr>
<tr>
<td>Left Dominance</td>
<td>- audio, - text list</td>
<td></td>
</tr>
<tr>
<td>Right Dominance</td>
<td>- audio, - text list</td>
<td></td>
</tr>
<tr>
<td>Visual Preference</td>
<td>- audio, - text list</td>
<td></td>
</tr>
<tr>
<td>Auditory Preference</td>
<td>(No change)</td>
<td></td>
</tr>
</tbody>
</table>

Recommendations ordered and based on significant differences with population mean. “Best Choice” indicators enabled better performance under metrics corresponding to usage goals, p<0.05. For user characteristic groups (left or right brain hemisphere dominance and visual or auditory information preference), Best Choice notations reflect change (“+” = addition, “−” = subtraction) to the general population findings.

Also in: 3.2.5

GP#:1261

When designing user interfaces, determine what user characteristics produce the biggest differences in performance and then design the user interface to maximize the benefits for all groups (Gwizdka & Chignell, 2004).

Also in: 4.9, 5

1.1 Age

1.1.1 Visual

A multimodal condition (visual and audio) especially improved performance on a secondary task for older participants. Potential explanations for these findings include the following: visual abilities decrease with age (so users need audio to compensate for visual loss), older participants may experience higher workload while driving; or older users may be less equipped to deal with the same level of workload (older participants reported more stress in general when driving). (Liu, 2001)

Also in: 1.1.4AV, 6.6.1, 6.7

GP#:1256

Visual search (looking for information at unexpected locations) is particularly sensitive to age decrements (Plude & Hoyer, 1985; as cited in Ponds, Brouwer, & van Wolffelaar, 1988)

Also in: 3.6.1
Middle-aged workers may incur a heavier visual load resulting from VDT (visual display terminal) use than that experienced by younger workers (Inoue, 2002).

Also in: 6.6.1

Middle-ages persons gradually lose their ability to focus at all distances, making the use of multifocal lenses critical. A decrease in visual-focus ability starts in the 20’s, and by the 40’s the ability has decreased by half. (Inoue, 2002)

Also in: 2.6.1

Older drivers tend to be less accurate and slower to respond than are younger adults. Older drivers also execute more eye movements to acquire signs. (Ho, Scialfa, Caird, & Graw, 2001)

Also in: 3.3.1

Older subjects (35+) were slower at completing a learning task based on computer/web design (note: cohort effect could have accounted for results) (Bradshaw & Johari, 2003).

Symbol comprehension may decrease with age (Hancock, Rogers, & Fisk, 2001).

Text/symbols that are too small may present a problem for older adults (Hancock, Rogers, & Fisk, 2001).

Also in: 4.1.2

A large amount of text presented in a dense or complex format will tax working memory, and complex symbols that are small, or that are accompanied by explanatory text that is too small to read, will be difficult for older adults and others with visual impairments to interpret (Hancock, Rogers, & Fisk, 2001).

Also in: 4.1.2, 4.1.4, 6.6.1

1.1.2 Audio

There are differences in pattern identification performance between older and younger subjects that appear to be directly related to poorer spatial resolution in the older group. Hearing acuity decreases rapidly after the age of 60. Also, as people age, thresholds increase, leading to poorer discriminative capabilities. The underlying cause of loss is usually attributed to either physiological changes in the skin or neurological factors. In aging skin, size, shape, and number of cells in the upper layers become variable and glands atrophy or become inactive. Alterations in mechanical properties of the skin, such as compliance, are not related to reduction in tactile sensitivity. (Cholewiak, Collins & Brill, 2001)

Also in: 1.1.3, 2.2.2, 2.2.3

1.1.3 Tactile

Sensitivity to tactile cues decreases with age (Cholewiak, Collins & Brill, 2001).

Also in: 2.2.3

There are differences in pattern identification performance between older and younger subjects that appear to be directly related to poorer spatial resolution in the older group. Hearing acuity decreases rapidly after the age of 60. Also, as people age, thresholds increase, leading to poorer discriminative capabilities. The
The underlying cause of loss is usually attributed to either physiological changes in the skin or neurological factors. In aging skin, size, shape, and number of cells in the upper layers become variable and glands atrophy or become inactive. Alterations in mechanical properties of the skin, such as compliance, are not related to reduction in tactile sensitivity. (Cholewiak, Collins & Brill, 2001)

**Also in:** 1.1.2, 2.2.2, 2.2.3

GP#:1173

As age increases, individuals have less sensitivity to tactile stimulation (Cholewiak, Collins, & Brill, 2001).

**Also in:** 2.2.3

1.1.4 Multimodal (AV, AT, TV, ATV)

Age is a factor to consider in multi-sensory conditions (Shumway-Cook & Woollacott, 2000).

- AV

A multimodal condition (visual and audio) especially improved performance on a secondary task for older participants. Potential explanations for these findings include the following: visual abilities decrease with age (so users need audio to compensate for visual loss), older participants may experience higher workload while driving; or older users may be less equipped to deal with the same level of workload (older participants reported more stress in general when driving). (Liu, 2001)

**Also in:** 1.1.1, 6.6.1, 6.7

- AT
- TV
- ATV

1.1.5 Not Specific to a Mode

Procedural knowledge can slow with age—does slowed procedural knowledge mimic what happens when inexperienced or novel users are working? (no cite necessary, just a thought)

**Also in:** 1.2.5

GP#:1136

Many transfer studies that consider age-related effects on performance only examine initial performance after a transfer in performance conditions. However, in multiple-task studies involving changes in performance conditions, it is important to examine practiced transfer performance because it allows for the stabilization of modified performance emphases. (Sit & Fisk, 1999)

**Also in:** 5.1.5

GP#:1137

It is important to provide product-specific, multiple-task practice before interpreting patterns of age-related differences (Sit & Fisk, 1999).

**Also in:** 5.1.5

GP#:1138

When performing usability tests on products that require task coordination, it is important to examine age-related performance after users have had sufficient experience to stabilize performance. (This principle could be applied to anyone (young or old) who is working a new task.) (Sit & Fisk, 1999)

**Also in:** 7.2.5

GP#:1255
Older participants (age 60 and older) have difficulty in dividing attention; this is due to actual difficulties in dual tasking, not just the additive effects of lower performance in each individual task (Ponds, Brouwer, & van Wolffelaar, 1988)

Also in: 6.3.5, 6.7

GP#:1315

Results show that balancing may be more attentionally demanding for older adults than young adults (Swan et al., 2004).

Also in: 6.3.5

GP#:1430

Contrary to previous research, Somberg & Salthouse (1982) suggest that there are no age-related differences in divided attention (i.e., dual tasking). Instead, other processes (e.g., memory, perceptual impairments) are responsible for the poorer performance of older individuals on individual tasks. Performance on individual tasks is worse to begin with, subsequently causing decrements in dual task contexts.

Also in: 6.3.5, 6.7

GP#:1508

Although most researchers tend to assume that our “resource size” is fixed, there is some support that it may change with long-term fluctuations in mood or age (Hasher & Zacks, 1979; Humphreys & Revelle, 1992); also, this study provides support that it can also change in the short-term in response to task demands (e.g., resources “shrink” to accommodate demand reduction). (Young & Stanton, 2002)

Also in: 2.6, 6.6.5

GP#:1698

Spatial and temporal acuity degrades with aging (Van Erp, 2002).

GP#:1724

Under conditions that control for age differences in single-task performance, age-related deficits in dividing attention are minimal unless the task possesses substantial memory demands, (Salthouse, Rogan & Prill, 1984; Somberg & Salthouse, 1982)

Also in: 6.3.5, 6.6.5, 6.7

1.2 Experience/Automaticity

After experience in tool-use, visual stimuli in the opposite hemifield to the stimulated hand could produce stronger crossmodal interactions than visual stimuli in the same anatomical hemifield, when the tools are crossed (Maravita, Spence, Kennett & Driver, 2002).

Also in: 3.7.1, 6.2.1

1.2.1 Visual

78% of pilots said it was easier to find the aircraft navigation pathway using goalpost vs. paving-stone display. Effects of type of symbology used could be nullified through practice. Some pilots had trouble interpreting a 2-D display to represent 3-D space. Situational Awareness outside of cockpit decreased from 44% to 14% from baseline to Highway in the Sky (HITS) condition. Pilots flying conventional instruments were significantly better at estimating heading and altitude than pilots using HITS display. 2 additions to the HITS display that might prove effective are the inclusion of air traffic on the display and inclusion of the synthetic terrain indicator. (Williams, 2002)

Also in: 3.2.1, 3.5.1, 3.8.1, 6.4.1

GP#:1503
Females performed slower than males on a learning task based on computer/web design, but only in a modified screenshot only-condition (versus the screenshot-text condition); this may reflect lower spatial ability or less experience with computers/posting to a webpage (Bradshaw & Johari, 2003).

**Also in:** 1.3.1, 1.4.1, 4.1.4

Expertise is another factor that may affect how attention is deployed and how objects in a scene are represented (Varakin, Levin, and Fidler, 2004).

**Also in:** 6.3.1

Wickens, Goh, Helleberg, Horrey & Talleur (2003) provide a model which can be used to diagnose non-optimal patterns and to compare scanning strategies of amateurs. This model also offers potential to assess when design features may, by increasing the effort of information access, lead to serious departures from optimal scan patterns.

**Also in:** 3.6.1, 5.1.1

1.2.2 Audio

Experience/automaticity of a task interacts with what mode of feedback is most helpful (audio, visual, haptic, bimodal, unimodal, or trimodal) on a computer drag and drop task. Trimodal was best for most experienced users. Auditory was best for all users. (Jacko et al, 2004)

**Also in:** 1.2.4 ATV, 3.7.2, 3.7.4 ATV, 6.1.2, 6.1.4 ATV

Listeners with more experience using an auditory display source can use that experience to aid comprehension (Rudmann, McCarley & Kramer, 2003).

**Also in:** 1.2.4 AV

No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing (Tannen, 2000).

**Also in:** 2.7.1, 2.7.2, 3.6.1, 3.8.4 AV, 4.1, 4.2

1.2.3 Tactile

Experience with a given mode may affect how useful it is for a task. Since people are generally less familiar/accustomed to getting information via tactile channels, it may be less useful than visual/audio (Akamatsu, Mackenzie & Hasbroucq, 1995; Poupyrev & Maruyama, 2003).

**Also in:** 1.2.4 AV

1.2.4 Multimodal (AV, AT, TV, ATV)

Whether multiple modes enhance performance may depend on the experience level of the user, such that less experienced users show fewer benefits to multimodal conditions (Emery, Edwards, Jacko, et al., 2003).

**Also in:** 1.2.5, 5.5.4, 5.5.5

Expert users prefer to interact with multimodal interfaces, whereas naïve users have no preference between unimodal or multimodal displays (De Angeli, Gerbino, Cassano, & Petrelli, 1998).

**Also in:** 1.2.5, 5.5.4, 5.5.5

GP#1186

GP#1206
A lane assist system (composed of tactile and visual cues meant to help drivers stay within a lateral distance and prevent collisions) may be useful for helping drivers stay within a limited lateral distance, but it also increased stress (possibly because of unfamiliarity with device). (Ward, Shankwitz, Gorgestani, Donath, Boer, & DeWaard, 2003; as cited in Alexander et al 2004)

Also in: 3.3.4 TV, 5

GP#:1234

Users with more expertise tend to choose complementary modes, while beginners tend to choose more redundant modes/devices (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Also in: 1.2.5, 4.8.3, 5.5.4, 5.5.5

GP#:1285

Expertise may moderate a person’s ability to process information efficiently, perhaps affecting ability to process information from multiple modes (Bellenkes, Wickens & Kramer, 1997).

Also in: 6

- AV

Also in: 1.2.3

GP#:1003

Experience with a given mode may affect how useful it is for a task. Since people are generally less familiar/accustomed to getting information via tactile channels, it may be less useful than visual/audio (Akamatsu, Mackenzie & Hasbroucq, 1995; Poupyrev & Maruyama, 2003).

Also in: 1.2.2, 3.7.2, 3.7.4 ATV, 6.1.2, 6.1.4 ATV

GP#:1002

Experience/automaticity of a task interacts with what mode of feedback is most helpful (audio, visual, haptic, bimodal, unimodal, or trimodal) on a computer drag and drop task. Trimodal was best for most experienced users. Auditory was best for all users. (Jacko et al, 2004)

Also in: 1.2.2, 3.7.2, 3.7.4 ATV, 6.1.2, 6.1.4 ATV

1.2.5 Not Specific to a Mode

GP#:1011

Procedural knowledge can slow with age—does slowed procedural knowledge mimic what happens when inexperienced or novel users are working? (no cite necessary, just a thought)

Also in: 1.1.5

GP#:1026

Determining whether a given mode is better than another mode, or whether multimodal is better than unimodal feedback very much depends on the criterion of interest. For example, user preference and perceived ease of use do not always coincide with performance data. User preference may be more a function of what is typically used (users prefer the familiar) and biases in expectations (expectation that multiple modes must be better than a single mode) (Akamatsu, MacKenzie, & Hasbroucq, 1995; Jeong & Gluck, 2003; Kaster, Pfeiffer, & Bauckhage, 2003).

Also in: 5.5.5, 7.3

GP#:1152

In a comparison of the behaviors/performance of novice and expert automobile drivers, novices had more lateral lane deviations and struggled in their performance of secondary tasks (e.g., putting in a cassette). Additionally, they glanced at the car’s instrument panel more often than the experts. These findings have
implications for automaticity: once users have sufficient driving experience, they are more able to successfully dual task while driving. (Landsdown, 2002)

Also in: 6.1.5

GP#:1186

Expert users prefer to interact with multimodal interfaces, whereas naïve users have no preference between unimodal or multimodal displays (De Angeli, Gerbino, Cassano, & Petrelli, 1998).

Also in: 1.2.4, 5.5.4, 5.5.5

GP#:1191

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

Also in: 3.1.1, 3.1.2, 3.1.4, 3.1.5, 3.5.5, 5.4.5, 6.4.5

GP#:1234

Users with more expertise tend to choose complementary modes, while beginners tend to choose more redundant modes/devices (Althoff, McIaun, Schuller, Morguet & Lang, 2001).

Also in: 1.2.4, 4.8.3, 5.5.4, 5.5.5

GP#:1284

Expertise may allow a person to become proficient at the most difficult tasks that one must face, presumably due to automaticity (Bellenkes, Wickens & Kramer, 1997).

Also in: 6.1.5

GP#:1384

Data from studies on target context support the use of allocentric coding of information because it improves performance. Performance also increased when the context is familiar. Target context led to a better awareness of perturbation. (Ferrel, Orliguet, Leifflen, Bard & Fleury, 2001)

Also in: 3.6.5, 5.4.5

GP#:1387

Ideas generated by persons outside of a particular job may not be as useful as those generated by the actual operator (Mackay, Fayard, Frobert & Medini, 1998).

Also in: 7.1.5

GP#:1434

Investigators should account for gender differences and user interface proficiency before using measurements acquired in a virtual environment to draw conclusions about people’s knowledge of a real-world place (Waller, Knapp & Hunt, 2001).

Also in: 1.3.5, 8.5

GP#:1436

Those interested in training complex cognitive skills should control for differences in user’s cognitive abilities and computer experience (Waller, Knapp & Hunt, 2001).

Also in: 1.4.5, 5.1.5

GP#:1643

Found no individual differences in the number of trials from a point of mastery to an automaticity criterion or from initial learning to the mastery criterion of a novel task (Sax, 1996).
1.3 Gender Differences

1.3.1 Visual

Females performed slower than males on a learning task based on computer/web design, but only in a modified screenshot only-condition (versus the screenshot-text condition); this may reflect lower spatial ability or less experience with computers/posting to a webpage (Bradshaw & Johari, 2003).

Also in: 1.2.1, 1.4.1, 4.1.4

1.3.2 Audio

1.3.3 Tactile

The ventral thorax is a relatively traffic free area of somewhat uniform sensitivity, at least in males (Geldard, 1960).

Also in: 2.1.3, 4.3

1.3.4 Multimodal (AV, AT, TV, ATV)

- AV
- AT
- TV
- ATV

1.3.5 Not Specific to a Mode

Investigators should account for gender differences and user interface proficiency before using measurements acquired in a virtual environment to draw conclusions about people’s knowledge of a real-world place (Waller, Knapp & Hunt, 2001).

Also in: 1.2.5, 8.5

1.4 Abilities (e.g., Spatial Ability)

1.4.1 Visual

Individuals with low spatial ability had significantly lower performance when searching for information in a desktop virtual reality environment (Modjeska & Chignell, 2003; as cited in Gwizdka & Chignell, 2004).

Also in: 8.1

1.4.2 Audio

As number of simultaneous audio displays (e.g., simultaneous talkers) increases, interpretation performance decreases and response time increases (probably due to increase in uncertainty). Increasing the number of talkers is more detrimental for asymmetric configurations of audio than for symmetric configurations. This particular study found no correlation between handedness and dependent variables. (Bolia, Nelson & Morley, 2001)

Also in: 2.1.2, 4.2.3, 4.2.4
1.4.3 Tactile

1.4.4 Multimodal (AV, AT, TV, ATV)

- AV
- AT
- TV

The maximum visual-haptic cue asynchrony or delay that participants tolerate was 45 ms (on average). The range in which stimuli were judged to be synchronous was centered around a visual delay of about 7 ms. This point of subjective simultaneity (PSS) was liable to individual differences. (Vogels, 2004)

Also in: 2.2.1, 2.2.4 TV, 2.7.4 TV, 4.5.2

- ATV

1.4.5 Not Specific to a Mode

Presentation formats should be tailored to a particular user’s abilities and to the task being performed (Maybury, 1995).

Also in: 2.2.1, 2.2.4 TV, 2.7.4 TV, 4.5.2

The best user functions are often the most invisible. For example, highly skilled controllers valued simplicity over functionality. (Mackay, Fayard, Frobert & Medini, 1998)

Also in: 4.9, 7.1.5

It is critical to first measure a baseline performance level across all participants, in order to more accurately determine the effect that a secondary task has on primary performance. If one is to determine the degree of effect upon performance that a stressor may exert, be it task- or environmentally-determined, individual differences in performance must be considered. (Chase et al, 2004)

Also in: 6.7, 7.2.5

It is important to control for single-task performance when measuring between-group differences in divided attention ability (e.g., differences in dual task ability) (Somberg & Salthouse, 1982).

Also in: 6.3.5, 6.7

Individual differences have the potential to impact performance in a simulation task more than the appearance of the training system (Waller, Knapp & Hunt, 2001).

Also in: 5.1.5

Those interested in training complex cognitive skills should control for differences in user’s cognitive abilities and computer experience (Waller, Knapp & Hunt, 2001).

Also in: 1.2.5, 5.1.5

Future mobile and educational interfaces should be designed with the goal of supporting the poorer attention span, impulse control, and higher error rates of users with an impulsive profile, especially in the case of mobil, in vehicle, military, and other applications that bear an unacceptably high cost for committing errors (Oviatt, Lunsford, and Coulston, 2005).

Also in: 3.2.5, 3.3.5, 4.9, 6.3.5
Individuals use cognitive styles that are applied consistently across similar tasks. Analytic participants acquire more effective skills during training than holistic participants and are not affected by the difficulty for training when transferring to novel stimuli. Holistic participants are affected by the difficulty of training, and initially perform more accurately in transfer to novel stimuli, if trained using hard comparisons. Easily trained holistic participants are more flexible in their strategies longitudinally than analytic participants are. Holistic participant’s strategies are malleable even after training. This leads to design implications not only for training strategies, but also for computer interface design. (Pratt, 2003)

Also in: 5.1.5, 6

Optimal attention control is an important feature that distinguishes better and more practiced dual task performers from those who are less skilled (Damos, 1991; as cited in Wickens, 2000).

Also in: 6.3.5, 6.7
2. Perception of Cues

2.1 Location

2.1.1 Visual

Positioning a color indicator in close proximity to a continuous analog display should be an efficient way to present two different sources of info (Meyer, 2001).

Also in: 4.1.1, 4.1.4, 4.1.6

GP#:1238

The human binocular field of vision is between $340^\circ-20^\circ$, the monocular field of vision is between $300^\circ-80^\circ$ (May & Badcock, 2002)

Also in: 2.6.1

GP#:1241

Visual familiarity, intentionality, an object’s physical characteristics, and the structure of the scene can all be active or passive “selectors.” The eye is a passive selector—high resolution info is preserved only at the center of the gaze. Visual acuity drops 50% when an object is located only 1º from the center of the fovea and an additional 35% when it is 8º from the center. (Forgus & Melamed, 1976; Landragin (2001); as cited in Kelleher & van Genabith, 2004)

Also in: 2.2.1, 2.6.1, 4.1.6

GP#:1343

An object’s prominence in a scene is dependent on both its centrality within the scene and its size (Kelleher & van Genabith, 2004).

Also in: 4.1.2

GP#:1344

The field of view of the human eye is 200º horizontally, and 125º vertically—this has implications for HMDs (Iwata, 2004).

Also in: 2.6.1, 4.1.5, 4.1.6, 8.1

GP#:1347

Two important factors in immersive display design are resolution and Field Of View. Image fidelity requires high resolution, measured in resolvable dots or effective pixels. Immersion requires wide FOV. Increasing FOV while maintaining high resolution requires an increase in effective pixels. (Lantz, 1997)

Also in: 4.1.3, 4.1.4

GP#:1375

When workload is high, operators tend to rely mainly on surface cues of displays, so it’s especially important to use cues consistently (e.g., colors) (Gilson, Mouloua, Graft, & McDonald, 2001).

Also in: 4.1.1, 6.6.5

GP#:1392

HMDs often degrade performance and lower presence because of their narrow field of view (FOV). The visual FOV of the [naked] human eye spans more than 180 degrees. (Seay, Krum, Hodges, & Ribarsky, 2001; Waller, 1999; as cited in Yang & Kim, 2004)

Also in: 2.6.1, 4.1.5, 6.4.1, 8.1

GP#:1402

Adding tactile/proprioceptive cues to visual cues can allow users to expand their geometric field of view without significantly distorting distance perception (Yang & Kim, 2004).

Also in: 2.1.4 TV, 2.7.4 TV, 4.5

GP#:1403
Immersed displays yield reduced accuracy, relative to 3D exocentric displays, on tasks that require information located behind or beside the user. This effect exists even when the information is available by panning or by referring to an inset map. (Wickens, Thomas, & Young, 2000)

Also in: 3.2.1, 4.1.4, 8.1

Placing single sounds in the most natural location (the front of the listener) is suboptimal compared with every other position, excluding the one directly behind the head. Therefore, in real world applications, it is better to see the speaker in front but listen to him/her from the side. (MacDonald et al., 2002)

Also in: 2.1.2

In a normal erect posture, the eye-ear line is typically 15 degrees above horizontal eye height. Therefore, visual displays should be placed 15 degrees below horizontal eye height. (Burgess-Limerick et al., 2000)

Also in: 4.1

Discretely-moving head-slaved displays have display edges in a constant position in the operator’s optic array; these edges might serve as reference lines to improve visual tasks (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.5

Situational awareness has been shown to diminish with a field of view less than 100 degrees (Reingold et al., 2003).

Also in: 3.5.1, 6.4.1

2.1.2 Audio

Three-dimensional auditory cues are very effective for alerting and attention management in multitask decision environments (Bellotti, Berta, DeGloria, & Margarone, 2002).

Also in: 3.1.2

Spatially segregating audio sources can improve a user’s comprehension of a target speaker. This phenomenon has been termed the “cocktail party effect.” (Rudmann, McCarley & Kramer, 2003)

Also in: 4.2

Some participants have a clear preference toward the right ear or left ear in terms of receiving auditory information (Lipschutz, Kelinsky, Damhaut, Wikler, & Goldman, 2002).

Also in: 5.5.2

Adaptive audio display technology will require the following: 1) intelligent prioritization and novel presentation algorithms, 2) computational auditory scene analysis techniques for evaluating external auditory constraints in real-time and 3) automated multidimensional sound processing techniques.

The use of properly designed, spatialized alerts can significantly reduce effort and improve response times in a highly demanding, dual-task setting with no effect on decision accuracy or other measures of performance (Brock et al., 2003).

Also in: 3.1.2, 4.2, 6.7
Displays must be capable of representing multiple resources of auditory information that might be static or moving (Wourms, Mansfield, & Cunningham (2001)).

Also in: 4.2

Positioning sounds to the left or right of the listener is superior to positioning them in front or back (MacDonald et al., 2002).

Also in: 4.2

When a speech sound is placed in front of the listener and a noise source is shifted from the center to the left or right, the signal-to-noise ratio will increase in one ear and decrease in the other (MacDonald et al., 2002).

Also in: 4.2

For verbal warnings, position on the interaural axis is the key factor to consider, rather than realism or maximum spacing (MacDonald et al., 2002).

Also in: 3.1.2, 4.2

Placing single sounds in the most natural location (the front of the listener) is suboptimal compared with every other position, excluding the one directly behind the head. Therefore, in real world applications, it is better to see the speaker in front but listen to him/her from the side. (MacDonald et al., 2002)

Also in: 2.1.1

In a sound-localization task, using a combination of stereo audio microphones and a head tracker can disambiguate sources from similar angles. (Siracusa, Morency, Wilson, Fisher, Darrell, 2003)

Also in: 3.6.2, 4.2

Spatialized audio cueing can lead to increased target detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman & Breda, 1998; Nelson et al, 1998, as cited in Tannen, 2000).

Also in: 3.6.2, 6.6.1, 6.6.2, 6.6.4 AV

The addition of spatialized sound to visual cueing reduced target designation time comparison to visual only; this occurred under conditions in which targets were really difficult to detect (e.g., ground targets initially outside FOV). The time advantage for fixed and adaptive multimodal cueing was 824 msec. (Tannen, 2000)

Also in: 2.7.4 AV, 3.6.1, 3.6.4 AV, 4.1.6

Auditory cueing should be used to improve visual target search performance, as perception of sound source is not limited by FOV or line-of-sight. Vision and audition can function “synergistically” in search tasks by encouraging auditory localization to direct the visual system toward objects in space, which can result in reduced search times. Gains in this respect are greatest when targets are presented outside FOV. Auditory cueing still reduces search times within 10 degrees of FOV by 175 msec. (McKinley, Ericson, & D’Angelo, 1994; Perrott, Cisneros, McKinley, & D’Angelo, 1996; Rudmann & Strybal, 1999; as cited in Tannen 2000)

Also in: 3.4.4 AV, 3.6.1, 3.6.2, 4.1.6, 4.4
The effectiveness of a sound cue in the central FOV was a positive function of angular distance from line-of-sight. Benefits were found for distal targets (by 100 msecs) but not for targets within central line-of-sight; therefore, benefits of auditory cueing in visual search tasks are strongest when targets are beyond an observer’s central FOV. (Perrot, Sadralodabai, Saberi, & Strybel, 1991; as cited in Tannen, 2000)

Also in: 2.1.4 AV, 3.6.4 AV, 4.4

As number of simultaneous audio displays (e.g., simultaneous talkers) increases, interpretation performance decreases and response time increases (probably due to increase in uncertainty). Increasing the number of talkers is more detrimental for asymmetric configurations of audio than for symmetric configurations. This particular study found no correlation between handedness and dependent variables. (Bolia, Nelson & Morley, 2001)

Also in: 1.4.2, 4.2.3, 4.2.4

The detection and identification of speech information presented binaurally against a background of competing speech messages is significantly enhanced when the target phrase is located in the right hemifield (Bolia, Nelson & Morley, 2001). This is relevant to the design of spatial audio adaptive interfaces, such as when there is a need to dynamically modify characteristics of a display in response to changes in the functional state of the operator, the vehicle, or the environment. (Hettinger, et al 1996; as cited in Bolia, Nelson & Morley, 2001)

Also in: 3.9.2, 4.2

Higher priority messages should be presented in the right hemifield, while lower priority messages should be presented in the left hemifield. (Bolia, Nelson & Morley, 2001)

Also in: 3.1.2, 3.9.2, 4.2

Target messages are more intelligible when presented against a distribution of signals that are symmetric than if they are distributed entirely to one side or the other of the midline (Bolia, Nelson & Morley, 2001).

Also in: 3.9.2, 4.2

2.1.3 Tactile

The back is more sensitive to tactors than the forearm (Piateski & Jones, 2005).

Sensitivity to tactors depends on size, density, frequency range, and nerve fiber branching of receptors (see charts) (Hale & Stanney, 2004). The roof of the mouth is very sensitive to vibrotactile stimulation, and the intensities required (10-20 V) are much lower than those required on the fingertips (25-30 V) (Tang & Beebe, 2000). The torso is less sensitive to tactors than the hand. The front of the torso is more sensitive than the back of the torso. There is greater sensitivity closer to the sagittal plane (the plane dividing the left and right halves of the body) (findings of other studies summarized in Lindeman, Sibert, Mendez, Patil, & Phifer, 2005). Participants could identify geospatial cues moving left/right on tongue with more accuracy than forward/backward (Tang & Beebe, 2000).

Also in: 2.2.3, 4.3.1

The middle of the belly seems to be an optimal place for haptic placement (Van Erp & Werkhoven, 1999).
Human tactile resources are sensitive to location, duration, frequency, and amplitude. Information received via the tactile sense can always be readily received, draws attention, is private, and can be used in a natural and intuitive way. (Van Erp & Van Veen, 2004)

**Also in:** 2.2.3, 2.6.3

Two stimuli that are presented at the same time within a certain distance are generally perceived as one stimulus (Cholewiak, 1988; as cited in van Erp & Verschoor, 2004). The cue is usually sensed as being located in the middle of the two stimuli (called the “apparent position”). (van Erp & Verschoor, 2004)

**Also in:** 3.5, 4

Perception of tactile cues increases when actuators are widely spaced and/or placed on an anatomical landmark (van Erp & Verschoor, 2004).

**GP#:1131**

In designing tactile devices, it is important to consider how close together vibrating tactors can be placed before their loci become indistinguishable (Cholewiak, Collins & Brill, 2001).

**Also in:** 2.2.3

Vibrotactile stimuli are most accurately identified when tactors are placed on “anchor points” (e.g., the navel or the spine) at the front and rear of the trunk (Cholewiak, Collins & Brill, 2001).

**GP#:1151**

Users experience enhanced accuracy of tactile stimuli when tactors are located near “anchor points” (e.g., the naval and spine) (Cholewiak, Collins, & Brill, 2001).

**GP#:1174**

Perceptions of tactile stimuli increase as the distance between tactors goes up (25mm versus 50mm) (Cholewiak, Collins, & Brill, 2001).

**Also in:** 2.2.3

Fingers and hands are the most sensitive areas of the body for perceiving tactile stimulation (Arroyo & Selker, 2003).

**GP#:1176**

The sensory saltation phenomenon should be considered (and possibly utilized) when designing tactile displays. Sensory saltation is an illusory phenomenon whereby a few tactile pulses that go off in succession in a linear array are perceived as more tactors going off in a straight line. (Tan & Pentland, 1997)

**GP#:1177**

The outer wrist is less sensitive to tactile stimulation than the inner wrist (Sklar & Sarter, 1999).

**GP#:1178**

The haptic sense is different from the visual sense in that it is localized to a small number of contact points with the external environment, is bi-directional in that it can both sense and interact with the world, it has very high resolution, and it is often socially-loaded.

Visualizations designed for the haptic sense should attempt to exploit the unique characteristics of the haptic sense rather than try to make visual standards fit haptic devices. (Wall & Brewster, 2005)

**Also in:** 2.6.1, 2.6.3, 2.7.1, 2.7.3
Touch, in comparison to other sensory modalities is more local and bidirectional which is linked to
closeness and intimacy (sense of togetherness) (Durlach & Slater, 2000; as cited in Basdogan, 2000).

Also in: 2.6.3

GP#:1357

There are two types of tactile stimulation: superficial stimulation by air pressure (induces stress only
near the surface), and stimulation of deep receptors (vibration applies stress to shallow and deep receptors).
It is possible to selectively stimulate the receptors at different depths, although the direction of the applied
surface forces is not controllable. Humans can discriminate a small difference in pressure distribution
within a small area on the skin, given different stimulus amplitude to shallow and deep receptors. This
discrimination ability degrades when only shallow receptors are stimulated. Superficial stimulation results
in feeling a finer virtual text than stimulator spacing and time-delayed signals like a brush across the skin.
(Asamura, Yokoyama & Shinoda, 1998)

Also in: 2.2.3, 4.3.1

GP#:1406

The human body perceives a resolution of .4cm JND (just noticeable difference) interval at center of
abdomen, 1.2 cm interval at side of abdomen; 1.8 cm interval at center of back, and 3.0 cm interval at sides
of back (Tsukada & Yasumura, 2004)

Also in: 2.2.3, 4.3.1

GP#:1407

Tactors on the back are perceived as weaker than those on the abdomen. (Tsukada & Yasumura, 2004)

Also in: 2.2.3

GP#:1492

There should be at least a couple of centimeters between tactors, as the skin perceive high-density
vibrations very efficiently (Schrope, 2001).

GP#:1512

Presenting sinusoidal bursts close in time to two different skin sites will result in a mutual masking effect,
perceived as either a change in threshold or in magnitude (Sherrick, 1964; as cited in Sherrick, 1991).

Also in: 2.2.3, 2.4.3

GP#:1614

The ventral thorax is a relatively traffic free area of somewhat uniform sensitivity, at least in males
(Geldard, 1960).

Also in: 1.3.3, 4.3

GP#:1615

In the chest, the useful range of stimulus amplitudes is limited to values of 50 to 400 microns (Geldard,
1960).

Also in: 4.3

GP#:1620

The following are psychophysical tactile interaction design guidelines based on psychophysical research:
(1) Haptic input must consider sensitivity to stimuli across various skin locations (for example, the two-
point threshold grows smaller from palm to fingertips, where spatial resolution is about 2.5 mm on the
index finger tip (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (2) To ensure that
receptors perceive individual cutaneous signals, stimuli must be at least 5.5 ms apart (Sherrick &
Cholewiak, 1986 as cited in Hale & Stanney, 2004); (3) To successfully activate an individual’s pressure
sensors, the force exerted must be greater than 0.06-0.2 Newtons per cm (Sherrick & Cholewiak, 1986;
Biggs & Srinivasan, 2002, both as cited in Hale & Stanney, 2004); (4) Pressure limits depend on body loci
and gender. Just-noticeable values range from 5 milligrams on a woman’s face to 355 mg on a man’s big toe (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (5) Vibration from a single probe must exceed 28 decibels (relative to a 1-microsecond peak) for 0.4-3 Hz frequencies for humans to perceive (Biggs & Srinivasan, 2002, as cited in Hale & Stanney, 2004); (6) For a user to feel a hard surface after initial contact, the haptic system must maintain active pressure; (6) Maintaining the sensation of textured surfaces requires relative motion between the surface and the skin.

Also in: 2.2.3, 2.7.3, 4.3.2

Dynamic tactile information (e.g., five tactors placed on the forearm vibrating sequentially) can be used to accurately reorient visual attention or vice versa (Hale & Stanney, 2004).

Also in: 4.1, 4.3.1, 6.3.1

The following are guidelines for detection of a stimulus: vibration stimuli can be detected when amplitude exceeds certain threshold; the skin is sensitive to vibrations between 20 and 500 Hz; and the fingers are more sensitive than the trunk (Van Erp, 2002).

Also in: 2.2.3

Lowest vibration thresholds are found: on glabrous skin as compared to hairy skin; with vibration frequencies in the range of 200-250 Hz; when stimulus duration increases; and when there is fixed surroundings around vibrating element (Van Erp, 2002).

Also in: 2.2.3

The following are guidelines for designing tactile displays for comfort: ensure comfort over longer periods of time - tactile displays worn on the body must be unobtrusive and comfortable; electrodes and vibrators can generate heat potentially causing burns; the comfortable stimuli range is 15-20 dB above the absolute threshold; and the vibrations of the hand-arm should always be limited; most critical frequencies are around 12 Hz. (Van Erp, 2002)

Also in: 2.2.3, 4.3, 5

The following design pitfalls should be avoided: spatial masking – location of stimulus is masked by another stimulus; temporal enhancement – affects subjective magnitude of second stimulus (temporal masking and adaptation are other temporal effects to consider); stimuli presented closely in time and space can alter the percept and may even result in a completely new percept (related to apparent motion). (Van Erp, 2002)

Also in: 2.3.3, 2.7.3, 4.3

(Hale & Stanney, 2004)
2.1.4 Multimodal (AV, AT, TV, ATV)

Interface designers should work toward presenting information sources in different modalities from the same spatial position when the goal is for people to efficiently monitor multiple sources of sensory information (Spence & Read, 2003).

Also in: 2.2.3, 4.3
It has been suggested that the more properties shared between two modalities, the stronger the observer’s unity assumption that information from different sensory channels can be attributed to the same distal event or object [14]. These properties include spatial location, motion, temporal patterning or rate [15], all of which can be impacted by temporal asynchrony in a multimodal display system. (Adelstein, Begault, Anderson & Wenzel, 2003)

Also in: 2.7.4, 4.8.2

When information must be combined from various sources located at different points in space (e.g., information from two maps), or different points in time (e.g., panning), or both, the composite mental picture will be less accurate than when all information is available in a single source (Wickens, Thomas, & Young, 2000).

Also in: 2.7.4, 3.2.1, 4.8.1, 4.9

The interval between stimuli required for participants to judge which modality comes first on 75% of the trials (JND) is 20msec when only two stimuli are presented (Hirsch & Sherrick, 1961) and remains constant across auditory, tactile, and visual stimuli (Bald, Berrien, Price, & Sprague, 1942; Rutschmann & Link, 1964) when presented from different locations. (Spence, Baddeley, Zampini, James, and Shore, 2003)

Also in: 2.2.4

• AV

Providing a visual display of a speaker that is congruent with the display of speech improves comprehension, especially as background noise increases. (MacLeod & Summerfield, 1987; as cited in Rudmann et al., 2003) Tracking or shadowing the speech of a target speaker while ignoring another distracting speaker is easier when the visual display of the target speaker is displayed away from the sound source rather than near it (Rudmann et al., 2003).

Also in: 4.1.9, 4.2.1, 4.2.5, 4.4.1, 4.4.3

In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003)

Also in: 2.1.4 TV, 2.2.4 AV, 2.2.4 TV, 2.6.4, 2.7.4 AV, 2.7.4 TV, 4.4.3, 4.5.3

Multimodal cueing (e.g., spatialized audio and visual) also reduced excessive head motion and lowered pilots’ workload by about 30%, as compared to conditions with no cues (Tannen, 2000).

Also in: 3.8.4 AV, 6.6.4 AV

The effectiveness of a sound cue in the central FOV was a positive function of angular distance from line-of-sight. Benefits were found for distal targets (by 100 msecs) but not for targets within central line-of-sight; therefore, benefits of auditory cueing in visual search tasks are strongest when targets are beyond an observer’s central FOV. (Perrot, Sadr-rollback, Saber, & Strybel, 1991; as cited in Tannen, 2000)

Also in: 2.1.2, 3.6.4 AV, 4.4

Auditory cueing is useful because it conveys general, rather than precise, information about target location. Visual search performance should be analyzed in two phases: localization (first stage, target is brought into FOV) and identification (next stage, precise target position within FOV is determined). Sound helped in
both stages of visual searching, with greater benefits of auditory cueing coming in the target localization stage. (Rudmann & Strybel, 1999; as cited in Tannen, 2000)

Also in: 3.6.4 AV

- AT
- TV

Adding tactile/proprioceptive cues to visual cues can allow users to expand their geometric field of view without significantly distorting distance perception (Yang & Kim, 2004).

Also in: 2.1.1, 2.7.4 TV, 4.5

In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003)

Also in: 2.1.4 AV, 2.2.4 AV, 2.2.4 TV, 2.6.4, 2.7.4 AV, 2.7.4 TV, 4.4.3, 4.5.3

- ATV

2.1.5 Not Specific to a Mode

When designing devices, keep in mind the sensory conduction time for the modality/location of device (van Erp & Verschoor, 2004).

Also in: 2.5.5

An operator’s reliance on and compliance with a warning system are strongly situational. It might be beneficial to place warnings close to other relevant info (Meyer, 2001).

Also in: 3.1.5, 5.4.5

To compensate for increases in working memory load when driving, drivers will focus on a subset of cars (cars located in close proximity) instead of each individual car (Gugerty, 1997)

Also in: 3.3.5, 6.6.5

A major factor in display design seems to be the computational demands related to different spatial filtering rather than the perceived location of the sources (MacDonald et al., 2002).

Also in: 4.9, 6.6.5

2.2 Threshold

2.2.1 Visual

Visual texture using the technique presented by Ware & Knight (1995) should be considered as a technique to add depth to information display, particularly topographic maps. Humans are most sensitive to patterns whose period is approximately 2 cycles/degree.

Also in: 4.1, 4.1.4, 4.3.1

GP#: 1319
Graphics and haptic update rates should be maintained at least around 30 Hz and 1000 HZ respectively to have satisfying experience interacting with a virtual environment (Basdogan et al., 2000).

**Also in: 2.2.3, 5.5.1, 5.5.3, 8.1, 8.3**

Visual familiarity, intentionality, an object’s physical characteristics, and the structure of the scene can all be active or passive “selectors.” The eye is a passive selector—high resolution info is preserved only at the center of the gaze. Visual acuity drops 50% when an object is located only 1º from the center of the fovea and an additional 35% when it is 8º from the center. (Forgus & Melamed, 1976; Landragin (2001); as cited in Kelleher & van Genabith, 2004)

**Also in: 2.1.1, 2.6.1, 4.1.6**

Because we are surface dwellers, our visual cognition has evolved to be much more sensitive to motion in the horizontal plane (Lantz, 1997).

**Also in: 2.6.1**

The interval between pulses (empty interval) is perceived to be longer with vibrotactile pulses than with visual light pulses (Van Erp & Werkhoven, 2004).

**Also in: 2.2.3, 4.1, 4.3.1**

Haptic rendering requires update rates significantly higher than graphics rendering (Walker & Salisbury, 2003).

**Also in: 2.2.3, 4.1, 4.3**

Frame rates of at least 10 frames of 10 frames per second are necessary for optic flow perception, which is critical for piloting. (Reingold, Loschky, McConkie & Stampe, 2003)

**Also in: 3.8.1, 4.1**

Frame rates of at least 10 frames per second are necessary for optic flow perception, which is critical in piloting (Reingold et. al., 2003).

**Also in: 2.6.1, 3.8.1, 4.1**

The maximum visual-haptic cue asynchrony or delay that participants tolerate was 45 ms (on average). The range in which stimuli were judged to be synchronous was centered around a visual delay of about 7 ms. This point of subjective simultaneity (PSS) was liable to individual differences. (Vogels, 2004)

**Also in: 1.4.4 TV, 2.2.4 TV, 2.7.4 TV, 4.5.2**

### 2.2.2 Audio

There are differences in pattern identification performance between older and younger subjects that appear to be directly related to poorer spatial resolution in the older group. Hearing acuity decreases rapidly after the age of 60. Also, as people age, thresholds increase, leading to poorer discriminative capabilities. The underlying cause of loss is usually attributed to either physiological changes in the skin or neurological factors. In aging skin, size, shape, and number of cells in the upper layers become variable and glands atrophy or become inactive. Alterations in mechanical properties of the skin, such as compliance, are not related to reduction in tactile sensitivity. (Cholewiak, Collins & Brill, 2001)

**Also in: 1.1.2, 1.1.3, 2.2.3**
Multimodal conditions (specifically audio-tactile) may be ideal in vigilance tasks to help improve detection rates and to prevent the performance decrement and threshold increases that unimodal conditions exhibit over time (Davenport, 1969).

**Also in:** 2.2.3, 2.2.4 AT, 3.4.4 AT

### 2.2.3 Tactile

Sensitivity to tactile cues decreases with age (Cholewiak, Collins & Brill, 2001).

**Also in:** 1.1.3

Ability to sense tactile cues may decrease when the user is experiencing cognitive load. In particular, the efficacy of tactile cues decreased when participants were in a zero-gravity situation, as is often experienced by pilots and astronauts (Bhargava, Scott, Traylor, Chung, Mrozek, Water & Tan, 2005).

**Also in:** 6.6.3

Sensitivity to tactors depends on size, density, frequency range, and nerve fiber branching of receptors (see charts) (Hale & Stanney, 2004). The roof of the mouth is very sensitive to vibrotactile stimulation, and the intensities required (10-20 V) are much lower than those required on the fingertips (25-30 V) (Tang & Beebe, 2000). The torso is less sensitive to tactors than the hand. The front of the torso is more sensitive than the back of the torso. There is greater sensitivity closer to the sagittal plane (the plane dividing the left and right halves of the body) (findings of other studies summarized in Lindeman, Sibert, Mendez, Patil, Hifner, 2005). Participants could identify geospatial cues moving left/right on tongue with more accuracy than forward/backward (Tang & Beebe, 2000).

**Also in:** 2.1.3, 4.3.1

Vibrations can be sensed up to 10 KHz and can be discriminated up to 320 Hz. An amplitude of 0.1 micrometers is sufficient. Pressure to the skin can be detected to 10 raised to the -5 power N (Munch & Dillman, 1997).

**Also in:** 8.3

As frequency of texture increases, perceived roughness of the surface increases. In tasks that require users to discriminate between two surfaces in terms of levels of roughness, frequency differences between the two surfaces must be more than 5 Hz. (McGee, Gray & Brewster, 2001)

**Also in:** 2.1.3, 2.6.3

Different frequencies of tactile cues may target different skin receptors. Spatial acuity is greater when higher background frequencies are used. The article details the Hertz requirements for users to accurately perceive the position of moving stimuli. (Summers, Chanter, Southall & Brady, 2001)

**Also in:** 1105

Traditionally obtained thresholds may only represent the categorical perception of a distance at which separation between two points is no longer ambiguous (Cholewiak, Collins & Brill, 2001).
In designing tactile devices, it is important to consider how close together vibrating tactors can be placed before their loci become indistinguishable (Cholewiak, Collins & Brill, 2001).

Also in: 2.1.3

There are differences in pattern identification performance between older and younger subjects that appear to be directly related to poorer spatial resolution in the older group. Hearing acuity decreases rapidly after the age of 60. Also, as people age, thresholds increase, leading to poorer discriminative capabilities. The underlying cause of loss is usually attributed to either physiological changes in the skin or neurological factors. In aging skin, size, shape, and number of cells in the upper layers become variable and glands atrophy or become inactive. Alterations in mechanical properties of the skin, such as compliance, are not related to reduction in tactile sensitivity. (Cholewiak, Collins & Brill, 2001)

Also in: 1.1.2, 1.1.3, 2.2.2

As age increases, individuals have less sensitivity to tactile stimulation (Cholewiak, Collins, & Brill, 2001).

Also in: 1.1.3

Perceptions of tactile stimuli increase as the distance between tactors goes up (25mm versus 50mm) (Cholewiak, Collins, & Brill, 2001).

Also in: 2.1.3

Multimodal conditions (specifically audio-tactile) may be ideal in vigilance tasks to help improve detection rates and to prevent the performance decrement and threshold increases that unimodal conditions exhibit over time (Davenport, 1969).

Also in: 2.2.2, 2.2.4 AT, 3.4.4 AT

Fingertip motion (kinesis) improves tactile perception (Foulke, 1991; as cited in Ramstein et al., 1996).

Also in: 4.3.1

Perceptions of presence increases in virtual realities as frame rate increases. Frame rates below 15 frames/sec produce anomalous results. Presence in a virtual environment can be measured using physiological measures. Change in heart rate is a more accurate measure than change in skin conductance or change in skin temperature. Adding simple passive haptic cues (such as a small platform users stand on so they can feel edges with their feet) increases presence in virtual environments. (Meehan, Insko, Whitton, & Brooks, 2002)

Also in: 6.4.3, 7.2.5, 8.1, 8.3

Graphics and haptic update rates should be maintained at least around 30 Hz and 1000 HZ respectively to have satisfying experience interacting with a virtual environment (Basdogan et al., 2000)

Also in: 2.2.1, 5.5.1, 5.5.3, 8.1, 8.3

There are two types of tactile stimulation: superficial stimulation by air pressure (induces stress only near the surface), and stimulation of deep receptors (vibration applies stress to shallow and deep receptors). It is possible to selectively stimulate the receptors at different depths, although the direction of the applied surface forces is not controllable. Humans can discriminate a small difference in pressure distribution within a small area on the skin, given different stimulus amplitude to shallow and deep receptors. This
discrimination ability degrades when only shallow receptors are stimulated. Superficial stimulation results in feeling a finer virtual text than stimulator spacing and time-delayed signals like a brush across the skin. (Asamura, Yokoyama & Shinoda, 1998)

Also in: 2.1.3, 4.3.1

GP#:1406

The human body perceives a resolution of 0.4 cm JND (just noticeable difference) interval at center of abdomen, 1.2 cm interval at side of abdomen; 1.8 cm interval at center of back, and 3.0 cm interval at sides of back (Tsukada & Yasumura, 2004)

Also in: 2.1.3, 4.3.1

GP#:1407

Tactors on the back are perceived as weaker than those on the abdomen. (Tsukada & Yasumura, 2004)

Also in: 2.1.3

GP#:1408

Temporal pulse intervals of 500 msec (250 msec on, 250 msec off) or less may prevent the user from accurately detecting tactors. (Tsukada & Yasumura, 2004)

Also in: 4.3

GP#:1437

The interval between pulses (empty interval) is perceived to be longer with vibrotactile pulses than with visual light pulses (Van Erp & Werkhoven, 2004).

Also in: 2.2.1, 4.1, 4.3.1

GP#:1438

Haptic rendering requires update rates significantly higher than graphics rendering (Walker & Salisbury, 2003).

Also in: 2.2.1, 4.1, 4.3

GP#:1439

Significantly speeding-up the rate of haptic rendering enables physical exploration of geometric datasets that have much greater dynamic range (Walker & Salisbury, 2003).

Also in: 3.7.3, 4.3

GP#:1485

Haptic interactions occur at two levels: (1) when contact occurs there is a net force (vector) experienced/generated by the user, and (2) the distribution of forces or tractions which occur at each contact site are perceived through the user’s mechanoreceptors, giving rise to the human tactile sense. (Salisbury, Brock, Massie, Swarup & Zilles, 1995)

Also in: 2.6.3, 4.3

GP#:1486

The perception of surface shape, compliance, texture, and friction can all be evoked through proper modulation of the net force exerted on the user (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.7.3, 4.3

GP#:1511

Displacements having frequencies below 1 Hz or above 3 kHz will not affect most touch receptors (Cholewiak & Collins; as cited in Sherrick, 1991).

Also in: 4.3

GP#:1512
Presenting sinusoidal bursts close in time to two different skin sites will result in a mutual masking effect, perceived as either a change in threshold or in magnitude (Sherrick, 1964; as cited in Sherrick, 1991).

Also in: 2.1.3, 2.4.3

GP#:1613

Two simultaneous acting vibrators feel no different from one, once the static pressure of each has adapted out, and provided the vibratory pattern is set up in all of them with the same onset (Geldard, 1960).

Also in: 4.3.1

GP#:1616

Between 0.1 and 2.0 seconds, there is a durational continuum within which the average observer can make about 25 distinctions, the steps being of the order of 0.05 second at the low end and 0.15 second at the high end of the range (Geldard, 1960).

Also in: 4.3

GP#:1619

The following are kinesthetic interaction design guidelines based on psychophysical research: to ensure more accurate limb position, use active rather than passive movement; avoid minute, precise joint rotations, particularly at distal segments; minimize fatigue by avoiding static positions at or near the end range of motion; surface stiffness of 400 Newtons per meter should effectively promote haptic information transfer; end-point forces of 3-4 Newtons should effectively promote haptic information transfer; add kinesthetic information to enhance objects’ spatial location; gestures should be intuitive and simple; minimize fatigue by avoiding frequent, awkward, or precise gestures; and avoid precise motion gestures, as making accurate or repeatable gestures with no tactile feedback is difficult. (Hale & Stanney, 2004)

Also in: 2.6.4, 2.7.3, 4.3.2

GP#:1620

The following are psychophysical tactile interaction design guidelines based on psychophysical research: (1) Haptic input must consider sensitivity to stimuli across various skin locations (for example, the two-point threshold grows smaller from palm to fingertips, where spatial resolution is about 2.5 mm on the index finger tip (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (2) To ensure that receptors perceive individual cutaneous signals, stimuli must be at least 5.5 ms apart (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (3) To successfully activate an individual’s pressure sensors, the force exerted must be greater than 0.06-0.2 Newtons per cm (Sherrick & Cholewiak, 1986; Biggs & Srinivasan, 2002, both as cited in Hale & Stanney, 2004); (4) Pressure limits depend on body loci and gender. Just-noticeable values range from 5 milligrams on a woman’s face to 355 mg on a man’s big toe (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (5) Vibration from a single probe must exceed 28 decibels (relative to a 1-microsecond peak) for 0.4-3 Hz frequencies for humans to perceive (Biggs & Srinivasan, 2002, as cited in Hale & Stanney, 2004); (6) For a user to feel a hard surface after initial contact, the haptic system must maintain active pressure; (6) Maintaining the sensation of textured surfaces requires relative motion between the surface and the skin.

Also in: 2.6.4, 2.7.3, 4.3.2

GP#:1695

The following are guidelines for detection of a stimulus: vibration stimuli can be detected when amplitude exceeds certain threshold; the skin is sensitive to vibrations between 20 and 500 Hz; and the fingers are more sensitive than the trunk (Van Erp, 2002).

Also in: 2.1.3

GP#:1696

Lowest vibration thresholds are found: on glabrous skin as compared to hairy skin; with vibration frequencies in the range of 200-250 Hz; when stimulus duration increases; and when there is fixed surroundings around vibrating element (Van Erp, 2002).

Also in: 2.1.3
The following are guidelines for designing tactile displays for comfort: ensure comfort over longer periods of time - tactile displays worn on the body must be unobtrusive and comfortable; electrodes and vibrators can generate heat potentially causing burns; the comfortable stimuli range is 15-20 dB above the absolute threshold; and the vibrations of the hand-arm should always be limited; most critical frequencies are around 12 Hz. (Van Erp, 2002)

Also in: 2.1.3, 4.3, 5

(Hale & Stanney, 2004)

Table 1. Haptic tactile skin mechanoreceptor characteristics.*

<table>
<thead>
<tr>
<th>Haptic Features</th>
<th>Pacinian Corpuscles</th>
<th>Ruffini Endings</th>
<th>Meissner Corpuscles</th>
<th>Merkel Disks</th>
<th>Hair Follicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin Type</td>
<td>Glabrous and hairy</td>
<td>Glabrous and hairy</td>
<td>Glabrous</td>
<td>Glabrous</td>
<td>Hairy</td>
</tr>
<tr>
<td>Stimulation Objective</td>
<td>Vibration, acceleration, roughness</td>
<td>Skin stretch, lateral force, motion direction, static force</td>
<td>Velocity, flutter, slip, grip control</td>
<td>Skin curvature, pressure, form, texture, edges</td>
<td>Touch</td>
</tr>
<tr>
<td>Stimulation Type</td>
<td>Skin motion</td>
<td>Skin motion and sustained skin deformation</td>
<td>Skin motion</td>
<td>Skin motion and sustained skin deformation</td>
<td>Hair motion</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>Very poor (2 cm)</td>
<td>Poor (1 cm)</td>
<td>Fair (3 – 5 mm)</td>
<td>Good (0.5 mm)</td>
<td></td>
</tr>
<tr>
<td>Stimulation Frequency</td>
<td>100 – 1,000</td>
<td>0.4 – 100</td>
<td>2 – 40</td>
<td>0.4 – 10</td>
<td></td>
</tr>
<tr>
<td>Interstimulus Interval</td>
<td>Five ms to perceive separate stimuli; 20 ms to perceive stimuli order</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Table 2. Haptic kinesthetic receptor characteristics.*

<table>
<thead>
<tr>
<th>Haptic Features</th>
<th>Golgi Endings</th>
<th>Ruffini Endings</th>
<th>Golgi Tendon Organs</th>
<th>Muscle Spindles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Joint ligaments</td>
<td>Joint capsules</td>
<td>Tendons</td>
<td>Muscles</td>
</tr>
<tr>
<td>Stimulation Objective</td>
<td>Joint movement at end range of motion</td>
<td>Joint movement, particularly at end range of motion</td>
<td>Active position sense Link to limb position Force</td>
<td>Active movement of muscles Conscious experience of body movement and position Weight supported by limb</td>
</tr>
<tr>
<td>Stimulation Type</td>
<td>Capsule stretch</td>
<td>Muscle tension and force</td>
<td>Muscle stretch/ rate of change vibration</td>
<td></td>
</tr>
<tr>
<td>Feedback Loop Range</td>
<td>0.5 – 1.7 Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Also in: 2.1.3, 4.3
2.2.4 Multimodal (AV, AT, TV, ATV)

The interval between stimuli required for participants to judge which modality comes first on 75% of the trials (JND) is 20msec when only two stimuli are presented (Hirsch & Sherrick, 1961) and remains constant across auditory, tactile, and visual stimuli (Bald, Berrien, Price, & Sprague, 1942; Rutschmann & Link, 1964) when presented from different locations. (Spence, Baddeley, Zampini, James, and Shore, 2003)

Also in: 2.1.4

- AV

The McGurk effect is a perceptual phenomenon in which vision alters speech perception (McGurk & MacDonald, 1976; as cited in Yang & Kim, 2004).

Also in: 6.2.4 AV

- AT

Multimodal conditions (specifically audio-tactile) may be ideal in vigilance tasks to help improve detection rates and to prevent the performance decrement and threshold increases that unimodal conditions exhibit over time (Davenport, 1969).

Also in: 2.2.2, 2.2.3, 3.4.4 AT

- TV

In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003)

Also in: 2.1.4 AV, 2.1.4 TV, 2.2.4 TV, 2.6.4, 2.7.4 AV, 2.7.4 TV, 4.4.3, 4.5.3

- ATV

The maximum visual-haptic cue asynchrony or delay that participants tolerate was 45 ms (on average). The range in which stimuli were judged to be synchronous was centered around a visual delay of about 7 ms. This point of subjective simultaneity (PSS) was liable to individual differences. (Vogels, 2004)

Also in: 1.4.4 TV, 2.2.1, 2.7.4 TV, 4.5.2

2.2.5 Not Specific to a Mode

Regardless of the modality being used, it is important to know what the shift threshold is for hyperacuity (van Erp & Verschoor, 2004).
2.3 Apparent Motion

2.3.1 Visual

Interactions often occur when stimuli are presented close together in space and in time. Changes in perception of apparent location and perceived magnitude of the stimuli when two vibrating points are brought close together spatially and temporally. (Bekesy, 1963, 1967; as cited in Cholewiak, Collins & Brill, 2004)


Also in: 2.3.2, 2.3.3

2.3.2 Audio

Interactions often occur when stimuli are presented close together in space and in time. Changes in perception of apparent location and perceived magnitude of the stimuli when two vibrating points are brought close together spatially and temporally. (Bekesy, 1963, 1967; as cited in Cholewiak, Collins & Brill, 2004)


Also in: 2.3.1, 2.3.3

2.3.3 Tactile

Vibrotactile stimuli may create “illusion of movement” of tactors, which means that one perceives movement when there is none (Bice, 1969).

It is important to consider that tactile feedback can lead to the perception of apparent motion. Static stimulation of tactors can cause the sensation of movement; the inner stimulus distance may increase to several centimeters before the illusion goes away. (van Erp & Verschoor, 2004)
Interactions often occur when stimuli are presented close together in space and in time. Changes in perception of apparent location and perceived magnitude of the stimuli when two vibrating points are brought close together spatially and temporally. (Bekesy, 1963, 1967; as cited in Cholewiak, Collins & Brill, 2004)


**Also in: 2.3.1, 2.3.2**

GP#:1703

The following design pitfalls should be avoided: spatial masking – location of stimulus is masked by another stimulus; temporal enhancement – affects subjective magnitude of second stimulus (temporal masking and adaptation are other temporal effects to consider); stimuli presented closely in time and space can alter the percept and may even result in a completely new percept (related to apparent motion). (Van Erp, 2002)

**Also in: 2.1.3, 2.7.3, 4.3**

2.3.4 Multimodal (AV, AT, TV, ATV)
- AV
- AT
- TV
- ATV

2.3.5 Not Specific to a Mode

2.4 Change Blindness/Change Detection

2.4.1 Visual

Some researchers have found that change blindness is not affected by practice (Resink, 2000; as cited in Durlach, 2004), but others found that if you are using a limited set of icons and symbols, training may help reduce/avoid change blindness. People still experience change blindness even if their primary task is to watch for changes. (Durlach, 2004)

**Also in: 5.1.1**

GP#:1077

Workstations with multiple windows, zooming maps, and pop-up menus can block change detection signals (Durlach, 2004).

**Also in: 4.1.4, 4.1.7**

GP#:1079

When users are faced with dual task situations, it is important to consider that a diversion of attention creates an opportunity for changes to occur on an unattended display. Because interruption to any task is a possibility, it has been suggested that all devices should draw the user’s attention to changed information when the operator resumes viewing a given display. (Divita, Obermayer, Nugent, Linvilleu, 2004)

**Also in: 3.1.1, 6.7**

GP#:1082

The visual mode is not good for detecting unexpected changes, so they have limited usefulness as alerts (Sklar & Sarter, 1999).

**Also in: 3.1.1**

GP#:1157
Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.3, 3.4.1, 3.4.3, 4.16, 6.3.1, 6.3.3, 6.6.1, 6.6.3, 6.7

Peripheral visual cues are good for detecting “dynamic discontinuities” (example, motion or luminance change) and require few resources, but tunnel vision may be a problem under conditions of stress and/or cognitive load (Leibowitz & Appelle, 1969; as cited in Sarter, 2001).

Also in: 3.4.1, 4.1.6, 6.4.1, 6.6.5

Because of inattentional blindness and contingent orienting (the fact that we’re more likely to detect changes when we’re expecting that particular signal type), visual flashing cues may not be an optimal method of capturing attention (Nikolic, Orr, & Sarter, 2004).

Also in: 3.1.1

The flicker-induced change-blindness paradigm can be used as a measure of where observers tend to direct their attention in a visual scene (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 6.3.1

Concerning change inattentiveness, several demonstrations using static images, dynamic displays, and videotaped events have shown that observers often fail to explicitly detect unexpected stimuli (Varakin, Levin, and Fidler, 2004).

Concerning change blindness, if a change in the visual array occurs while the eye is moving, the smearing on the retina will obscure the transient association with the change and the change may be missed (Varakin, Levin, & Fidler, 2004).

Almost anything that occludes a change induced motion signal, or makes it less salient, can induce change blindness (Varakin, Levin, & Fidler, 2004).

Change detection is facilitated when post-change cues allow observers to restrict the comparison process to one region of a scene (Varakin, Levin, & Fidler, 2004).

Also in: 4.1.4

There is evidence that change blindness is sometimes associated with a broad failure to sufficiently represent information (Varakin, Levin, & Fidler, 2004).

People think they will always see things that they actually will not, an effect known as change blindness blindness (CBB) (Varakin, Levin, & Fidler, 2004).

2.4.2 Audio

Auditory system is extremely sensitive to change, even when outside focus of attention (Wenzel, 1994; as cited in Althoff et al., 2003).
The auditory system is extremely sensitive to change, even when it is not being attended to (Wenzel, 1994).

2.4.3 Tactile

When several tactors go off in a certain pattern, and then that pattern is changed, it is often hard for users to detect these changes. This phenomenon is similar to change blindness/deafness (Gallace, Tan, & Spence, 2005).

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Presenting sinusoidal bursts close in time to two different skin sites will result in a mutual masking effect, perceived as either a change in threshold or in magnitude (Sherrick, 1964; as cited in Sherrick, 1991).

People are better able to discriminate changes in friction in standard surfaces than changes in stiffness or texture (Wall & Brewster, 2003).

In tactile tasks, people can detect negative changes between a reference stimulus and a target stimulus better than positive changes (Wall & Brewster, 2003).

2.4.4 Multimodal (AV, AT, TV, ATV)
- AV
- AT
- TV
- ATV

2.4.5 Not Specific to a Mode

Systems should provide users with tools that facilitate change-detection (Durlach, 2004).

Interruptions exacerbate change blindness (Durlach, 2004).

A secondary simultaneous task can slow change detection even if the distracting task requires different modalities from the primary task (Durlach, 2004).
Attention is required to perceive change. Attention can only be focused on one object, or a small group of objects, at a time. (Divita, Obermayer, Nugent, Linvilleu, 2004)

Researchers need to look at non-arbitrary and meaningful changes in the context of change blindness, rather than just focusing on laboratory changes that are meaningless to the user/task (Divita, Obermayer, Nugent, Linvilleu, 2004).

Although it may appear that a user has experienced change blindness or inattentional blindness, he/she still may have internalized much of the information (Varakin, Levin & Fidler, 2004).

The consequences of failing to detect a change are not always detrimental, so treat change detection with the importance that is appropriate for each context/scenario (Varakin, Levin & Fidler, 2004).

Automation of decision-making may reduce the operator’s awareness of the system and of certain dynamic features of the work environment. Humans tend to be less aware of changes that are under control of another agent (whether that agent is automated or another human). (Kaber, Omal, & Endsley, 1999 as cited in Parasuraman, Sheridan & Wickens, 2000)

2.5 Latency Issues (delay in perception of cue, compared to presentation)

2.5.1 Visual

Auditory signals are detected more quickly than visual signals and tend to produce an alerting or orienting response (Wourms, Mansfield, & Cunningham, 2001).

Advantages of graphical visual displays over text-based displays: graphical displays enhance memory, and images are processed faster than words (Plaue, Miller, & Stasko, 2004).

Longer latencies for high-clutter scenes occurred because of the presence of a greater number of fixations required in order to locate a target (Adams, 1988; as cited in Ho, Scialfa, Caird, & Graw, 2001).

Reaction times can be halved when tactile presentation of information replaces straight visual stimuli (Schrope, 2001).
Helmet mounted display (HMD) allowed participants to demonstrate superior performance as measured by target detection latencies of accurately cued targets (Yeh, Merlo, Wickens, & Brandenburg, 2003).

In-place displays such as fade and blast are better than motion-based displays like ticker for rapid identification of items. Participants had lower monitoring latency when using the fade and blast than when using the ticker. This seems to extend prior results indicating that moving text is more difficult to read than static text (Sekey and Tietz, 1982; Granaas et al., 1984; As cited in McCrickard, Catrambone, Chewar & Stasko, 2003)

Manipulating the attention of the participant can influence the perception of simultaneity—the stimulus cued by the experimenter is usually perceived earlier. This was shown for stimuli presented within audio-tactile modalities (Stone, 1926), within the auditory modality (Needham, 1936), and within the visual modality (Stemach & Herdman, 1991; as cited in Vogels, 2004).

Delays (typical of those found in long distance telecollaboration) inhibit the ability of users to collaborate using haptic or visual communication at a distance. Delay can result in dissociation between the state of the system at the two end stations, which can cause differences in the response of operators who are compensating for perceived errors. (Allison, Zacher, Wang & Shu, 2004)

2.5.2 Audio

Auditory signals are detected more quickly than visual signals and tend to produce an alerting or orienting response (Wourms, Mansfield, & Cunningham, 2001).

2.5.3 Tactile

Using the tactile modality may help improve completion times over using the visual modality from a physiological standpoint (Poupyrev, Maruyama, & Rekimoto, 2002, p. 51).

Haptic processing is dependent on stored representations at each of various subsystems—this could be relevant to any set of resources: if incoming information matches or activates representations within a system, the result may be faster and more detailed representations. If stored representations are unavailable or irrelevant, then processing will be constrained to work on sensory input alone. This will affect processing time because receptors have limited parallel processing capacity. This usually results in longer processing times. (Booth & Schmidt-Tjzrksen, 2001)
Reaction times can be halved when tactile presentation of information replaces straight visual stimuli (Schrope, 2001).

Delays (typical of those found in long distance telecollaboration) inhibit the ability of users to collaborate using haptic or visual communication at a distance. Delay can result in dissociation between the state of the system at the two end stations, which can cause differences in the response of operators who are compensating for perceived errors. (Allison, Zacher, Wang & Shu, 2004)

2.5.4 Multimodal (AV, AT, TV, ATV)

- **AV**
  
  Manipulating the attention of the participant can influence the perception of simultaneity—the stimulus cued by the experimenter is usually perceived earlier. This was shown for stimuli presented within audio-tactile modalities (Stone, 1926), within the auditory modality (Needham, 1936), and within the visual modality (Stemach & Herdman, 1991; as cited in Vogels, 2004)

- **AT**
  
  In the absence of visual cues, multimodal conditions (audio-tactile) led to higher accuracy, lower response time, and less workload compared to unimodal conditions in deciphering a 2d bar graph (Yu & Brewster, 2002).

- **TV**
- **ATV**

2.5.5 Not Specific to a Mode

When designing devices, keep in mind the sensory conduction time for the modality/location of device (van Erp & Verschoor, 2004).

People are slower to respond to an event in one modality if they have just responded to an event in a different modality (modality-shifting effect) (Spence & Driver, 1997).

In virtual environments using tele-operators, latency is universally detrimental because it results in a mismatch between motor action and simulated sensory feedback. Delay can interfere with coordination and planning of motor actions. (Ellis et al, 1997; Park & Kenyon, 1999; as cited in Allison, Zacher, Wang & Shu, 2004)
2.6 General Resource Issues

Although most researchers tend to assume that our “resource size” is fixed, there is some support that it may change with long-term fluctuations in mood or age (Hasher & Zacks, 1979; Humphreys & Revelle, 1992); also, this study provides support that it can also change in the short-term in response to task demands (e.g., resources “shrink” to accommodate demand reduction). (Young & Stanton, 2002)

Also in: 1.1.5, 6.6.5

2.6.1 Visual resources

Seeing is often the user’s first step in gaining information from a system (Varakin, Levin & Fidler, 2004).

There are cognitive biases relevant to vision. For example, we can not “unsee” a pattern once it has been recognized. Automated fusion methods supporting human analysis may provide aids to reduce cognitive biases, improve the understanding of heterogeneous, multi-source data, and provide increased opportunities for data discovery. (Hall & Shaw 2002)

Also in: 6

There is some evidence that performance decrements associated with tactile patterns (compared to visual patterns) is a consequence of the inferior acuity of skin compared to the visual system (Cholewiak, Collins & Brill, 2001).

Also in: 2.6.3, 4.3.1

The visual sense dominates over audio and tactile resources (Arroyo & Selker, 2003).

Also in: 2.6.2, 2.6.3

The visual part of the brain is more stimulated by aural presentation than by visual presentation, though it is unclear why (Medvedev, Rudas, Pakhomov, Ivanitskii, Il'yichenok, & Ivanitskii, 2003).

Also in: 6.2.1, 6.2.2, 6.3.1

The tactile channel has an unlimited field of view (FOV), as opposed to the visual channel which has a field of view of 180 degrees. Therefore, tactile cues can be used to communicate information about parts of the field of view normally blocked in the visual channel. (Van Erp & Van Veen, 2004)

Also in: 2.6.3

The human binocular field of vision is between 340°-20°, the monocular field of vision is between 300°-80° (May & Badcock, 2002).

Also in: 2.1.1

The haptic sense is different from the visual sense in that it is localized to a small number of contact points with the external environment, is bi-directional in that it can both sense and interact with the world, it has very high resolution, and it is often socially-loaded.

Visualizations designed for the haptic sense should attempt to exploit the unique characteristics of the haptic sense rather than try to make visual standards fit haptic devices. (Wall & Brewster, 2005)
Visual attention is known to be influenced by cognitive (top-down, bottom-up) factors. Looking at neural systems with an fMRI showed that even during relatively simple simulated driving task, visual, motor and cognitive processes interacted in complex ways. (Graydon et al., 2004)

Also in: 3.3.1, 6

Visual perception of objects automatically recruits semantic knowledge about related objects (Postle, D’Esposito & Corkin, 2005).

Also in: 2.7.1, 6

The visual environment presents more information than we can process, so our brain selects regions in a “visual buffer” for detailed processing. Attention is greatest at a single point in the visual buffer and diminishes gradually from that point. (Kelleher & van Genabith, 2004)

Also in: 6.3.1

Visual familiarity, intentionality, an object’s physical characteristics, and the structure of the scene can all be active or passive “selectors.” The eye is a passive selector—high resolution info is preserved only at the center of the gaze. Visual acuity drops 50% when an object is located only 1º from the center of the fovea and an additional 35% when it is 8º from the center. (Forgus & Melamed, 1976; Landragin (2001); as cited in Kelleher & van Genabith, 2004)

Also in: 2.1.1, 2.2.1, 4.1.6

The field of view of the human eye is 200º horizontally, and 125º vertically—this has implications for HMDs (Iwata, 2004).

Also in: 2.1.1, 4.1.5, 4.1.6, 8.1

Our visual system is good at recognizing edges in images—edge-detection represents a significant reduction in the complexity of a scene (Morris & Joshi, 2003).

Also in: 4.1.4

Humans use optic flow as an important navigational cue (Morris & Joshi, 2003).

Also in: 2.3.1, 3.2.1

A lot of our cognitive information is derived from a small portion of our visual field of view (FOV). The fovial region of the eye (< 2º of our total FOV) contains most of our photoreceptors. Eye and head motion allow us to take in more information. Head displacement and navigation create optic flow and motion parallax, which is sensed by our peripheral vision and used to judge motion. (Lantz, 1997)

Also in: 2.3.1, 3.2.1, 4.1.6, 6

Ideally, we want a display that can stimulate our entire retina while allowing freedom of eye rotation, head rotation and physical displacement (Lantz, 1997).

Also in: 4.1

Because we are surface dwellers, our visual cognition has evolved to be much more sensitive to motion in the horizontal plane (Lantz, 1997).
Driving a car requires some head motion, but most of the user’s time is spent looking forward and exercising his/her peripheral vision (Lantz, 1997).

Middle-ages persons gradually lose their ability to focus at all distances, making the use of multifocal lenses critical. A decrease in visual-focus ability starts in the 20’s, and by the 40’s the ability has decreased by half. (Inoue, 2002)

HMDs often degrade performance and lower presence because of their narrow field of view (FOV). The visual FOV of the [naked] human eye spans more than 180 degrees. (Seay, Krum, Hodges, & Ribarsky, 2001; Waller, 1999; as cited in Yang & Kim, 2004)

The visual system is composed of multiple “channels,” each of which is tuned to a particular attribute (color, motion, depth, and size) (Long & Zovod, 2002).

Vision usually dominates the integrated visual-haptic percept; however, in some circumstances like judging an object’s texture, the combined percept is clearly affected by haptics (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation and vise versa (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

Some pre-attentive features, such as blinking, can be distracting and can interfere with the gestalt perception process (Kim & Hoffmann, 2003).

People tend to code messages visually: where messages involve spatial orientation or guidance, where fine discrimination is needed, where complex or unfamiliar material is to be comprehended, where reference data have to be immediately available or when simultaneous comparisons need to be made, where a recipient of information has to make relatively prompt selection of data from larger stocks of information, and where auditory reception is hampered by unfavorable environmental conditions. (Geldard, 1960)

When viewing near objects, the medial recti muscles are activated. When raising the eyes, the medial recti muscles are also activated, which is why individuals prefer to look downward to view near targets. Therefore, the potential for visual fatigue associated with placing visual displays at a level higher than optimal is increased for closer displays. (Burgess-Limerick et al., 2000)
Posture adopted to view any target represents a compromise between visual and musculoskeletal demands (Burgess-Limerick et al., 2000).

Also in: 2.6.4

A common assumption related to visual attention is that parallel processing occurs without attention (preattentive), and that serial processing requires attention. There are examples that refute this assumption; specifically, targets that are processed serially and do not trigger “pop-out” can actually be discriminated from distracters in a dual-task situation. Moreover, targets that are processed in parallel cannot be discriminated from distracters when attention is occupied by some other concurrent task. Preattentive (preattention) processing implies parallel processing. In practice, this is constrained by the size of the receptive fields. (VanRullen et al., 2004)

Also in: 3.6.1, 6.3.1, 6.7

Preattentive tasks that result in parallel visual search rely on neuronal selectivity present in early visual areas (e.g., orientation, color), whereas preattentive tasks that result in serial visual search rely on higher level neuronal selectivity (e.g., color-orientation conjunctions, animals, faces). Differences are typically accompanied by size of receptive fields. (VanRullen et al., 2004)

Also in: 3.6.1, 6.7

Role of visual attention is twofold: (1) to dynamically generate neuronal selectivity that are not explicitly implemented in the visual system at the level of single neurons and (2) to resolve spatial ambiguities that arise when multiple stimuli fall in the same receptive field. (VanRullen et al., 2004)

Also in: 6.3.1

Frame rates of at least 10 frames per second are necessary for optic flow perception, which is critical in piloting (Reingold et al., 2003).

Also in: 2.2.1, 3.8.1, 4.1

Access to foveal vision is very limited and can’t be easily shared in dual task situations (e.g., one can’t read two things at once); auditory processing is similar (e.g., one can’t listen to two speakers at once) (Wickens, 2000).

Also in: 2.6.2, 4.1.6, 4.2, 6.7

The sensory modality most affected by sensorimotor discord is the tactile sense (e.g., one can only touch things that are close, so touch is more local and intimate than vision or audition) (Durlach & Slater, 2000; as cited in Allison, Zacher, Wang & Shu, 2004).

Also in: 2.6.2, 2.6.3, 4.3.4

2.6.2 Audio resources

There may be a performance decrement when two tasks both require the auditory mode (Brucken, Plass & Leutner, 2004).

Also in: 4.2.3, 6.7.2

The visual sense dominates over audio and tactile resources (Arroyo & Selker, 2003).

Also in: 2.6.1, 2.6.3
The human audio system can relegate some sounds into background while still monitoring them (Simpson, Bolia, & Draper, 2004).

**Also in:** 3.4.2, 4.2.1

Sound has a natural role in actions involving mechanical impact and vibration, so auditory display should be used to augment virtual haptic interfaces (Adelstein, Begault, Anderson & Wenzel, 2003).

**Also in:** 4.6.3, 8.3, 8.4 AT

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

**Also in:** 3.7.4 AT, 3.7.4 TV, 4.5.3, 4.6.3, 5.2.2, 6.3.2

Both ears are important in the detection of speech, as the obstruction of the ear either closest to or farthest from the speech signal results in impaired performance. (Dirks & Wilson as cited in MacDonald, 2002).

Recent work in neural network modeling suggests that the use of a single ear to localize sounds is not enough to achieve a level of performance comparable to that of using both ears (Janko et al as cited in MacDonald, 2002).

Irrelevant sounds do not have to be presented at the same time as the material they corrupt. Disruption due to irrelevant sound is enduring (it does not habituate) (Banbury et. al., 2001).

**Also in:** 4.2.4

Access to foveal vision is very limited and can’t be easily shared in dual task situations (e.g., one can’t read two things at once); auditory processing is similar (e.g., one can’t listen to two speakers at once) (Wickens, 2000).

**Also in:** 2.6.1, 4.1.6, 4.2, 6.7

The sensory modality most affected by sensorimotor discord is the tactile sense (e.g., one can only touch things that are close, so touch is more local and intimate than vision or audition) (Durlach & Slater, 2000; as cited in Allison, Zacher, Wang & Shu, 2004).

**Also in:** 2.6.1, 2.6.3, 4.3.4

Left hemisphere specializations have been found for the perception of speech (Kimura, 1961, 1967), and for the temporal resolution of brief auditory stimuli (Brown & Nicholls, 1997). Right hemisphere specializations have been reported for pitch discrimination (Sidtis, 1981) and auditory space perception. (Altman, 1983; Altman, Balonov, & Deglin, 1979; Bisiach et al, 1984; Burke et al, 1994; as cited in Bolia, Nelson & Morley, 2001)

**Also in:** 6

### 2.6.3 Tactile resources
Human tactile resources are sensitive to location, duration, frequency, and amplitude. Information received via the tactile sense can always be readily received, draws attention, is private, and can be used in a natural and intuitive way. (Van Erp & Van Veen, 2004)

Also in: 2.1.3, 2.2.3

There is some evidence that performance decrements associated with tactile patterns (compared to visual patterns) is a consequence of the inferior acuity of skin compared to the visual system (Cholewiak, Collins & Brill, 2001).

Also in: 2.6.1, 4.3.1

The visual sense dominates over audio and tactile resources (Arroyo & Selker, 2003).

Also in: 2.6.1, 2.6.2

The tactile channel has an unlimited field of view (FOV), as opposed to the visual channel which has a field of view of 180 degrees. Therefore, tactile cues can be used to communicate information about parts of the field of view normally blocked in the visual channel. (Van Erp & Van Veen, 2004)

Also in: 2.6.1

The body’s sense of motion is inextricably linked to its sense of touch (O’Modhrain, 2004).

GP#:1215

The haptic sense is different from the visual sense in that it is localized to a small number of contact points with the external environment, is bi-directional in that it can both sense and interact with the world, it has very high resolution, and it is often socially-loaded.

Visualizations designed for the haptic sense should attempt to exploit the unique characteristics of the haptic sense rather than try to make visual standards fit haptic devices. (Wall & Brewster, 2005)

Also in: 2.1.3, 2.6.1, 2.7.1, 2.7.3

Touch, in comparison to other sensory modalities is more local and bidirectional which is linked to closeness and intimacy (sense of togetherness) (Durlach & Slater, 2000; as cited in Basdogan, 2000).

Also in: 2.1.3

Touch is a powerful signal for emotional content and can contribute to losses in subtle non-verbal communication cues—hapticons can strengthen meaning and expression (Rovers & van Essen, 2004).

Also in: 3.9.3, 4.3.1

Haptic interactions occur at two levels: (1) when contact occurs there is a net force (vector) experienced/generated by the user, and (2) the distribution of forces or tractions which occur at each contact site are perceived through the user’s mechanoreceptors, giving rise to the human tactile sense (Salisbury, Brock, Massie, Swarup & Zilles, 1995)

Also in: 2.2.3, 4.3

GP#:1571
Vision usually dominates the integrated visual-haptic percept; however, in some circumstances like judging an object’s texture, the combined percept is clearly affected by haptics (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

**Also in:** 2.6.1, 4.5.1

**GP:#1572**

Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation and vise versa (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

**Also in:** 2.6.1, 4.5.1

**GP:#1606**

The relationship between the values of haptic properties and perceived magnitude might be non-linear (Wall & Brewster, 2003).

**Also in:** 4.3

**GP:#1617**

Cutaneous sensation can transmit language, rates, amounts, directions, or anything falling on a unidimensional or bidimensional continuum (Geldard, 1960).

**GP:#1780**

The sensory modality most affected by sensorimotor discord is the tactile sense (e.g., one can only touch things that are close, so touch is more local and intimate than vision or audition) (Durlach & Slater, 2000; as cited in Allison, Zacher, Wang & Shu, 2004).

**Also in:** 2.6.1, 2.6.2, 4.3.4

### 2.6.4 Physical resources

Force feedback (gravity wells) can reduce the time it takes to point and click on targets on a computer screen. This is even more pronounced when fine motor ability is impaired (as may be the case when users are on a plane/tank/ship that vibrates). (Hwang, Keates, Langdon, & Clarkson, 2003)

**Also in:** 3.6.3, 4.3.3

**GP:#1200**

Driving a car requires some head motion, but most of the user’s time is spent looking forward and exercising his/her peripheral vision (Lantz, 1997).

**Also in:** 2.6.1, 3.3.1

**GP:#1376**

Wearing multifocal lenses may help the posture of an individual (more so than bifocal lenses), because they allow the user to raise their chin while looking at a computer terminal (Inoue, 2002).

**Also in:** 4.1, 5

**GP:#1391**

In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003)

**Also in:** 2.1.4 AV, 2.1.4 TV, 2.2.4 AV, 2.2.4 TV, 2.7.4 AV, 2.7.4 TV, 4.4.3, 4.5.3

**GP:#1517**

The following are kinesthetic interaction design guidelines based on psychophysical research: to ensure more accurate limb position, use active rather than passive movement; avoid minute, precise joint rotations, particularly at distal segments; minimize fatigue by avoiding static positions at or near the end range of
motion; surface stiffness of 400 Newtons per meter should effectively promote haptic information transfer; end-point forces of 3-4 Newtons should effectively promote haptic information transfer; add kinesthetic information to enhance objects’ spatial location; gestures should be intuitive and simple; minimize fatigue by avoiding frequent, awkward, or precise gestures; and avoid precise motion gestures, as making accurate or repeatable gestures with no tactile feedback is difficult. (Hale & Stanney, 2004)

Also in: 2.2.3, 2.7.3, 4.3.2

GP#:1705

Posture adopted to view any target represents a compromise between visual and musculoskeletal demands (Burgess-Limerick et al., 2000).

Also in: 2.6.1

GP#:1781

The hand (or other effector) is both a sensor and an end-effector; thus, a haptic device is typically a display and an input device. In a real environment, this input-output pairing implies a lawful synchrony between user actions and sensory feedback. (Allison, Zacher, Wang & Shu, 2004)

Also in: 2.7.4, 4.3.4

GP#:1783

The human motor system has remarkable ability to adapt to changing relations between sensory input and motor output (Allison, Zacher, Wang & Shu, 2004).

Also in: 2.7.5

2.7 General Cues Issues

2.7.1 Visual modality

Reducing the resolution of the visual display to that of the tactile display results in higher root-mean-square (RMS) errors and longer tracking delays. However, even when resolution effects are taken into account, visual tracking performance is still better than tactile tracking performance. (Van Erp & Verschoor, 2000)

Also in: 2.7.3, 3.6.1, 3.6.3, 4.1.3

GP#:1140

Audio is not as prevalent as tactile with regards to data analysis and inspection when visual information is absent (Ramloll, Yu, Brewster, Riedel, Burton, & Dimigen, 2000).

Also in: 2.7.2, 2.7.3, 3.11, 4.7.1 ATV

GP#:1219

In the real world there are “natural cues,” but things are more complicated in a three-dimensional display: it is hard to achieve the same understanding with a scaled down version of the real world and a limited field of view. It is difficult for the operator to perceive distance, altitude, sizes, etc. in a limited field of view because of scaling problems, abstract object design, and the limited number of natural cues. However, in some tasks, such as landing, display size and field of view have less of an impact. (Comstock, Glaab, Prinzel & Elliot, 2001; as cited in Andersson & Alm, 2002)

Also in: 3.8.1, 4.1.2, 4.1.4

GP#:1222

When multiple information is presented visually, it must be processed serially, rather than in parallel (Sarter, 2000).

Also in: 6.7.1

GP#:1250

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)
Performance on tasks using Visual Visual with tactile input (VVt) was significantly better than Tactile Visual (TV), Tactile Tactile with visual input (TTv), and Tactile Tactile (TT). The results suggest that bilateral posterior portion of the intraparietal sulcus is involved in the integration of visual and tactile sensory information. (Saito et al., 2003)

Auditory signals are detected more quickly than visual signals and tend to produce an alerting or orienting response (Wourms, Mansfield, & Cunningham, 2001).

The haptic sense is different from the visual sense in that it is localized to a small number of contact points with the external environment, is bi-directional in that it can both sense and interact with the world, it has very high resolution, and it is often socially-loaded.

Visualizations designed for the haptic sense should attempt to exploit the unique characteristics of the haptic sense rather than try to make visual standards fit haptic devices. (Wall & Brewster, 2005)

By presenting information multimodally (A-V) with a visual distraction did better than expected vs. Visual only. (A-V) presentation of text based and picture based learning materials induced less cognitive load than visual only presentation of the same materials. (Brünken et al., 2004)

Visual perception of objects automatically recruits semantic knowledge about related objects (Postle, D’Esposito & Corkin, 2005).

Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information (Tsukada & Yasumura, 2004)

Without a perceptual border indicating region to be attended to, the user’s attention may actually spread to the entire visual hemifield in which the attended position is located (Hughes & Zimba, 1985; as cited in Haimson & Anderson, 2002).
Observers find it difficult to follow a prescribed path of saccades through dense arrays of symbols (Hooge & Erkelens, 1998; as cited in Haimson & Anderson, 2002)

Also in: 4.1.4, 7.1.1

A smaller map with a wide field of view (FOV) displayed in the corner of a 3D map display can reduce tunnel vision (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 4.1.2, 4.1.4, 6.4.1

Velocities below 40 degrees/sec have no practical impact on visual performance, but performance degradation does occur at higher speeds (Long & Zovod, 2002).

Increased contrast, in a visual display, is known to increase visual acuity (Heath 1956, Legge et al. 1987), image clarity (Poynter 1992), saccadic length (Roufs et al 1988) and comfort (Roufs et al 1991; as cited in Sheedy et al., 2003).

Also in: 4.1.1, 4.1.3, 7.1.1

Decreased luminance in a visual display has been shown to cause a decrease in visual acuity (Sheedy et al, 2003).

Also in: 4.1.1

When a north-up map is employed for primary/secondary navigational display, it’s beneficial to provide a visual momentum wedge to depict the user’s momentary direction of gaze and viewing angle on the represented world (on the map) (Olmos, Liang & Wickens, 1997).

Also in: 3.2.1, 4.1.4, 4.1.5

Tactile hallucinations (though less prevalent in manifestation) of size often accompany stronger visual hallucinations of size (Halpern, 1959).

Also in: 2.7.3, 2.7.4 TV, 6.2.4 TV

Visual perception of size has a dynamic character and is combined with a simultaneous similar disturbance in the sphere of the brain that processes tactile input (Halpern, 1959).

Also in: 2.7.3, 2.7.4 TV

Visibility in the visible spectrum doesn’t necessarily follow in the IR spectrum (Freeman, 2002).

In visual displays, the benefits of reduced scanning outweigh the cost of clutter (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 3.6.1, 4.1.4

Inappropriate screen cues can have a significant effect on 3D percepts, and the size of that effect depends strongly on viewing condition (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

Also in: 4.1.4
The following hypotheses have been posited on the Illusions of Visual Bandwidth: people might overestimate how much visual information can be attended to simultaneously; designers overestimate the number of locations that a user will typically attend to; and people may overestimate the representational consequences for having attended to an object or location. (Varakin, Levin, & Fidler, 2004)

Also in: 4.1, 6.3.1, 6.6.1

When designing or using a gaze-contingent multiresolutional display, there is always a tradeoff between computation & bandwidth savings and decrements in perception & performance (Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 4.1.3

The inherent multi-dimensionality of sound in time, timbre and space often renders it to be the preferred means of transmission of data, information, and alerts in human-computer interfaces. By using auditory displays, numerous streams of data can be presented concurrently, offloading the visual system to perform other tasks. (Roginska, 2004)

Also in: 2.7.2, 3.1.2, 4.2, 4.8.1, 6.7.2

Time-sharing/dual task performance was found to be most efficient in a multimodal condition (e.g., visual in one ear, computer screen on opposite side), which is consistent with Wickens (1980). The finding is complicated because visual intramodal task performance was nearly as good as intermodal task performance, and auditory intramodal task performance was relatively poor compared to the other two conditions. Support was also found for parallel processing. (Rojas, 1996)

Also in: 2.7.2, 2.7.4 AV, 6.7.2

Single-cue information is lost when cues from within the same sensory modality (e.g., disparity and texture gradients in vision) are combined, but not when different modalities (vision and haptics) are combined (Hillis, Ernst, Banks & Landy, 2002).

Also in: 2.7.4 TV, 4.1

Haptic and visual signals for object size do not always come from the same object (e.g., touching one object while looking at another); mandatory combination of haptic and visual cues would be misleading in such cases (Hillis, Ernst, Banks & Landy, 2002).

Also in: 2.7.3, 2.7.4 TV

In a within-modal case, texture and disparity cues at the same retinal location almost always come from the same object. Thus, mandatory cue combination would be beneficial if errors in the texture and disparity estimates were a more likely cause of discrepancy than actual signal differences. Therefore, there would be evolutionary or developmental pressure to relay on the combined estimate, instead of the single-cue estimates. (Hillis, Ernst, Banks & Landy, 2002)

Also in: 4.1

The nervous system combines visual and haptic information similar to a minimum likelihood integrator. Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation. (Ernst & Banks, 2002)

Also in: 2.7.3, 2.7.4 TV, 6
No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing. (Tannen, 2000)

Also in: 1.2.2, 2.7.2, 3.6.1, 3.8.4 AV, 4.1, 4.2

GP#: 1707

Spatial orientation improves when the ambient visual modality is stimulated with a peripheral image (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.6

GP#: 1767

The point of subjective simultaneity (PSS) shifts towards visual delays when attention is directed to a visual cue, and towards haptic delays when participants direct attention to a haptic stimulus (Vogels, 2001).

Also in: 2.7.3, 2.7.4 TV, 4.5.2, 6.3.1, 6.3.3

GP#: 1800

(Hale & Stanney, 2004)

Also in: 2.7.3, 3.11, 4.1, 4.3, 4.9, 8.3, 8.6, 8.7
<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
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</table>
| Graphics           | Graphics are better than text or auditory instructions for communicating spatial information:  
  • Use graphics to illustrate components (e.g., equipment diagram) or spatial relationships (e.g., map, floor plan) and to clarify concepts/complex tasks (Williams, 1998).  
  • Combine graphics with text to improve comprehension (European Telecommunications Standards Institute, 2002). |
| Text               | Text may be used to convey detailed long information, procedures, instructions, labels, annotations, and clarifications (Wetzel, Radtke, & Stern, 1994).                                                                 |
| Animation          | • Animation may be effectively used as a redundant visual cue (Park & Hopkirs, 1993).  
  • Use motion to enhance detection of objects in periphery or overcome poor illumination.  
  • Use animation to demonstrate sequential actions in procedural tasks.                                                              |
| General layout     | Use “Gestalt Rules” to increase users’ understanding of relations between elements (Palmer, 1992):  
  • Place related objects close together.  
  • Enclose related objects by lines or boxes.  
  • Move or change related objects together.  
  • Related objects should look alike (e.g., shape, color, size or typography).                                                                 |
| Color              | • Use color to aid visual search, indicate state, draw attention, communicate qualitative/quantitative differences (Post, 1997).  
  • Design displays that require relative judgment via color (“differentiation tasks”); avoid absolute judgment (“recognition tasks”) via color (Sanders & McCormick, 1993). |
| Group relations    | Use numbered lists to show groups of related items, with a specific order (Watzman, 2003).  
  • Use flow charts to show relationships/steps involved in a process.  
  • Use tables to show relationships between categories of ideas.  
  • Use project plan tables to show relationships of tasks over time.                                                                 |
| Evaluate and       | Use rating tables to evaluate items against several criteria (Watzman, 2003).  
  • Use comparison tables to evaluate items against one criteria.  
  • Use matrix graphs to compare more than one item to more than one variable.  
  • Use bar charts to compare several things in relation to one variable.  
  • Use pie charts to compare relative parts that make up a whole.                                                                 |
| Hierarchy concepts | Use organizational charts to show hierarchical structure (Watzman, 2003).  
  • Use illustrations and/or text to show basic concepts.  
  • Use illustrations with text and/or icons, other graphics, complex images, interactive components to show abstract concepts. |
| 2D/3D              | • To extract critical information use 2D graphs, as users often perform better with respect to accuracy and ease (Watzman, 2003).  
  • Incorporate 3D into graphics to enhance aesthetics.                                                                                   |

*Note.* 2D = two-dimensional; 3D = three-dimensional.

Also in: 4.3
2.7.2 Audio modality

Audio is not as prevalent as tactile with regards to data analysis and inspection when visual information is absent (Ramloll, Yu, Brewster, Riedel, Burton, & Dimigen, 2000).

Also in: 2.7.1, 2.7.3, 3.11, 4.7.1

Tactile and audio cues may be good for alerts of status change (compared to visual) because they’re omnidirectional (don’t require a particular head orientation) and can be used to guide attention to a particular location in the cockpit. The downside is that audio cues are hard to suppress, making them less desirable for non-emergency cues

Tactile cues can effectively communicate information on airspeed, angle of attack, energy state, and other flight parameters (Zlotnick, 1988; as cited in Sarter, 2001), but may impede performance on other tasks (Gilliland & Schlegel, 1994; as cited in Sarter, 2001).

Also in: 3.1.1, 3.1.2, 3.1.3, 3.8.1, 3.8.2, 3.8.3, 4.2.3

Auditory signals are detected more quickly than visual signals and tend to produce an alerting or orienting response (Wourms, Mansfield, & Cunningham, 2001).

Also in: 2.5.1, 2.5.2, 2.7.1, 3.1.1, 3.1.2

Advantages of audio displays (compared to visual displays) for alarms: audio alarms are naturally interpreted as a warning signal, have faster neural transmission compared to visual (especially important for time-critical warnings). (Mowbray & Gebhard, 1969; as cited in Simpson, Bolia, & Draper, 2004)

Verbal communication is often the most direct/efficient/unambiguous method of information transfer; it allows information exchange regarding events that are now in the visual field (Simpson, Bolia, & Draper, 2004).

Also in: 3.1.1, 3.1.2, 3.9.2, 6, 5.3.2

Auditory cues are considered essential for maintaining a strong sense of presence (the world seems “dead” without sound) (Simpson, Bolia, & Draper, 2004).

Also in: 6.4.2

Users tend to rely on a sound’s onset as the cue, rather than other features occurring later in a signal (Adelstein, Begault, Anderson & Wenzel, 2003).

Also in: 4.2, 5.2.2

Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

Also in: 2.7.1, 2.7.4, 2.7.4 AV, 3.11, 4.9, 5.2.5

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information. (Tsukada & Yasumura, 2004)
Separating sounds in both real and virtual spaces has been shown to increase the intelligibility of speech paired with a noise masker (Doll & Hanna as cited in MacDonald et al., 2002).

Spoken words like “deadly, danger and lethal” are rated as more arousing than words like “warning or caution” (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Female voices seem to connote more urgency than male voices for conveying warnings. If a male or female voice is synthesized, the gender effect of the speaker seems to disappear (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Changes in all three acoustic parameters produce steeper changes than do changes in just one or two of them (Hellier, Edworth, Weedon, Walters, Adams, 2002).

It is possible to imbue urgency into synthesized speech warnings simply through the use of the three major acoustic parameters (Hellier, Edworth, Weedon, Walters, Adams, 2002).

The inherent multi-dimensionality of sound in time, timbre and space often renders it to be the preferred means of transmission of data, information, and alerts in human-computer interfaces. By using auditory displays, numerous streams of data can be presented concurrently, offloading the visual system to perform other tasks. (Roginska, 2004)

Time-sharing/dual task performance was found to be most efficient in a multimodal condition (e.g., visual in one ear, computer screen on opposite side), which is consistent with Wickens (1980). The finding is complicated because visual intramodal task performance was nearly as good as intermodal task performance, and auditory intramodal task performance was relatively poor compared to the other two conditions. Support was also found for parallel processing. (Rojas, 1996)

No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing (Tannen, 2000).
Without supplementary visual cueing, virtual auditory cueing led to increased detection rates and decreased detection times, and to reductions in subjective workload. It also improved the efficiency of search patterns (Cunningham et. al., 1995; Cunningham et. al., 1998; as cited in Tannen, 2000).

Also in: 3.6.2, 6.6.2

Stanney et. al., 2004

<table>
<thead>
<tr>
<th>Table 2: Auditory Design Guidelines</th>
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</thead>
<tbody>
<tr>
<td><strong>Presentation</strong></td>
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<td>General–thresholds</td>
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(Continued)
Tactile modality

Tactile information is often perceived as single stimulus when two tactile stimuli are presented simultaneously. Do we get the same effect when pairing tactile stimuli with other modes?
Interface designers need to consider the range of textural information available. Simulating large textures can inhibit the user’s movements so much that their ability to stay on the textured surface is negatively affected. (McGee, Gray & Brewster, 2001)

Continuous tactile displays are better than discrete. Differences for separate directions are smaller for continuously shifting stimuli, than for discretely shifting stimuli. (Shimizu & Wake, 1982; as cited in van Erp & Verschoor, 2004)

Reducing the resolution of the visual display to that of the tactile display results in higher root-mean-square (RMS) errors and longer tracking delays. However, even when resolution effects are taken into account, visual tracking performance is still better than tactile tracking performance. (Van Erp & Verschoor, 2000)

A static surround may allow for the spread of surface waves but will not pass through deeper tissues, where many of the cutaneous receptors lie (e.g., hairy skin). The velocity of traveling waves in the human skin not only depends on the viscoelastic properties of the skin itself, but also on factors as varied as vibration frequency, skin temperature, and whether underlying tissue is bone, fat, muscle, or a combination. (Cholewiak, Collins & Brill, 2001)

Audio is not as prevalent as tactile with regards to data analysis and inspection when visual information is absent (Ramloll, Yu, Brewster, Riedel, Burton, & Dimigen, 2000).

Tactile and audio cues can be processed in parallel (Sarter, 2000).

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)

Performance on tasks using Visual Visual with tactile input (VVt) was significantly better than Tactile Visual (TV), Tactile Tactile with visual input (TTv), and Tactile Tactile (TT). The results suggest that bilateral posterior portion of the intraparietal sulcus is involved in the integration of visual and tactile sensory information. (Saito et al., 2003)

The haptic sense is different from the visual sense in that it is localized to a small number of contact points with the external environment, is bi-directional in that it can both sense and interact with the world, it has very high resolution, and it is often socially-loaded.
Visualizations designed for the haptic sense should attempt to exploit the unique characteristics of the haptic sense rather than try to make visual standards fit haptic devices. (Wall & Brewster, 2005)

**Also in:** 2.1.3, 2.6.1, 2.6.3, 2.7.1

**GP#**:1339

Interacting cognitive subsystems (ICS) theory suggests that information flows in a highly parallel and modular architecture of distributed cognitive resources. It takes into account cognition and affect simultaneously.

Haptic info can access the level of meaning in a relatively direct manner (within the framework of ICS). Representations can be related to the active aims and goals of the perceiver. (Booth & Schmidt-Tjørksen, 2001)

**Also in:** 6.7

**GP#**:1340

Sense of touch may actually be dependent on diverse cognitive resources (high level knowledge), availability of cues for object identification, perceptual bias by other modalities (4, 5, 6) and cross modal attention. (Interacting cognitive subsystems theory). (Booth & Schmidt-Tjørksen, 2001)

**Also in:** 3.6.3, 6.2.3, 6.3.3

**GP#**:1405

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information. (Tsukada & Yasumura, 2004)

**Also in:** 2.7.1, 2.7.2, 3.11, 4.1, 4.2, 4.3, 6.7

**GP#**:1486

The perception of surface shape, compliance, texture, and friction can all be evoked through proper modulation of the net force exerted on the user (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

**Also in:** 2.2.3, 4.3

**GP#**:1487

A haptic rendering system must be able to give the sensation of free space (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

**Also in:** 4.3

**GP#**:1489

The sensation of sustained contact with a virtual surface requires that the user be able to push into the virtual surface and experience compressive contact forces of sufficient magnitude, to make it feel solid (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

**Also in:** 4.3, 8.3

**GP#**:1490

Imposing tangential forces on users while they stroke a virtual surface adds an important sense of realness to perception of objects (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

**Also in:** 4.3, 8.3

**GP#**:1498

Tactile hallucinations (though less prevalent in manifestation) of size often accompany stronger visual hallucinations of size (Halpern, 1959).

**Also in:** 2.7.1, 2.7.4 TV, 6.2.4 TV

**GP#**:1499
Visual perception of size has a dynamic character and is combined with a simultaneous similar disturbance in the sphere of the brain that processes tactile input (Halpern, 1959).

Also in: 2.7.1, 2.7.4 TV

When using vibrotactile devices to transmit symbols, a scanning technique works better than whole symbol exposure (Loomis, 1974; as cited in Sherrick 1991).

Also in: 4.3

People are better able to discriminate changes in friction in standard surfaces than changes in stiffness or texture (Wall & Brewster, 2003).

Also in: 2.4.3

In tactile tasks, people can detect negative changes between a reference stimulus and a target stimulus better than positive changes (Wall & Brewster, 2003).

Also in: 2.4.3

Tacticion is a good break in sense; cutaneous sensations are highly attention demanding, thus they may be good for emergency messages (Geldard, 1960).

Also in: 3.1.3, 6.3.3

Unlike static pressure, mechanical vibration, when applied to the skin, does not stay within bounds unless something is in place to prevent its spread (Geldard, 1960).

Also in: 4.3.1

Electricity is the great “nonadequate” stimulus - it triggers everything (Geldard, 1960).

The following are kinesthetic interaction design guidelines based on psychophysical research: to ensure more accurate limb position, use active rather than passive movement; avoid minute, precise joint rotations, particularly at distal segments; minimize fatigue by avoiding static positions at or near the end range of motion; surface stiffness of 400 Newtons per meter should effectively promote haptic information transfer; end-point forces of 3-4 Newtons should effectively promote haptic information transfer; add kinesthetic information to enhance objects’ spatial location; gestures should be intuitive and simple; minimize fatigue by avoiding frequent, awkward, or precise gestures; and avoid precise motion gestures, as making accurate or repeatable gestures with no tactile feedback is difficult. (Hale & Stanney, 2004)

Also in: 2.2.3, 2.6.4, 4.3.2

The following are psychophysical tactile interaction design guidelines based on psychophysical research: (1) Haptic input must consider sensitivity to stimuli across various skin locations (for example, the two-point threshold grows smaller from palm to fingertips, where spatial resolution is about 2.5 mm on the index finger tip (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (2) To ensure that receptors perceive individual cutaneous signals, stimuli must be at least 5.5 ms apart (Sherrick & C.Holewiak, 1986 as cited in Hale & Stanney, 2004); (3) To successfully activate an individual’s pressure sensors, the force exerted must be greater than 0.06-0.2 Newtons per cm (Sherrick & Cholewiak, 1986; Biggs & Srinivasan, 2002, both as cited in Hale & Stanney, 2004); (4) Pressure limits depend on body loci and gender. Just-noticeable values range from 5 milligrams on a woman’s face to 355 mg on a man’s big toe (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (5) Vibration from a single probe must exceed 28 decibels (relative to a 1-microsecond peak) for 0.4-3 Hz frequencies for humans to perceive
(Biggs & Srinivasan, 2002, as cited in Hale & Stanney, 2004); (6) For a user to feel a hard surface after initial contact, the haptic system must maintain active pressure; (6) Maintaining the sensation of textured surfaces requires relative motion between the surface and the skin.

Also in: 2.1.3, 2.2.3, 4.3.2

GP#:1651

Haptic and visual signals for object size do not always come from the same object (e.g., touching one object while looking at another); mandatory combination of haptic and visual cues would be misleading in such cases (Hillis, Ernst, Banks & Landy, 2002).

Also in: 2.7.1, 2.7.4 TV

GP#:1653

The nervous system combines visual and haptic information similar to a minimum likelihood integrator. Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation. (Ernst & Banks, 2002)

Also in: 2.7.1, 2.7.4 TV, 6

GP#:1694

Two common techniques to generate vibration are: (1) based on a moving coil or (2) on a DC motor with an eccentric weight mounted on it (Van Erp, 2002).

Also in: 4.3.1

GP#:1697

Detection and percept of a stimulus is effected by the waveform (Van Erp, 2002).

Also in: 4.3

GP#:1701

Simultaneous or sequential presentation of multiple tactile messages on the same display can result in tactile clutter and reduced comprehension (Van Erp, 2002).

Also in: 4.3, 6.6.3

GP#:1703

The following design pitfalls should be avoided: spatial masking – location of stimulus is masked by another stimulus; temporal enhancement – affects subjective magnitude of second stimulus (temporal masking and adaptation are other temporal effects to consider); stimuli presented closely in time and space can alter the percept and may even result in a completely new percept (related to apparent motion). (Van Erp, 2002)

Also in: 2.1.3, 2.3.3, 4.3

GP#:1750

Soldiers appreciate tactile navigation system for its ease of use and enabling of eyes-free and hands-free navigation (Elliott et. al., 1997).

Also in: 3.2.3, 5.5.3, 7.1.3

GP#:1767

The point of subjective simultaneity (PSS) shifts towards visual delays when attention is directed to a visual cue, and towards haptic delays when participants direct attention to a haptic stimulus (Vogels, 2001).

Also in: 2.7.1, 2.7.4 TV, 4.5.2, 6.3.1, 6.3.3

GP#:1800
<table>
<thead>
<tr>
<th>Benefit</th>
<th>Visual Display (VD)</th>
<th>VD + Tactile Interface</th>
<th>VD + Positional Actuator</th>
<th>VD + Probe-Based (Force Feedback) System</th>
<th>VD + Exoskeleton System</th>
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</thead>
<tbody>
<tr>
<td><strong>Tactile perception</strong></td>
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<tr>
<td>Texture Perception</td>
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<td></td>
<td></td>
<td>Possible to judge with same accuracy as when using fingertip</td>
<td>If tactile actuators are present in fingertips, possible to judge texture</td>
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<tr>
<td>(hard/soft, smooth/rough, and so on)</td>
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<tr>
<td><strong>2D form perception</strong></td>
<td></td>
<td>Relative depth in field of view (FOV)</td>
<td>Tactile can be ignored when irrelevant Cross-modal cueing effects useful</td>
<td>Not useful</td>
<td>If tactile actuators are present in fingertips, possible to judge 2D form perception</td>
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<tr>
<td>(spatial acuity, pattern recognition, curvature perception, and so on)</td>
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<tr>
<td><strong>Kinesthetic perception</strong></td>
<td></td>
<td>Relative depth of objects in FOV</td>
<td>Allow egocentric frame of reference within personal space Gestures used to navigate environment Kinesthetic target location has less decay than visual target location</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
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<tr>
<td>Spatial awareness/position (for example, objects in environment, limb with respect to trunk, body with respect to environment)</td>
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<td>Visual proprioception within FOV</td>
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<tr>
<td><strong>3D form perception</strong></td>
<td>Identification and discrimination depend on viewing angle No indication of weight</td>
<td>Deformability through force feedback aid discrimination and identification Adding force to virtual scene increases presence</td>
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<tr>
<td>(length discrimination, weight, and shape identification, for example)</td>
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(Hale & Stanney, 2004)
Also in: 2.7.1, 3.11, 4.1, 4.3, 4.9, 8.3, 8.6, 8.7

GP#:1804
(Stanney et. al., 2004)
### Table 3: Haptic Design Guidelines

<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
</table>
| Tactile               | * Vibrotactile sense is comparable in discriminatory ability to audition for frequencies up to about 50 Hz (Miller & Zeleznik, 1999; Sherrick & Cholewiak, 1986).  
                        | * Detection of vibration for a single probe is about 28 dB (relative to 1 μV peak) for 0.4 to 3 Hz.  
                        | * To ensure user perceives individual signals, stimuli must be separated by at least 5.5 msec and preferably > 10 msec.  
                        | * To successfully activate a user’s pressure sensors, force exerted must be > 0.06 to 0.2 N/cm².  
                        | * Humans can detect pressure variations up to .0002 in per 100 msec, with an optimal response at 400 Hz, and loss of sensitivity below 50 Hz and above 600 Hz.  
                        | * Tactile input must consider sensitivity to stimuli across various skin locations (i.e., 2-point threshold becomes smaller from palm to fingertips).  
                        | * Spatial resolution of a point stimulus on finger pad is about 0.15 mm and for a 2-point limen about 1 mm.  
                        | * Amplitudes above 0.6 mm to 0.8 mm are painful.  
                        | * Humans can detect presence of a 2 μm high single dot and a 0.075 μm high grating.  
                        | * Be aware that surface characteristics of a stimulus influence sensation of touch.  
                        | * Avoid use of tactual displays in low temperature environments because tactual sensitivity is degraded.  |
| Alerts and warnings    | Tactile cues can provide effective alerts via vibrations or variations in pressure: they can be augmented by or substituted for auditory warning cues (e.g., automatic alerts, reception of coded messages such as Braille; Posner, 1976):  
                        | * If using tactile cues for warnings, it is important to note humans can identify about four haptic intensities, about five durations, and about nine different frequencies (20% difference needed between levels; Geldard, 1972).  |
| Tactile localization   | Tactile cues can be augmented by or substituted for visual tasks to aid localization (e.g., identification of controls, tactual maps as navigation aids, tracking task displays):  
                        | * Humans can detect about seven haptic locations on the chest (Geldard, 1972).  
                        | * Use distal body parts if high spatial resolution is required (above 4 cm any body part can be used; Sherrick & Cholewiak, 1986).  
                        | * Tactile input can be incorporated into complex applications to provide orientation/direction (Rupert, 1997).  
                        | * Tactile location cues (e.g., up or down) can resolve spatial disorientation.  
                        | * To convey movement, one can leverage the spatiotemporal illusion of movement (i.e., sensory saltation) using 3 to 6 mechanical sensors placed no greater than 10 cm apart along the back, which emit vibratory pulses with an interstimulus duration of 50 msec (Sherrick & Cholewiak, 1986).  |

(continued)
<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture, softness,</td>
<td>Tactile cues can be used to convey properties of simple objects (complex objects require multimodal presentation; Popescu, Burdea, &amp; Treffitz, 2002):</td>
</tr>
<tr>
<td>surface viscosity</td>
<td>• Sensation of textured surfaces requires some relative motion between surface and skin to be maintained.</td>
</tr>
<tr>
<td></td>
<td>• For a hard surface to be felt after initial contact active pressure must be maintained.</td>
</tr>
<tr>
<td></td>
<td>• Soft surfaces exert and maintain a slight positive reaction against the skin after the initial contact without active pressure or relative motion.</td>
</tr>
<tr>
<td>Kinesthetic</td>
<td>Kinesthetic cues can stimulate anticipation of a change, provide feedback confirming reception of a user input, provide an indication of current state, guide user interaction toward a desired position or location, make clear distinctions between orthogonal directions, and aid discrimination (e.g., length) and identification (e.g., shape; Miller &amp; Zeleznik, 1999):</td>
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<tr>
<td></td>
<td>• To maintain optimal hand–eye coordination, the delay (i.e., lag) between sensing and kinesthetic feedback should be less than 100 msec.</td>
</tr>
<tr>
<td></td>
<td>• When interacting with objects, allow adequate time for users to respond kinesthetically (minimum 250 msec for simple reaction time).</td>
</tr>
<tr>
<td></td>
<td>• Avoid static positions at or near end range of motion to reduce fatigue.</td>
</tr>
<tr>
<td>Gestures</td>
<td>Gestures can be used to communicate meaningful information in isolation (e.g., hand signals) or in combination with speech and/or visual information (e.g., ‘put that there,’ Oviatt, 1997; Turk, 2002):</td>
</tr>
<tr>
<td></td>
<td>• Adding gesture to speech offers speed, high-bandwidth information, flexibility of input modes, enhanced error avoidance, and relative ease of use.</td>
</tr>
<tr>
<td></td>
<td>• Gestures should be intuitive and simple; avoid increasing user’s cognitive load with numerous or complex gestures.</td>
</tr>
<tr>
<td></td>
<td>Gestures can be used to manipulate the environment (Oviatt, 1997; Turk, 2002). Gestures are a natural, flexible input mode, and can effectively be used for control and navigation:</td>
</tr>
<tr>
<td></td>
<td>• Avoid temporal segmentation of gestures.</td>
</tr>
<tr>
<td></td>
<td>• Avoid frequent, awkward, or precise gestures to minimize user fatigue.</td>
</tr>
<tr>
<td></td>
<td>• Gestures can be effectively used for spatial tasks (e.g., resizing, moving objects; Popescu et al., 2002, Turk, 2002):</td>
</tr>
<tr>
<td></td>
<td>• Inform user of types of for which gestures allowed and what affect each will have on system interaction.</td>
</tr>
<tr>
<td></td>
<td>• Avoid precise motion gestures, as it is difficult to make highly accurate or repeatable gestures with no tactile feedback.</td>
</tr>
<tr>
<td>Kinesthetic localization</td>
<td>Kinesthetic cues (e.g., movement cues, impedance) can aid spatial location memory (Popescu et al., 2002):</td>
</tr>
<tr>
<td></td>
<td>• Kinesthetic is best coupled with other modalities to aid location memory of objects in space relative to one’s location.</td>
</tr>
</tbody>
</table>
2.7.4 Multimodal (AV, AT, TV, ATV)

Multimodal interfaces should be able to flex and adapt to handle natural environmental fluctuations like power outages or being damaged (Oviatt et al., 2004).

It has been suggested that the more properties shared between two modalities, the stronger the observer’s unity assumption that information from different sensory channels can be attributed to the same distal event or object [14]. These properties include spatial location, motion, temporal patterning or rate [15], all of which can be impacted by temporal asynchrony in a multimodal display system. (Adelstein, Begault, Anderson & Wenzel, 2003)

Synesthesia occurs when a person receives stimuli via one sensory channel, but he/she perceives it along another sensory channel (e.g., A person may see objects of a particular shape, but perceive the shapes as tasting differently) (Loftin, 2003).

Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

When information must be combined from various sources located at different points in space (e.g., information from two maps), or different points in time (e.g., panning), or both, the composite mental picture will be less accurate than when all information is available in a single source (Wickens, Thomas, & Young, 2000).
The point of subjective simultaneity (PSS) shifts towards visual delays when attention is directed to a visual cue, and towards haptic delays when participants direct attention to a haptic stimulus (Vogels, 2001).

The hand (or other effector) is both a sensor and an end-effector; thus, a haptic device is typically a display and an input device. In a real environment, this input-output pairing implies a lawful synchrony between user actions and sensory feedback. (Allison, Zacher, Wang & Shu, 2004)

By presenting information multimodally (A-V) with a visual distraction did better than expected vs. Visual only. (A-V) presentation of text based and picture based learning materials induced less cognitive load than visual only presentation of the same materials. (Brünken et al., 2004)
Haptic-audio combination has not been explored to a large extent, studies most focus on visual-auditory (see [10] for concise summary). The temporal thresholds are very high for visual-haptic asynchrony. (Adelstein, Begault, Anderson & Wenzel, 2003)

**Also in:** 2.7.4 AT, 4.5.2

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Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

**Also in:** 2.7.1, 2.7.2, 2.7.4, 3.11, 4.9, 5.2.5

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In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment task. (Spence, Baddeley, Zampini, James, and Shore, 2003)

**Also in:** 2.1.4 AV, 2.1.4 TV, 2.2.4 AV, 2.2.4 TV, 2.6.4, 2.7.4 TV, 4.4.3, 4.5.3

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Time-sharing/dual task performance was found to be most efficient in a multimodal condition (e.g., visual in one ear, computer screen on opposite side), which is consistent with Wickens (1980). The finding is complicated because visual intramodal task performance was nearly as good as intermodal task performance, and auditory intramodal task performance was relatively poor compared to the other two conditions. Support was also found for parallel processing. (Rojas, 1996)

**Also in:** 2.7.1, 2.7.2, 6.7.2

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Visual and audio (redundant) cues can result in reduced visual scanning in a tracking task, compared to a visual-only display (Seagull, 2002).

**Also in:** 2.7.4-AV, 3.4.1, 3.4.4-AV, 3.6.1, 3.6.4-AV

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The addition of spatialized sound to visual cueing reduced target designation time comparison to visual only; this occurred under conditions in which targets were really difficult to detect (e.g., ground targets initially outside FOV). The time advantage for fixed and adaptive multimodal cueing was 824 msec. (Tannen, 2000)

**Also in:** 2.1.2, 3.6.1, 3.6.4 AV, 4.1.6

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No advantage was found for presenting multimodal info (e.g., spatialized audio and visual) adaptively over presenting it in fixed format (Tannen, 2000).

**Also in:** 3.8.4 AV

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- **AT**

Results suggest that the posterior portion of the intraparietal sulcus (PIP), close to the parieto-occipital sulcus, is involved in the integration of visual and tactile sensory information (Saito, Okada, Morita, Yonekura, and Sadato, 2003).

**Also in:** 6

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Tactile and audio cues can be processed in parallel (Sarter, 2000).
Research on multimodal haptic-audio perceptual performance points to the benefit of deliberately adding sound to haptic interfaces [3, 7, 8, 9]. Specifically modeling and simulating sounds from physics that arise in response to real and virtual mechanical interactions [2, 5]. (Adelstein, Begault, Anderson & Wenzel, 2003)

Haptic-audio combination has not been explored to a large extent, studies most focus on visual-auditory (see [10] for concise summary). The temporal thresholds are very high for visual-haptic asynchrony. (Adelstein, Begault, Anderson & Wenzel, 2003)

• TV

Visual cues frequently dominate when visual and haptic cues are provided (Hale & Stanney, 2004).

Visual displays enhanced with tactile feedback or haptic interfaces seem to enhance performance (Ho, Nikolic, Waters, & Sarter, 2004).

Performance on tasks using Visual Visual with tactile input (VVt) was significantly better than Tactile Visual (TV), Tactile Tactile with visual input (TTv), and Tactile Tactile (TT). The results suggest that bilateral posterior portion of the intraparietal sulcus is involved in the integration of visual and tactile sensory information. (Saito et al., 2003)

Adding tactile/proprioceptive cues to visual cues can allow users to expand their geometric field of view without significantly distorting distance perception (Yang & Kim, 2004).

Tactile hallucinations (though less prevalent in manifestation) of size often accompany stronger visual hallucinations of size (Halpern, 1959).

Visual perception of size has a dynamic character and is combined with a simultaneous similar disturbance in the sphere of the brain that processes tactile input (Halpern, 1959).

In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003)
Confusion and control instabilities in the multimodal system can be minimized by avoiding time lags between visual and haptic loops (Hale & Stanney, 2004).

Also in: 4.5, 6.6.4

Cross-modal cueing effects used within multimodal displays should follow an external spatial frame-of-reference (posture-independent) model rather than a hemispheric (anatomical) model (Hale & Stanney, 2004).

Also in: 6.2.4 TV

If touch is potentially response-relevant, vision and touch stimuli can become cognitively linked, which may hinder the effectiveness of conveying additional information tactually (Hale & Stanney, 2004).

Also in: 6.2.4 TV

Single-cue information is lost when cues from within the same sensory modality (e.g., disparity and texture gradients in vision) are combined, but not when different modalities (vision and haptics) are combined (Hillis, Ernst, Banks & Landy, 2002).

Also in: 2.7.1, 4.1

Haptic and visual signals for object size do not always come from the same object (e.g., touching one object while looking at another); mandatory combination of haptic and visual cues would be misleading in such cases (Hillis, Ernst, Banks & Landy, 2002).

Also in: 2.7.1, 2.7.3,

The nervous system combines visual and haptic information similar to a minimum likelihood integrator. Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation. (Ernst & Banks, 2002)

Also in: 2.7.1, 2.7.3, 6

The maximum visual-haptic cue asynchrony or delay that participants tolerate was 45 ms (on average). The range in which stimuli were judged to be synchronous was centered around a visual delay of about 7 ms. This point of subjective simultaneity (PSS) was liable to individual differences. (Vogels, 2004)

Also in: 1.4.4 TV, 2.2.1, 2.2.4 TV, 4.5.2

- ATV

Despite improved performance with multimodal feedback (visual, audio, and tactile versus visual-only), completion times in virtual reality tasks (peg-in-hole) are still significantly slower than their real-life counterpart tasks (Gupta, Sheridan, & Whitney, 1997).

Also in: 3.7.4 ATV, 8.1, 8.4, 8.6, 8.4 ATV

2.7.5 Not Specific to a Mode

Performance efficiency may be improved by hemispheric integrity. This may be because the hemispheres of the brain are cross-linked and one side (i.e. right) controls the other side (i.e. left) side of the body and vice-versa. (Shub et al., 1997)

Also in: 6.2.5
Papers that address the influence of the time difference between haptic media and audio/visual media and the effect of auditory cues on the haptic perception (Harada, Ohno & Sato (1998); as cited in Ishibashi, Kanbara & Tasaka, 2004).

Also in: 4.2.3, 4.3.4, 4.7.1

A critical issue in designing an information display is determining what type of data “best” maps onto which sensory input channel. The nature of the information to be displayed can immediately suggest the sensory channel of choice. (Loftin, 2003)

Also in: 4.9

Nyquist theorem states that a signal must be sampled with a rate twice as fast as the maximum frequency in the signal in order to reconstruct it: \( f_{\text{nyquist}} = 2f_{\text{max}} \). A method called grouped sampling takes the method of modified fixed sampling a step further. It uses the approach of identifying the minimum sampling rate (in KHz) for different groups of sensors. (Shahab et al., 2001)

Also in: 4.9

Stimuli perceived inside the head result in a more accurate and faster response than externalized stimuli (Roginska, 2004).

Also in: 6

When interacting with displays containing different augmenting cues, the mental models developed by the user after interaction with the interface are different from each other (Eberts, 1988).

Also in: 4.9, 6

The human motor system has remarkable ability to adapt to changing relations between sensory input and motor output (Allison, Zacher, Wang & Shu, 2004).

Also in: 2.6.4
3. Functions Appropriateness

3.1 Alert

3.1.1 Visual

Multiple modes may be more beneficial in some tasks (i.e., spatial domains) compared to others (Oviatt, 1999). Each mode may be particularly useful for certain tasks. Not all modes are equally able to transmit certain information (Emery, Edwards, Jacko, et al., 2003; Oviatt, 1999; van Esch-Bussemakers & Cremers, 2004).

When performing a demanding visual task, cueing or alarming with another modality seems to decrease reaction time and increase performance (Yeh & Wickens, 2001; Maltz & Shinar, 2004).

Also in: 3.1.4

When users are faced with dual task situations, it is important to consider that a diversion of attention creates an opportunity for changes to occur on an unattended display. Because interruption to any task is a possibility, it has been suggested that all devices should draw the user’s attention to changed information when the operator resumes viewing a given display. (Divita, Obermayer, Nugent, Linvilleu, 2004)

Also in: 2.4.1, 6.7

Advantages of instant messaging communication systems include the ability to communicate with multiple people at once, rapid responses to inquiries, and the ability to access archived chat sessions for clarification (Cummings, 2004).

Also in: 3.9.1

Drawbacks of instant messaging systems are that they can be disruptive and the flow of conversation can be awkward in the absence of non-verbal cues. These limitations are especially bad in time-pressured scenarios because interrupting the primary task (with the instant messages) increases mental processing time and leads to errors on the primary task. (Cummings, 2004)

Also in: 3.9.1, 4.1.7, 6.6.5, 6.7

When instant messaging systems are used concurrently with a primary task, users may fixate on instant messages rather than the primary task. This may result in a loss of situational awareness and a performance decrement. (Cummings, 2004)

Also in: 3.5.1, 6.4.1

Military personnel experience difficulties in receiving large amounts of information through chat and then synthesizing knowledge from this information (Cummings, 2004).

The visual mode is not good for detecting unexpected changes, so they have limited usefulness as alerts (Sklar & Sarter, 1999).

Also in: 2.4.1

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help
free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

**Also in:** 3.1.2, 3.1.3, 3.3.1, 3.3.2, 3.3.3, 6.7

**GP#:1164**

Interruption cues should not increase stress more than they have to, as increases in stress can have adverse impacts on performance. Visual cues (ambient light intensity changes) were superior as an interruption cue compared to tactile cues (ambient heat changes), as measured by errors and reaction time. This is probably because heat was associated with danger and may have increased stress levels. (Arroyo & Selker, 2003)

**Also in:** 3.1.3

**GP#:1166**

Offloading alerts from the visual to the tactile mode was especially beneficial as cognitive load increased; there were fewer differences between conditions (visual, tactile, and visual/tactile) at lower states of cognitive workload (Sklar & Sarter, 1999).

**Also in:** 3.1.3, 3.1.4TV, 6.6.1, 6.6.3, 6.6.4TV

**GP#:1191**

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

**Also in:** 1.2.5, 3.1.2, 3.1.4, 3.1.5, 3.5.5, 5.4.5, 6.4.5

**GP#:1237**

Unconditional displays show the current state of information. A conditional display is shown only when data meets a pre-determined criteria (i.e. stock hits certain price, email from certain person). (Miller & Stasko, 2002)

**Also in:** 4.1.6

**GP#:1244**

Attention-directing signals should be designed to be picked up in parallel to ongoing tasks, provide information on the significance of the interruption, and allow for evaluation that doesn’t require foveal attention (Woods, 1995; as cited in Sarter, 2001).

**Also in:** 3.1.5, 6.3.1

**GP#:1251**

Tactile and audio cues may be good for alerts of status change (compared to visual) because they’re omnidirectional (don’t require a particular head orientation) and can be used to guide attention to a particular location in the cockpit. The downside is that audio cues are hard to suppress, making them less desirable for non-emergency cues)

Tactile cues can effectively communicate information on airspeed, angle of attack, energy state, and other flight parameters (Zlotnick, 1988; as cited in Sarter, 2001), but may impede performance on other tasks (Gilliland & Schlegel, 1994; as cited in Sarter, 2001).

**Also in:** 2.7.2, 3.1.2, 3.1.3, 3.8.1, 3.8.2, 3.8.3, 4.2.3

**GP#:1253**

Because of inattentional blindness and contingent orienting (the fact that we’re more likely to detect changes when we’re expecting that particular signal type), visual flashing cues may not be an optimal method of capturing attention (Nikolic, Orr, & Sarter, 2004).

**Also in:** 2.4.1
Auditory signals are detected more quickly than visual signals and tend to produce an alerting or orienting response (Wourms, Mansfield, & Cunningham, 2001).

Also in: 2.5.1, 2.5.2, 2.7.1, 2.7.2, 3.1.2

Advantages of audio displays (compared to visual displays) for alarms: audio alarms are naturally interpreted as a warning signal, have faster neural transmission compared to visual (especially important for time-critical warnings). (Mowbray & Gebhard, 1969; as cited in Simpson, Bolia, & Draper, 2004)

Verbal communication is often the most direct/efficient/unambiguous method of information transfer; it allows information exchange regarding events that are now in the visual field (Simpson, Bolia, & Draper, 2004)

Also in: 2.7.2, 3.1.2, 3.9.2, 6, 5.3.2

AIM is a good example of adding audio to reduce visual load—the sound of a door opening accompanied by little icon next to name that pops up on list (Rovers & van Essen, 2004).

Also in: 3.1.4 AV, 6.6.4 AV, 6.6.5

Compared to visual warning signals, auditory and tactile signals are more effective at drawing cross-modal attention to particular positions (Spence & Driver, 1997).

Also in: 3.1.2, 3.1.3, 6.2

Detection times of deviations in visual and redundant (visual and audio) alarm conditions were not significantly different, but were faster than with the auditory display (Seagull, 2002).

Also in: 3.1.2, 3.1.4 AV

Slow fade animation provides the best all-around support for a notification task in a secondary display when used with a browsing task. Results from the second experiment show no deficiencies for slow fade animation under any of the primary or secondary task metrics. Although other animation implementations may allow better performance under different and specific design objectives, slow fade minimizes performance tradeoffs best. (McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 4.1

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

Also in: 3.1.2, 3.2.1, 3.8.1, 4.1, 4.2, 6.3.1, 6.3.2, 6.3.4 AV, 6.7
Tactile cues may be better than auditory cues for alert mechanisms, as they are less arousing while still increasing performance (Diamond, Kass, Andrasik, Raj, & Rupert, 2002).

Auditory icons (aurally presented sounds meant to represent a physical event, such as breaking glass, screeching tires, etc) are more accurately identified than conventional auditory warning signals (beeps/tones), but respondents are skeptical of the new technology (Belz, Robinson, & Casal, 1999).

When considering collisions in an automobile driving task, auditory icons and auditory warnings led to equivalent performance in unimodal conditions. However, when visual displays were added to augment the aural cues, auditory icons did significantly better than auditory warnings. (Bellotti, Berta, DeGloria & Margame, 2002)
Auditory icons, or representational sounds, may be useful as warning devices in vehicles, based on the decreased braking response times for impending front-to-rear collisions and a reduction in the occurrence of accidents for impending side collisions (Belz, Robinson, & Casal, 1999).

Three-dimensional auditory cues are very effective for alerting and attention management in multitask decision environments (Bellotti, Berta, DeGloria, & Margarone, 2002).

Both audio (speech) and tactile modes can be effective for communicating warnings in a driving task. However, audio cues were better for law-enforcement related warnings (e.g., excessive speed), as tactile cues were easier to ignore. On the other hand, tactile cues were better for safety-related warnings (e.g., near accidents) because they were perceived faster than audio cues. (Martens & van Winsum, 2001)

Audio cues may be particularly deficient (compared to tactile) in time-critical situations, probably because speech messages take longer to deliver and interpret (Martens & van Winsum, 2001).

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

Differences between types of visual displays in an aviation task (immersive 3-D, exocentric 3-D, and 2-D coplanar) disappeared when audio warnings of hazards and color coding cues (red, yellow, and green to indicate altitude conditions; color coding between map views to facilitate coordination) were added (Olmos, Wickens, & Chudy, 2000).

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

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Also in: 2.7.2, 3.1.1, 3.1.3, 3.8.1, 3.8.2, 3.8.3, 4.2.3

Adaptive audio display technology will require the following: 1) intelligent prioritization and novel presentation algorithms, 2) computational auditory scene analysis techniques for evaluating external auditory constraints in real-time and 3) automated multidimensional sound processing techniques.

The use of properly designed, spatialized alerts can significantly reduce effort and improve response times in a highly demanding, dual-task setting with no effect on decision accuracy or other measures of performance. (Brock et al., 2003)

Also in: 2.1.2, 4.2, 6.7

Auditory signals are detected more quickly than visual signals and tend to produce an alerting or orienting response (Wourms, Mansfield, & Cunningham, 2001).

Also in: 2.5.1, 2.5.2, 2.7.1, 2.7.2, 3.1.1

Advantages of audio displays (compared to visual displays) for alarms: audio alarms are naturally interpreted as a warning signal, have faster neural transmission compared to visual (especially important for time-critical warnings). (Mowbray & Gebhard, 1969; as cited in Simpson, Bolia, & Draper, 2004)

Verbal communication is often the most direct/efficient/unambiguous method of information transfer; it allows information exchange regarding events that are now in the visual field (Simpson, Bolia, & Draper, 2004)

Also in: 2.7.2, 3.1.1, 3.9.2, 5.3.2, 6

High volume sound can serve as a warning that a moving object is close to the user (Morris & Joshi, 2003).

Also in: 2.1.2, 4.2

Compared to visual warning signals, auditory and tactile signals are more effective at drawing cross-modal attention to particular positions (Spence & Driver, 1997).

Also in: 3.1.1, 3.1.3, 6.2

For verbal warnings, position on the interaural axis is the key factor to consider, rather than realism or maximum spacing (MacDonald et al., 2002).

Also in: 2.1.2, 4.2

Spoken words like “deadly, danger and lethal” are rated as more arousing than words like “warning or caution” (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 4.2, 6.3.2

Female voices seem to connote more urgency than male voices for conveying warnings. If a male or female voice is synthesized, the gender effect of the speaker seems to disappear (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 4.2, 6.3.2
It is possible to imbue urgency into synthesized speech warnings simply through the use of the three major acoustic parameters (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 4.2

People tend to code messages auditorily: rapidly successive data are to be resolved, where the recipient is preoccupied with other tasks or in a condition of reduced alertness, and one wishes to break in with unexpected messages or warnings, when highly meaningful materials are to be apprehended and remembered, where flexibility of message transmission is important, where out of a large mass of data we wish to present information germane to the issue at hand, and where visual reception is less available. (Geldard, 1960)

Also in: 4.2, 6.1.2, 6.3.2, 6.6.2

The inherent multi-dimensionality of sound in time, timbre and space often renders it to be the preferred means of transmission of data, information, and alerts in human-computer interfaces. By using auditory displays, numerous streams of data can be presented concurrently, offloading the visual system to perform other tasks. (Roginska, 2004)

Also in: 2.7.1, 2.7.2, 4.2, 4.8.1, 6.7.2

Detection times of deviations in visual and redundant (visual and audio) alarm conditions were not significantly different, but were faster than with the auditory display (Seagull, 2002).

Also in: 3.1.1, 3.1.4 AV

Higher priority messages should be presented in the right hemifield, while lower priority messages should be presented in the left hemifield (Bolia, Nelson & Morley, 2001).

Also in: 2.1.2, 3.9.2, 4.2

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

Also in: 3.1.1, 3.2.1, 3.8.1, 4.1, 4.2, 6.3.1, 6.3.4 AV, 6.3.2, 6.7
3.1.3 Tactile

Tactile information is less error-prone when used for feedback (i.e., alerts, warnings) than when used to give instruction (Tan, 2000).

Tactile cues may be better than auditory cues for alert mechanisms, as they are less arousing while still increasing performance (Diamond, Kass, Andrasik, Raj, & Rupert, 2002).


The tactile modality is good for presenting spatial, warning, and communication information to drivers (Van Erp & Van Veen, 2004).
Tactile cues are good for alert mechanisms because there are few competing demands for these resources (Sklar & Sarter, 1999).

Both audio (speech) and tactile modes can be effective for communicating warnings in a driving task. However, audio cues were better for law-enforcement related warnings (e.g., excessive speed), as tactile cues were easier to ignore. On the other hand, tactile cues were better for safety-related warnings (e.g., near accidents) because they were perceived faster than audio cues. (Martens & van Winsum, 2001)

Audio cues may be particularly deficient (compared to tactile) in time-critical situations, probably because speech messages take longer to deliver and interpret (Martens & van Winsum, 2001).

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

Interruption cues should not increase stress more than they have to, as increases in stress can have adverse impacts on performance. Visual cues (ambient light intensity changes) were superior as an interruption cue compared to tactile cues (ambient heat changes), as measured by errors and reaction time. This is probably because heat was associated with danger and may have increased stress levels. (Arroyo & Selker, 2003)

Offloading alerts from the visual to the tactile mode was especially beneficial as cognitive load increased; there were fewer differences between conditions (visual, tactile, and visual/tactile) at lower states of cognitive workload (Sklar & Sarter, 1999).

Tactile and audio cues may be good for alerts of status change (compared to visual) because they’re omnidirectional (don’t require a particular head orientation) and can be used to guide attention to a particular location in the cockpit. The downside is that audio cues are hard to suppress, making them less desirable for non-emergency cues.

Tactile cues can effectively communicate information on airspeed, angle of attack, energy state, and other flight parameters (Zlotnick, 1988; as cited in Sarter, 2001), but may impede performance on other tasks (Gilliland & Schlegel, 1994; as cited in Sarter, 2001).

Haptic effects and hapticons used in conjunction with IM: Email and IM primarily use textual messages—extended with audio-visual cues. Hapticons are small, programmed force patterns that can communicate a basic notion similar to regular icons in a graphic interface. These vibration patterns only become hapticons after users start to recognize the patterns and associate them with a particular meaning. (Rovers & van Essen, 2004)
Compared to visual warning signals, auditory and tactile signals are more effective at drawing cross-modal attention to particular positions (Spence & Driver, 1997).

Also in: 3.1.1, 3.1.2, 6.2

Tactition is a good break in sense; cutaneous sensations are highly attention demanding, thus they may be good for emergency messages (Geldard, 1960).

Also in: 2.7.3, 6.3.3

If touch can be entirely ignored, visual spatial attention tasks won’t affect tactile processing, allowing it to convey additional information (such as a tactile warning) (Hale & Stanney, 2004).

Also in: 4.5.1, 6.3.1

3.1.4 Multimodal (AV, AT, TV, ATV)

When performing a demanding visual task, cueing or alarming with another modality seems to decrease reaction time and increase performance (Yeh & Wickens, 2001; Maltz & Shinar, 2004).

Also in: 3.1.1

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

Also in: 1.2.5, 3.1.1, 3.1.2, 3.1.5, 3.5.5, 5.4.5, 6.4.5

• AV

Dual-modality displays (auditory icon and visual display; auditory warning and visual display) led to better reaction times than having no display. However, auditory icons did just as well without the visual display, suggesting that unimodal auditory displays can be sufficient. (Bellotti, Berta, DeGloria & Margarone, 2002)

Also in: 3.3.4AV, 4.2.2

When considering collisions in an automobile driving task, auditory icons and auditory warnings led to equivalent performance in unimodal conditions. However, when visual displays were added to augment the aural cues, auditory icons did significantly better than auditory warnings. (Bellotti, Berta, DeGloria & Margame, 2002)

Also in: 3.1.2, 3.3.2, 3.3.4AV, 4.2.2

AIM is a good example of adding audio to reduce visual load—the sound of a door opening accompanied by little icon next to name that pops up on list (Rovers & van Essen, 2004).

Also in: 3.1.1, 6.6.4 AV, 6.6.6

Detection times of deviations in visual and redundant (visual and audio) alarm conditions were not significantly different, but were faster than with the auditory display (Seagull, 2002).
Offloading alerts from the visual to the tactile mode was especially beneficial as cognitive load increased; there were fewer differences between conditions (visual, tactile, and visual/tactile) at lower states of cognitive workload (Sklar & Sarter, 1999).

Interruptions exacerbate change blindness (Durlach, 2004).

The most appropriate time and place for interruptions to a primary task is after the user evaluates expectations and forms a new goal (e.g., when users reaches a task boundary or period of low interaction) (Norman, 1996). An example of this is when an operator is merely monitoring a system and is not engaged in any decision-making evaluations. However, interruptions can not always be timed accordingly, unless you can predict dynamic situations. (Cummings, 2004)

When designing adaptive communication interfaces it is important to consider the following questions: How would the operator’s knowledge states and decision processes be affected by receiving instant messages? When should an adaptive chat management tool interrupt the operator and under what conditions? Is there a principled way for this tool to infer the operator’s workload and his/her ability to cognitively attend to communication messages? How will an adaptive chat management strategy affect overall human performance, situational awareness, and frustration? (Cummings, 2004)

Predicted best points for interruption correspond to moments between fine units with large degree of agreement. Predicted worst points correspond to moments during fine-units with a small degree of agreement (so between commonly understood tasks vs. between ill-defined tasks). (Adamczyk & Bailey, 2004)

An attention manager that attempts to identify opportune moments in a users task sequence for an interruption to occur, BASED on a deeper cognitive representation of user’s task can significantly decrease the disruptive effects on user emotional state and social attributions. (Adamczyk & Bailey, 2004).

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

Interpretations of the behavior of an interrupting application can turn users away from future application use [16, 27] and influence attitude towards the info the application provides [31] (Adamczyk & Bailey, 2004).

An operator’s reliance on and compliance with a warning system are strongly situational. It might be beneficial to place warnings close to other relevant info (Meyer, 2001).

Attention-directing signals should be designed to be picked up in parallel to ongoing tasks, provide information on the significance of the interruption, and allow for evaluation that doesn’t require foveal attention (Woods, 1995; as cited in Sarter, 2001).

Alarms that distinguish whether system failure is possible, probable, or certain (likelihood alarm displays) are better than traditional alarms (that just signal that some sort of attention is needed) when workload is high (Sorkin, Kantrowitz, & Kantrowitz, 1988; as cited in Sarter, 2001).

Interruptions to audio tasks are acknowledged more slowly than interruptions to visual tasks (Latorella, 1999; as cited in Sarter, 2001).

Peripheral displays must address two sets of user attention issues: (1) context about the user (e.g., interruptibility, primary task, focus of attention; and (2) attention management (e.g., abstraction and transitions, which are independent of context) (Matthews, Dey, Mankoff, Carter & Rattenbury, 2004).

Peripheral displays must support three characteristics to manage connection between information importance and user attention: (1) abstraction (extracting features/reducing fidelity of info to make it easier to read at a glance than raw input); (2) notification levels (differences in information importance); and (3) transitions (effects on a display that attract appropriate amount of attention from user based on new notification level) (Matthews, Dey, Mankoff, Carter & Rattenbury, 2004).

The “cry-wolf effect” refers to the fact that people often cease to respond to warnings if the frequency of nonvalid warnings is high (Sorkin, 1988; as cited in Maltz & Meyer, 2001).

Automation bias occurs when we rely too strongly on warnings (at expense of other indicators of problems) (Mosier, Skitka, Heers, & Burdick, 1998; as cited in Maltz & Meyer, 2001).
Both the cry-wolf effect and automation bias are more likely to occur under high workload conditions (Parasuraman, Molloy, & Singh, 1993; as cited in Maltz & Meyer, 2001).

Also in: 5.4.5, 6.6.5

Participants adjust their reliance on warnings according to their diagnostic value (so modes that are less reliable won’t be interpreted) but not completely (so unreliable cues can be more detrimental than no cues) (Maltz & Meyer, 2001).

Also in: 5.4.5

Participants learn to match probability of response to an alarm with the probability that the alarm gives true information (Bliss, Gilson, & Deaton, 1995; as cited in Seagull & Sanderson, 2001).

Also in: 5.1.5, 5.4.5

Alarms often increase operator workload rather than decrease it because of so many false alarms (Cook & Woods, 1996; as cited in Seagull & Sanderson, 2001).

Also in: 6.6.5

When multiple alarms go off simultaneously, and the alarm of interest is known to be unreliable (50-60% reliability), the likelihood that a user will perceive the alarm as important (in need of a response) increases as number of other alarms going off goes up (especially in proportion to number of alarms in array), as the spatial/temporal proximity of the alarms increases, and according to whether the other alarms going off are “related” to the alarm of interest (e.g., Two engine lights). (Gilson, Mouloua, Graft, & McDonald, 2001)

Also in: 5.4.5, 6.3.5

3.2 Navigation

3.2.1 Visual

It is difficult for users to maintain a sense of compass directions when displayless interfaces are used. If it is not feasible to provide users with a map for navigation, augmenting verbal directions with non-speech audio cues may reduce workload. (Baca & Picone, 2005)

Also in: 3.2.2, 6.6.1, 6.6.2

Whether a participant generally prefers visual information or audio information can have implications for performance. Specifically, visual-preference participants went fastest when graphic route descriptions were provided, while audio-preference participants did best with audio cues. (Chewar & McCrickard, 2002)

Also in: 3.2.2, 5.5.1, 5.5.2

For tasks that require users to go through a maze on a screen, providing users with a navigational map is detrimental to performance. Participants in this condition performed worse than participants who received audio cues, as well as those that were not provided with any additional cues. (Chewar & McCrickard, 2002)

GP#:1169

In an aviation setting, immersive three-dimensional displays (a pilot’s eye view) were better for local guidance tasks, but exocentric three-dimensional displays (from above/behind the plane) were better for responding to threats (Olmos, Wickens, & Chudy, 2000).

Also in: 3.8.1
Azimuth angles and elevation judgments are very difficult to make from visual displays. The assessment of symbol relation is also very difficult, regardless of aspect angle. To improve performance, designers need to optimize design solutions and add more or alternative depth cues. If you accept the design constraints of keeping the horizon visible, it is obvious that a vertical aspect angle change is not the way to improve direction assessments. (Andersson & Alm, 2002)

Also in: 3.6.1, 4.1.2

78% of pilots said it was easier to find the aircraft navigation pathway using goalpost vs. paving-stone display. Effects of type of symbology used could be nullified through practice. Some pilots had trouble interpreting a 2-D display to represent 3-D space. Situational Awareness outside of cockpit decreased from 44% to 14% from baseline to Highway in the Sky (HITS) condition. Pilots flying conventional instruments were significantly better at estimating heading and altitude than pilots using HITS display. 2 additions to the HITS display that might prove effective are the inclusion of air traffic on the display and inclusion of the synthetic terrain indicator. (Williams, 2002)

Also in: 1.2.1, 3.5.1, 3.8.1, 6.4.1

Humans use optic flow as an important navigational cue (Morris & Joshi, 2003).

Also in: 2.3.1, 2.6.1

A lot of our cognitive information is derived from a small portion of our visual field of view (FOV). The fovial region of the eye (< 2º of our total FOV) contains most of our photoreceptors. Eye and head motion allow us to take in more information. Head displacement and navigation create optic flow and motion parallax, which is sensed by our peripheral vision and used to judge motion. (Lantz, 1997)

Also in: 2.3.1, 2.6.1, 4.1.6, 6

Navigating using visual maps is often difficult because it requires mapping 2D information to a 3D environment, and maps offer a lot of information that users don’t need; thus, it’s better to provide specific directional cues (if there was a way to remove unnecessary information and make mapping between 2D and 3D easier, then maps could be more helpful) (Tsukada & Yasumura, 2004)

Also in: 4.1.4

Navigating is best supported by an immersive viewpoint display, in part because this frame of reference is similar to the view that a navigator has when traveling through real space (Wickens, Thomas, & Young, 2000).

Also in: 4.1.4, 8.1

Users have a more difficult time estimating distances in immersed and exocentric 3D displays as compared with 2D displays (Wickens, Thomas, & Young, 2000).

Also in: 4.1.4, 8.1

A smaller map with a wide field of view (FOV) displayed in the corner of a 3D map display can reduce tunnel vision (Wickens, Thomas, & Young, 2000).

Also in: 2.7.1, 4.1.2, 4.1.4, 6.4.1
There is evidence that an exocentric 3D display best supports both navigation and situational awareness tasks (Wickens, Thomas, & Young, 2000).

\textit{Also in: 3.5.1, 4.1.4}

GP#:1445

Immersed displays yield reduced accuracy, relative to 3D exocentric displays, on tasks that require information located behind or beside the user. This effect exists even when the information is available by panning or by referring to an inset map (Wickens, Thomas, & Young, 2000).

\textit{Also in: 2.1.1, 4.1.4, 8.1}

GP#:1448

Immersive displays are best for assessing line-of-sight visibility, and provide better guidance than 2D displays when used in aviation settings (Wickens, Thomas, & Young, 2000).

\textit{Also in: 3.8.1, 4.1, 8.1}

GP#:1452

When information must be combined from various sources located at different points in space (e.g., information from two maps), or different points in time (e.g., panning), or both, the composite mental picture will be less accurate than when all information is available in a single source (Wickens, Thomas, & Young, 2000).

\textit{Also in: 2.1.4, 2.7.4, 4.8.1, 4.9}

GP#:1472

When a north-up map is employed for primary/secondary navigational display, it’s beneficial to provide a visual momentum wedge to depict the user’s momentary direction of gaze and viewing angle on the represented world (on the map) (Olmos, Liang & Wickens, 1997).

\textit{Also in: 2.7.1, 4.1.4, 4.1.5}

GP#:1598

The use of density on maps is an important tool for enhancing situation awareness; displaying different saturations to represent troop movement allows users to achieve higher levels of situational awareness rapidly (Kim & Hoffmann, 2003).

\textit{Also in: 3.5.1, 3.6.1, 4.1, 6.4.1}

GP#:1599

Three visual tools (density, clustering, and lethality assessment) can enhance the situational awareness of a military commander on the battlefield. They can provide visual abstractions of an actual battle, not just terrain visualization. (Kim & Hoffmann, 2003)

\textit{Also in: 3.5.1, 4.1, 6.4.1}

GP#:1633

Better task-map coherence resulted in better attention switching strategies, reduced navigation errors, and better performance (Prabhu, 1996).

\textit{Also in: 6.3.1}

GP#:1675

Modalities required for VR simulation varies by task (piloting task requires tactile and visual cues, while visual alone is okay for navigation/monitoring tasks) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

\textit{Also in: 3.8.4, 8.1, 8.4 TV}

GP#:1749

Tactile navigation system was as effective as the GPS and more effective than the compass system with regard to how quickly soldiers reached waypoints. Soldiers more confidently deviate from the planned navigation.
route to go around obstacle with the tactile system (as compared to GPS and compass systems). (Elliott et. al., 1997)

Also in: 3.2.3

GP#:1762

People travel less far in orthogonal than oblique environments, even when the distances they can see are equivalent (Ruddle & Peruch, 2004).

Also in: 4.1

GP#:1763

Global landmarks promote quicker spatial learning of a visual perimeter (Ruddle & Peruch, 2004).

Also in: 4.1.4, 5.1.1

GP#:1791

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

Also in: 3.1.1, 3.1.2, 3.8.1, 4.1, 4.2, 6.3.1, 6.3.4 AV, 6.3.2, 6.7

3.2.2 Audio

It is difficult for users to maintain a sense of compass directions when displayless interfaces are used. If it is not feasible to provide users with a map for navigation, augmenting verbal directions with non-speech audio cues may reduce workload. (Baca & Picone, 2005)

Also in: 3.2.1, 6.6.1, 6.6.2

GP#:1120

Whether a participant generally prefers visual information or audio information can have implications for performance. Specifically, visual-preference participants went fastest when graphic route descriptions were provided, while audio-preference participants did best with audio cues. (Chewar & McCrickard, 2002)

Also in: 3.2.1, 5.5.1, 5.5.2

GP#:1125

In a task that required users to go through a maze on a screen, providing users with audio cues resulted in many users taking short halting steps until the next audio command was issued. Thus, devices could be enhanced by allowing a user to request audio cues whenever he/she wants them. (Chewar & McCrickard, 2002)

Also in: 5.2.2

3.2.3 Tactile

Tactile feedback seems to be best for interruption management (Hale & Stanney, 2004; Ho, 2004; Hopp, Smith, Clegg, & Heggestad, 2005; Enriquez, Afonin, Yager, & Mclean, 2001), spatial/navigational tasks (Hale & Stanney, 2004; Keyson, 1997; van Esch-Bussemakers & Cremers, 2004), hand/eye coordination tasks (Akamatsu, 1992; Hale & Stanney, 2004), and virtual tasks that utilize haptic cues to add realism (McGee, Gray, Brewster, 2001).

Also in: 3.1.3, 8.3

GP#:1749
Tactile navigation system was as effective as the GPS and more effective than the compass system with regard to how quickly soldiers reached waypoints. Soldiers more confidently deviate from the planned route to go around obstacle with the tactile system (as compared to GPS and compass systems). (Elliott et. al., 1997)

Also in: 3.2.1

GP#:1750

Soldiers appreciate tactile navigation system for its ease of use and enabling of eyes-free and hands-free navigation (Elliott et. al., 1997).

Also in: 2.7.3, 5.5.3, 7.1.3

GP#:1751

Tactile navigation system shows promise for operational effectiveness, particularly in situations where there is a need for soldiers to attend to other task demand (e.g., target detection) or to deviate from the planned route (e.g., obstacles, enemy invasion) (Elliott et. al. 1997).

Also in: 3.6.5, 6.7

3.2.4 Multimodal (AV, AT, TV, ATV)

The direct manipulation of a GUI interface resulted in fewer errors on average, but was not significantly less than when interacting multimodally (e.g., pen/voice map device). Time needed to repair an error was significantly less with a multimodal device. (Cohen, McGee, & Clow, 2000)

Also in: 4.8

GP#:1587

Infrared and indirect vision systems are useful in situations where direct vision is poor or impossible. These displays need high-resolution for tasks such as target identification, and wide fields of view for tasks such as orientation and tactile maneuvering. (Reingold, Looschky, McConkie & Stampe, 2003)

Also in: 3.6.1, 4.1.3, 4.1.6

• AV
• AT
• TV
• ATV

3.2.5 Not Specific to a Mode

It could be practical to design systems that are able to quickly and accurately determine user perceptual and processing preferences, using this information to adapt the display accordingly (e.g., determine what kind of route description/display to use) (Chewar & McCrickard, 2002).

Also in: 5.5

GP#:1121

This table provides guidelines for system design after prioritizing usage goals of navigation. It summarizes the findings/conclusions relevant to making a device best for certain kind of users (it addresses some individual differences) (Chewar & McCrickard, 2002).
Use a body-centered frame of reference (as opposed to a device-centered frame of reference) to reduce susceptibility to sensory overload and to allow users to orient themselves to the direction of travel (Traylor & Tan, 2002; as cited in O’Modhrain, 2004).

Individuals need to be actively engaged (actually driving) in the navigation/driving task to increase their sense of situation awareness (Gugerty, 1997).

Most devices require action on the user’s part—Driving devices such as GPS navigation systems add an extra element of complexity into the vehicle (Burnett, Summerskill & Porter, 2004).

Few people (less than 3% of those surveyed) felt that it wasn’t dangerous to use an in-vehicle navigation system while driving, yet there are an increasing number of crashes associated with the use of vehicle navigation systems (Burnett, Summerskill & Porter, 2004).

One way to define task values is “total glance time”, a measure of visual distraction, and static task time surrogate measures (Green 1998; as cited in Burnett, Summerskill & Porter, 2004). The 15 second rule: any navigation task that is accessible by the driver while the vehicle is in motion should have a static total task time of less than 15 seconds.

A fully functioning system for navigational aid should incorporate methods of inputting the destination and user preferences in terms of the route to be taken by the user (Sokoler et al., 2002).

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**Table 1. Route Description Representation Differences ($p<0.05$)**

<table>
<thead>
<tr>
<th>Usage Goal</th>
<th>User Characteristic</th>
<th>Best Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal Navigation Time</td>
<td>General Population</td>
<td>1. audio, 2. graphic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left Dominance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Dominance</td>
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<tr>
<td></td>
<td></td>
<td>Visual Preference</td>
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<td></td>
<td></td>
<td>Auditory Preference</td>
</tr>
<tr>
<td>Minimal Navigation Errors</td>
<td>General Population</td>
<td>1. graphic, 2. audio, 3. text list</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left Dominance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Dominance</td>
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<tr>
<td></td>
<td></td>
<td>Visual Preference</td>
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<tr>
<td></td>
<td></td>
<td>Auditory Preference</td>
</tr>
<tr>
<td>Minimal Distraction to Focal View</td>
<td>General Population</td>
<td>1. text list, 2. audio</td>
</tr>
<tr>
<td></td>
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<td>Left Dominance</td>
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<tr>
<td></td>
<td></td>
<td>Right Dominance</td>
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<td>Visual Preference</td>
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<td></td>
<td></td>
<td>Auditory Preference</td>
</tr>
</tbody>
</table>

Recommendations ordered and based on significant differences with population mean. “Best Choice” indicators enabled better performance under metrics corresponding to usage goals, $p<0.05$. For user characteristic groups (left or right brain hemisphere dominance and visual or auditory information preference), Best Choice notations reflect changes (+/- = addition, subtraction) to the general population findings.

**Also in: 1**

**GP#:1216**

**Also in: 3.5.5, 4.9, 6.4.5, 8.5**

**GP#:1262**

**Also in: 3.3.5, 3.5.5, 6.3.5, 6.4.5**

**GP#:1351**

**Also in: 3.3.5, 3.11, 4.9**

**GP#:1353**

**Also in: 3.3.5, 5.5.5, 7.3**

**GP#:1355**

**Also in: 3.3.5**

**GP#:1458**
Primary navigation displays should be track-up (Olmos, Liang & Wickens, 1997).

Future mobile and educational interfaces should be designed with the goal of supporting the poorer attention span, impulse control, and higher error rates of users with an impulsive profile, especially in the case of mobil, in vehicle, military, and other applications that bear an unacceptably high cost for committing errors (Oviatt, Lunsford, and Coulston, 2005).

There is evidence for shared resources in driving and navigation (Prabhu, 1996).

Combining visual cueing with auditory cueing might exacerbate clutter that is already high in cockpits (Tannen, 2000).

One way to counteract clutter is to use an adaptive interface, where automation controls the delivery of information to pilots, so that they get the right information in the right format at the right time, and aren’t otherwise exposed to it. This has been shown to be helpful to pilots during landing and navigation (cites Brickman et al 1996, Moroney, 1999; Hettinger, Cress, Brickman & Haas, 1996; Hollinagel, 1988, as cited in Tannen, 2000).

Better task-map coherence resulted in better attention switching strategies, reduced navigation errors, and better performance (Prabhu, 1996).

People’s movements are affected by the configuration of their environment, and perimeter edge following is a strategy that is frequently adopted by trained searchers; when perimeter was not clearly defined, participants did not adopt this strategy, and when the perimeter was defined, participants followed the perimeter edge during early stages of spatial learning and then took shortcuts through the environment center to target objects (Ruddle & Peruch, 2004).

3.3 Driving
   3.3.1 Visual

To avoid visual overload while driving, offloading critical information to other modalities must be explored, “and the most promising and robust of these modalities is audition” (Belz, Robinson, & Casal, 1999).
In an automobile driving task, dash-mounted visual displays for collision avoidance had detrimental effects on reaction time, as compared to other types of displays or having no display at all. This suggests that visual displays may lead to overload of the visual channel in driving tasks. (Bellotti, Berta, DeGloria & Margame, 2002)

GP#:1159

In an automobile driving task, auditory and auditory/visual displays led to better response times, more correct turns, and less workload compared to visual-only conditions. The fewest errors were committed by operators using the multimode display (auditory/visual), and the most subjective workload was experienced in the visual-only condition. These results support Wickens's Multiple Resource Theory, showing that offloading from visual (to audio) can lead to performance improvements. (Liu, 2001)

GP#:1163

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

Also in: 3.1.1, 3.1.2, 3.1.3, 3.3.2, 3.3.3, 6.7

GP#:1281

Visual attention is known to be influenced by cognitive (top-down, bottom-up) factors. Looking at neural systems with an fMRI showed that even during relatively simple simulated driving task, visual, motor and cognitive processes interacted in complex ways. (Graydon et al., 2004)

Also in: 2.6.1, 6

GP#:1354

Several researchers are developing methodologies for predicting how safe a design for an in-vehicle information or communications system is likely to be and the potential for excessive visual distraction when carrying out specific tasks. (Green, 1999; Noy et al, in press; as cited in Burnett, Summerskill & Porter, 2004)

Also in: 3.3.5, 7.2.5

GP#:1376

Driving a car requires some head motion, but most of the user's time is spent looking forward and exercising his/her peripheral vision (Lantz, 1997).

Also in: 2.6.1, 2.6.4

GP#:1427

Older drivers tend to be less accurate and slower to respond than are younger adults. Older drivers also execute more eye movements to acquire signs. (Ho, Scialfa, Caird, & Graw, 2001)

Also in: 1.1.1

GP#:1592

Operators are not comfortable driving a Jeep with a 40° field of view, but were more confident with a 120° field of view (McGovern, 1993; van Erp, 1997; as cited in Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 4.1.6, 5.5.1

GP#:1711

A wide field of view is required for proper lane-keeping and accurate spatial orientation (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.6

GP#:1714
Head-slaved displays can improve vehicle control and tracking accuracy in driving and target detection tasks (Kappe, van Erp, & Korteling, 1999).

Also in: 3.6.1, 4.1.5

### 3.3.2 Audio

GP#:1058

Auditory icons (aurally presented sounds meant to represent a physical event, such as breaking glass, screeching tires, etc) had better response times (a measure of cognitive load) than conventional auditory warnings and no display conditions, but drivers are not used to auditory icons yet. (Belz, Robinson, & Casal, 1999).

Also in: 3.1.2, 4.2.2, 5

GP#:1060

When considering collisions in an automobile driving task, auditory icons and auditory warnings led to equivalent performance in unimodal conditions. However, when visual displays were added to augment the aural cues, auditory icons did significantly better than auditory warnings. (Bellotti, Berta, DeGloria & Margame, 2002)

Also in: 3.1.2, 3.1.4AV, 3.3.4AV, 4.2.2

GP#:1061

Auditory icons, or representational sounds, may be useful as warning devices in vehicles, based on the decreased braking response times for impending front-to-rear collisions and a reduction in the occurrence of accidents for impending side collisions (Belz, Robinson, & Casal, 1999).

Also in: 3.1.2, 4.2.2

GP#:1100

Tactile displays that present driving behavior feedback result in lower user workload than auditory displays (Van Erp & Van Veen, 2004).

Also in: 3.3.3, 6.6.2, 6.6.3

GP#:1161

Both audio (speech) and tactile modes can be effective for communicating warnings in a driving task. However, audio cues were better for law-enforcement related warnings (e.g., excessive speed), as tactile cues were easier to ignore. On the other hand, tactile cues were better for safety-related warnings (e.g., near accidents) because they were perceived faster than audio cues. (Martens & van Winsum, 2001)

Also in: 3.1.2, 3.1.3, 3.3.3

GP#:1163

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

Also in: 3.1.1, 3.1.2, 3.1.3, 3.3.1, 3.3.3, 6.7

GP#:1282

Search performance was decreased when participants simultaneously heard and responded to questions about prose passages while driving. For dual-task condition, participants are less accurate in identifying signs, took longer to do searches and showed more prolonged fixations indicating more effortful processing. Subjective measures of workload supported these findings. (McPhee et al., 2004)

Also in: 6.6.2, 6.7

GP#:1394
Speech-based interactions (e.g., cell phone use) that occur while a user is driving have dire effects on driving performance, resulting in up to a 4-fold increase in crash risk (Redelmeier & Tibshirani, 1997; Violanti, 1997 as cited in Lee, Caven, Haake & Brown, 2001).

Also in: 3.3.4 AV, 6.7

GP#:1395

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.4 AV, 6.6.2, 6.6.4 AV, 6.7, 7.1.2, 7.1.4 AV

3.3.3 Tactile

The tactile modality is good for presenting spatial, warning, and communication information to drivers (Van Erp & Van Veen, 2004).

Also in: 3.1.3

GP#:1097

When tactile in-car displays were utilized in an automobile driving task, drivers had to learn to trust the tactile device (Van Erp & Van Veen, 2004).

Also in: 5.4.3

GP#:1099

Tactile displays that present driving behavior feedback result in lower user workload than auditory displays (Van Erp & Van Veen, 2004).

Also in: 3.3.2, 6.6.2, 6.6.3

GP#:1100

Both audio (speech) and tactile modes can be effective for communicating warnings in a driving task. However, audio cues were better for law-enforcement related warnings (e.g., excessive speed), as tactile cues were easier to ignore. On the other hand, tactile cues were better for safety-related warnings (e.g., near accidents) because they were perceived faster than audio cues. (Martens & van Winsum, 2001)

Also in: 3.1.2, 3.1.3, 3.3.2

GP#:1161

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

Also in: 3.1.1, 3.1.2, 3.1.3, 3.3.1, 3.3.2, 6.7

3.3.4 Multimodal (AV, AT, TV, ATV)

- AV

To avoid visual overload while driving, offloading critical information to other modalities must be explored, “and the most promising and robust of these modalities is audition” (Belz, Robinson, & Casal, 1999).

Also in: 3.3.1

GP#:1055

Dual-modality displays (auditory icon and visual display; auditory warning and visual display) led to better reaction times than having no display. However, auditory icons did just as well without the visual display,

GP#:1059
suggesting that unimodal auditory displays can be sufficient. (Bellotti, Berta, DeGloria & Margarone, 2002)

Also in: 3.1.4 AV, 4.2.2

GP#:1060

When considering collisions in an automobile driving task, auditory icons and auditory warnings led to equivalent performance in unimodal conditions. However, when visual displays were added to augment the aural cues, auditory icons did significantly better than auditory warnings. (Bellotti, Berta, DeGloria & Margame, 2002)

Also in: 3.1.2, 3.1.4 AV, 3.3.2, 4.2.2

GP#:1394

Speech-based interactions (e.g., Cell phone use) that occur while a user is driving have dire effects on driving performance, resulting in up to a 4-fold increase in crash risk (Redelmeier & Tibshirani, 1997; Violanti, 1997 as cited in Lee, Caven, Haake & Brown, 2001).

Also in: 3.3.2, 6.7

GP#:1395

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.2, 6.4.2, 6.4.4 AV, 6.6.2, 6.6.4 AV, 6.7, 7.1.2, 7.1.4 AV

• AT
• TV

GP#:1206

A lane assist system (composed of tactile and visual cues meant to help drivers stay within a lateral distance and prevent collisions) may be useful for helping drivers stay within a limited lateral distance, but it also increased stress (possibly because of unfamiliarity with device). (Ward, Shankwitz, Gorgestani, Donath, Boer, & DeWaard, 2003; as cited in Alexander et al 2004)

Also in: 1.2.4, 5

• ATV

3.3.5 Not Specific to a Mode

GP#:1009

When attentional requirements are too low, there is danger that driver awareness might be reduced because of monotony. In this case there may be too much automaticity. Arousal/stimulation or higher attentional requirements could be more effective. When attentional requirements are too high, the user will be forced to prioritize competing tasks (Liu, 2003).

Also in: 6.1.5, 6.3.5

GP#:1098

Poorly designed in-car displays can negatively affect safety (Van Erp & Van Veen, 2004).

GP#:1152

In a comparison of the behaviors/performance of novice and expert automobile drivers, novices had more lateral lane deviations and struggled in their performance of secondary tasks (e.g., putting in a cassette). Additionally, they glanced at the car’s instrument panel more often than the experts. These findings have implications for automaticity: once users have sufficient driving experience, they are more able to successfully dual task while driving. (Landsdown, 2002)

Also in: 1.2.5, 6.1.5

GP#:1262
Individuals need to be actively engaged (actually driving) in the navigation/driving task to increase their sense of situation awareness (Gugerty, 1997).

Also in: 3.2.5, 3.5.5, 6.3.5, 6.4.5

To compensate for increases in working memory load when driving, drivers will focus on a subset of cars (cars located in close proximity) instead of each individual car (Gugerty, 1997).

Also in: 2.1.5, 6.6.5

Most devices require action on the user’s part-- Driving devices such as GPS navigation systems add an extra element of complexity into the vehicle (Burnett, Summerskill & Porter, 2004).

Also in: 3.2.5, 3.11, 4.9

Few people (less than 3% of those surveyed) felt that it wasn’t dangerous to use an in-vehicle navigation system while driving, yet there are an increasing number of crashes associated with the use of vehicle navigation systems (Burnett, Summerskill & Porter, 2004).

Also in: 3.2.5, 5.5.5, 7.3

Several researchers are developing methodologies for predicting how safe a design for an in-vehicle information or communications system is likely to be and the potential for excessive visual distraction when carrying out specific tasks (Green, 1999; Noy et al, in press; as cited in Burnett, Summerskill & Porter, 2004).

Also in: 3.3.1, 7.2.5

One way to define task values is “total glance time”, a measure of visual distraction, and static task time surrogate measures (Green 1998; as cited in Burnett, Summerskill & Porter, 2004). The 15 second rule: any navigation task that is accessible by the driver while the vehicle is in motion should have a static total task time of less than 15 seconds.

Also in: 3.2.5

In-driver support systems (rather than automation systems) should be used to help increase driving performance; automation is generally meant to improve performance by reducing workload, but excessively low mental demands can be detrimental to performance – possibly worse than overload (Hancock & Parasuraman, 1992; Hancock & Verwey, 1997; as cited in Young & Stanton, 2002).

Also in: 6.6.5

Automating longitudinal control may be better than automating lateral control (or both) in a driving task, as the typical negative effects of underload with automation were not different between this condition and manual condition (no automation) (Young & Stanton, 2002).

Also in: 6.6.5

Future mobile and educational interfaces should be designed with the goal of supporting the poorer attention span, impulse control, and higher error rates of users with an impulsive profile, especially in the case of mobil, in vehicle, military, and other applications that bear an unacceptably high cost for committing errors (Oviatt, Lunsford, and Coulston, 2005).

Also in: 1.4.5, 3.2.5, 4.9, 6.3.5
There is evidence for shared resources in driving and navigation (Prabhu, 1996).

Also in: 3.2.5, 6.7.2

3.4 Vigilance Tasks/Peripheral Information

3.4.1 Visual

If there is a radar display, it helps to have an inner ring to help gauge distance (Haimson et al., 2004).

Also in: 3.6.1, 4.1.4

Tactile cues are useful (especially compared to visual cues) for tasks that require monitoring and an awareness of transitional states. Tactile and visual/tactile conditions were superior to a visual-only condition in a series of concurrent monitoring tasks, as evidenced by faster reaction times and more detections. (Sklar & Sarter, 1999)

Also in: 3.4.3, 3.4.4 TV

Visual-audio conditions lead to higher detection rates in vigilance tasks, compared to visual-only and audio-only conditions (Buckner & McGrath, 1961; as cited in Davenport, 1969).

Also in: 3.4.2, 3.4.4 AV

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.3, 4.16, 6.3.1, 6.3.3, 6.6.1, 6.6.3, 6.7

Peripheral visual cues are good for detecting “dynamic discontinuities” (example, motion or luminance change) and require few resources, but tunnel vision may be a problem under conditions of stress and/or cognitive load (Leibowitz & Appelle, 1969; as cited in Sarter, 2001).

Also in: 2.4.1, 4.1.6, 6.4.1, 6.6.5

Higher contrast on a visual display leads to better detection. Caffeine may enhance detection on a short term target detection vigilance task when administered at 1.1mg/kg. (Temple et al., 2000)

Also in: 3.6.1, 4.1.1, 6.3.1

In graphics-based interfaces, use of icons (vs. text) and their grouping has positive effect on scanning speed: spatial grouping of icons increases scanning speed, and use of icons (vs. text) in GUI increases scanning speed of target file (Niemela & Saarinen, 2000).

Also in: 3.6.1, 4.1.4

Minimizing scanning between flight instruments and the far domain contributes substantially to the head-up display (HUD) performance advantage (Martin-Emerson & Wickens, 1997).

Also in: 3.8.1, 4.1.5

Visual and audio (redundant) cues can result in reduced visual scanning in a tracking task, compared to a visual-only display (Seagull, 2002).
Visual search tasks (e.g., using visual resources to search the environment) can be made easier/more effective by providing a visual display (e.g., representing the environment in relation to oneself), rather than simply relying on visual resources/searching the environment. This study used pilots and compared visual search with or without a display (which provided geospatial information about nearby planes in relation to his/her own plane vs. having to look out the window of the plane for information about other planes). (Prinzo, 2003)

Guidelines for displays exhibiting high compatibility between display and mental task:
1. Integrate and collage related relevant information in a manner that allows visual comopairisons that make use of quick glances
2. Allow allocators to manage incidents rather than just calls.
3. Indicate the level of certainty in the information received.
4. Allow a spiral visual search pattern to locate the next nearest ambulance available to an incident (location).
5. Allow for assigning of temporary intermediate planning states and intentions. (Blandford & Wong, 2004)

In-place displays such as fade and blast are better than motion-based displays like ticker for rapid identification of items. Participants had lower monitoring latency when using the fade and blast than when using the ticker. This seems to extend prior results indicating that moving text is more difficult to read than static text. (Sekey and Tietz, 1982; Granaas et al., 1984; As cited in McCrickard, Catrambone, Chewar & Stasko, 2003)

Motion-based displays such as a ticker are better than in-place animations for comprehension and memorability, except when a cue is provided. While in-place displays aid rapid identification, participants who used the ticker obtained better detailed awareness than those who used the blast and the fade. This suggests that if it is essential to remember specific details of monitored information, and application of detailed awareness relies on first demonstrating basic awareness (rather than being cued), a motion-based display should be used. (McCrickard, Catrambone, Chewar & Stasko, 2003)

Visual-audio conditions lead to higher detection rates in vigilance tasks, compared to visual-only and audio-only conditions (Buckner & McGrath, 1961; as cited in Davenport, 1969).

Performance decreases over time in vigilance tasks (the “vigilance decrement”); this appears to be due to limitations in the amount of effortful control that we can exert rather than the simple withdrawal of attention (mindlessness). Devices should be designed for vigilance tasks in a way that reduces the need for effortful attention (e.g., offloading to audio). (Grier, Warm, Dember, Matthews, Galinsky, Szalma, & Parasuraman, 2003)
The human audio system can relegate some sounds into background while still monitoring them (Simpson, Bolia, & Draper, 2004).

Also in: 2.6.2, 4.2.1

GP#:1647
Performance in a tracking task was degraded least in an auditory condition, and most in a redundant multimodal condition (visual and audio). This is an example of a negative redundancy gain. (Seagull, 2002)

Also in: 3.4.4-AV, 3.6.2, 3.6.4-AV, 4.1.9, 4.2.5

3.4.3 Tactile

Tactile cues are useful (especially compared to visual cues) for tasks that require monitoring and an awareness of transitional states. Tactile and visual/tactile conditions were superior to a visual-only condition in a series of concurrent monitoring tasks, as evidenced by faster reaction times and more detections. (Sklar & Sarter, 1999)

Also in: 3.4.1, 3.4.4TV

GP#:1165
Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.1, 4.1.6, 6.3.1, 6.3.3, 6.6.1, 6.6.3, 6.7

3.4.4 Multimodal (AV, AT, TV, ATV)

• AV

Visual-audio conditions lead to higher detection rates in vigilance tasks, compared to visual-only and audio-only conditions (Buckner & McGrath, 1961; as cited in Davenport, 1969).

Also in: 3.4.1, 3.4.2

GP#:1203
Performance in a tracking task was degraded least in an auditory condition, and most in a redundant multimodal condition (visual and audio). This is an example of a negative redundancy gain. (Seagull, 2002)

Also in: 3.4.2, 3.6.2, 3.6.4-AV, 4.1.9, 4.2.5

GP#:1648
Visual and audio (redundant) cues can result in reduced visual scanning in a tracking task, compared to a visual-only display (Seagull, 2002).

Also in: 2.7.4-AV, 3.4.1, 3.6.1, 3.6.4-AV

GP#:1662
Auditory cueing should be used to improve visual target search performance, as perception of sound source is not limited by FOV or line-of-sight. Vision and audition can function “synergistically” in search tasks by encouraging auditory localization to direct the visual system toward objects in space, which can result in reduced search times. Gains in this respect are greatest when targets are presented outside FOV. Auditory cueing still reduces search times within 10 degrees of FOV by 175 msec. (McKinley, Ericson, & D’Angelo, 1994; Perrott, Cisneros, McKinley, & D’Angelo, 1996; Rudmann & Strybal, 1999; as cited in Tannen 2000)

Also in: 2.1.2, 3.6.1, 3.6.2, 4.1.6, 4.4
- **AT**
  Multimodal conditions (specifically audio-tactile) may be ideal in vigilance tasks to help improve detection rates and to prevent the performance decrement and threshold increases that unimodal conditions exhibit over time (Davenport, 1969).

  Also in: 2.2.2, 2.2.3, 2.2.4 AT

- **TV**
  Visual scanning and target detection tasks seem to be facilitated with tactile stimulation in terms of effectiveness and operator affinity. Several studies have indicated that when tactile is used along with visual, response times are faster and accuracy is more precise. Often the explanation stems from the idea that participants react before they fully process the situation (they avoid overthinking) (Akamatsu & Sato, 1994; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; He & Agah, 2001).

  Also in: 3.6.4 TV, 6.1.1

- **ATV**
  Tactile cues are useful (especially compared to visual cues) for tasks that require monitoring and an awareness of transitional states. Tactile and visual/tactile conditions were superior to a visual-only condition in a series of concurrent monitoring tasks, as evidenced by faster reaction times and more detections. (Sklar & Sarter, 1999)

  Also in: 3.4.1, 3.4.3

3.4.5 Not Specific to a Mode

Modality expectation is very important in attention allocation/vigilance tasks (McFarlane, 1999; as cited in Sarter, 2001).

Also in: 5.2.5, 5.4.5

Performance decreases over time in vigilance tasks (the “vigilance decrement”); this appears to be due to limitations in the amount of effortful control that we can exert rather than the simple withdrawal of attention (mindlessness). Devices should be designed for vigilance tasks in a way that reduces the need for effortful attention (e.g., offload to audio). (Grier, Warm, Dember, Matthews, Galinsky, Szalma, & Parasuraman, 2003)

Also in: 3.4.2, 6.3.5

Vigilance decrements often occur after 20-30 minutes on a vigilance task; thus, vigilance tasks should be designed for short segments, or have some sort of change every so often to increase arousal/attention (Singleton, 1989; as cited in Young & Stanton, 2002).

Also in: 6.3.5

3.5 Situation Awareness

Two stimuli that are presented at the same time within a certain distance are generally perceived as one stimulus (Cholewiak, 1988; as cited in van Erp & Verschoor, 2004). The cue is usually sensed as being located in the middle of the two stimuli (called the “apparent position”) (van Erp & Verschoor, 2004).

Also in: 2.1.3, 4

3.5.1 Visual
When instant messaging systems are used concurrently with a primary task, users may fixate on instant messages rather than the primary task. This may result in a loss of situational awareness and a performance decrement. (Cummings, 2004)

Also in: 3.1.1, 6.4.1

78% of pilots said it was easier to find the aircraft navigation pathway using goalpost vs. paving-stone display. Effects of type of symbology used could be nullified through practice. Some pilots had trouble interpreting a 2-D display to represent 3-D space. Situational Awareness outside of cockpit decreased from 44% to 14% from baseline to Highway in the Sky (HITS) condition. Pilots flying conventional instruments were significantly better at estimating heading and altitude than pilots using HITS display. 2 additions to the HITS display that might prove effective are the inclusion of air traffic on the display and inclusion of the synthetic terrain indicator. (Williams, 2002)

Also in: 1.2.1, 3.2.1, 3.8.1, 6.4.1

There is evidence that an exocentric 3D display best supports both navigation and situational awareness tasks (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 4.1.4

A modest advantage of 3D visual display (over 2D) was found for flight control, but not for situational awareness (Olmos, Liang & Wickens, 1997).

Also in: 3.8.1, 4.1.4

Head-up displays may paradoxically make pilots less aware to unexpected and potentially dangerous events that can happen outside of the aircraft; this is known as cognitive capture or cognitive tunneling (Tufano, 1997; Wickens & Long, 1995, as cited in Varakin, Levin, & Fidler, 2004).

Also in: 3.8.1, 4.1.5, 6.3.1, 6.4.1

The use of density on maps is an important tool for enhancing situation awareness; displaying different saturations to represent troop movement allows users to achieve higher levels of situational awareness rapidly (Kim & Hoffmann, 2003).

Also in: 3.2.1, 3.6.1, 4.1, 6.4.1

Three visual tools (density, clustering, and lethality assessment) can enhance the situational awareness of a military commander on the battlefield. They can provide visual abstractions of an actual battle, not just terrain visualization. (Kim & Hoffmann, 2003)

Also in: 3.2.1, 4.1, 6.1.4

Guidelines for displays exhibiting high compatibility between display and mental task:
1. Integrate and collate related relevant information in a manner that allows visual comparisons that make use of quick glances
2. Allow allocutors to manage incidents rather than just calls.
3. Indicate the level of certainty in the information received.
4. Allow a spiral visual search pattern to locate the next nearest ambulance available to an incident (location).
5. Allow for assigning of temporary intermediate planning states and intentions.
(Blandford & Wong, 2004)

Also in: 3.4.1, 3.6.1, 4.1, 6.4.1
Motion-based displays such as a ticker are better than in-place animations for comprehension and memorability, except when a cue is provided. While in-place displays aid rapid identification, participants who used the ticker obtained better detailed awareness than those who used the blast and the fade. This suggests that if it is essential to remember specific details of monitored information, and application of detailed awareness relies on first demonstrating basic awareness (rather than being cued), a motion-based display should be used. (McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 3.4.1, 4.1.4, 6.4.1

Situational awareness has been shown to diminish with a field of view less than 100 degrees (Reingold et. al., 2003).

Also in: 2.1.1, 6.4.1

3.5.2 Audio

Spatial audio has potential to enhance SA at all three of Endsley’s levels: (1) Recognizing the relevant elements in a situation, (2) Comprehending the meaning of these elements, and, on the basis of this understanding, (3) Predicting the system status into the immediate future (Simpson, Bolia, & Draper, 2004).

Also in: 6.4.2

3.5.3 Tactile

3.5.4 Multimodal (AV, AT, TV, ATV)

- AV
- AT
- TV
- ATV

3.5.5 Not Specific to a Mode

Training operators on how to use a given device, as well as the device’s limitations, is crucial for maintaining situational awareness (Varakin, Levin & Fidler, 2004).

Also in: 5.1, 6.4.5

Even though automated mediation could lower user workload, a loss of situational awareness could result since not all messages deemed significant would be seen by the controller (Cummings, 2004).

Also in: 6.4.5, 6.6.5

Situational awareness can decrease under high workload situations because of competition for attention; it can also decrease under low workload conditions due to boredom and complacency (Cummings, 2004).

Also in: 6.3.5, 6.4.5, 6.6.5

General design principles relevant for sustaining situational awareness include the following: organize information around goals; present level two situational awareness information directly to support comprehension; support global situational awareness; support trade-offs between goal-driven and data-driven processing; make critical cues for schema activation salient; take advantage of parallel processing capabilities; and use information filtering carefully. (Endsley, Bolte, & Jones, 2003)
Levels of uncertainty correspond to levels of situational awareness: you can have uncertainty in perception (data uncertainty), comprehension uncertainty, projection uncertainty, and decision uncertainty. Strategies for reducing uncertainty include searching for more information, relying on defaults, conflict resolution, thresholding, bet-hedging and contingency planning, and narrowing options. When designing a device, explicitly define missing information, support sensor reliability assessment, use data salience in support of certainty, and represent information timeliness. (Endsley, Bolte, & Jones, 2003)

In designing a device, there are several layers of complexity to consider, including system complexity, operational complexity, cognitive complexity (composed of display complexity and task complexity), apparent complexity (face validity), and as always, the user’s mental model. To manage the complexity of a system, consider the following principles: avoid “feature creep” (adding more and more bells and whistles); map system functions to the goals and mental models of users; provide system transparency and observability; provide consistency and standardization on controls across different displays and systems; and minimize task complexity. (Endsley, Bolte, & Jones, 2003)

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

Use a body-centered frame of reference (as opposed to a device-centered frame of reference) to reduce susceptibility to sensory overload and to allow users to orient themselves to the direction of travel (Traylor & Tan, 2002; as cited in O’Modhrain, 2004).

Individuals need to be actively engaged (actually driving) in the navigation/driving task to increase their sense of situation awareness (Gugerty, 1997).

### 3.6 Target Detection

#### 3.6.1 Visual

If there is a radar display, it helps to have an inner ring to help gauge distance (Haimson et al., 2004).

Tactile tracking performance is worse than visual tracking performance, regardless of whether it is the target or the cursor that is presented in the tactile modality (Van Erp & Verschoor, 2000).
Reducing the resolution of the visual display to that of the tactile display results in higher root-mean-square (RMS) errors and longer tracking delays. However, even when resolution effects are taken into account, visual tracking performance is still better than tactile tracking performance. (Van Erp & Verschoor, 2000)

Also in: 2.7.1, 2.7.3, 3.6.3, 4.1.3

GP#:1185

The efficacy of three-dimensional audio cues in aiding target acquisition may be reduced when there is a secondary visual task (Pierno, Caria, Glover, & Castiello, 2005).

Also in: 3.6.2, 3.6.4AV, 6.7

GP#:1223

Making judgments of azimuth and elevation are very difficult in static scenarios (Andersson & Alm, 2002).

Also in: 3.8.1, 4.1.2, 4.1.4

GP#:1224

The three-dimensional heading of objects was easier to estimate for abstract symbols (sphere, cube and pyramid) than for arrow symbols. Additionally, symbols directed straight against the operator were extremely difficult to perceive regardless of symbol shape. This provides support for the notion that direction content in abstract symbols with velocity vectors is stronger than built-in directional information in arrow symbols. In contradiction to other symbols tested, the sphere symbol was correctly identified regardless of the three-dimensional direction it was in. Finally, shape was not a good way to distinguish between categories of targets in a three-dimensional context. (Andersson & Alm, 2002)

Also in: 4.1.2

GP#:1225

Azimuth angles and elevation judgments are very difficult to make from visual displays. The assessment of symbol relation is also very difficult, regardless of aspect angle. To improve performance, designers need to optimize design solutions and add more or alternative depth cues. If you accept the design constraints of keeping the horizon visible, it is obvious that a vertical aspect angle change is not the way to improve direction assessments. (Andersson & Alm, 2002)

Also in: 3.2.1, 4.1.2

GP#:1254

Visual design principles for target detection tasks: use different colors for target and background, minimize visual distance from target (by angle of view), try not to include other dynamically changing stimuli in visual display (effects are compounded when these are combined) (Nikolic, Orr, & Sarter, 2004).

Also in: 4.1.1, 4.1.4

GP#:1256

Visual search (looking for information at unexpected locations) is particularly sensitive to age decrements (Plude & Hoyer, 1985; as cited in Ponds, Brouwer, & van Wolffelaar, 1988).

Also in: 1.1.1

GP#:1265

Higher contrast on a visual display leads to better detection. Caffeine may enhance detection on a short term target detection vigilance task when administered at 1.1mg/kg (Temple et al., 2000).

Also in: 3.4.1, 4.1.1, 6.3.1

GP#:1288

In graphics-based interfaces, use of icons (vs. text) and their grouping has positive effect on scanning speed: spatial grouping of icons increases scanning speed, and use of icons (vs. text) in GUI increases scanning speed of target file. (Niemela & Saarinen, 2000)

Also in: 3.4.1, 4.1.4
Performance on communication tasks and visual search tasks is vastly improved with spatial audio cues (Bolia & Nelson, 2003; as cited in Simpson, Bolia & Draper, 2004).

Also in: 3.6.4 AV, 3.9.4 AV

Spatial audio cues reduce visual target acquisition and identification times by a factor of 2 to 5 in simple visual scenes and much more in complex visual scenes (Bolia, D’Angelo, & McKinley, 1999, as cited in Simpson, Bolia, & Draper, 2004).

Also in: 3.6.4 AV

Partitioning a radar display into task-relevant regions with a range ring facilitates inside-to-outside search (Haimson & Anderson, 2002).

Also in: 4.1.4

Range rings or the partitioning of a display allows more focused attention and limits the repeated analysis of distractors (Haimson & Anderson, 2002).

Also in: 4.1.4, 6.3.1

Visual clutter (the nontarget information in a scene) can hinder sign acquisition (in this case a picture of a traffic sign in a street scene) in a bottom-up or top-down manner (Cole & Hughes, 1984; Engel, 1971, 1976; Hughes & Cole, 1986; Shoptaugh & Whitaker, 1984; as cited in Ho, Scialfa, Caird, & Graw (2001).

Also in: 4.1.4

Longer latencies for high-clutter scenes occurred because of the presence of a greater number of fixations required in order to locate a target (Adams, 1988; as cited in Ho, Scialfa, Caird, & Graw, 2001).

Also in: 2.5.1, 4.1.4

High clutter scenes are associated with poorer search performance (Ho, Scialfa, Caird, & Graw, 2001).

Also in: 4.1.4

Pilots using electronic 3D visual display format have difficulty identifying the precise location of surrounding targets (Olmos, Liang & Wickens, 1997).

Also in: 3.8.1, 4.1.4

Top-down operations, such as voluntarily scanning a visual scene for information, are impaired by the addition of a concurrent auditory task (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 3.6.4 AV, 4.4.1, 6.7

Visual scanning is adversely affected by divided attention (e.g., dual task context) (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 6.3.1, 6.7

GP#:1537
Target cuing is one form of stage one automation, which is automation that implicitly or explicitly guides attention to areas of the world that the automation infers are important for the human user (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 6.1.1, 6.3.1

**GP#:1539**

Head-up display benefits were particularly amplified with conformal imagery like target cueing (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 4.1.5

**GP#:1541**

In visual displays, the benefits of reduced scanning outweigh the cost of clutter (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 2.7.1, 4.1.4

**GP#:1542**

Helmet mounted display (HMD) allowed participants to demonstrate superior performance as measured by target detection latencies of accurately cued targets (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 2.5.1, 4.1.5

**GP#:1543**

Performance tradeoffs between helmet-mounted displays and hand-held devices need to be considered when looking for low salience targets that are uncued (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 4.1.5

**GP#:1544**

In visual displays, the costs of clutter outweigh scanning costs, which may be due to too much information being displayed on the helmet-mounted display (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 4.1.4, 4.1.5

**GP#:1590**

Infrared and indirect vision systems are useful in situations where direct vision is poor or impossible. These displays need high-resolution for tasks such as target identification, and wide fields of view for tasks such as orientation and tactile maneuvering. (Reingold, Loschky, McConkie & Stampe, 2003)

**Also in:** 3.2.4, 4.1.3, 4.1.6

**GP#:1598**

The use of density on maps is an important tool for enhancing situation awareness; displaying different saturations to represent troop movement allows users to achieve higher levels of situational awareness rapidly (Kim & Hoffmann, 2003).

**Also in:** 3.2.1, 3.5.1, 4.1, 6.4.1

**GP#:1607**

Green seems to be the hardest color to work with in a visual space, in terms of target location and differentiation from other colors, whereas white and yellow seem to be the best (Smallman & Boynton, 1990).

**Also in:** 4.1.1

**GP#:1648**

Visual and audio (redundant) cues can result in reduced visual scanning in a tracking task, compared to a visual-only display (Seagull, 2002).

**Also in:** 2.7.4-AV, 3.4.1, 3.4.4-AV, 3.6.4-AV

**GP#:1654**
Spatialized audio cueing can lead to increased target detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman & Breda, 1998; Nelson et al, 1998, as cited in Tannen, 2000).

**Also in:** 2.1.2, 6.6.1, 6.6.2, 6.6.4 AV

GP#:1657

The addition of spatialized sound to visual cueing reduced target designation time comparison to visual only; this occurred under conditions in which targets were really difficult to detect (e.g., ground targets initially outside FOV). The time advantage for fixed and adaptive multimodal cueing was 824 msec. (Tannen, 2000)

**Also in:** 2.1.2, 2.7.4 AV, 3.6.4 AV, 4.1.6

GP#:1658

No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing (Tannen, 2000).

**Also in:** 1.2.2, 2.7.1, 2.7.2, 3.8.4 AV, 4.1, 4.2

GP#:1662

Auditory cueing should be used to improve visual target search performance, as perception of sound source is not limited by FOV or line-of-sight. Vision and audition can function “synergistically” in search tasks by encouraging auditory localization to direct the visual system toward objects in space, which can result in reduced search times. Gains in this respect are greatest when targets are presented outside FOV. Auditory cueing still reduces search times within 10 degrees of FOV by 175 msec. (McKinley, Ericson, & D’Angelo, 1994; Perrott, Cisneros, McKinley, & D’Angelo, 1996; Rudmann & Strybal, 1999; as cited in Tannen 2000)

**Also in:** 2.1.2, 3.4.4 AV, 3.6.2, 4.1.6, 4.4

GP#:1673

Visual search tasks (e.g., using visual resources to search the environment) can be made easier/more effective by providing a visual display (e.g., representing the environment in relation to oneself), rather than simply relying on visual resources/searching the environment. This study used pilots and compared visual search with or without a display (which provided geospatial information about nearby planes in relation to his/her own plane vs. having to look out the window of the plane for information about other planes). (Prinzo, 2003)

**Also in:** 3.4.1, 3.8.1, 4.1.4

GP#:1684

Guidelines for displays exhibiting high compatibility between display and mental task:
1. Integrate and collate related relevant information in a manner that allows visual comopairsons that make use of quick glances
2. Allow allocators to manage incidents rather than just calls.
3. Indicate the level of certainty in the information received.
4. Allow a spiral visual search pattern to locate the next nearest ambulance available to an incident (location).
5. Allow for assigning of temporary intermediate planning states and intentions.
(Blandford & Wong, 2004)

**Also in:** 3.4.1, 3.5.1, 4.1, 6.4.1

GP#:1714

Head-slaved displays can improve vehicle control and tracking accuracy in driving and target detection tasks (Kappe, van Erp, & Korteling, 1999).

**Also in:** 3.3.1, 4.1.5
A common assumption related to visual attention is that parallel processing occurs without attention (preattentive), and that serial processing requires attention. There are examples that refute this assumption; specifically, targets that are processed serially and do not trigger “pop-out” can actually be discriminated from distracters in a dual-task situation. Moreover, targets that are processed in parallel cannot be discriminated from distracters when attention is occupied by some other concurrent task. Preattentive (preattentive) processing implies parallel processing. In practice, this is constrained by the size of the receptive fields. (VanRullen et al., 2004)

Also in: 2.6.1, 6.3.1, 6.7

Preattentive tasks that result in parallel visual search rely on neuronal selectivity present in early visual areas (e.g., orientation, color), whereas preattentive tasks that result in serial visual search rely on higher level neuronal selectivity (e.g., color-orientation conjunctions, animals, faces). Differences are typically accompanied by size of receptive fields. (VanRullen et al., 2004)

Also in: 2.6.1, 6.7

Two independent dimensions are needed to account for the variety of visual discrimination tasks: one with respect to visual search performance (parallel versus serial dimension) and the other with respect to dual-task performance (the preattentive versus attentive dimension) (VanRullen et al., 2004).

Also in: 6.3.1, 6.7

Multiresolutional systems are better at producing target acquisition results than are joystick systems (Reingold et. al., 2003).

Also in: 3.6.4 TV

Human visual search performance can be explained largely in terms of the cognitive strategy that is used to coordinate the relevant perceptual and motor processes. A clear and useful visual hierarchy triggers a fundamentally different visual search strategy and effectively gives the user greater control over the visual navigation. Cognitive strategies will be an important component of a predictive visual search tool. (Hornof, 2004)

Also in: 6, 6.5.1

Wickens, Goh, Helleberg, Horrey & Talleur (2003) provide a model which can be used to diagnose non-optimal patterns and to compare scanning strategies of amateurs. This model also offers potential to assess when design features may, by increasing the effort of information access, lead to serious departures from optimal scan patterns.

Also in: 1.2.1, 5.1.1

3.6.2 Audio

The efficacy of three-dimensional audio cues in aiding target acquisition may be reduced when there is a secondary visual task (Pierno, Caria, Glover, & Castiello, 2005).

Also in: 3.6.1, 3.6.4AV, 6.7

In a target detection task, audio and tactile modes were found to be interdependent (Davenport, 1969).

Also in: 3.6.3, 6.2.2, 6.2.3, 6.2.4 AT
In a sound-localization task, using a combination of stereo audio microphones and a head tracker can disambiguate sources from similar angles (Siracusa, Morency, Wilson, Fisher, Darrell, 2003).

Also in: 2.1.2, 4.2

Performance in a tracking task was degraded least in an auditory condition, and most in a redundant multimodal condition (visual and audio). This is an example of a negative redundancy gain. (Seagull, 2002)

Also in: 3.4.2, 3.4.4-AV, 3.6.4-AV, 4.1.9, 4.2.5

Auditory cueing should be used to improve visual target search performance, as perception of sound source is not limited by FOV or line-of-sight. Vision and audition can function “synergistically” in search tasks by encouraging auditory localization to direct the visual system toward objects in space, which can result in reduced search times. Gains in this respect are greatest when targets are presented outside FOV. Auditory cueing still reduces search times within 10 degrees of FOV by 175 msec. (McKinley, Ericson, & D’Angelo, 1994; Perrott, Cisneros, McKinley, & D’Angelo, 1996; Rudmann & Strybal, 1999; as cited in Tannen 2000)

Also in: 2.1.2, 3.4.4 AV, 3.6.1, 4.1.6, 4.4

Spatialized audio cueing can lead to increased target detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman & Breda, 1998; Nelson et al, 1998, as cited in Tannen, 2000).

Also in: 2.1.2, 6.6.1, 6.6.2, 6.6.4 AV

Auditory cueing is effective in the acquisition of targets located in highly distracting environments (Perrot, Sadralodabai, Saberi, & Strybel, 1991; as cited in Tannen, 2000).

Also in: 2.7.2

Virtual audio may be particularly useful in assisting the localization of targets under non-optimal visual conditions, such as ground target detection (Tannen, 2000).

Also in: 8.2

Without supplementary visual cueing, virtual auditory cueing led to increased detection rates and decreased detection times, and to reductions in subjective workload. It also improved the efficiency of search patterns (Cunningham et. al., 1995; Cunningham et. al., 1998; as cited in Tannen, 2000).

Also in: 2.7.2, 6.6.2

3.6.3 Tactile

Tactile tracking performance is worse than visual tracking performance, regardless of whether it is the target or the cursor that is presented in the tactile modality (Van Erp & Verschoor, 2000).

Also in: 3.6.1

Reducing the resolution of the visual display to that of the tactile display results in higher root-mean-square (RMS) errors and longer tracking delays. However, even when resolution effects are taken into account, visual tracking performance is still better than tactile tracking performance. (Van Erp & Verschoor, 2000)

Also in: 2.7.1, 2.7.3, 3.6.1, 4.1.3
For the tactile modality, compensatory tracking performance is better than pursuit performance (Van Erp & Verschoor, 2000).

External disturbances in dynamic tactile stimuli cause large time delays. However, no additional processing time seems to be required for tactile cursors in pursuit tracking or for tactile targets in compensatory tracking. (Van Erp & Verschoor, 2000)

The tactile channel can be used to present information on the direction of a goal, as the set-point in a tracking task, or as an actively controlled cursor in pursuit tracking tasks (Van Erp & Verschoor, 2000).

Force feedback (gravity wells) can reduce the time it takes to point and click on targets on a computer screen. This is even more pronounced when fine motor ability is impaired (as may be the case when users are on a plane/tank/ship that vibrates). (Hwang, Keates, Langdon, & Clarkson, 2003)

Also in: 2.6.4, 4.3.3

In a target detection task, audio and tactile modes were found to be interdependent (Davenport, 1969).

Also in: 3.6.2, 6.2.2, 6.2.3, 6.2.4 AT

Sense of touch may actually be dependent on diverse cognitive resources (high level knowledge), availability of cues for object identification, perceptual bias by other modalities (4, 5,6) and cross modal attention. (Interacting cognitive subsystems theory) (Booth & Schmidt-Tjørksen, 2001).

Also in: 2.7.3, 6.2.3, 6.3.3

3.6.4 Multimodal (AV, AT, TV, ATV)
  • AV

The efficacy of three-dimensional audio cues in aiding target acquisition may be reduced when there is a secondary visual task (Pierno, Caria, Glover, & Castiello, 2005).

Also in: 3.6.1, 3.6.2, 6.7

Performance on communication tasks and visual search tasks is vastly improved with spatial audio cues (Bolia & Nelson, 2003; as cited in Simpson, Bolia & Draper, 2004).

Also in: 3.6.1, 3.9.4 AV

Spatial audio cues reduce visual target acquisition and identification times by a factor of 2 to 5 in simple visual scenes and much more in complex visual scenes (Bolia, D’Angelo, & McKinley, 1999, as cited in Simpson, Bolia, & Draper, 2004).

Also in: 3.6.1

Top-down operations, such as voluntarily scanning a visual scene for information, are impaired by the addition of a concurrent auditory task (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 3.6.1, 4.4.1, 6.7
Performance in a tracking task was degraded least in an auditory condition, and most in a redundant multimodal condition (visual and audio). This is an example of a negative redundancy gain. (Seagull, 2002)

Also in: 3.4.2, 3.4.4-AV, 3.6.2, 4.1.9, 4.2.5

Visual and audio (redundant) cues can result in reduced visual scanning in a tracking task, compared to a visual-only display (Seagull, 2002).

Also in: 2.7.4-AV, 3.4.1, 3.4.4-AV, 3.6.1

The addition of spatialized sound to visual cueing reduced target designation time comparison to visual only; this occurred under conditions in which targets were really difficult to detect (e.g., ground targets initially outside FOV). The time advantage for fixed and adaptive multimodal cueing was 824 msec. (Tannen, 2000)

Also in: 2.1.2, 2.7.4 AV, 3.6.1, 4.1.6

The effectiveness of a sound cue in the central FOV was a positive function of angular distance from line-of-sight. Benefits were found for distal targets (by 100 msec) but not for targets within central line-of-sight; therefore, benefits of auditory cueing in visual search tasks are strongest when targets are beyond an observer’s central FOV. (Perrot, Sadralodabai, Saberi, & Strybel, 1991; as cited in Tannen, 2000)

Also in: 2.1.2., 2.1.4 AV, 4.4

Auditory cueing is useful because it conveys general, rather than precise, information about target location. Visual search performance should be analyzed in two phases: localization (first stage, target is brought into FOV) and identification (next stage, precise target position within FOV is determined). Sound helped in both stages of visual searching, with greater benefits of auditory cueing coming in the target localization stage. (Rudmann & Strybel, 1999; as cited in Tannen, 2000)

Also in: 2.1.4 AV

- AT
- TV

Visual scanning and target detection tasks seem to be facilitated with tactile stimulation in terms of effectiveness and operator affinity. Several studies have indicated that when tactile is used along with visual, response times are faster and accuracy is more precise. Often the explanation stems from the idea that participants react before they fully process the situation (they avoid overthinking) (Akamatsu & Sato, 1994; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; He & Agah, 2001).

Also in: 3.4.4TV, 6.1.1

Adding haptic location information (e.g., through active position pointing) to a visual display enhances target placement memory (Hale & Stanney, 2004).

Also in: 4.5

If the visual system is overloaded, object identification information can be provided haptically without adding significant cognitive load (Hale & Stanney, 2004).

Also in: 6.6.4 TV
Multiresolutional systems are better at producing target acquisition results than are joystick systems (Reingold et al., 2003).

Also in: 3.6.1

- ATV

  3.6.5 Not Specific to a Mode

Data from studies on target context support the use of allocentric coding of information because it improves performance. Performance also increased when the context is familiar. Target context led to a better awareness of perturbation. (Ferrel, Orliguet, Leiffen, Bard & Fleury, 2001)

Also in: 1.2.5, 5.4.5

Observers have an imperfect memory for distractors they have recently rejected in the course of search (Horowitz & Wolfe, 2001; as cited in Haimson & Anderson, 2002).

Also in: 6

Tactile navigation system shows promise for operational effectiveness, particularly in situations where there is a need for soldiers to attend to other task demand (e.g., target detection) or to deviate from the planned route (e.g., obstacles, enemy invasion) (Elliott et al., 1997).

Also in: 3.2.3, 6.7

People’s movements are affected by the configuration of their environment, and perimeter edge following is a strategy that is frequently adopted by trained searchers; when perimeter was not clearly defined, participants did not adopt this strategy, and when the perimeter was defined, participants followed the perimeter edge during early stages of spatial learning and then took shortcuts through the environment center to target objects. (Ruddle & Peruch, 2004)

Also in: 3.2.5, 5.1.5

3.7 Object Manipulation

  3.7.1 Visual

Redundant cues may be particularly beneficial for more difficult tasks. For example, in a tapping task and a dragging/dropping task performance differences between unimodal (visual or tactile) and multimodal (visual and tactile) were only apparent at higher difficulty levels (Poupyrev, Okabe, & Maruyama, 2004).

Also in: 3.7.4, 3.7.4 TV

After experience in tool-use, visual stimuli in the opposite hemifield to the stimulated hand could produce stronger crossmodal interactions than visual stimuli in the same anatomical hemifield, when the tools are crossed (Maravita, Spence, Kennett & Driver, 2002).

Also in: 1.2, 6.2.1

The ability to manipulate objects is strongly related to sources of sensory information gathered prior to and after contact with objects. Visual and haptic feedback are key sources of sensory info used when acquiring and manipulating objects. (Mason, Walji, Lee & MacKenzie, 2001)

Also in: 3.7.3

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3.7.2 Audio

Experience/automaticity of a task interacts with what mode of feedback is most helpful (audio, visual, haptic, bimodal, unimodal, or trimodal) on a computer drag and drop task. Trimodal was best for most experienced users. Auditory was best for all users. (Jacko et al, 2004)

Also in: 1.2.2, 1.2.4 ATV, 3.7.4 ATV, 6.1.2, 6.1.4 ATV

3.7.3 Tactile

Interface designers need to consider the range of textural information available. Simulating large textures can inhibit the user’s movements so much that their ability to stay on the textured surface is negatively affected. (McGee, Gray & Brewster, 2001)

Also in: 2.7.3, 8.3

3.7.4 Multimodal (AV, AT, TV, ATV)

Redundant cues may be particularly beneficial for more difficult tasks. For example, in a tapping task and a dragging/dropping task performance differences between unimodal (visual or tactile) and multimodal (visual and tactile) were only apparent at higher difficulty levels (Poupyrev, Okabe, & Maruyama, 2004).

Also in: 3.7.1, 3.7.4 TV

- AV
- AT

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

Also in: 2.6.2, 3.7.4 TV, 4.5.3, 4.6.3, 5.2.2, 6.3.2
• TV

Relevant cues may be particularly beneficial for more difficult tasks. For example, in a tapping task and a dragging/dropping task performance differences between unimodal (visual or tactile) and multimodal (visual and tactile) were only apparent at higher difficulty levels (Poupyrev, Okabe, & Maruyama, 2004).

Also in: 3.7.1, 3.7.4

• ATV

Object identification, object manipulation, and spatial awareness tasks may be the most advantageous for combining visual and haptic cues (Hale & Stanney, 2004).

Prolonged active use of tools (over several minutes) can modify visual-tactile spatial integration, so that visual stimuli located at the current position of the tool’s far end now interact most with tactile stimuli on whichever hand wields the connecting tool (Maravita, Spence, Kennett & Driver, 2002).

Also in: 6.2.4 VT

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

Also in: 2.6.2, 3.7.4 AT, 4.5.3, 4.6.3, 5.2.2, 6.3.2

3.7.5 Not Specific to a Mode

3.8 Flying Pilots

3.8.1 Visual

Modes should be chosen based on the intuitiveness of information interpretation (i.e., match the purpose of the information with the sense that is best able to handle it). In response to numerous aviation accidents caused by spatial disorientation, engineers added more visual displays for pilots. However, this did not reduce the occurrence of accidents, partially because the visual channels were overloaded (so the new information was not being processed), but also because tactile cues are more naturally interpreted as orientation cues (we use proprioception naturally in real-life), compared to visual cues. (Rupert, 2000)

Also in: 3.8.2, 5.3.1, 5.3.3

GP#:1155

GP#:1169
In an aviation setting, immersive three-dimensional displays (a pilot’s eye view) were better for local guidance tasks, but exocentric three-dimensional displays (from above/behind the plane) were better for responding to threats (Olmos, Wickens, & Chudy, 2000).

Also in: 3.2.1

GP#:1170

Differences between types of visual displays in an aviation task (immersive 3-D, exocentric 3-D, and 2-D coplanar) disappeared when audio warnings of hazards and color coding cues (red, yellow, and green to indicate altitude conditions; color coding between map views to facilitate coordination) were added (Olmos, Wickens, & Chudy, 2000).

Also in: 3.1.2, 4.1.1

GP#:1222

In the real world there are “natural cues,” but things are more complicated in a three-dimensional display; it is hard to achieve the same understanding with a scaled down version of the real world and a limited field of view. It is difficult for the operator to perceive distance, altitude, sizes, etc. in a limited field of view because of scaling problems, abstract object design, and the limited number of natural cues. However, in some tasks, such as landing, display size and field of view have less of an impact. (Comstock, Glaab, Prinzel & Elliot, 2001; as cited in Andersson & Alm, 2002)

Also in: 2.7.1, 4.1.2, 4.1.4

GP#:1223

Making judgments of azimuth and elevation are very difficult in static scenarios (Andersson & Alm, 2002).

Also in: 3.6.1, 4.1.2, 4.1.4

GP#:1251

Tactile and audio cues may be good for alerts of status change (compared to visual) because they’re omnidirectional (don’t require a particular head orientation) and can be used to guide attention to a particular location in the cockpit. The downside is that audio cues are hard to suppress, making them less desirable for non-emergency cues)

Tactile cues can effectively communicate information on airspeed, angle of attack, energy state, and other flight parameters (Zlotnick, 1988; as cited in Sarter, 2001), but may impede performance on other tasks (Gilliland & Schlegel, 1994; as cited in Sarter, 2001).

Also in: 2.7.2, 3.1.1, 3.1.2, 3.1.3, 3.8.2, 3.8.3, 4.2.3

GP#:1278

Ecological displays (those that extend across the central visual and peripheral visual fields and present information in a manner that is visually consistent with information available in the real world) allow for more accurate control (when compared with central or peripheral displays) in low-control velocity flight simulation tasks (Weinstein & Wickens, 1992).

Also in: 4.1.4, 4.1.6

GP#:1298

Head-up presentation of flight path guidance information and supporting alphanumeric data superior to head-down display (Martin-Emerson & Wickens, 1997).

Also in: 4.1.5

GP#:1299

Minimizing scanning between flight instruments and the far domain contributes substantially to the head-up display (HUD) performance advantage (Martin-Emerson & Wickens, 1997).

Also in: 3.4.1, 4.1.5

GP#:1312
78% of pilots said it was easier to find the aircraft navigation pathway using goalpost vs. paving-stone display. Effects of type of symbology used could be nullified through practice. Some pilots had trouble interpreting a 2-D display to represent 3-D space. Situational Awareness outside of cockpit decreased from 44% to 14% from baseline to Highway in the Sky (HITS) condition. Pilots flying conventional instruments were significantly better at estimating heading and altitude than pilots using HITS display. 2 additions to the HITS display that might prove effective are the inclusion of air traffic on the display and inclusion of the synthetic terrain indicator. (Williams, 2002)

Also in: 1.2.1, 3.2.1, 3.5.1, 6.4.1

GP#:1448

Immersive displays are best for assessing line-of-sight visibility, and provide better guidance than 2D displays when used in aviation settings (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 4.1, 8.1

GP#:1473

Pilots using electronic 3D visual display format have difficulty identifying the precise location of surrounding targets (Olmos, Liang & Wickens, 1997).

Also in: 3.6.1, 4.1.4

GP#:1474

A modest advantage of 3D visual display (over 2D) was found for flight control, but not for situational awareness (Olmos, Liang & Wickens, 1997).

Also in: 3.5.1, 4.1.4

GP#:1493

Thirty percent of civil air crashes have been attributed to pilot spatial disorientation, caused by faulty or misleading visual/vestibular system inputs – a problem that can be ameliorated by the use of intuitive tactile inputs (Schrope, 2001).

Also in: 3.8.4 TV, 5.3.3, 6.4.1, 6.4.4 TV

GP#:1581

Head-up displays may paradoxically make pilots less aware to unexpected and potentially dangerous events that can happen outside of the aircraft; this is known as cognitive capture or cognitive tunneling (Tufano, 1997; Wickens & Long, 1995, as cited in Varakin, Levin, & Fidler, 2004).

Also in: 3.5.1, 4.1.5, 6.3.1, 6.4.1

GP#:1593

Frame rates of at least 10 frames of 10 frames per second are necessary for optic flow perception, which is critical for piloting (Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 2.2.1, 4.1

GP#:1594

Remote piloting requires a wider field of view than teleoperations (Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 4.1.6

GP#:1629

If pilots cannot physically rotate their heads to the side, then visual conditions need to be designed that include incongruent conditions between the flight symbology and background scene (Ercoline, Self & Matthews, 2002).

Also in: 4.1.4, 4.1.6

GP#:1661
Pilots scan near-domain information about system functions (presented by cockpit instrumentation) and far-domain information about local airspace and terrain features (out the window). Pilots have tried to develop efficient scanning methods to cope with these demands, but switching between domains is challenging because it requires rapid changes in line-of-sight (LOS) and optical focus, often under adverse physical conditions. Switching is also cognitively demanding because pilots have to pick-up and synthesize information across domains, thus creating a high potential for error (cites Weinstein & Wickens, 1992). (Tannen, 2000)

Also in: 6.6.1, 6.7

GP#:1669

Single-seat cockpits have limited space for information display, and there is already a high display load in cockpits. Too many displays may contribute to information overload, increasing the probability of pilot error. (Reising, Liggett & Munns, 1999; Weinstein & Wickens, 1992; as cited in Tannen, 2000)

Also in: 4.1.4, 6.6.1

GP#:1673

Visual search tasks (e.g., using visual resources to search the environment) can be made easier/more effective by providing a visual display (e.g., representing the environment in relation to oneself), rather than simply relying on visual resources/searching the environment. This study used pilots and compared visual search with or without a display (which provided geospatial information about nearby planes in relation to his/her own plane vs. having to look out the window of the plane for information about other planes). (Prinzo, 2003)

Also in: 3.4.1, 3.6.1, 4.1.4

GP#:1717

Cockpit predictor displays have shown that pilot workload decreases and hazard detection performance improves with the addition of predictive information concerning the flight path of neighboring aircraft (Morphew & Wickens, 1998 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 6.6.1

GP#:1718

The horizontal situation indicator in the cockpit provides the pilot with a graphic display of the projected flight plan and the current position of the aircraft; this, more than any other automated system in the cockpit, has been credited with reducing the workload of the pilot (Wiener, 1988 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 4.1.4, 6.6.1

GP#:1735

Frame rates of at least 10 frames per second are necessary for optic flow perception, which is critical in piloting (Reingold et. al., 2003).

Also in: 2.2.1, 2.6.1, 4.1

GP#:1791

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

Also in: 3.1.1, 3.1.2, 3.2.1, 4.1, 4.2, 6.3.1, 6.3.2, 6.3.4 AV, 6.7

GP#:1793

Visual in-cockpit technology should be adopted with caution for single-pilot operations, and that adopting other design or training features should be considered to address the attentional implications of that
technology (this is true for cockpit displays of traffic information which may not be knowledgeable of all outside traffic). Design and training should be performed in conjunction if redundant display modalities are chosen, so that benefits of redundancy can be realized. (Wickens, Goh, Helleberg, Horrey & Talleur, 2003)

Also in: 4.1, 4.8.3, 5.1.1, 6.3.1

3.8.2 Audio

Modes should be chosen based on the intuitiveness of information interpretation (i.e., match the purpose of the information with the sense that is best able to handle it). In response to numerous aviation accidents caused by spatial disorientation, engineers added more visual displays for pilots. However, this did not reduce the occurrence of accidents, partially because the visual channels were overloaded (so the new information was not being processed), but also because tactile cues are more naturally interpreted as orientation cues (we use proprioception naturally in real-life), compared to visual cues. (Rupert, 2000)

Also in: 3.8.1, 5.3.1, 5.3.3

3.8.3 Tactile

Tactile and audio cues may be good for alerts of status change (compared to visual) because they’re omnidirectional (don’t require a particular head orientation) and can be used to guide attention to a particular location in the cockpit. The downside is that audio cues are hard to suppress, making them less desirable for non-emergency cues.

Tactile cues can effectively communicate information on airspeed, angle of attack, energy state, and other flight parameters (Zlotnick, 1988; as cited in Sarter, 2001), but may impede performance on other tasks (Gilliland & Schlegel, 1994; as cited in Sarter, 2001).

Also in: 2.7.2, 3.1.1, 3.1.2, 3.1.3, 3.8.1, 3.8.3, 4.2.3

3.8.4 Multimodal (AV, AT, TV, ATV)
Modalities required for VR simulation varies by task (piloting task requires tactile and visual cues, while visual alone is okay for navigation/monitoring tasks) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

Also in: 3.2.1, 8.1, 8.4 TV

- AV

No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing (Tannen, 2000).

Also in: 1.2.2, 2.7.1, 2.7.2, 3.6.1, 4.1, 4.2

Multimodal cueing (e.g., spatialized audio and visual) also reduced excessive head motion and lowered pilots’ workload by about 30%, as compared to conditions with no cues (Tannen, 2000).

Also in: 2.1.4 AV, 6.6.4 AV

No advantage was found for presenting multimodal info (e.g., spatialized audio and visual) adaptively over presenting it in fixed format (Tannen, 2000).

Also in: 2.7.4 AV

- AT
- TV

Thirty percent of civil air crashes have been attributed to pilot spatial disorientation, caused by faulty or misleading visual/vestibular system inputs – a problem that can be ameliorated by the use of intuitive tactile inputs (Schrope, 2001).

Also in: 3.8.1, 5.3.3, 6.4.1, 6.4.4 TV

- ATV

3.8.5 Not Specific to a Mode

Pilots did not fare well at responding to the presence of other events, especially when the event occurred simultaneously with a mode transition (Varakin, Levin, and Fidler, 2004).

Remote piloting and teleoperation require real-time information and fast updating so hand-eye coordination doesn’t degrade (Reingold, Loschky, McConkie & Stampe, 2003).

Combining visual cueing with auditory cueing might exacerbate clutter that is already high in cockpits (Tannen, 2000).

Also in: 3.2.5, 4.1.4

One way to counteract clutter is to use an adaptive interface, where automation controls the delivery of information to pilots, so that they get the right information in the right format at the right time, and aren’t otherwise exposed to it. This has been shown to be helpful to pilots during landing and navigation (cites Brickman et al 1996, Moroney, 1999; Hettinger, Cress, Brickman & Haas, 1996; Hollinagel, 1988, as cited in Tannen, 2000).
3.9 Communication (includes shadowing)

3.9.1 Visual

Advantages of instant messaging communication systems include the ability to communicate with multiple people at once, rapid responses to inquiries, and the ability to access archived chat sessions for clarification (Cummings, 2004).

Drawbacks of instant messaging systems are that they can be disruptive and the flow of conversation can be awkward in the absence of non-verbal cues. These limitations are especially bad in time-pressured scenarios because interrupting the primary task (with the instant messages) increases mental processing time and leads to errors on the primary task. (Cummings, 2004)

In a dual task situation, visual information should be conveyed in terms of relative position whenever possible to allow for optimal probability of accurate communication and primary task sustainability (Tessendorf, Chewar, Ndiwalana, Pryor, McCrickard & North, 2002).

Most people group types of messages by color pattern. Messages can be kept secret since only the message recipient knows what message the color pattern refers to. It is difficult to associate messages to color patterns, and it is difficult to later recall the association. (Tarasewich et al., 2004)

Haptic feedback is better than visual feedback in establishing a sense of togetherness in a shared virtual environment. This may have implications of remote virtual displays for various area of the military collaborating remotely on a task. (Basdogan et al., 2000)

Operators working in teams may have to modify their communication strategy based on their proximity to other team members. A communication style based on body language and visual signals may work well when people are close, but audio messages may work better when they are further apart. (Mackay, Fayard, Frobert & Medini, 1998)

When using characters smaller than .25° or larger than 2° in user interfaces, reading rates decrease rapidly with decreasing luminance rates (Ojanpaa & Nasanen, 2003).

Reading rates are fastest when color combinations with large brightness differences (e.g., black on white, black on yellow) are used (Ojanpaa and Nasanen, 2004).
Reference devoted to research findings and design principles regarding how physical text layout affects reading from screen (Dyson, 2004).

Also in: 4.1.4

GP#:1782

Delays (typical of those found in long distance telecollaboration) inhibit the ability of users to collaborate using haptic or visual communication at a distance. Delay can result in dissociation between the state of the system at the two end stations, which can cause differences in the response of operators who are compensating for perceived errors. (Allison, Zacher, Wang & Shu, 2004)

Also in: 2.5.1, 2.5.3, 3.9.3, 4.1.7, 4.3.4

3.9.2 Audio

GP#:1073

As more distracting voices are added to an audio conversation tracking task, it becomes harder to track target words. Also, as the number of distracting voices goes up, it becomes increasingly beneficial to augment audio cues with a video display of the target speaker. (Rudmann, McCarley & Kramer, 2003)

Also in: 3.9.4 AV, 4.2.3, 4.4.3

GP#:1332

Advantages of audio displays (compared to visual displays) for alarms: audio alarms are naturally interpreted as a warning signal, have faster neural transmission compared to visual (especially important for time-critical warnings) (Mowbray & Gebhard, 1969; as cited in Simpson, Bolia, & Draper, 2004).

Verbal communication is often the most direct/efficient/unambiguous method of information transfer; it allows information exchange regarding events that are now in the visual field (Simpson, Bolia, & Draper, 2004).

Also in: 2.7.2, 3.1.1, 3.1.2, 5.3.2, 6

GP#:1388

Operators working in teams may have to modify their communication strategy based on their proximity to other team members. A communication style based on body language and visual signals may work well when people are close, but audio messages may work better when they are further apart. (Mackay, Fayard, Frobert & Medini, 1998)

Also in: 3.9.1

GP#:1787

The detection and identification of speech information presented binaurally against a background of competing speech messages is significantly enhanced when the target phrase is located in the right hemifield (Bolia, Nelson & Morley, 2001). This is relevant to the design of spatial audio adaptive interfaces, such as when there is a need to dynamically modify characteristics of a display in response to changes in the functional state of the operator, the vehicle, or the environment. (Hettinger, et al 1996; as cited in Bolia, Nelson & Morley, 2001)

Also in: 2.1.2, 4.2

GP#:1788

Higher priority messages should be presented in the right hemifield, while lower priority messages should be presented in the left hemifield (Bolia, Nelson & Morley, 2001).

Also in: 2.1.2, 3.1.2, 4.2

GP#:1789

Target messages are more intelligible when presented against a distribution of signals that are symmetric than if they are distributed entirely to one side or the other of the midline (Bolia, Nelson & Morley, 2001).

Also in: 2.1.2, 4.2
Both hemifields should not be used in the design of spatial audio displays for speech communication (Bolia, Nelson & Morley, 2001).

Also in: 4.2

3.9.3 Tactile

Haptic feedback is better than visual feedback in establishing a sense of togetherness in a shared virtual environment. This may have implications of remote virtual displays for various area of the military collaborating remotely on a task. (Basdogan et al., 2000)

Also in: 3.9.1, 8.1, 8.3

Haptic devices: It is difficult to communicate haptic events in words or pictures, rapid prototyping is more effective than language in conveying haptic ideas. People can learn haptic skills fairly quickly. A simple haptic device can support complex interactions. (Fogg, Cutler, Arnold & Eisbach, 1998)

Also in: 4.3, 5.1.3

Touch is a powerful signal for emotional content and can contribute to losses in subtle non-verbal communication cues—hapticons can strengthen meaning and expression (Rovers & van Essen, 2004).

Also in: 2.6.3, 4.3.1

Delays (typical of those found in long distance telecollaboration) inhibit the ability of users to collaborate using haptic or visual communication at a distance. Delay can result in dissociation between the state of the system at the two end stations, which can cause differences in the response of operators who are compensating for perceived errors. (Allison, Zacher, Wang & Shu, 2004)

Also in: 2.5.1, 2.5.3, 3.9.1, 4.1.7, 4.3.4

3.9.4 Multimodal (AV, AT, TV, ATV)

Tasks that involve communicating information should be evaluated in terms of whether the information must be remembered or used to simply inform the user. If the information must be remembered, it is important to use the most effective means possible (i.e., combination of modes); however, if it is used to inform the user, subjective appeal should be considered most important. (Elting, Zwickel, and Malaka, 2002)

Also in: 3.9.5, 5.5.5, 6.6.5

• AV

As more distracting voices are added to an audio conversation tracking task, it becomes harder to track target words. Also, as the number of distracting voices goes up, it becomes increasingly beneficial to augment audio cues with a video display of the target speaker. (Rudmann, McCarley & Kramer, 2003)

Also in: 3.9.2, 4.2.3, 4.4.3

Performance on communication tasks and visual search tasks is vastly improved with spatial audio cues (Bolia & Nelson, 2003; as cited in Simpson, Bolia & Draper, 2004).

Also in: 3.6.1, 3.6.4 AV

• AT
High-bandwidth audio information can attenuate the effects of tactile cues in distributed collaboration situations (Sallnas, Rassmus-Grohn, & Sjostrom, 2000).

Also in: 3.9.4AT

- TV
- ATV

Haptic effects and hapticons used in conjunction with IM: Email and IM primarily use textual messages-extended with audio-visual cues. Hapticons are small, programmed force patterns that can communicate a basic notion similar to regular icons in a graphic interface. These vibration patterns only become hapticons after users start to recognize the patterns and associate them with a particular meaning. (Rovers & van Essen, 2004)

Also in: 3.1.3, 4.3.1, 5.2.3

3.9.5 Not Specific to a Mode

Tasks that involve communicating information should be evaluated in terms of whether the information must be remembered or used to simply inform the user. If the information must be remembered, it is important to use the most effective means possible (i.e., combination of modes); however, if it is used to inform the user, subjective appeal should be considered most important. (Elting, Zwickel, and Malaka, 2002)

Also in: 3.9.4, 5.5.5, 6.6.5

3.10 Environmental

Multimodal interfaces should be able to flex and adapt to handle natural environmental fluctuations like power outages or being damaged (Oviatt et al., 2004).

Also in: 2.7.4, 4.8, 4.9

People tend to code messages visually: where messages involve spatial orientation or guidance, where fine discrimination is needed, where complex or unfamiliar material is to be comprehended, where reference data have to be immediately available or when simultaneous comparisons need to be made, where a recipient of information has to make relatively prompt selection of data from larger stocks of information, and where auditory reception is hampered by unfavorable environmental conditions. (Geldard, 1960)

Also in: 2.6.1, 4.1, 6.6.1

3.11 Miscellaneous

Vision and touch are more precise and have shorter latencies than hearing for the perception of object properties, but hearing is better for temporal events (Arroyo & Selker, 2003).

Audio is not as prevalent as tactile with regards to data analysis and inspection when visual information is absent (Ramloll, Yu, Brewster, Riedel, Burton, & Dimigen, 2000).

Also in: 2.7.1, 2.7.2, 2.7.3, 4.7.1ATV

For graphical terrain displays: 3D display led to better accuracy for A-see-B tasks (can you see point B from point A?) but 2D displays led to better accuracy for A-hi-B tasks (is point A or B higher?) (Hollands, Ivanovic, & Enomoto, 2003); other studies have shown that 2D displays are good for judging relative position while 3D displays are good for understanding shape and output (St. John, Cowen, Smallman, & Oonk, 2001; Wickens & Thomas, 2000; as cited in Hollands, Ivanovic & Draper, 2004)
Most devices require action on the user’s part-- Driving devices such as GPS navigation systems add an extra element of complexity into the vehicle (Burnett, Summerskill & Porter, 2004).

In the absence of visual cues, multimodal conditions (audio-tactile) led to higher accuracy, lower response time, and less workload compared to unimodal conditions in deciphering a 2d bar graph (Yu & Brewster, 2002).

In the absence of visual cues, audio cues were better than haptic cues for determining which bar in a bar graph was highest/lowest, but tactile cues were better for determining which two bars were closest in size (Yu & Brewster, 2002).

Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information (Tsukada & Yasumura, 2004)

The best visual display for global-understanding tasks (e.g., battlefield command) is one which offers an initial view of the battlefield in exocentric perspective, allowing the user to zoom in to an immersive view, but which also then pops back to an exocentric position (Wickens, Thomas, & Young, 2000).

The space “hidden” from the user in an exocentric 3D environment is larger to the extent that the “tether” of the exocentric display is shorter (i.e. the viewpoint is closer to the point of interest or “anchor”) (Wickens, Thomas, & Young, 2000).

People perform best with tabular displays when locating specific values; alternatively, graphical displays are better when people must interpolate, forecast, or judge data trends (LaLomia, Coovert & Salas, 1988).

Representing the physical environment (e.g., weather, terrain) and opposing forces (e.g., computer generated forces) in an information display is critical in creating effective military simulations (Oswalt, 1995).
Distributed and parallel processing of simulation functionality is likely to be an increased requirement, as complex models represent many more aspects of a combat environment (Oswalt, 1995).

Advances in technology do not mitigate the need for thorough design and thoughtful implementation. For example, the design of military simulations still combines science and art (Oswalt, 1995).

### Table 3. Theorized benefits of adding haptic devices to visual displays (added modalities are in parentheses).

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Visual Display (VD)</th>
<th>VD + Tactile Interface</th>
<th>VD + Positional Actuator</th>
<th>VD + Probe-Based (Force Feedback) System</th>
<th>VD + Exoskeleton System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tactile perception</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texture Perception (hard/soft, smooth/rough, and so on)</td>
<td></td>
<td>More accurate judgment of softness and roughness than visual alone</td>
<td>Possible to judge with same accuracy as when using fingertip</td>
<td>If tactile actuators are present in fingertips, possible to judge texture</td>
<td></td>
</tr>
<tr>
<td>2D form perception (spatial acuity, pattern recognition, curvature perception, and so on)</td>
<td>Relative depth in field of view (FOV)</td>
<td>Tactile can be ignored when irrelevant</td>
<td>Cross-modal cueing effects useful</td>
<td>If tactile actuators are present in fingertips, possible to judge 2D form perception</td>
<td></td>
</tr>
<tr>
<td><strong>Kinesthetic perception</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial awareness/position (for example, objects in environment, limb with respect to trunk, body with respect to environment)</td>
<td>Relative depth of objects in FOV</td>
<td>Allow egocentric frame of reference within personal space</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
<td></td>
</tr>
<tr>
<td>3D form perception (length discrimination, weight, and shape identification, for example)</td>
<td>Identification and discrimination depend on viewing angle and no indication of weight</td>
<td>Deformability through force feedback aids discrimination and identification</td>
<td>Adding force to virtual object increases presence</td>
<td>Improved weight discrimination of objects</td>
<td></td>
</tr>
</tbody>
</table>

(Hale & Stanney, 2004)

Also in: 2.7.1, 2.7.3, 4.1, 4.3, 4.9, 8.3, 8.6, 8.7
4. General Display Design Considerations

Two stimuli that are presented at the same time within a certain distance are generally perceived as one stimulus (Cholewiak, 1988; as cited in van Erp & Verschoor, 2004). The cue is usually sensed as being located in the middle of the two stimuli (called the “apparent position”). (van Erp & Verschoor, 2004)

Also in: 2.1.3, 3.5

4.1 Visual

Feature search is more efficient than conjunction search (Hollands, Parker, McFadden & Boothby, 2002). Feature search can be performed fast and without much attention for targets that can be identified by certain features. Conjunction search is a serial search for targets that have to be identified by a conjunction of specific features (it is much slower and requires conscious attention).

Eight guidelines related to when/how to use multiple/coordinated sets of views simultaneously. (Baldonado & Kuchinsky, 2000)

<table>
<thead>
<tr>
<th>Rule</th>
<th>Summary</th>
<th>Major Positive Impacts on Utility</th>
<th>Major Negative Impacts on Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diversity</td>
<td>Use multiple views when there is a diversity of attributes, models, user profiles, levels of abstraction, or genres.</td>
<td>memory</td>
<td>learning computational overhead display space overhead</td>
</tr>
<tr>
<td>Complementarity</td>
<td>Use multiple views when different views bring out correlations and/or disparities.</td>
<td>memory comparison context switching</td>
<td>learning computational overhead display space overhead</td>
</tr>
<tr>
<td>Decomposition</td>
<td>Partition complex data into multiple views to create manageable chunks and to provide insight into the interaction among different dimensions.</td>
<td>memory comparison</td>
<td>learning computational overhead display space overhead</td>
</tr>
<tr>
<td>Parsimony</td>
<td>Use multiple views minimally.</td>
<td>learning computational overhead display space overhead</td>
<td>memory comparison context switching</td>
</tr>
<tr>
<td>Space/Time Resource Optimization</td>
<td>Balance the spatial and temporal costs of presenting multiple views with the spatial and temporal benefits of using the views.</td>
<td>comparison computational overhead display space overhead</td>
<td></td>
</tr>
<tr>
<td>Self-Evidence</td>
<td>Use perceptual cues to make relationships among multiple views more apparent to the user.</td>
<td>learning comparison</td>
<td>computational overhead</td>
</tr>
<tr>
<td>Consistency</td>
<td>Make the interfaces for multiple views consistent, and make the states of multiple views consistent.</td>
<td>learning comparison</td>
<td>computational overhead</td>
</tr>
<tr>
<td>Attention Management</td>
<td>Use perceptual techniques to focus the user’s attention on the right view at the right time.</td>
<td>memory context switching</td>
<td>computational overhead</td>
</tr>
</tbody>
</table>

Table 1: Summary of rules and areas of major impact on utility.

Closely match the material on hard copies and computer screens to eliminate the decrements in reading speed and accuracy that may otherwise result from presenting information on computer screens (Garland & Noyes, 2004).

Differences in knowledge retrieval (between hard and soft copies) were time-related and suggest that repeated exposure and rehearsal of computer-based information is necessary to equate knowledge.
application with that achievable from hard copy. This difference might be due to cognitive interference caused by CRT monitor refresh rates (flicker on CRT monitors), fluctuating luminance, or contrast levels. (Garland & Noyes, 2004)

GP#:1209

In a dual task situation, visual information should be conveyed in terms of relative position whenever possible to allow for optimal probability of accurate communication and primary task sustainability (Tessendorf, Chewar, Ndiwalana, Pryor, McCrickard & North, 2002).

Also in: 3.9.1, 6.7

GP#: 1279

Visual texture using the technique presented by Ware & Knight (1995) should be considered as a technique to add depth to information display, particularly topographic maps. Humans are most sensitive to patterns whose period is approximately 2 cycles/degree.

Also in: 2.2.1, 4.1.4, 4.3.1

GP#:1289

Pictorial nature of icons (not just their implementation, as previously posited) seems to improve user performance at interface; thus, when using GUI and search speed is important, icons are preferable to text (Niemela & Saarinen, 2000)

GP#:1373

Ideally, we want a display that can stimulate our entire retina while allowing freedom of eye rotation, head rotation and physical displacement. (Lantz, 1997).

Also in: 2.6.1

GP#:1377

The span of absolute judgment and span of immediate memory impose severe limitations on the amount of information that humans are able to receive/process/remember. Miller (1956) thought people should use only one sensory channel at a time, but he also concluded that humans can usefully perceive about 7 different variables presented in a single sensory modality. Considering the latter conclusion, using only visual displays would not optimal because it would limit human information perception bandwidth. (Miller, 1956; as cited in Loftin, 2003)

Also in: 6, 6.7.2

GP#:1391

Wearing multifocal lenses may help the posture of an individual (more so than bifocal lenses), because they allow the user to raise their chin while looking at a computer terminal (Inoue, 2002).

Also in: 2.6.4, 5

GP#:1405

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information (Tsukada & Yasumura, 2004)

Also in: 2.7.1, 2.7.2, 2.7.3, 3.11, 4.2, 4.3, 6.7

GP#:1437

The interval between pulses (empty interval) is perceived to be longer with vibrotactile pulses than with visual light pulses (Van Erp & Werkhoven, 2004).

Also in: 2.2.1, 2.2.3, 4.3.1

GP#:1438

Haptic rendering requires update rates significantly higher than graphics rendering (Walker & Salisbury, 2003).
Immersive displays are best for assessing line-of-sight visibility, and provide better guidance than 2D displays when used in aviation settings (Wickens, Thomas, & Young, 2000).

The decision of how many and which viewpoints to use in a display should be guided by task analysis (Wickens, Thomas, & Young, 2000).

With mobile devices, keeping interactions minimally demanding of cognitive and visual attention is a core design issue (Hinckley et al., 2005).

Background channels (for peripheral tasks) should be kept free for sensing of typical, naturally occurring gestures by the user. Foreground interactions should be reserved for atypical special cases where user wishes to explicitly control something. (Hinckley et al., 2005)

The following errors should be considered with regard to foreground-background interaction: background becomes foreground when it should not (e.g., PDA screen changes from landscape to portrait when resting in user’s lap); background fails to become foreground when it should (e.g., user holds PDA like phone but gesture is not recognized); foreground manipulation is incorrectly interpreted as background activity (e.g., user tips PDA to avoid glare and display changes orientation); foreground burdens user with tasks that could be automated in the background (e.g., user explicitly switches display format, which could have been automated if user knew that sensors supported this function). (Hinckley et al., 2005)

The following are three guidelines for designers of visual displays: designers should (1) consider how different quantities are encoded within any chosen representational format, (2) consider the full range of alternative varieties of a given task, and (3) balance the cost of familiarization with the computational advantages of less familiar representations (Peebles & Cheng, 2003).

The following hypotheses have been posited on the Illusions of Visual Bandwidth: people might overestimate how much visual information can be attended to simultaneously; designers overestimate the number of locations that a user will typically attend to; and people may overestimate the representational consequences for having attended to an object or location. (Varakin, Levin, & Fidler, 2004)

Across all performance variables, both visual and auditory indicators showed similar results and are significantly better than an interface configuration without a context switch indicator (Trouvain & Schlick, 2004).

It is not unrealistic to substitute a visual indicator completely by its auditory equivalent (Trouvain & Schlick, 2004).
Frame rates of at least 10 frames of 10 frames per second are necessary for optic flow perception, which is critical for piloting (Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 2.2.1, 3.8.1

The use of density on maps is an important tool for enhancing situation awareness; displaying different saturations to represent troop movement allows users to achieve higher levels of situational awareness rapidly (Kim & Hoffmann, 2003).

Also in: 3.2.1, 3.5.1, 3.6.1, 6.4.1

Three visual tools (density, clustering, and lethality assessment) can enhance the situational awareness of a military commander on the battlefield. They can provide visual abstractions of an actual battle, not just terrain visualization. (Kim & Hoffmann, 2003)

Also in: 3.2.1, 3.5.1, 6.4.1

People tend to code messages visually: where messages involve spatial orientation or guidance, where fine discrimination is needed, where complex or unfamiliar material is to be comprehended, where reference data have to be immediately available or when simultaneous comparisons need to be made, where a recipient of information has to make relatively prompt selection of data from larger stocks of information, and where auditory reception is hampered by unfavorable environmental conditions. (Geldard, 1960)

Also in: 2.6.1, 3.10, 6.6.1

Dynamic tactile information (e.g., five tactors placed on the forearm vibrating sequentially) can be used to accurately reorient visual attention or vice versa (Hale & Stanney, 2004).

Also in: 2.1.3, 4.3.1, 6.3.1

Single-cue information is lost when cues from within the same sensory modality (e.g., disparity and texture gradients in vision) are combined, but not when different modalities (vision and haptics) are combined (Hillis, Ernst, Banks & Landy, 2002).

Also in: 2.7.1, 2.7.4 VT

In a within-modal case, texture and disparity cues at the same retinal location almost always come from the same object. Thus, mandatory cue combination would be beneficial if errors in the texture and disparity estimates were a more likely cause of discrepancy than actual signal differences. Therefore, there would be evolutionary or developmental pressure to relay on the combined estimate, instead of the single-cue estimates. (Hillis, Ernst, Banks & Landy, 2002)

Also in: 2.7.1

No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing (Tannen, 2000).

Also in: 1.2.2, 2.7.1, 2.7.2, 3.6.1, 3.8.4 AV, 4.2

Guidelines for displays exhibiting high compatibility between display and mental task:
1. Integrate and collate related relevant information in a manner that allows visual comparisons that make use of quick glances.
2. Allow allocators to manage incidents rather than just calls.
3. Indicate the level of certainty in the information received.
4. Allow a spiral visual search pattern to locate the next nearest ambulance available to an incident (location).
5. Allow for assigning of temporary intermediate planning states and intentions.

(Blandford & Wong, 2004)

Also in: 3.4.1, 3.5.1, 3.6.1, 6.4.1

GP#:1689

Slow fade animation provides the best all-around support for a notification task in a secondary display when used with a browsing task. Results from the second experiment show no deficiencies for slow fade animation under any of the primary or secondary task metrics. Although other animation implementations may allow better performance under different and specific design objectives, slow fade minimizes performance tradeoffs best. (McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 3.1.1

GP#:1704

When viewing near objects, the medial recti muscles are activated. When raising the eyes, the medial recti muscles are also activated, which is why individuals prefer to look downward to view near targets. Therefore, the potential for visual fatigue associated with placing visual displays at a level higher than optimal is increased for closer displays. (Burgess-Limerick et al., 2000)

Also in: 2.6.1

GP#:1706

In a normal erect posture, the eye-ear line is typically 15 degrees above horizontal eye height. Therefore, visual displays should be placed 15 degrees below horizontal eye height. (Burgess-Limerick et al., 2000)

Also in: 2.1.1

GP#:1735

Frame rates of at least 10 frames per second are necessary for optic flow perception, which is critical in piloting (Reingold et. al., 2003).

Also in: 2.2.1, 2.6.1, 3.8.1

GP#:1762

People travel less far in orthogonal than oblique environments, even when the distances they can see are equivalent (Ruddle & Peruch, 2004).

Also in: 3.2.1

GP#:1791

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

Also in: 3.1.1, 3.1.2, 3.2.1, 3.8.1, 4.2, 6.3.1, 6.3.2, 6.3.4 AV, 6.7

GP#:1793

Visual in-cockpit technology should be adopted with caution for single-pilot operations, and that adopting other design or training features should be considered to address the attentional implications of that technology (this is true for cockpit displays of traffic information which may not be knowledgeable of all outside traffic). Design and training should be performed in conjunction if redundant display modalities
are chosen, so that benefits of redundancy can be realized. (Wickens, Goh, Helleberg, Horrey & Talleur, 2003)

Also in: 3.8.1, 4.8.3, 5.1.1, 6.3.1

GP#:1800

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Visual Display (VD)</th>
<th>VD + Tactile Interface</th>
<th>VD + Positional Actuator</th>
<th>VD + Probe-Based (Force Feedback) System</th>
<th>VD + Exoskeleton System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile perception</td>
<td></td>
<td></td>
<td></td>
<td>Possible to judge</td>
<td></td>
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<tr>
<td>(hard/soft, smooth/ rough, and so on)</td>
<td></td>
<td></td>
<td></td>
<td>with same accuracy as when using</td>
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<td></td>
<td></td>
<td>fingertips</td>
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<tr>
<td>2D form perception</td>
<td>Relative depth in</td>
<td>Tactile can be</td>
<td>Cross-modal</td>
<td>If tactile actuators</td>
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<td>(spatial acuity, pattern</td>
<td>field of view (FOV)</td>
<td>ignored when</td>
<td>cueing effects</td>
<td>are present in</td>
<td></td>
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<tr>
<td>recognition, curvature perception,</td>
<td></td>
<td>irrelevant</td>
<td>useful</td>
<td>fingertips, possible to judge</td>
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<tr>
<td>and so on</td>
<td></td>
<td>(FOV)</td>
<td></td>
<td>texture</td>
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<tr>
<td>Kinesthetic perception</td>
<td>Relative depth of</td>
<td>Allow egocentric</td>
<td>Force feedback enhance</td>
<td>Force feedback</td>
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<td>(for example, objects in environment,</td>
<td>objects in FOV</td>
<td>frame of reference</td>
<td>distance judgments</td>
<td>enhances distance</td>
<td></td>
</tr>
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<td>limb with respect to trunk, body</td>
<td>Visual proprioception</td>
<td>within personal space</td>
<td>within personal space</td>
<td>within personal space</td>
<td></td>
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<tr>
<td>with respect to environment)</td>
<td>within FOV</td>
<td></td>
<td>(arm's reach)</td>
<td>(arm’s reach)</td>
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<tr>
<td>3D form perception</td>
<td>Identification and</td>
<td>Deformability</td>
<td>Adding force to</td>
<td></td>
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<tr>
<td>(length discrimination, weight, and</td>
<td>discrimination</td>
<td>through force</td>
<td>virtual object increases</td>
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<tr>
<td>shape identification, for example)</td>
<td>depend on viewing</td>
<td>feedback aid</td>
<td>presence</td>
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<td></td>
<td>angle</td>
<td>discrimination and</td>
<td>improved weight</td>
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<td>identification</td>
<td>discrimination of</td>
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<td></td>
<td>Improved object</td>
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<td></td>
<td>interaction</td>
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</tbody>
</table>

(Hale & Stanney, 2004)

Also in: 2.7.1, 2.7.3, 3.11, 4.3, 4.9, 8.3, 8.6, 8.7

GP#:1801
4.1.1 Color/Contrast

Simplifying screen layout and incorporating high contrast can make visual displays more effective (Jacko et al., 2004).

Also in: 4.1.4

When working with a visual display visual performance is enhanced when the display is larger, more realistic, less cluttered, well contrasted, and when operators are familiarized and have more control (Wickens & Long, 1995; Yeh, Wickens & Seagull, 1999; Gulliver, Serif & Ghinea, 2004; Yeh & Wickens, 2001; Zhou, Cheok, Yang & Qiu, 2004).

Also in: 4.1.2, 4.1.4, 5.1.1

Incorporate color into visual displays to aid in target detection. Color is more accurately identified than size, brightness, or shape (Brown, Newsome & Glinert, 1989).

Also in: 4.1.2

Don’t use LCD monitors when off-axis viewing is likely and color coding is used (Hollands, Parker, McFadden & Boothby, 2002).
Using redundant information of color and target shape is a useful display technique; this helps with CRT displays and on-axis LCD display usage (Hollands, Parker, McFadden & Boothby, 2002).

Also in: 4.1.2, 4.1.4

Differences between types of visual displays in an aviation task (immersive 3-D, exocentric 3-D, and 2-D coplanar) disappeared when audio warnings of hazards and color coding cues (red, yellow, and green to indicate altitude conditions; color coding between map views to facilitate coordination) were added (Olmos, Wickens, & Chudy, 2000).

Also in: 3.1.2, 3.8.1

Colors can enhance visual displays by adding intuitiveness. For example, consider using red to indicate problems, yellow for warnings, and green when everything is operating normally. Additionally, when multiple displays are being used simultaneously, it is beneficial to match similar information across displays by using consistent colors. (Olmos, Wickens, & Chudy, 2000)

Positioning a color indicator in close proximity to a continuous analog display should be an efficient way to present two different sources of info (Meyer, 2001).

Also in: 2.1.1, 4.1.4, 4.1.6

Visual design principles for target detection tasks: use different colors for target and background, minimize visual distance from target (by angle of view), try not to include other dynamically changing stimuli in visual display (effects are compounded when these are combined) (Nikolic, Orr, & Sarter, 2004).

Also in: 3.6.1, 4.1.4

Higher contrast on a visual display leads to better detection. Caffeine may enhance detection on a short term target detection vigilance task when administered at 1.1mg/kg (Temple et al., 2000).

Also in: 3.4.1, 3.6.1, 6.3.1

Most people group types of messages by color pattern. Messages can be kept secret since only the message recipient knows what message the color pattern refers to. It is difficult to associate messages to color patterns, and it is difficult to later recall the association. (Tarasewich et al., 2004)

Also in: 3.9.1, 5.1.1, 5.3.1

Objects that are created by combining color and shape or size do not create emergent features.

Combining spatial and non spatial dimensions like colors or shapes into a single object facilitates initial parallel processing of both dimensions in a way that will support both focused attention and information integration.

Using separate colors for each indicator disrupted information integration. Using common colors disrupted focused attention relative to performance with monochrome display.

Using unique color borders compensated for the loss of distinctiveness of individual dimensions and lead to improvement in both attentional and integrational performance.

Current data suggest that the extra time (200-400ms) needed to process color information is probably
worthwhile given the increase in the accuracy of check reading and given that the accuracy of integrations was not disrupted by color. (Wickens and Andre, 1990)

Also in: 4.1.2, 6.3.1, 6.7

GP#:1392

When workload is high, operators tend to rely mainly on surface cues of displays, so it’s especially important to use cues consistently (e.g., colors) (Gilson, Mouloua, Graft, & McDonald, 2001).

Also in: 2.1.1, 6.6.5

GP#:1462

Increased contrast, in a visual display, is known to increase visual acuity (Heath 1956, Legge et al. 1987), image clarity (Poynter 1992), saccadic length (Roufs et al 1988) and comfort (Roufs et al 1991; as cited in Sheedy et al., 2003).

Also in: 2.7.1, 4.1.3, 7.1.1

GP#:1463

Decreased luminance in a visual display has been shown to cause a decrease in visual acuity (Sheedy et al, 2003).

Also in: 2.7.1

GP#:1464

Contrast enhancing filters (CEFs) in a visual display have not been found to increase legibility, user reading speed, letter counting or user comfort. In fact, CEFs have been found to increase user discomfort for CRTs (Cathode Ray Tubes), although the researchers note that this finding was counterintuitive because the purpose CEFs were designed to reduce glare and enhance readability of a screen, etc. (Sheedy et al, 2003)

Also in: 4.1.4, 7.1.1

GP#:1551

When using characters smaller than .25° or larger than 2° in user interfaces, reading rates decrease rapidly with decreasing luminance rates (Ojanpaa & Nasanen, 2003).

Also in: 3.9.1, 4.1.2, 4.1.3

GP#:1552

The use of more than one color in a user interface tends to reduce luminance contrast (Ojanpaa and Nasanen, 2004).

GP#:1553

Reading rates are fastest when color combinations with large brightness differences (e.g., black on white, black on yellow) are used (Ojanpaa and Nasanen, 2004).

Also in: 3.9.1

GP#:1554

The difference in luminance between text and background should always be sufficient (Ojanpaa and Nasanen, 2004).

GP#:1607

Green seems to be the hardest color to work with in a visual space, in terms of target location and differentiation from other colors, whereas white and yellow seem to be the best (Smallman & Boynton, 1990).

Also in: 3.6.1

GP#:1608

Basic colors segregate well, not because they are universally named but because they are well separated in color space (Smallman & Boynton, 1990).
4.1.2 Size/Shape

When working with a visual display visual performance is enhanced when the display is larger, more realistic, less cluttered, well contrasted, and when operators are familiarized and have more control (Wickens & Long, 1995; Yeh, Wickens & Seagull, 1999; Gulliver, Serif & Ghinea, 2004; Yeh & Wickens, 2001; Zhou, Cheok, Yang & Qiu, 2004).

Also in: 4.1.1, 4.1.4, 5.1.1

GP#:1106

Incorporate color into visual displays to aid in target detection. Color is more accurately identified than size, brightness, or shape (Brown, Newsome & Glinert, 1989).

Also in: 4.1.1

GP#:1110

Using redundant information of color and target shape is a useful display technique; this helps with CRT displays and on-axis LCD display usage (Hollands, Parker, McFadden & Boothby, 2002).

Also in: 4.1.1, 4.1.4

GP#:1222

In the real world there are “natural cues,” but things are more complicated in a three-dimensional display; it is hard to achieve the same understanding with a scaled down version of the real world and a limited field of view. It is difficult for the operator to perceive distance, altitude, sizes, etc. in a limited field of view because of scaling problems, abstract object design, and the limited number of natural cues. However, in some tasks, such as landing, display size and field of view have less of an impact. (Comstock, Glaab, Prinzell & Elliot, 2001; as cited in Andersson & Alm, 2002)

Also in: 2.7.1, 3.8.1, 4.1.4

GP#:1223

Making judgments of azimuth and elevation are very difficult in static scenarios (Andersson & Alm, 2002).

Also in: 3.6.1, 3.8.1, 4.1.4

GP#:1224

The three-dimensional heading of objects was easier to estimate for abstract symbols (sphere, cube and pyramid) than for arrow symbols. Additionally, symbols directed straight against the operator were extremely difficult to perceive regardless of symbol shape. This provides support for the notion that direction content in abstract symbols with velocity vectors is stronger than built-in directional information in arrow symbols. In contradiction to other symbols tested, the sphere symbol was correctly identified regardless of the three-dimensional direction it was in. Finally, shape was not a good way to distinguish between categories of targets in a three-dimensional context. (Andersson & Alm, 2002)

Also in: 3.6.1

GP#:1225

Azimuth angles and elevation judgments are very difficult to make from visual displays. The assessment of symbol relation is also very difficult, regardless of aspect angle. To improve performance, designers need to optimize design solutions and add more or alternative depth cues. If you accept the design constraints of keeping the horizon visible, it is obvious that a vertical aspect angle change is not the way to improve direction assessments. (Andersson & Alm, 2002)

Also in: 3.2.1, 3.6.1

GP#:1309

Objects that are created by combining color and shape or size do not create emergent features.

Combining spatial and non spatial dimensions like colors or shapes into a single object facilitates initial parallel processing of both dimensions in a way that will support both focused attention and information
integration.

Using separate colors for each indicator disrupted information integration. Using common colors disrupted focused attention relative to performance with monochrome display.

Using unique color borders compensated for the loss of distinctiveness of individual dimensions and lead to improvement in both attentional and integrational performance.

Current data suggest that the extra time (200-400ms) needed to process color information is probably worthwhile given the increase in the accuracy of check reading and given that the accuracy of integrations was not disrupted by color. (Wickens and Andre, 1990)

Also in: 4.1.1, 6.3.1, 6.7

GP#:1344

An object’s prominence in a scene is dependent on both its centrality within the scene and its size (Kelleher & van Genabith, 2004).

Also in: 2.1.1

GP#:1410

Image scale factor (the degree to which the image is magnified or minimized compared to actual image) is a major factor in the inducement of simulator sickness (Draper et al., 2001).

Also in: 8.1

GP#:1418

When engaging in two dissimilar tasks (e.g., visual and verbal), it is visual template complexity, not display size that affects the level of interference resulting from the dual task (Bourke & Duncan, 2005).

Also in: 4.1.4, 4.4.1, 6.7

GP#:1442

A smaller map with a wide field of view (FOV) displayed in the corner of a 3D map display can reduce tunnel vision (Wickens, Thomas, & Young, 2000).

Also in: 2.7.1, 3.2.1, 4.1.4, 6.4.1

GP#:1551

When using characters smaller than .25º or larger than 2º in user interfaces, reading rates decrease rapidly with decreasing luminance rates (Ojanpaa & Nasanen, 2003).

Also in: 3.9.1, 4.1.1, 4.1.3

GP#:1688

Smaller displays result in faster identification of changing information. This may be related to the amount of information that a viewer can read at a glance. Larger displays may make it difficult to obtain desired information. (McCrickard, Catrambone, Chewar & Stasko, 2003)

GP#:1691

Text/symbols that are too small may present a problem for older adults (Hancock, Rogers, & Fisk, 2001).

Also in: 1.1.1

GP#:1692

A large amount of text presented in a dense or complex format will tax working memory, and complex symbols that are small, or that are accompanied by explanatory text that is too small to read, will be difficult for older adults and others with visual impairments to interpret (Hancock, Rogers, & Fisk, 2001).

Also in: 1.1.1, 4.1.4, 6.6.1

4.1.3 Resolution
Reducing the resolution of the visual display to that of the tactile display results in higher root-mean-square (RMS) errors and longer tracking delays. However, even when resolution effects are taken into account, visual tracking performance is still better than tactile tracking performance. (Van Erp & Verschoor, 2000)

Also in: 2.7.1, 2.7.3, 3.6.1, 3.6.3

Two important factors in immersive display design are resolution and Field Of View. Image fidelity requires high resolution, measured in resolvable dots or effective pixels. Immersion requires wide FOV. Increasing FOV while maintaining high resolution requires an increase in effective pixels. (Lantz, 1997)

Also in: 2.1.1, 4.1.4

Increased contrast, in a visual display, is known to increase visual acuity (Heath 1956, Legge et al. 1987), image clarity (Poynter 1992), saccadic length (Roufs et al 1988) and comfort (Roufs et al 1991; as cited in Sheedy et al., 2003).

Also in: 2.7.1, 4.1.1, 7.1.1

When using characters smaller than .25º or larger than 2º in user interfaces, reading rates decrease rapidly with decreasing luminance rates (Ojanpaa & Nasanen, 2003).

Also in: 3.9.1, 4.1.1, 4.1.2

Infrared and indirect vision systems are useful in situations where direct vision is poor or impossible. These displays need high-resolution for tasks such as target identification, and wide fields of view for tasks such as orientation and tactile maneuvering. (Reingold, Loschky, McConkie & Stampe, 2003)

Also in: 3.2.4, 3.6.1, 4.1.6

The following are the specifications of a good gaze-tracking system: 1: plug and play; 2: unobtrusive; 3: accurate; 4: high temporal resolution; 5: high spatial resolution with low noise; 6: ability to determine gaze in a wraparound view (310º); 7: affordable. (Reingold, Loschky, McConkie & Stampe, 2003)

Also in: 4.1.6

When designing or using a gaze-contingent multiresolutional display, there is always a tradeoff between computation & bandwidth savings and decrements in perception & performance (Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 2.7.1

A visual display that is tailored to the properties of the human visual system (more detail at focus, less detail in the periphery) may be as effective as a traditional display with uniform resolution; this saves a lot of bandwidth and computer hardware expense (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.6

In immersive VR environments, greater importance should be given to the speed of updating than to display resolution (Reingold et. al., 2003).

Also in: 8.1
Reducing the visual processing load by decreasing resolution in the periphery is important in the development of artificial vision systems (Reingold et. al., 2003).

Also in: 4.1.6, 6.6.1

GP#:1738

The ultimate goal for gaze-contingent multiresolutional displays (GCMRDs) is to produce savings by substantially reducing peripheral image resolution and/or detail and yet, to the user, be undetectably different from a normal image (Reingold et. al., 2003).

Also in: 4.1.4, 4.1.6

4.1.4 Layout

Simplifying screen layout and incorporating high contrast can make visual displays more effective (Jacko et al, 2004).

Also in: 4.1.1

GP#:1012

If there is a radar display, it helps to have an inner ring to help gauge distance (Haimson et al., 2004).

Also in: 3.4.1, 3.6.1

GP#:1016

There are general advantages of menu breadth over depth. For example, it is better to have more information on each of four menu screens than have less information on each of eight menu screens (Wickens & Seidler, 1997).

GP#:1017

When working with a visual display visual performance is enhanced when the display is larger, more realistic, less cluttered, well contrasted, and when operators are familiarized and have more control (Wickens & Long, 1995; Yeh, Wickens & Seagull, 1999; Gulliver, Serif & Ghinea, 2004; Yeh & Wickens, 2001; Zhou, Cheok, Yang & Qiu, 2004).

Also in: 4.1.1, 4.1.2, 5.1.1

GP#:1049

Workstations with multiple windows, zooming maps, and pop-up menus can block change detection signals (Durlach, 2004).

Also in: 2.4.1, 4.1.7

GP#:1079

When designing effective displays, include those graphical features that can be decoded most effectively. The way a process is represented can affect the potential for operators to misinterpret a single sensor value as standing for the state of a higher-order process. It is not always an issue of choosing one format or mode over another, but rather a determination of how to combine sources of evidence, develop effective representations, and coordinate multiple representations in the process of representation design. All representations, in making some aspects of the world more salient than others, have the potential to be misleading. (Bennett, Malek & Woods, 2000)

Also in: 4.1.8, 4.1.9, 5.3

GP#:1102

Using redundant information of color and target shape is a useful display technique; this helps with CRT displays and on-axis LCD display usage (Hollands, Parker, McFadden & Boothby, 2002).

Also in: 4.1.1, 4.1.2

GP#:1110

GP#:1172
Graphics displays are ideal when there are a lot of quantitative or relational facts to present or for concrete or spatial information, while natural language is better for abstract concepts/processes (Maybury, 1995).

Also in: 4.2

GP#:1221

A single 3D perspective view was found to more efficient than three 2D views for understanding the shape of simple blocks and natural terrain. The 2D views were better than the 3D views for understanding the relative positions of two objects and two terrain locations.

With 2D views, no single view can provide information about all three dimensions of an object; to present a third dimension, a separate view must be added. Information about the shape of an object or scene must then be combined mentally, which is both hard and time-consuming. A perspective view is easier to use because it integrates the dimensions into a single view.

Benefits of 3D views:
1) 3D views are useful for shape and layout understanding because they (a) integrate all three dimensions into a single rendering, (b) are receptive to supplementary depth cues, and (c) allow features of an object to be depicted that would be invisible in a normal 2D view.

2) 3D views allow extra depth cues to be added, such as shadows, object scaling (i.e., distant object features are drawn smaller), texture gradients, and shading, making 3D shape immediately apparent. Each additional depth cue adds to the portrayal of depth. In fact, the benefits of each cue appear to be independent and additive (Bruno & Cutting, 1988; as cited in John et al, 2001).

3) 3D views allow the illustration of object features that could be hidden in a 2D view.

Benefits of 2D views:
2D views are useful for judging relative positions because normal viewing angles they require (e.g., top-down, side, front) minimize distortion. 2D views can also minimize ambiguity. Example: a user can easily switch among a set of 2D views to obtain exact information about each dimension of interest. In contrast, each dimension of a 3D view is confounded with ambiguity spread across all three dimensions. This ambiguity and distortion can make relative-position judgments of any precision difficult. (John, Cowen, Smallman, & Oonk, 2001)

GP#:1222

In the real world there are “natural cues,” but things are more complicated in a three-dimensional display; it is hard to achieve the same understanding with a scaled down version of the real world and a limited field of view. It is difficult for the operator to perceive distance, altitude, sizes, etc. in a limited field of view because of scaling problems, abstract object design, and the limited number of natural cues. However, in some tasks, such as landing, display size and field of view have less of an impact. (Comstock, Glaab, Prinz & Elliot, 2001; as cited in Andersson & Alm, 2002)

Also in: 2.7.1, 3.8.1, 4.1.2

GP#:1223

Making judgments of azimuth and elevation are very difficult in static scenarios (Andersson & Alm, 2002). Also in: 3.6.1, 3.8.1, 4.1.2

GP#:1236

Data displayed in browsers should be available, easily accessible, up-to-date, and should consolidate info from a variety of sources. Representation should be calm and “refined”, not demanding attention from the user. The user should be allowed to personalize the graphics browser display. Displays should hide sensitive data from public view. (Miller & Stasko, 2002)

Also in: 4.1.6, 5.5.5

GP#:1238
Positioning a color indicator in close proximity to a continuous analog display should be an efficient way to present two different sources of info (Meyer, 2001).

**Also in:** 2.1.1, 4.1.1, 4.1.6

**GP#:1254**

Visual design principles for target detection tasks: use different colors for target and background, minimize visual distance from target (by angle of view), try not to include other dynamically changing stimuli in visual display (effects are compounded when these are combined) (Nikolic, Orr, & Sarter, 2004).

**Also in:** 3.6.1, 4.1.1

**GP#:1278**

Ecological displays (those that extend across the central visual and peripheral visual fields and present information in a manner that is visually consistent with information available in the real world) allow for more accurate control (when compared with central or peripheral displays) in low-control velocity flight simulation tasks (Weinstein & Wickens, 1992).

**Also in:** 3.8.1, 4.1.6

**GP#: 1279**

Visual texture using the technique presented by Ware & Knight (1995) should be considered as a technique to add depth to information display, particularly topographic maps. Humans are most sensitive to patterns whose period is approximately 2 cycles/degree.

**Also in:** 2.2.1, 4.1, 4.3.1

**GP#:1288**

In graphics-based interfaces, use of icons (vs. text) and their grouping has positive effect on scanning speed: spatial grouping of icons increases scanning speed, and use of icons (vs. text) in GUI increases scanning speed of target file (Niemela & Saarinen, 2000).

**Also in:** 3.4.1, 3.6.1

**GP#:1291**

The impact of display layout on performance depends on the event type: high priority events handled quicker and more accurately in full screen layout (Parush, 2004).

**Also in:** 6.7

**GP#:1292**

A reduction in visual load (e.g., full screen layout with a single event log) is more supportive of a supervisory task that requires focused attention on one event type. In contrast, a reduction in operational load (e.g., full screen layout with five event logs) is more supportive of supervisory tasks that require divided attention across different event types of different handling priority. (Parush, 2004)

**Also in:** 6.6.1, 6.7

**GP#:1328**

For graphical terrain displays: 3D display led to better accuracy for A-see-B tasks (can you see point B from point A?) but 2D displays led to better accuracy for A-hi-B tasks (is point A or B higher?) (Hollands, Ivanovic, & Enomoto, 2003); other studies have shown that 2D displays are good for judging relative position while 3D displays are good for understanding shape and output (St. John, Cowen, Smallman, & Oonk, 2001; Wickens & Thomas, 2000; as cited in Hollands, Ivanovic & Draper, 2004)

**Also in:** 3.11

**GP#:1329**

Gradual transitions between visual displays (3D and 2D) aids response time/accuracy for task switching compared to discrete (sequential) transitions (Hollands, Ivanovic, & Enomoto, 2003).

**Also in:** 6.7.1
In a comparison of 3 different visual displays (ranging from very graphical to very text-based), overall preference didn’t match recall performance (WebPortal, which was in the middle in terms of graphics/text, was preferred most, but InfoCanvas had the best recall) (Plaue, Miller, & Stasko, 2004).

Also in: 5.5.1, 7.3

Advantages of graphical visual displays over text-based displays: graphical displays enhance memory, and images are processed faster than words (Plaue, Miller, & Stasko, 2004).

Also in: 2.5.1

The rapid display and three-dimensional manipulation of data facilitates the use of motion parallax to discern three-dimensional shape (Carlbom, et al., 1992).

Also in: 2.3.1

Our visual system is good at recognizing edges in images—edge-detection represents a significant reduction in the complexity of a scene (Morris & Joshi, 2003).

Also in: 2.6.1

Clutter or sparsity in visual representations can have negative effects ranging from decreased user performance to diminished visual appeal. Clutter can result in over-plotting (certain objects aren’t visible because they are occluded by other objects). Sparsity can result in inefficient use of available display space. Non-linear magnification schemes can be used to minimize clutter in a display. (Woodruff, Landay & Stonebraker, 1999)

Also in: 5.5.1

Principle of Constant information density—cartographic literature [7]. The number of objects per display unit should be constant. The amount of information should remain constant as the user interacts with a visualization. Design guidelines for zooming are provided. (Woodruff, Landay & Stonebraker, 1999)

GP#:1375

Two important factors in immersive display design are resolution and Field Of View. Image fidelity requires high resolution, measured in resolvable dots or effective pixels. Immersion requires wide FOV. Increasing FOV while maintaining high resolution requires an increase in effective pixels. (Lantz, 1997)

Also in: 2.1.1, 4.1.3

Graphic displays have advantages over tables [6] (Krol, Reich, Pavone & Fuhrman, 2004).

GP#:1382

Navigating using visual maps is often difficult because it requires mapping 2D information to a 3D environment, and maps offer a lot of information that users don’t need; thus, it’s better to provide specific directional cues (if there was a way to remove unnecessary information and make mapping between 2D and 3D easier, then maps could be more helpful). (Tsukada & Yasumura, 2004)

Also in: 3.2.1

When engaging in two dissimilar tasks (e.g., visual and verbal), it is visual template complexity, not display size that affects the level of interference resulting from the dual task (Bourke & Duncan, 2005).

Also in: 4.1.2, 4.4.1, 6.7
Without a perceptual border indicating region to be attended to, the user’s attention may actually spread to the entire visual hemifield in which the attended position is located (Hughes & Zimba, 1985; as cited in Haimson & Anderson, 2002).

Also in: 2.7.1, 6.3.1, 8.1

Partitioning a radar display into task-relevant regions with a range ring facilitates inside-to-outside search (Haimson & Anderson, 2002).

Also in: 3.6.1

Observers find it difficult to follow a prescribed path of saccades through dense arrays of symbols (Hooge & Erkelens, 1998; as cited in Haimson & Anderson, 2002).

Also in: 2.7.1, 7.1.1

Range rings or the partitioning of a display allows more focused attention and limits the repeated analysis of distractors (Haimson & Anderson, 2002).

Also in: 3.6.1, 6.3.1

Visual clutter (the nontarget information in a scene) can hinder sign acquisition (in this case a picture of a traffic sign in a street scene) in a bottom-up or top-down manner (Cole & Hughes, 1984; Engel, 1971, 1976; Hughes & Cole, 1986; Shoptaugh & Whitaker, 1984; as cited in Ho, Scialfa, Caird, & Graw (2001).

Also in: 3.6.1

Longer latencies for high-clutter scenes occurred because of the presence of a greater number of fixations required in order to locate a target (Adams, 1988; as cited in Ho, Scialfa, Caird, & Graw, 2001).

Also in: 2.5.1, 3.6.1

High clutter scenes are associated with poorer search performance (Ho, Scialfa, Caird, & Graw, 2001).

Also in: 3.6.1

Navigating is best supported by an immersive viewpoint display, in part because this frame of reference is similar to the view that a navigator has when traveling through real space (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 8.1

Users have a more difficult time estimating distances in immersed and exocentric 3D displays as compared with 2D displays (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 8.1

A smaller map with a wide field of view (FOV) displayed in the corner of a 3D map display can reduce tunnel vision (Wickens, Thomas, & Young, 2000).

Also in: 2.7.1, 3.2.1, 4.1.2, 6.4.1
There is evidence that an exocentric 3D display best supports both navigation and situational awareness tasks (Wickens, Thomas, & Young, 2000).

**Also in:** 3.2.1, 3.5.1

GP#:1445

Immersed displays yield reduced accuracy, relative to 3D exocentric displays, on tasks that require information located behind or beside the user. This effect exists even when the information is available by panning or by referring to an inset map (Wickens, Thomas, & Young, 2000).

**Also in:** 2.1.1, 3.2.1, 8.1

GP#:1446

Users may experience difficulty integrating (comparing) objects in a scene when panning is required (Wickens, Thomas, & Young, 2000).

**Also in:** 6, 7.1

GP#:1449

The best visual display for global-understanding tasks (e.g., battlefield command) is one which offers an initial view of the battlefield in exocentric perspective, allowing the user to zoom in to an immersive view, but which also then pops back to an exocentric position (Wickens, Thomas, & Young, 2000).

**Also in:** 3.11, 8.1

GP#:1450

The space “hidden” from the user in an exocentric 3D environment is larger to the extent that the “tether” of the exocentric display is shorter (i.e. the viewpoint is closer to the point of interest or “anchor”) (Wickens, Thomas, & Young, 2000).

**Also in:** 3.11, 8.1

GP#:1451

Image panning takes time, and users are even less likely to pan in high-demand, time–critical situations (Wickens, Thomas, & Young, 2000).

**Also in:** 5.2.1, 6.6.1

GP#:1454

Guidelines for handling human errors:
1) Make the action more perceptible (i.e. the possibility of activating the execution of another likely wrong action should be reduced, a given action should provide unambiguous information for the ongoing activity, even before the attainment of the end state);
2) Use multi-sensory feedback;
3) Display messages at a high level but with specific content (i.e. multilevel error messages, error message tells you it can not comply with your request, but there is a “since” or “because” button you can use to receive more info);
4) Provide an activity log (people depend on external memory aids);
5) Allow comparisons (comparisons between outputs is a useful source of information for action evaluation);
6) Make results available to users as soon as possible and allow the user to have control of the format display (suggestions for this include, i) exploiting layout, ii) exaggerating the differences, iii) stressing the aspects relevant to the just performed task);
7) Provide result explanations (i.e. make it extremely easy to determine why an input was not successful. If an input causes an error, indicate the varying factors that may have led to the error and the best way to fix it. (Rizzo et al., 1996, 116-118)

**Also in:** 4.8, 4.9, 5.3.5, 7.1.5

GP#:1464

Contrast enhancing filters (CEFs) in a visual display have not been found to increase legibility, user reading speed, letter counting or user comfort. In fact, CEFs have been found to increase user discomfort for CRTs
(Cathode Ray Tubes), although the researchers note that this finding was counterintuitive because the purpose CEFs were designed to reduce glare and enhance readability of a screen, etc. (Sheedy et al, 2003)

Also in: 4.1.1, 7.1.1

GP#:1472

When a north-up map is employed for primary/secondary navigational display, it’s beneficial to provide a visual momentum wedge to depict the user’s momentary direction of gaze and viewing angle on the represented world (on the map) (Olmos, Liang & Wickens, 1997).

Also in: 2.7.1, 3.2.1, 4.1.5

GP#:1473

Pilots using electronic 3D visual display format have difficulty identifying the precise location of surrounding targets (Olmos, Liang & Wickens, 1997).

Also in: 3.6.1, 3.8.1

GP#:1474

A modest advantage of 3D visual display (over 2D) was found for flight control, but not for situational awareness (Olmos, Liang & Wickens, 1997).

Also in: 3.5.1, 3.8.1

GP#:1475

People perform best with tabular displays when locating specific values; alternatively, graphical displays are better when people must interpolate, forecast, or judge data trends (LaLomia, Coover & Salas, 1988).

Also in: 3.11

GP#:1477

Without additional enhancements, the multiple-view 2D visual display is superior (in terms of improved user performance on telerobotic tasks) to either the 3D monocular or 3D stereoscopic displays (Park & Woldstad, 2000).

GP#:1478

When appropriate enhancements (e.g., translucent cylinder enhancement) is added to 3D displays, user performance in telerobotic tasks (e.g., ability to grasp object), improves to a level comparable to that of multiple-view 2D display (Park & Woldstad, 2000).

GP#:1479

Contrary to previous study outcomes, stereoscopic displays were found to provide no advantage over monocular displays in improving user performance in telerobotic tasks (e.g., ability to grasp object) (Park & Woldstad, 2000).

GP#:1480

Representing the physical environment (e.g., weather, terrain) and opposing forces (e.g., computer generated forces) in an information display is critical in creating effective military simulations (Oswalt, 1995).

Also in: 3.11, 4.9

GP#:1500

Pictures are better for presenting contextual information while text is better for displaying specific operational steps; procedural instruction is best conveyed using a combination of the two (Booher, 1975; as cited in Bradshaw & Johari, 2003).

Also in: 4.1.9

GP#:1501
Visualizing steps (e.g., screenshots on a computer) is good for procedural learning tasks; task completion time suffers when text is added to visualizations (specifying the steps) (Bradshaw & Johari, 2003).

Also in: 4.1.7, 5.1.1

GP#:1503

Females performed slower than males on a learning task based on computer/web design, but only in a modified screenshot only-condition (versus the screenshot-text condition); this may reflect lower spatial ability or less experience with computers/posting to a webpage (Bradshaw & Johari, 2003).

Also in: 1.2.1, 1.3.1, 1.4.1

GP#:1514

Designers of graphical interfaces should consider not only alternative representational formats but also how different quantities are encoded within any chosen format (Peebles & Chen, 2003).

GP#:1515

When selecting a graphical interface it is not enough to consider only the form of the representation in relation to a typical task, but also the full range of alternative varieties of the task (Peebles & Chen, 2003).

GP#:1516

When choosing a graphical representation, one shouldn’t always choose the most familiar to the target user, but should instead balance the cost of familiarization with computational advantages of less familiar representations (Peebles & Chen, 2003).

Also in: 5.5.1

GP#:1530

The following guidelines should be considered in designing mobile sensing devices: automatic power control – the device turns itself on when user picks it up; listening detection – holding device like a cell phone automatically records voice memos; portrait/landscape switching – device changes the display format when the user holds it at a new orientation; tilt scroll – the user can tilt the device to scroll the contents of the display. (Hinckley et al., 2005)

GP#:1538

Costs of scanning associated with head down presentations generally outweigh the costs of clutter associated with head up presentations, therefore generally favoring gead-up displays (Fadden and Wickens, 1997, Martin-Emerson & Wickens, 1997 as cited in Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 4.1.5

GP#:1541

In visual displays, the benefits of reduced scanning outweigh the cost of clutter (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 2.7.1, 3.6.1

GP#:1544

In visual displays, the costs of clutter outweigh scanning costs, which may be due to too much information being displayed on the helmet-mounted display (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 3.6.1, 4.1.5

GP#:1573

Inappropriate screen cues can have a significant effect on 3D percepts, and the size of that effect depends strongly on viewing condition (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

Also in: 2.7.1

GP#:1577

Change detection is facilitated when post-change cues allow observers to restrict the comparison process to one region of a scene (Varakin, Levin, & Fidler, 2004).
If pilots cannot physically rotate their heads to the side, then visual conditions need to be designed that include incongruent conditions between the flight symbology and background scene (Ercoline, Self & Matthews, 2002).

Users are willing to permanently give up a portion of their computer screen space for a peripheral awareness application if the information presented is easily customized and individually relevant (Cadiz, Venolia, Jancke, & Gupta, 2002).

Combining visual cueing with auditory cueing might exacerbate clutter that is already high in cockpits (Tannen, 2000).

One way to counteract clutter is to use an adaptive interface, where automation controls the delivery of information to pilots, so that they get the right information in the right format at the right time, and aren’t otherwise exposed to it. This has been shown to be helpful to pilots during landing and navigation (cites Brickman et al 1996, Moroney, 1999; Hettinger, Cress, Brickman & Haas, 1996; Hollinagel, 1988, as cited in Tannen, 2000).

Single-seat cockpits have limited space for information display, and there is already a high display load in cockpits. Too many displays may contribute to information overload, increasing the probability of pilot error. (Reising, Liggett & Munns, 1999; Weinstein & Wickens, 1992; as cited in Tannen, 2000).

Reference devoted to research findings and design principles regarding how physical text layout affects reading from screen (Dyson, 2004).

Visual search tasks (e.g., using visual resources to search the environment) can be made easier/more effective by providing a visual display (e.g., representing the environment in relation to oneself), rather than simply relying on visual resources/searching the environment. This study used pilots and compared visual search with or without a display (which provided geospatial information about nearby planes in relation to his/her own plane vs. having to look out the window of the plane for information about other planes). (Prinzo, 2003)

Visual displays should not depend on simultaneous viewing as an organizational theme; so if there is a considerable amount of information to present to users, it is better to organize the information into a framework (like a “room metaphor”), rather than just squeezing more information into the display (cluster objects in rooms by category). If there is enough information where “multiple rooms” are needed, connecting hallways should not be included and rooms should be placed right next to one another. (Colle & Reid, 2003)
Results suggest that there is a resource competition between working memory demands of information storage, and the perceptual cognitive demand of reading each menu screen and deciding the appropriate option to select (Wickens and Seidler, 1997).

Also in: 6.6.1

The CAVE system outperformed head-mounted displays; however, the CAVE system requires 3 fixed projectors oriented at 270° and is not portable (Werkhoven and Bakker, 1998).

Also in: 4.1.5, 7.2.1

Configural displays are more effective than separable displays for the performance of high-level property tasks. The pattern is less clear for low-level data tasks - participants had greater difficulty completing the low-level data probes than they did completing the high-level probes. Performance was significantly faster and more accurate with composite visual displays than with baseline displays. (Bennett et. al., 2000)

Also in: 6.6.1

Animation can be used in secondary displays with minimal negative impact on certain primary tasks. While other work (Maglio and Campbell, 2000) seems to suggest otherwise, both experiments supported this claim. The difference may result from a primary task that is less cognitively demanding and uses smoother, slower animations. (As cited in McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 6.6.1

In-place displays such as fade and blast are better than motion-based displays like ticker for rapid identification of items. Participants had lower monitoring latency when using the fade and blast than when using the ticker. This seems to extend prior results indicating that moving text is more difficult to read than static text (Sekey and Tietz, 1982; Granaas et al., 1984; As cited in McCrickard, Catrambone, Chewar & Stasko, 2003).

Also in: 2.5.1, 3.4.1

Motion-based displays such as a ticker are better than in-place animations for comprehension and memorability, except when a cue is provided. While in-place displays aid rapid identification, participants who used the ticker obtained better detailed awareness than those who used the blast and the fade. This suggests that if it is essential to remember specific details of monitored information, and application of detailed awareness relies on first demonstrating basic awareness (rather than being cued), a motion-based display should be used. (McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 3.4.1, 3.5.1, 6.4.1

A large amount of text presented in a dense or complex format will tax working memory, and complex symbols that are small, or that are accompanied by explanatory text that is too small to read, will be difficult for older adults and others with visual impairments to interpret (Hancock, Rogers, & Fisk, 2001).

Also in: 1.1.1, 4.1.2, 6.6.1

The display should have a large field of view in order for the ambient visual modality to be stimulated properly, but it doesn’t have to be continuous (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.6
The horizontal situation indicator in the cockpit provides the pilot with a graphic display of the projected flight plan and the current position of the aircraft; this, more than any other automated system in the cockpit, has been credited with reducing the workload of the pilot (Wiener, 1988 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 3.8.1, 6.6.1

GP#:1730

The following are guiding objectives to building ambient varieties of peripheral displays: (1) personalized – information source and representation should be customized to user preference; (2) flexible – variety of info sources should be available for display; (3) consolidated – moderate number (5-15) of information sources should be consolidated and presented in one location; (4) accurate – system should accurately communicate the current state of monitored information; (5) appealing – the system should be fun to use and an aesthetically pleasing addition to the user environment. (Stasko et. al., 2004)

Also in: 4.1.6, 5.4.1, 5.5.1

GP#:1731

Design and location of a graph’s legend and its spatial relationship to the data area are extremely important in determining a graph’s usability. Graph designs should be kept simple, leaving legends in close proximity to the data they represent, and should avoid unwarranted and/or complex multi-dimensional representations. (Renshaw et. al., 2004)

GP#:1732

Gaze-contingent multiresolutional displays (GCMRDs) are useful in high-performance flight simulators because of the wide field of view and high resolution needed (Reingold et. al., 2003).

GP#:1738

The ultimate goal for gaze-contingent multiresolutional displays (GCMRDs) is to produce savings by substantially reducing peripheral image resolution and/or detail and yet, to the user, be undetectably different from a normal image (Reingold et. al., 2003).

Also in: 4.1.3, 4.1.6

GP#:1763

Global landmarks promote quicker spatial learning of a visual perimeter (Ruddle & Peruch, 2004).

Also in: 3.2.1, 5.1.1

4.1.5 Heads up displays

Head-up presentation of flight path guidance information and supporting alphanumeric data superior to head-down display (Martin-Emerson & Wickens, 1997).

Also in: 3.8.1

GP#:1298

Minimizing scanning between flight instruments and the far domain contributes substantially to the head-up display (HUD) performance advantage (Martin-Emerson & Wickens, 1997).

Also in: 3.4.1, 3.8.1

GP#:1310

In a head mounted display (HMD)-based virtual environment (VE) system with head tracker, if overall latency is longer than 200ms it will result in motion sickness. Motion parallax can help people perceive depth better than just wearing stereo glasses. Latency compensation aids in the accurate location of 3-D sound by at least 50%. (Wu et al., 1997)

Also in: 2.5.1, 8.1

GP#:1347
The field of view of the human eye is 200º horizontally, and 125º vertically—this has implications for HMDs (Iwata, 2004).

Also in: 2.1.1, 2.6.1, 4.1.6, 8.1

GP#:1402

HMDs often degrade performance and lower presence because of their narrow field of view (FOV). The visual FOV of the [naked] human eye spans more than 180 degrees (Seay, Krum, Hodges, & Ribarovsky, 2001; Waller, 1999; as cited in Yang & Kim, 2004).

Also in: 2.1.1, 2.6.1, 6.4.1, 8.1

GP#:1471

Primary navigation displays should be track-up (Olmos, Liang & Wickens, 1997).

Also in: 3.2.5

GP#:1472

When a north-up map is employed for primary/secondary navigational display, it’s beneficial to provide a visual momentum wedge to depict the user’s momentary direction of gaze and viewing angle on the represented world (on the map) (Olmos, Liang & Wickens, 1997).

Also in: 2.7.1, 3.2.1, 4.1.4

GP#:1538

Costs of scanning associated with head down presentations generally outweigh the costs of clutter associated with head up presentations, therefore generally favoring head-up displays (Fadden and Wickens, 1997, Martin-Emerson & Wickens, 1997 as cited in Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 4.1.4

GP#:1539

Head-up display benefits were particularly amplified with conformal imagery like target cueing (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 3.6.1

GP#:1540

Helmet-mounted displays amplified a form of attentional tunneling (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 6.3.1

GP#:1542

Helmet mounted display (HMD) allowed participants to demonstrate superior performance as measured by target detection latencies of accurately cued targets (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 2.5.1, 3.6.1

GP#:1543

Performance tradeoffs between helmet-mounted displays and hand-held devices need to be considered when looking for low salience targets that are uncued (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 3.6.1

GP#:1544

In visual displays, the costs of clutter outweigh scanning costs, which may be due to too much information being displayed on the helmet-mounted display (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 3.6.1, 4.1.4

GP#:1545
The amount of data presented on a helmet-mounted display represents only a small subset of information that will be displayed to ground soldiers in the future, and there are already detrimental clutter effects (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 6.6.1

GP#:1546

Practical implications for design of helmet-mounted displays:
Designers should consider the potential consequences of attention guidance presented on an HUD. Cuing benefits decrease as cue precision is degraded, but imprecise cuing is better than no cuing at all. Trust in the automated cuing information influences attention allocation strategies. It may help to widen attentional breadth by signaling cue precision, when presenting cues of low spatial resolution. Operators need to be informed about the spatial resolution of the displayed guidance information and to balance this knowledge with the information provided by an automated system. The use of a simulated HMD does not alter the pattern of behavior relative to an actual HMD. The presentation of information on an HMD combined with the real world or any noisy environment may be intrusive to the operator’s task. Ground soldiers need to search and filter through multiple sources of information, and as task demands increase, reliance on any automated system may increase as well. (Yeh, Merlo, Wickens, & Brandenburg, 2003)

Also in: 5.4.1, 6.6.1

GP#:1581

Head-up displays may paradoxically make pilots less aware to unexpected and potentially dangerous events that can happen outside of the aircraft; this is known as cognitive capture or cognitive tunneling (Tufano, 1997; Wickens & Long, 1995, as cited in Varakin, Levin, & Fidler, 2004).

Also in: 3.5.1, 3.8.1, 6.3.1, 6.4.1

GP#:1667

Head-mounted displays have highly constrained visual fields, so they lend themselves to the inclusion of other modalities (Davis, 1997; as cited in Tannen, 2000).

Also in: 4.1.6

GP#:1680

The CAVE system outperformed head-mounted displays; however, the CAVE system requires 3 fixed projectors oriented at 270° and is not portable (Werkhoven and Bakker, 1998).

Also in: 4.1.4, 7.2.1

GP#:1708

Discretely-moving head-slaved displays have a positive effect on spatial orientation (Kappe, van Erp, & Korteling, 1999).

GP#:1709

Discretely-moving head-slaved displays have display edges in a constant position in the operator’s optic array; these edges might serve as reference lines to improve visual tasks (Kappe, van Erp, & Korteling, 1999).

Also in: 2.1.1

GP#:1713

Using head-slaved displays, viewing error was decreased when more peripheral information was available (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.6

GP#:1714

Head-slaved displays can improve vehicle control and tracking accuracy in driving and target detection tasks (Kappe, van Erp, & Korteling, 1999).

Also in: 3.3.1, 3.6.1
Changes in the virtual viewing direction resulting in a rotation of the virtual environment makes users uncomfortable. Head-slaved displays let the user perceive a more stable environment. (Kappe, van Erp, & Korteling, 1999)

Also in: 5, 8.1

Proprioceptive feedback (via head-mounted display) was found to have no significant effect on the rate at which participants developed spatial knowledge (contrary to other study findings) (Ruddle & Peruch, 2004).

Also in: 4.3, 5.1.1

### 4.1.6 Peripheral vs. focal displays

Motion or animation should be kept at a minimum. Motion or animation, when used, should not be continuous. Discrete animation seems ideal for update feedback. Visual feedback is better than auditory feedback for visual information. Scrolling direction does not seem to matter (Matthews et al.). Displays using inattention: animations that are repetitive and gradual are best- fading, rolling and tickering are not distracting. (Maglio & Campbell, 2000)

Also in: 4.2

Visual guidelines for focal images cannot be extended to images displayed as a secondary task in a dual task situation. The difference in an image’s ability to convey meaning decreases when it moves from focal to secondary task situation. Display attributes for secondary tasks should be based on acceptable amounts of primary task performance degradation (Chewar, McCrickard, Ndiwalana, North, Pryor, Tessendorf, 2002).

Also in: 6.7

Data displayed in browsers should be available, easily accessible, up-to-date, and should consolidate info from a variety of sources. Representation should be calm and “refined”, not demanding attention from the user. The user should be allowed to personalize the graphics browser display. Displays should hide sensitive data from public view. (Miller & Stasko, 2002)

Also in: 4.1.4, 5.5.5

Unconditional displays show the current state of information. A conditional display is shown only when data meets a pre-determined criteria (i.e. stock hits certain price, email from certain person). (Miller & Stasko, 2002)

Also in: 3.1.1

Positioning a color indicator in close proximity to a continuous analog display should be an efficient way to present two different sources of info (Meyer, 2001).

Also in: 2.1.1, 4.1.1, 4.1.4

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.1, 3.4.3, 6.3.1, 6.3.3, 6.6.1, 6.6.3, 6.7
Peripheral visual cues are good for detecting “dynamic discontinuities” (example, motion or luminance change) and require few resources, but tunnel vision may be a problem under conditions of stress and/or cognitive load (Leibowitz & Appelle, 1969; as cited in Sarter, 2001).

Also in: 2.4.1, 3.4.1, 6.4.1, 6.6.5

GP#:1278

Ecological displays (those that extend across the central visual and peripheral visual fields and present information in a manner that is visually consistent with information available in the real world) allow for more accurate control (when compared with central or peripheral displays) in low-control velocity flight simulation tasks (Weinstein & Wickens, 1992).

Also in: 3.8.1, 4.1.4

GP#:1305

There is a general agreement in research community that peripheral displays are difficult to design, build, and evaluate (Mathews, Dey, Mankoff, Carter & Rattenbury, 2004).

GP#:1306

Peripheral displays must address two sets of user attention issues: (1) context about the user (e.g., interruptibility, primary task, focus of attention; and (2) attention management (e.g., abstraction and transitions, which are independent of context) (Matthews, Dey, Mankoff, Carter & Rattenbury, 2004).

Also in: 3.1.5, 6.3.1

GP#:1307

Peripheral displays must support three characteristics to manage connection between information importance and user attention: (1) abstraction (extracting features/reducing fidelity of info to make it easier to read at a glance than raw input); (2) notification levels (differences in information importance); and (3) transitions (effects on a display that attract appropriate amount of attention from user based on new notification level) (Matthews, Dey, Mankoff, Carter & Rattenbury, 2004).

Also in: 3.1.5, 6.3.1

GP#:1343

Visual familiarity, intentionality, an object’s physical characteristics, and the structure of the scene can all be active or passive “selectors.” The eye is a passive selector—high resolution info is preserved only at the center of the gaze. Visual acuity drops 50% when an object is located only 1º from the center of the fovea and an additional 35% when it is 8º from the center. (Forgus & Melamed, 1976; Landragin (2001); as cited in Kelleher & van Genabith, 2004)

Also in: 2.1.1, 2.2.1, 2.6.1

GP#:1347

The field of view of the human eye is 200º horizontally, and 125º vertically—this has implications for HMDs (Iwata, 2004).

Also in: 2.1.1, 2.6.1, 4.1.5, 8.1

GP#:1372

A lot of our cognitive information is derived from a small portion of our visual field of view (FOV). The fovial region of the eye (< 2º of our total FOV) contains most of our photoreceptors. Eye and head motion allow us to take in more information. Head displacement and navigation create optic flow and motion parallax, which is sensed by our peripheral vision and used to judge motion. (Lantz, 1997)

Also in: 2.3.1, 2.6.1, 3.2.1, 6

GP#:1447

Subjects using immersive displays “anchor” their judgments based on what is visible directly in front of them, rather than panning to see what is beside or behind them (Wickens, Thomas, & Young, 2000).

Also in: 8.1
Infrared and indirect vision systems are useful in situations where direct vision is poor or impossible. These displays need high-resolution for tasks such as target identification, and wide fields of view for tasks such as orientation and tactile maneuvering. (Reingold, Loschky, McConkie & Stampe, 2003)

Also in: 3.2.4, 3.6.1, 4.1.3

Operators are not comfortable driving a Jeep with a 40° field of view, but were more confident with a 120° field of view (McGovern, 1993; van Erp, 1997; as cited in Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 3.3.1, 5.5.1

Remote piloting requires a wider field of view than teleoperations (Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 3.8.1

The following are the specifications of a good gaze-tracking system: 1: plug and play; 2: unobtrusive; 3: accurate; 4: high temporal resolution; 5: high spatial resolution with low noise; 6: ability to determine gaze in a wraparound view (310°); 7: affordable. (Reingold, Loschky, McConkie & Stampe, 2003)

Also in: 4.1.3

If pilots cannot physically rotate their heads to the side, then visual conditions need to be designed that include incongruent conditions between the flight symbology and background scene (Ercoline, Self & Matthews, 2002).

Also in: 3.8.1, 4.1.4

Users are willing to permanently give up a portion of their computer screen space for a peripheral awareness application if the information presented is easily customized and individually relevant (Cadiz, Venolia, Jancke, & Gupta, 2002).

Also in: 4.1.4, 5.5.1

Dynamic objects in peripheral vision tend to be very distracting (Cadiz, Venolia, Jancke, & Gupta, 2002).

Also in: 6.3.1

One of the reasons Sideshow, a peripheral awareness system, was so successful was because user input was integrated from the beginning of the design process (Cadiz, Venolia, Jancke, & Gupta, 2002).

Also in: 7.2.1

The addition of spatialized sound to visual cueing reduced target designation time comparison to visual only; this occurred under conditions in which targets were really difficult to detect (e.g., ground targets initially outside FOV). The time advantage for fixed and adaptive multimodal cueing was 824 msec. (Tannen, 2000)

Also in: 2.1.2, 2.7.4 AV, 3.6.1, 3.6.4 AV

Auditory cueing should be used to improve visual target search performance, as perception of sound source is not limited by FOV or line-of-sight. Vision and audition can function “synergistically” in search tasks.
by encouraging auditory localization to direct the visual system toward objects in space, which can result in reduced search times. Gains in this respect are greatest when targets are presented outside FOV. Auditory cueing still reduces search times within 10 degrees of FOV by 175 msec. (McKinley, Ericson, & D’Angelo, 1994; Perrott, Cisneros, McKinley, & D’Angelo, 1996; Rudmann & Strybal, 1999; as cited in Tannen 2000)

Also in: 2.1.2, 3.6.1, 3.6.2, 3.4.4 AV, 4.4

GP#:1667

Head-mounted displays have highly constrained visual fields, so they lend themselves to the inclusion of other modalities (Davis, 1997; as cited in Tannen, 2000).

Also in: 4.1.5

GP#:1707

Spatial orientation improves when the ambient visual modality is stimulated with a peripheral image (Kappe, van Erp, & Korteling, 1999).

Also in: 2.7.1

GP#:1710

The display should have a large field of view in order for the ambient visual modality to be stimulated properly, but it doesn’t have to be continuous (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.4

GP#:1711

A wide field of view is required for proper lane-keeping and accurate spatial orientation (Kappe, van Erp, & Korteling, 1999).

Also in: 3.3.1

GP#:1712

There is a significant trend for spatial orientation to improve when ambient visual modality is stimulated with a sparse peripheral image (Kappe, van Erp, & Korteling, 1999).

GP#:1713

Using head-slaved displays, viewing error was decreased when more peripheral information was available (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.5

GP#:1716

A visual display that is tailored to the properties of the human visual system (more detail at focus, less detail in the periphery) may be as effective as a traditional display with uniform resolution; this saves a lot of bandwidth and computer hardware expense (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.3

GP#:1729

Calm technology will move easily from the periphery of our attention, to the center, and back. The following are differences between ambient and peripheral displays: ambient displays typically communicate one (or few at most) pieces of information and aesthetics and visual appeal of the display is paramount; peripheral displays refer to systems out of a person’s primary focus of attention and may communicate one or more pieces of information (thus, ambient displays are a proper subset of peripheral displays). (Stasko et. al., 2004)

Also in: 6.3.5

GP#:1730

The following are guiding objectives to building ambient varieties of peripheral displays: (1) personalized – information source and representation should be customized to user preference; (2) flexible – variety of info sources should be available for display; (3) consolidated – moderate number (5-15) of information
sources should be consolidated and presented in one location; (4) accurate – system should accurately communicate the current state of monitored information; (5) appealing – the system should be fun to use and an aesthetically pleasing addition to the user environment. (Stasko et. al., 2004)

Also in: 4.1.4, 5.4.1, 5.5.1

Reducing the visual processing load by decreasing resolution in the periphery is important in the development of artificial vision systems (Reingold et. al., 2003).

Also in: 4.1.3, 6.6.1

The ultimate goal for gaze-contingent multiresolutional displays (GCMRDs) is to produce savings by substantially reducing peripheral image resolution and/or detail and yet, to the user, be undetectably different from a normal image (Reingold et. al., 2003).

Also in: 4.1.3, 4.1.4

Access to foveal vision is very limited and can’t be easily shared in dual task situations (e.g., one can’t read two things at once); auditory processing is similar (e.g., one can’t listen to two speakers at once) (Wickens, 2000).

Also in: 2.6.1, 2.6.2, 4.2, 6.7

4.1.7 Interference

Workstations with multiple windows, zooming maps, and pop-up menus can block change detection signals (Durlach, 2004).

Also in: 2.4.1, 4.1.4

Drawbacks of instant messaging systems are that they can be disruptive and the flow of conversation can be awkward in the absence of non-verbal cues. These limitations are especially bad in time-pressured scenarios because interrupting the primary task (with the instant messages) increases mental processing time and leads to errors on the primary task. (Cummings, 2004)

Also in: 3.1.1, 3.9.1, 6.6.5, 6.7

Knowledge transitions may be more rapid for those learning from printed material, as compared to those learning from computer screens. This indicates less interference and more readily applied knowledge when printed materials are used. (Garland & Noyes, 2004)

Also in: 4.2.3, 4.4.1, 6.2.4, 6.7

Interference is greater when two visual tasks are performed together or when two auditory tasks are performed together, than when a visual task is combined with an auditory task (Treisman & Davies, 1973; Duncan et al., 1997; as cited in Bourke & Duncan, 2005).

Also in: 4.2.3, 4.4.1, 6.2.4, 6.7

Visualizing steps (e.g., screenshots on a computer) is good for procedural learning tasks; task completion time suffers when text is added to visualizations (specifying the steps) (Bradshaw & Johari, 2003).

Also in: 4.1.4, 5.1.1

Delays (typical of those found in long distance telecollaboration) inhibit the ability of users to collaborate using haptic or visual communication at a distance. Delay can result in dissociation between the state of
the system at the two end stations, which can cause differences in the response of operators who are compensating for perceived errors. (Allison, Zacher, Wang & Shu, 2004)

Also in: 2.5.1, 2.5.3, 3.9.1, 3.9.3, 4.3.4

4.1.8 Synchronization

When designing effective displays, include those graphical features that can be decoded most effectively. The way a process is represented can affect the potential for operators to misinterpret a single sensor value as standing for the state of a higher-order process. It is not always an issue of choosing one format or mode over another, but rather a determination of how to combine sources of evidence, develop effective representations, and coordinate multiple representations in the process of representation design. All representations, in making some aspects of the world more salient than others, have the potential to be misleading. (Bennett, Malek & Woods, 2000)

Also in: 4.1.4, 4.1.9, 5.3

GP#:1409

Large time delays between control input and visual scene update adversely influence task performance in virtual environments (Ebenholtz, 1992; Kennedy et al., 1990; as cited in Draper et al., 2001).

Also in: 8.1

GP#:1411

Fixed time delays of up to 250 ms are not major contributors to simulator sickness (Draper et al., 2001).

Also in: 8.1

GP#:1676

Motion sickness in VR settings is particularly problematic when a sensory decoupling arises (e.g., visual indicated motion reference frame differs from physically indicated motion reference frame) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

Also in: 8.1, 8.5

GP#:1766

Manipulating the attention of the participant can influence the perception of simultaneity—the stimulus cued by the experimenter is usually perceived earlier. This was shown for stimuli presented within audio-tactile modalities (Stone, 1926), within the auditory modality (Needham, 1936), and within the visual modality (Stemach & Herdman, 1991; as cited in Vogels, 2004).

Also in: 2.5.1, 2.5.2, 2.5.4 AV, 4.2.4, 4.6.2, 6.3

GP#:1784

Visual feedback reduced performance times and underforce errors, compared to haptic feedback, at various levels of delay (between presentation of cues); however, visual feedback interacts with delay such that at 200 milliseconds, the modes are equal. Visual feedback can also increase the number of overforce errors committed. (Allison, Zacher, Wang & Shu, 2004)

Also in: 4.3.5, 8.1, 8.4 TV

4.1.9 Redundant information

When designing effective displays, include those graphical features that can be decoded most effectively. The way a process is represented can affect the potential for operators to misinterpret a single sensor value as standing for the state of a higher-order process. It is not always an issue of choosing one format or mode over another, but rather a determination of how to combine sources of evidence, develop effective representations, and coordinate multiple representations in the process of representation design. All representations, in making some aspects of the world more salient than others, have the potential to be misleading. (Bennett, Malek & Woods, 2000)

Also in: 4.1.4, 4.1.8, 5.3
Providing a visual display of a speaker that is congruent with the display of speech improves comprehension, especially as background noise increases. (MacLeod & Summerfield, 1987; as cited in Rudmann et al., 2003) Tracking or shadowing the speech of a target speaker while ignoring another distracting speaker is easier when the visual display of the target speaker is displayed away from the sound source rather than near it (Rudmann et al., 2003).

Also in: 2.1.4 AV, 4.2.1, 4.2.5, 4.4.1, 4.4.3

GP#:1500

Pictures are better for presenting contextual information while text is better for displaying specific operational steps; procedural instruction is best conveyed using a combination of the two (Booher, 1975; as cited in Bradshaw & Johari, 2003).

Also in: 4.1.4

GP#:1647

Performance in a tracking task was degraded least in an auditory condition, and most in a redundant multimodal condition (visual and audio). This is an example of a negative redundancy gain. (Seagull, 2002)

Also in: 3.4.2, 3.4.4AV, 3.6.2, 3.6.4-AV, 4.2.5

4.2 Audio

GP#:1007

Motion or animation should be kept at a minimum. Motion or animation, when used, should not be continuous. Discrete animation seems ideal for update feedback. Visual feedback is better than auditory feedback for visual information. Scrolling direction does not seem to matter (Matthews et al.). Displays using inattention: animations that are repetitive and gradual are best- fading, rolling and tickering are not distracting. (Maglio & Campbell, 2000)

Also in: 4.1.6

GP#:1074

Spatially segregating audio sources can improve a user’s comprehension of a target speaker. This phenomenon has been termed the “cocktail party effect” (Rudmann, McCarley & Kramer, 2003).

Also in: 2.1.2

GP#:1107

When considering offloading to another modality, determine whether complex information can be presented usefully in an auditory path, and whether auditory and visual cues can be combined to facilitate the processing of information (Brown, Newsome & Glinert, 1989).

Also in: 4.4

GP#:1172

Graphics displays are ideal when there are a lot of quantitative or relational facts to present or for concrete or spatial information, while natural language is better for abstract concepts/processes (Maybury, 1995).

Also in: 4.1.4

GP#:1194

Three technologies that will be required for auditory displays include the following: intelligent prioritization and novel presentation algorithms; computational auditory scene analysis techniques for evaluating external auditory constraints in real-time; and automated multidimensional sound processing techniques. (Brock, Ballas, and McClimens, 2003)

GP#:1270
Adaptive audio display technology will require the following: 1) intelligent prioritization and novel presentation algorithms, 2) computational auditory scene analysis techniques for evaluating external auditory constraints in real-time and 3) automated multidimensional sound processing techniques.

The use of properly designed, spatialized alerts can significantly reduce effort and improve response times in a highly demanding, dual-task setting with no effect on decision accuracy or other measures of performance. (Brock et al., 2003)

Also in: 2.1.2, 3.1.2, 6.7

GP#:1273

Displays must be capable of representing multiple resources of auditory information that might be static or moving (Wourms, Mansfield, & Cunningham, 2001).

Also in: 2.1.2

GP#:1371

Users tend to rely on a sound’s onset as the cue, rather than other features occurring later in a signal (Adelstein, Begault, Anderson & Wenzel, 2003).

Also in: 2.7.2, 5.2.2

GP#:1405

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information. (Tsukada & Yasumura, 2004)

Also in: 2.7.1, 2.7.2, 2.7.3, 3.11, 4.1, 4.3, 6.7

GP#:1455

Providing a visual display of a speaker that is congruent with the display of speech improves comprehension, especially as background noise increases. (MacLeod & Summerfield, 1987; as cited in Rudmann et al., 2003) Tracking or shadowing the speech of a target speaker while ignoring another distracting speaker is easier when the visual display of the target speaker is displayed away from the sound source rather than near it (Rudmann et al., 2003).

Also in: 4.2.1, 4.2.5, 4.4.1, 4.4.3

GP#:1456

Subjects are capable of judging roughness (texture) in VR on the basis of sound alone (Lederman, 1979; as cited in Peeva, 2004). There is expected to be a significant negative correlation between texture roughness and pitch with rougher texture being associated with lower pitch (Peeva, 2004).

Also in: 8.2

GP#:1520

3-D auditory displays of virtual reality can be used as a way to facilitate multi-channel listening processes (MacDonald et al., 2002).

Also in: 8.2

GP#:1522

Positioning sounds to the left or right of the listener is superior to positioning them in front or back (MacDonald et al., 2002).

Also in: 2.1.2

GP#:1527

For verbal warnings, position on the interaural axis is the key factor to consider, rather than realism or maximum spacing (MacDonald et al., 2002).

Also in: 2.1.2, 3.1.2
Spoken words like “deadly, danger and lethal” are rated as more arousing than words like “warning or caution” (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 3.1.2, 6.3.2

Female voices seem to connote more urgency than male voices for conveying warnings. If a male or female voice is synthesized, the gender effect of the speaker seems to disappear. (Hellier, Edworth, Weedon, Walters, Adams, 2002)

Also in: 2.7.2, 3.1.2, 6.3.2

Changes in all three acoustic parameters produce steeper changes than do changes in just one or two of them (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2

It is possible to imbue urgency into synthesized speech warnings simply through the use of the three major acoustic parameters (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 3.1.2

Across all performance variables, both visual and auditory indicators showed similar results and are significantly better than an interface configuration without a context switch indicator (Trouvain & Schlick, 2004).

Also in: 4.1

It is not unrealistic to substitute a visual indicator completely by its auditory equivalent (Trouvain & Schlick, 2004).

Also in: 4.1

In a sound-localization task, using a combination of stereo audio microphones and a head tracker can disambiguate sources from similar angles (Siracusa, Morency, Wilson, Fisher, Darrell, 2003).

Also in: 2.1.2, 3.6.2

People tend to code messages auditorily: rapidly successive data are to be resolved, where the recipient is preoccupied with other tasks or in a condition of reduced alertness, and one wishes to break in with unexpected messages or warnings, when highly meaningful materials are to be apprehended and remembered, where flexibility of message transmission is important, where out of a large mass of data we wish to present information germane to the issue at hand, and where visual reception is less available. (Geldard, 1960)

Also in: 3.1.2, 6.1.2, 6.3.2, 6.6.2

The inherent multi-dimensionality of sound in time, timbre and space often renders it to be the preferred means of transmission of data, information, and alerts in human-computer interfaces. By using auditory displays, numerous streams of data can be presented concurrently, offloading the visual system to perform other tasks. (Roginska, 2004)

Also in: 2.7.1, 2.7.2, 3.1.2, 4.8.1, 6.7.2
The presentation of information via auditory displays can lead to increased situational awareness (Roginska, 2004).

Also in: 6.4.2

GP#:1658

No benefits were found for supplementary auditory cueing, as compared to visual cueing alone in various target type/FOV combinations; this may be attributable to the limited resolution of the auditory cueing system, as well as pilots’ reliance on visual displays and their lack of experience with spatialized auditory cueing (Tannen, 2000).

Also in: 1.2.2, 2.7.1, 2.7.2, 3.6.1, 3.8.4 AV, 4.1

GP#:1745

Sound appears to have obligatory access to memory; even when attention is directed elsewhere, sound is recorded and processed by the brain. Nonspeech sounds, such as tones, can be as disruptive to performance as speech. (Banbury et. al., 2001)

Also in: 6.3.2

GP#:1774

Access to foveal vision is very limited and can’t be easily shared in dual task situations (e.g., one can’t read two things at once); auditory processing is similar (e.g., one can’t listen to two speakers at once) (Wickens, 2000).

Also in: 2.6.1, 2.6.2, 4.1.6, 6.7

GP#:1787

The detection and identification of speech information presented binaurally against a background of competing speech messages is significantly enhanced when the target phrase is located in the right hemifield (Bolia, Nelson & Morley, 2001). This is relevant to the design of spatial audio adaptive interfaces, such as when there is a need to dynamically modify characteristics of a display in response to changes in the functional state of the operator, the vehicle, or the environment. (Hettinger, et al 1996; as cited in Bolia, Nelson & Morley, 2001)

Also in: 2.1.2, 3.9.2

GP#:1788

Higher priority messages should be presented in the right hemifield, while lower priority messages should be presented in the left hemifield (Bolia, Nelson & Morley, 2001).

Also in: 2.1.2, 3.1.2, 3.9.2

GP#:1789

Target messages are more intelligible when presented against a distribution of signals that are symmetric than if they are distributed entirely to one side or the other of the midline (Bolia, Nelson & Morley, 2001).

Also in: 2.1.2, 3.9.2

GP#:1790

Both hemifields should not be used in the design of spatial audio displays for speech communication (Bolia, Nelson & Morley, 2001).

Also in: 3.9.2

GP#:1791

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.
### Table 2: Auditory Design Guidelines

<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>General—thresholds</td>
<td>• Sounds should be approximately 500 msec in duration to be heard (Sanders &amp; McCormick, 1993).</td>
</tr>
<tr>
<td></td>
<td>• Sound frequencies generally should be between 20 and 20000 Hz to be heard; preferably between 500 and 3000 Hz.</td>
</tr>
<tr>
<td></td>
<td>• For sound traveling long distances (e.g., &gt; 1000 ft), use frequencies below 1000 Hz, as higher frequencies will not travel as far.</td>
</tr>
<tr>
<td></td>
<td>• Sound intensity should be between about 40 to 120 dB (SPL) to be heard, sounds above 120 dB can cause pain.</td>
</tr>
<tr>
<td>Speech</td>
<td>• Set speech output speed at 150 to 160 words per minutes; do not exceed 210 (European Telecommunications Standards Institute, 2002).</td>
</tr>
<tr>
<td></td>
<td>• Utilize intensity differences to aid in the discrimination of speech stimuli (Jancke, Shah, Posse, Grosse-Ryuken &amp; Muller-Gartner, 1998).</td>
</tr>
<tr>
<td></td>
<td>• Never present two verbal tasks at the same time (e.g., two messages; ETSI, 2002).</td>
</tr>
<tr>
<td></td>
<td>• Avoid background speech (even a whisper at 50dB), which impairs reading and memory (Hapeshi &amp; Jones, 1992).</td>
</tr>
<tr>
<td></td>
<td>• Synthetic speech has been shown to hinder verbal learning and should be avoided if possible.</td>
</tr>
</tbody>
</table>

(Continued)
### Table 2 (continued)

<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
</table>
| **Sound localization and pitch** | Auditory cues can be spatialized to indicate direction, location, and movement:  
  - When using sound localization, use an ITD of at least 10 to 50 μsec in azimuth rather than elevation (Blauert, 1996).  
  - If using spatialized audio cues to communicate direction or location, it is important to note that localization performance decreases as the source approaches the median plane and distance to the source increases (especially beyond 1 m; Kandell, Schwartz, & Jessell, 1995).  
  - Use dynamic cues to aid sound localization in the median plane (i.e., IID/ITD of zero; Fisher & Freedman, 1968; Middlebrooks & Green, 1991).  
  - If using spatialized audio cues to communicate movement, position source in front of the listener (i.e., 0 deg azimuth; do not exceed ± 40 deg; Strybel, Manligas, & Perrott, 1992).  
  - Dynamic localization of sounds are poorest in extreme azimuth (> 40 deg) and elevation (> 80 deg of horizontal plane; Strybel et al., 1992).  
  - Use spatialized audio to aid identification of auditory messages in noisy environments (Mulgund, Stokes, Turino, & Devine, 2002).  
  - Use spatialized audio to guide navigation tasks (e.g., convey waypoints or object/person locations; Mulgund et al., 2002).  
  - Use supernormal auditory localization to exaggerate normal auditory cues (Shinn-Cunningham, Durlach, & Held, 1998a, 1998b).  
  - Avoid using sound localization for absolute judgments (Caelli & Porter, 1980; Kraemer, 1994). |
| **Alerts and warnings** | Use auditory cues for rapid cueing of critical information, such as for warnings and alarms (Sanders & McCormick, 1993).  
  - Auditory warnings are effective for messages dealing with time-relevant events or continuously changing information and when requiring immediate action (Welch & Warren, 1986).  
  - Do not use auditory warning messages if information requires future referencing (Blackwood et al., 1997).  
  - Keep spectral components of a warning 15 dB above threshold imposed by background noise (Patterson, 1989).  
  - Incorporating apparent motion in the design of auditory warning sounds will make the warning more salient. |
| **Auditory cues** | Use tones for communicating limited information sources (e.g., start and stop time; Blackwood et al., 1997).  
  - Use complex sounds for alarms (e.g., deviations in rhythm, pitch, loudness, timbre).  
  - Speech is most effective for rapid communication of complex, multidimensional information sources.  
  - If auditory cues are used as a quantitative indicator, use speech as it involves minimum time or errors in attaining an exact value.  
  - Use timbres (i.e., sound quality) with multiple harmonics as an effective grouping cue (Brewster, 2003).  
  - Avoid using auditory cues for high resolution display of quantitative information (Kramer, 1994). |

*Note. IID = interaural intensity differences; ITD = interaural time differences.*

Also in: 2.7.2

### 4.2.1 Foreground vs. background noise

The human audio system can relegate some sounds into background while still monitoring them (Simpson, Bolia, & Draper, 2004). 

GP#:1337
Providing a visual display of a speaker that is congruent with the display of speech improves comprehension, especially as background noise increases. (MacLeod & Summerfield, 1987; as cited in Rudmann et al., 2003) Tracking or shadowing the speech of a target speaker while ignoring another distracting speaker is easier when the visual display of the target speaker is displayed away from the sound source rather than near it. (Rudmann et al., 2003)

4.2.2 Auditory icons

Auditory icons (aurally presented sounds meant to represent a physical event, such as breaking glass, screeching tires, etc) are more accurately identified than conventional auditory warning signals (beeps/tones), but respondents are skeptical of the new technology (Belz, Robinson, & Casal, 1999).

Dual-modality displays (auditory icon and visual display; auditory warning and visual display) led to better reaction times than having no display. However, auditory icons did just as well without the visual display, suggesting that unimodal auditory displays can be sufficient. (Bellotti, Berta, DeGloria & Margarone, 2002)

When considering collisions in an automobile driving task, auditory icons and auditory warnings led to equivalent performance in unimodal conditions. However, when visual displays were added to augment the aural cues, auditory icons did significantly better than auditory warnings. (Bellotti, Berta, DeGloria & Margame, 2002)

Auditory icons, or representational sounds, may be useful as warning devices in vehicles, based on the decreased braking response times for impending front-to-rear collisions and a reduction in the occurrence of accidents for impending side collisions (Belz, Robinson, & Casal, 1999).

4.2.3 Interference

There may be a performance decrement when two tasks both require the auditory mode (Brucken, Plass & Leutner, 2004).

As more distracting voices are added to an audio conversation tracking task, it becomes harder to track target words. Also, as the number of distracting voices goes up, it becomes increasingly beneficial to augment audio cues with a video display of the target speaker. (Rudmann, McCarley & Kramer, 2003)
Tactile and audio cues may be good for alerts of status change (compared to visual) because they’re omnidirectional (don’t require a particular head orientation) and can be used to guide attention to a particular location in the cockpit. The downside is that audio cues are hard to suppress, making them less desirable for non-emergency cues.

Tactile cues can effectively communicate information on airspeed, angle of attack, energy state, and other flight parameters (Zlotnick, 1988; as cited in Sarter, 2001), but may impede performance on other tasks (Gilliland & Schlegel, 1994; as cited in Sarter, 2001).

Papers that address the influence of the time difference between haptic media and audio/visual media and the effect of auditory cues on the haptic perception (Harada, Ohno & Sato (1998); as cited in Ishibashi, Kanbara & Tasaka, 2004).

Interference is greater when two visual tasks are performed together or when two auditory tasks are performed together, than when a visual task is combined with an auditory task (Treisman & Davies, 1973; Duncan et al., 1997; as cited in Bourke & Duncan, 2005).

Memory is susceptible to interference by irrelevant sound, especially in maintenance of order in short-term memory (Banbury et. al., 2001).

As number of simultaneous audio displays (e.g., simultaneous talkers) increases, interpretation performance decreases and response time increases (probably due to increase in uncertainty). Increasing the number of talkers is more detrimental for asymmetric configurations of audio than for symmetric configurations. This particular study found no correlation between handedness and dependent variables. (Bolia, Nelson & Morley, 2001)

4.2.4 Synchronization

Audio displays must be head-coupled to provide a stable acoustic environment with dynamic cues correlated with head motion (Wourms, Mansfield, & Cunningham, 2001).
As number of simultaneous audio displays (e.g., simultaneous talkers) increases, interpretation performance decreases and response time increases (probably due to increase in uncertainty). Increasing the number of talkers is more detrimental for asymmetric configurations of audio than for symmetric configurations. This particular study found no correlation between handedness and dependent variables. (Bolia, Nelson & Morley, 2001)

4.2.5 Redundant information

Providing a visual display of a speaker that is congruent with the display of speech improves comprehension, especially as background noise increases. (MacLeod & Summerfield, 1987; as cited in Rudmann et al., 2003) Tracking or shadowing the speech of a target speaker while ignoring another distracting speaker is easier when the visual display of the target speaker is displayed away from the sound source rather than near it. (Rudmann et al., 2003)

Auditory alarm problems include high rates of false alarms, interruptive, uninformative, stress-inducing acoustic profiles for alarm sounds, and alarms that are acoustically indistinguishable from one-another (Seagull, 2002).

Auditory displays can communicate information redundant to or independent of visual displays, potentially offloading some visual workload to the auditory channel (Seagull, 2002).

Performance in a tracking task was degraded least in an auditory condition, and most in a redundant multimodal condition (visual and audio). This is an example of a negative redundancy gain. (Seagull, 2002)

4.3 Tactile

Continuous tactile displays are better than discrete. Differences for separate directions are smaller for continuously shifting stimuli, than for discretely shifting stimuli. (Shimizu & Wake, 1982; as cited in van Erp & Verschoor, 2004)

When designing a haptic device, it is important to remember that people can learn haptic skills fairly quickly, and a simple haptic device can support complex interactions (Fogg, Cutler, Arnold, and Eisbach, 1998).

When designing a haptic interface, use a familiar-shaped tool handle (as opposed to a multipurpose, generic handle) to allow a skill acquired in the real world to transfer to a virtual environment (O’Modhain, 2004).
Haptic devices: It is difficult to communicate haptic events in words or pictures, rapid prototyping is more effective than language in conveying haptic ideas. People can learn haptic skills fairly quickly. A simple haptic device can support complex interactions. (Fogg, Cutler, Arnold & Eisbach, 1998)

Also in: 3.9.3, 5.1.3

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information (Tsukada & Yasumura, 2004)

Also in: 2.7.1, 2.7.2, 2.7.3, 3.11, 4.1, 4.2, 6.7

Temporal pulse intervals of 500 msec (250 msec on, 250 msec off) or less may prevent the user from accurately detecting tactors (Tsukada & Yasumura, 2004).

Also in: 2.2.3

Haptic rendering requires update rates significantly higher than graphics rendering (Walker & Salisbury, 2003).

Also in: 2.2.1, 2.2.3, 4.1

Significantly speeding-up the rate of haptic rendering enables physical exploration of geometric datasets that have much greater dynamic range (Walker & Salisbury, 2003).

Also in: 2.2.3, 3.7.3

Haptic interactions occur at two levels: (1) when contact occurs there is a net force (vector) experienced/generated by the user, and (2) the distribution of forces or tractions which occur at each contact site are perceived through the user’s mechanoreceptors, giving rise to the human tactile sense (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.2.3, 2.6.3

The perception of surface shape, compliance, texture, and friction can all be evoked through proper modulation of the net force exerted on the user (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.2.3, 2.7.3

A haptic rendering system must be able to give the sensation of free space (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.7.3

The sensation of sustained contact with a virtual surface requires that the user be able to push into the virtual surface and experience compressive contact forces of sufficient magnitude, to make it feel solid (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.7.3, 8.3
Imposing tangential forces on users while they stroke a virtual surface adds an important sense of realness to perception of objects (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

**Also in: 2.7.3, 8.3**

GP#:1511

Displacements having frequencies below 1 Hz or above 3 kHz will not affect most touch receptors (Cholewiak & Collins; as cited in Sherrick, 1991).

**Also in: 2.2.3**

GP#:1513

When using vibrotactile devices to transmit symbols, a scanning technique works better than whole symbol exposure (Loomis, 1974; as cited in Sherrick 1991).

**Also in: 2.7.3**

GP#:1601

Carbon fibers can be used in tactile nodes to reduce their weight and improve their mechanical properties (Mazzzone, Spagno, & Kunz, 2003).

**GP#:1602**

The number of nodes in haptic fabric determines the resolution and smoothness of the fabric (Mazzzone, Spagno, & Kunz, 2003).

**GP#:1606**

The relationship between the values of haptic properties and perceived magnitude might be non-linear (Wall & Brewster, 2003).

**Also in: 2.6.3**

GP#:1614

The ventral thorax is a relatively traffic free area of somewhat uniform sensitivity, at least in males. (Geldard, 1960)

**Also in: 1.3.3, 2.1.3**

GP#:1615

In the chest, the useful range of stimulus amplitudes is limited to values of 50 to 400 microns (Geldard, 1960).

**Also in: 2.1.3**

GP#:1616

Between 0.1 and 2.0 seconds, there is a durational continuum within which the average observer can make about 25 distinctions, the steps being of the order of 0.05 second at the low end and 0.15 second at the high end of the range (Geldard, 1960).

**Also in: 2.2.3**

GP#:1693

The major requirements for a haptic visualization method are constant haptic refresh rate, fast force calculations, fast incremental rendering, fast data modification, and consistent haptic and volume rendering (Avila & Sobierajski, 1996).

**Also in: 8.3**

GP#:1697

Detection and percept of a stimulus is effected by the waveform (Van Erp, 2002).

**Also in: 2.7.3**

GP#:1699
The following are guidelines on tactile information coding: code information by subjective magnitude; code information by frequency; code information by temporal patterns; and code information by location (Van Erp, 2002).

**GP#**:1700

It is important to make tactile messages self-explanatory (Van Erp, 2002).

**Also in**: 5.3.3

**GP#**:1701

Simultaneous or sequential presentation of multiple tactile messages on the same display can result in tactile clutter and reduced comprehension (Van Erp, 2002).

**Also in**: 2.7.3, 6.6.3

**GP#**:1702

The following are guidelines for designing tactile displays for comfort: ensure comfort over longer periods of time - tactile displays worn on the body must be unobtrusive and comfortable; electrodes and vibrators can generate heat potentially causing burns; the comfortable stimuli range is 15-20 dB above the absolute threshold; and the vibrations of the hand-arm should always be limited; most critical frequencies are around 12 Hz. (Van Erp, 2002)

**Also in**: 2.1.3, 2.2.3, 5

**GP#**:1703

The following design pitfalls should be avoided: spatial masking – location of stimulus is masked by another stimulus; temporal enhancement – affects subjective magnitude of second stimulus (temporal masking and adaptation are other temporal effects to consider); stimuli presented closely in time and space can alter the percept and may even result in a completely new percept (related to apparent motion) (Van Erp, 2002).

**Also in**: 2.1.3, 2.3.3, 2.7.3

**GP#**:1753

The integration of haptics with traditional geometric modeling will increase the bandwidth of HCI, thus shortening the time-consuming design cycle (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

**Also in**: 8.3

**GP#**:1755

Haptic rendering requires (1) sensing the position of user’s finger, (2) locating the nearest point of the surface, and (3) appropriately generating a force to be applied to the finger (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

**Also in**: 8.3

**GP#**:1759

Proprioceptive feedback (via head-mounted display) was found to have no significant effect on the rate at which participants developed spatial knowledge (contrary to other study findings) (Ruddle & Peruch, 2004).

**Also in**: 4.1.5, 5.1.1

**GP#**:1799

(Hale & Stanney, 2004)
Table 1. Haptic tactile skin mechanoreceptor characteristics.*

<table>
<thead>
<tr>
<th>Haptic Features</th>
<th>Pacinian Corporules</th>
<th>Ruffini Endings</th>
<th>Meissner Corporules</th>
<th>Merkel Disks</th>
<th>Hair Follicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin Type</td>
<td>Glabrous and hairy</td>
<td>Glabrous and hairy</td>
<td>Glabrous</td>
<td>Glabrous</td>
<td>Hairy</td>
</tr>
<tr>
<td>Stimulation Objective (physical parameters to be sensed)</td>
<td>Vibration, acceleration, roughness</td>
<td>Skin stretch, lateral force, motion direction, static force</td>
<td>Velocity, flutter, slip, grip control</td>
<td>Skin curvature, pressure, form, texture, edges</td>
<td>Touch</td>
</tr>
<tr>
<td>Stimulation Type</td>
<td>Skin motion</td>
<td>Skin motion and sustained skin deformation</td>
<td>Skin motion</td>
<td>Skin motion and sustained skin deformation</td>
<td>Hair motion</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>Very poor (2 cm)</td>
<td>Poor (1 cm)</td>
<td>Fair (3 – 5 mm)</td>
<td>Good (0.5 mm)</td>
<td></td>
</tr>
<tr>
<td>Stimulation Frequency Range (Hz)</td>
<td>100 – 1,000</td>
<td>0.4 – 100</td>
<td>2 – 40</td>
<td>0.4 – 10</td>
<td></td>
</tr>
<tr>
<td>Interstimulus Interval</td>
<td>Five ms to perceive separate stimuli; 20 ms to perceive stimulus order</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Table 2. Haptic kinesthetic receptor characteristics.*

<table>
<thead>
<tr>
<th>Haptic Features</th>
<th>Golgi Endings</th>
<th>Ruffini Endings</th>
<th>Golgi Tendon Organs</th>
<th>Muscle Spindles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Joint ligaments</td>
<td>Joint capsules</td>
<td>Tendons</td>
<td>Muscles</td>
</tr>
<tr>
<td>Stimulation Objective (physical parameters to be sensed)</td>
<td>Joint movement at end range of motion</td>
<td>Joint movement, particularly at end range of motion</td>
<td>Active position sense link to limb position force</td>
<td>Active movement of muscles</td>
</tr>
<tr>
<td>Stimulation Type</td>
<td>Joint tension at extreme positions</td>
<td>Capsule stretch</td>
<td>Muscle tension and force</td>
<td>Muscle stretch/rate of change vibration</td>
</tr>
</tbody>
</table>


Also in: 2.1.3, 2.2.3
GP#:1800
Table 3. Theorized benefits of adding haptic devices to visual displays (added modalities are in parentheses).

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Visual Display (VD)</th>
<th>VD + Tactile Interface</th>
<th>VD + Positional Actuator</th>
<th>VD + Probe-Based (Force Feedback) System</th>
<th>VD + Exoskeleton System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile perception</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(hard/soft, smooth/rough, and so on)</td>
<td>More accurate judgment of softness and roughness than visual alone</td>
<td>Possible to judge with same accuracy as when using fingertip</td>
<td>If tactile actuators are present in fingertips, possible to judge texture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D form perception</td>
<td>Relative depth in field of view (FOV)</td>
<td>Tactile can be ignored when irrelevant Cross-modal cueing effects useful</td>
<td>Not useful</td>
<td>If tactile actuators are present in fingertips, possible to judge 2D form perception</td>
<td></td>
</tr>
<tr>
<td>Kinesthetic perception</td>
<td>Spatial awareness/position (for example, objects in environment, limb with respect to trunk, body with respect to environment)</td>
<td>Relative depth of objects in FOV Visual proprioception within FOV</td>
<td>Allow egocentric frame of reference within personal space Gestures used to navigate environment Kinesthetic target location has less decay than visual target location</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
</tr>
<tr>
<td>3D form perception</td>
<td>Identification and discrimination depend on viewing angle No indication of weight</td>
<td>Deformability through force feedback aid discrimination and identification Adding force to virtual scene increases presence</td>
<td>Improved weight discrimination of objects Improved object interaction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Hale & Stanney, 2004)
Also in: 2.7.1, 2.7.3, 3.11, 4.1, 4.9, 8.3, 8.6, 8.7

GP#:1802
(Stanney et. al., 2004)
Table 1: Visual design guidelines

<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
</table>
| Graphics     | Graphics are better than text or auditory instructions for communicating spatial information:  
|              | • Use graphics to illustrate components (e.g., equipment diagrams) or spatial relationships (e.g., map, floor plan) and to clarify concepts/complex tasks (Williams, 1998).  
|              | • Combine graphics with text to improve comprehension (European Telecommunications Standards Institute, 2002).  
| Text         | Text may be used to convey detailed long information, procedures, instructions, labels, annotations, and clarifications (Wetzel, Radtke, & Stern, 1994).  
| Animation    | • Animation may be effectively used as a redundant visual cue (Park & Hopkins, 1993).  
|              | • Use motion to enhance detection of objects in periphery or overcome poor illumination.  
|              | • Use animation to demonstrate sequential actions in procedural tasks.  
| General layout | Use “Gestalt Rules” to increase users’ understanding of relations between elements (Palmer, 1992):  
|              | • Place related objects close together.  
|              | • Enclose related objects by lines or boxes.  
|              | • Move or change related objects together.  
|              | • Related objects should look alike (e.g., shape, color, size or typography).  
| Color        | • Use color to aid visual search, indicate state, draw attention, communicate qualitative/quantitative differences (Post, 1997).  
|              | • Design displays that require relative judgment via color (“differentiation tasks”); avoid absolute judgment (“recognition tasks”) via color (Sanders & McCormick, 1993).  
| Group relations | Use numbered lists to show groups of related items, with a specific order (Watzman, 2003).  
|              | • Use flow charts to show relationships/steps involved in a process.  
|              | • Use tables to show relationships between categories of ideas.  
|              | • Use project plan tables to show relationships of tasks over time.  
| Evaluate and compare | Use rating tables to evaluate items against several criteria (Watzman, 2003).  
|              | • Use comparison tables to evaluate items against one criteria.  
|              | • Use matrix graphs to compare more than one item to more than one variable.  
|              | • Use bar charts to compare several things in relation to one variable.  
|              | • Use pie charts to compare relative parts that make up a whole.  
| Hierarchy concepts | Use organizational charts to show hierarchical structure (Watzman, 2003).  
|              | • Use illustrations and/or text to show basic concepts.  
|              | • Use illustrations with text and/or icons, other graphics, complex images, interactive components to show abstract concepts.  
| 2D/3D        | • To extract critical information use 2D graphs, as users often perform better with respect to accuracy and ease (Watzman, 2003).  
|              | • Incorporate 3D into graphics to enhance aesthetics.  

Note. 2D = two-dimensional; 3D = three-dimensional.

Also in: 2.7.1

GP#:1804
(Stanney et. al., 2004)
<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
</table>
| Tactile                | • Vibrotactile sense is comparable in discriminatory ability to audition for frequencies up to about 50 Hz (Miller & Zeleznik, 1999; Sherrick & Cholewiak, 1986).  
                          • Detection of vibration for a single probe is about 28 dB (relative to 1 µ peak) for 0.4 to 3 Hz.  
                          • To ensure user perceives individual signals, stimuli must be separated by at least 5.5 msec and preferably > 10 msec.  
                          • To successfully activate a user’s pressure sensors, force exerted must be > 0.06 to 0.2 N/cm².  
                          • Humans can detect pressure variations up to .0002 in per 100 msec, with an optimal response at 400 Hz, and loss of sensitivity below 50 Hz and above 600 Hz.  
                          • Tactile input must consider sensitivity to stimuli across various skin locations (i.e., 2-point threshold becomes smaller from palm to fingertips).  
                          • Spatial resolution of a point stimulus on finger pad is about 0.15 mm and for a 2-point limen about 1 mm.  
                          • Amplitudes above 0.6 mm to 0.8 mm are painful.  
                          • Humans can detect presence of a 2 µm high single dot and a 0.075 µm high grating.  
                          • Be aware that surface characteristics of a stimulus influence sensation of touch.  
                          • Avoid use of tactual displays in low temperature environments because tactual sensitivity is degraded. |
| Alerts and warnings    | Tactile cues can provide effective alerts via vibrations or variations in pressure; they can be augmented by or substituted for auditory warning cues (e.g., automatic alerts, reception of coded messages such as Braille; Posner, 1976):  
                          • If using tactile cues for warnings, it is important to note humans can identify about four haptic intensities, about five durations, and about nine different frequencies (20% difference needed between levels; Geldard, 1972). |
| Tactile localization   | Tactile cues can be augmented by or substituted for visual tasks to aid localization (e.g., identification of controls, tactual maps as navigation aids, tracking-task displays):  
                          • Humans can detect about seven haptic locations on the chest (Geldard, 1972).  
                          • Use distal body parts if high spatial resolution is required (above 4 cm any body part can be used; Sherrick & Cholewiak, 1986).  
                          • Tactile input can be incorporated into complex applications to provide orientation/direction (Rupert, 1997).  
                          • Tactile location cues (e.g., up or down) can resolve spatial disorientation.  
                          • To convey movement, one can leverage the spatiotemporal illusion of movement (i.e., sensory saltation) using 3 to 6 mechanical sensors placed no greater than 10 cm apart along the back, which emit vibratory pulses with an interstimulus duration of 50 msec (Sherrick & Cholewiak, 1986). |

(continued)
<table>
<thead>
<tr>
<th>Presentation</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture, softness,</td>
<td>Tactile cues can be used to convey properties of simple objects (complex objects require multimodal presentation; Popescu, Burdea, &amp; Treffitz, 2002):</td>
</tr>
<tr>
<td>surface viscosity</td>
<td>- Sensation of textured surfaces requires some relative motion between surface and skin to be maintained.</td>
</tr>
<tr>
<td></td>
<td>- For a hard surface to be felt after initial contact active pressure must be maintained.</td>
</tr>
<tr>
<td></td>
<td>- Soft surfaces exert and maintain a slight positive reaction against the skin after the initial contact without active pressure or relative motion.</td>
</tr>
<tr>
<td>Kinesthetic</td>
<td>Kinesthetic cues can stimulate anticipation of a change, provide feedback confirming reception of a user input, provide an indication of current state, guide user interaction toward a desired position or location, make clear distinctions between orthogonal directions, and aid discrimination (e.g., length) and identification (e.g., shape; Miller &amp; Zeleznik, 1999):</td>
</tr>
<tr>
<td></td>
<td>- To maintain optimal hand–eye coordination, the delay (i.e., lag) between sensing and kinesthetic feedback should be less than 100 msec.</td>
</tr>
<tr>
<td></td>
<td>- When interacting with objects, allow adequate time for users to respond kinesthetically (minimum 250 msec for simple reaction time).</td>
</tr>
<tr>
<td></td>
<td>- Avoid static positions at or near end range of motion to reduce fatigue.</td>
</tr>
<tr>
<td>Gestures</td>
<td>Gestures can be used to communicate meaningful information in isolation (e.g., hand signals) or in combination with speech and/or visual information (e.g., ‘put that there;’ Oviatt, 1997; Turk, 2002):</td>
</tr>
<tr>
<td></td>
<td>- Adding gesture to speech offers speed, high-bandwidth information, flexibility of input modes, enhanced error avoidance, and relative ease of use.</td>
</tr>
<tr>
<td></td>
<td>- Gestures should be intuitive and simple; avoid increasing user’s cognitive load with numerous or complex gestures.</td>
</tr>
<tr>
<td></td>
<td>Gestures can be used to manipulate the environment (Oviatt, 1997; Turk, 2002). Gestures are a natural, flexible input mode, and can effectively be used for control and navigation:</td>
</tr>
<tr>
<td></td>
<td>- Avoid temporal segmentation of gestures.</td>
</tr>
<tr>
<td></td>
<td>- Avoid frequent, awkward, or precise gestures to minimize user fatigue.</td>
</tr>
<tr>
<td></td>
<td>- Gestures can be effectively used for spatial tasks (e.g., resizing, moving objects; Popescu et. al., 2002; Turk, 2002):</td>
</tr>
<tr>
<td></td>
<td>- Inform user of types of for which gestures allowed and what affect each will have on system interaction.</td>
</tr>
<tr>
<td></td>
<td>- Avoid precise motion gestures, as it is difficult to make highly accurate or repeatable gestures with no tactile feedback.</td>
</tr>
<tr>
<td>Kinesthetic localization</td>
<td>Kinesthetic cues (e.g., movement cues, impedance) can aid spatial location memory (Popescu et. al., 2002):</td>
</tr>
<tr>
<td></td>
<td>- Kinesthetic is best coupled with other modalities to aid location memory of objects in space relative to one’s location.</td>
</tr>
<tr>
<td></td>
<td>(continued)</td>
</tr>
</tbody>
</table>
4.3.1 Type of tactile cue

Sensitivity to tactors depends on size, density, frequency range, and nerve fiber branching of receptors (see charts) (Hale & Stanney, 2004). The roof of the mouth is very sensitive to vibrotactile stimulation, and the intensities required (10-20 V) are much lower than those required on the fingertips (25-30 V) (Tang & Beebe, 2000). The torso is less sensitive to tactors than the hand. The front of the torso is more sensitive than the back of the torso. There is greater sensitivity closer to the sagittal plane (the plane dividing the left and right halves of the body) (findings of other studies summarized in Lindeman, Sibert, Mendez, Patil, & Phifer, 2005). Participants could identify geospatial cues moving left/right on tongue with more accuracy than forward/backward (Tang & Beebe, 2000).

Also in: 2.1.3, 2.2.3

There is some evidence that performance decrements associated with tactile patterns (compared to visual patterns) is a consequence of the inferior acuity of skin compared to the visual system (Cholewiak, Collins & Brill, 2001).

Also in: 2.6.1, 2.6.3

When designing haptic virtual environments, consider the following principles: provide easy-to-find waypoints; do not remove buttons but rather gray them out and provide a different texture so they will still serve as waypoints; use enlarged interaction points so they are easier to see; the texture of the manipulandum (the object the user manipulates) impacts how the user interacts with the haptic device; the characteristics of the manipulandum transfer to the represented object; use rounded edges when representing an image haptically, as users have difficulty tracking sharp edges; and users perceive angles to be more acute in haptic images. (Sjostrom, 2001)

Also in: 8.1, 8.3

Fingertip motion (kinesis) improves tactile perception (Foulke, 1991; as cited in Ramstein et al., 1996).

Also in: 2.2.3
Visual texture using the technique presented by Ware & Knight (1995) should be considered as a technique to add depth to information display, particularly topographic maps. Humans are most sensitive to patterns whose period is approximately 2 cycles/degree.

Also in: 2.2.1, 4.1, 4.1.4

Textures generally worked better than forces for emphasis and annotation in haptic devices. Power requirements of embedded haptic feedback are the greatest challenge, particularly for portable displays. Continuous interaction through a haptically actuated device rather than discrete button/key presses can produce simple yet powerful tools that leverage physical intuition. (Snibbe, MacLean, Shaw, Roderick, Verplank & Scheeff, 2001)

Also in: 5.3.3

There are two types of tactile stimulation: superficial stimulation by air pressure (induces stress only near the surface), and stimulation of deep receptors (vibration applies stress to shallow and deep receptors). It is possible to selectively stimulate the receptors at different depths, although the direction of the applied surface forces is not controllable. Humans can discriminate a small difference in pressure distribution within a small area on the skin, given different stimulus amplitude to shallow and deep receptors. This discrimination ability degrades when only shallow receptors are stimulated. Superficial stimulation results in feeling a finer virtual text than stimulator spacing and time-delayed signals like a brush across the skin. (Asamura, Yokoyama & Shinoda, 1998)

Also in: 2.1.3, 2.2.3

Haptic effects and hapticons used in conjunction with IM: Email and IM primarily use textual messages—extended with audio-visual cues. Hapticons are small, programmed force patterns that can communicate a basic notion similar to regular icons in a graphic interface. These vibration patterns only become hapticons after users start to recognize the patterns and associate them with a particular meaning. (Rovers & van Essen, 2004)

Also in: 3.1.3, 3.9.4 ATV, 5.2.3

Touch is a powerful signal for emotional content and can contribute to losses in subtle non-verbal communication cues—hapticons can strengthen meaning and expression (Rovers & van Essen, 2004).

Also in: 2.6.3, 3.9.3

The human body perceives a resolution of .4cm JND (just noticeable difference) interval at center of abdomen, 1.2 cm interval at side of abdomen; 1.8 cm interval at center of back, and 3.0 cm interval at sides of back (Tsukada & Yasumura, 2004).

Also in: 2.1.3, 2.2.3

The interval between pulses (empty interval) is perceived to be longer with vibrotactile pulses than with visual light pulses (Van Erp & Werkhoven, 2004).

Also in: 2.2.1, 2.2.3, 4.1

Pneumatic tactors give a more powerful vibration than electrically driven vibrators, and are less hazardous than plugging the user into an electrical source (Schrope, 2001).
Pneumatic tactors are much lighter than electrically driven vibrators (Schrope, 2001).

Unlike static pressure, mechanical vibration, when applied to the skin, does not stay within bounds unless something is in place to prevent its spread (Geldard, 1960).

Two simultaneous acting vibrators feel no different from one, once the static pressure of each has adapted out, and provided the vibratory pattern is set up in all of them with the same onset (Geldard, 1960).

Dynamic tactile information (e.g., five tactors placed on the forearm vibrating sequentially) can be used to accurately reorient visual attention or vice versa (Hale & Stanney, 2004).

Two common techniques to generate vibration are: (1) based on a moving coil or (2) on a DC motor with an eccentric weight mounted on it (Van Erp, 2002).

4.3.2 Planes of motion

Stronger force feedback and more degrees of freedom can be beneficial to performance when only haptic cues are available, but when haptic and audio cues are combined, there was no difference (between PHANToM and Wingman) (Yu & Brewster, 2002).

The following are kinesthetic interaction design guidelines based on psychophysical research: to ensure more accurate limb position, use active rather than passive movement; avoid minute, precise joint rotations, particularly at distal segments; minimize fatigue by avoiding static positions at or near the end range of motion; surface stiffness of 400 Newtons per meter should effectively promote haptic information transfer; end-point forces of 3-4 Newtons should effectively promote haptic information transfer; add kinesthetic information to enhance objects’ spatial location; gestures should be intuitive and simple; minimize fatigue by avoiding frequent, awkward, or precise gestures; and avoid precise motion gestures, as making accurate or repeatable gestures with no tactile feedback is difficult. (Hale & Stanney, 2004)

The following are psychophysical tactile interaction design guidelines based on psychophysical research: (1) Haptic input must consider sensitivity to stimuli across various skin locations (for example, the two-point threshold grows smaller from palm to fingertips, where spatial resolution is about 2.5 mm on the index finger tip (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (2) To ensure that receptors perceive individual cutaneous signals, stimuli must be at least 5.5 ms apart (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (3) To successfully activate an individual’s pressure sensors, the force exerted must be greater than 0.06-0.2 Newtons per cm (Sherrick & Cholewiak, 1986; Biggs & Srinivasan, 2002, both as cited in Hale & Stanney, 2004); (4) Pressure limits depend on body loci and gender. Just-noticeable values range from 5 milligrams on a woman’s face to 355 mg on a man’s big toe (Sherrick & Cholewiak, 1986 as cited in Hale & Stanney, 2004); (5) Vibration from a single probe must exceed 28 decibels (relative to a 1-microsecond peak) for 0.4-3 Hz frequencies for humans to perceive (Biggs & Srinivasan, 2002, as cited in Hale & Stanney, 2004); (6) For a user to feel a hard surface after
initial contact, the haptic system must maintain active pressure; (6) Maintaining the sensation of textured surfaces requires relative motion between the surface and the skin.

Also in: 2.1.3, 2.2.3, 2.7.3

4.3.3 Force feedback

Force feedback (gravity wells) can reduce the time it takes to point and click on targets on a computer screen. This is even more pronounced when fine motor ability is impaired (as may be the case when users are on a plane/tank/ship that vibrates). (Hwang, Keates, Langdon, & Clarkson, 2003)

Also in: 2.6.4, 3.6.3

Stronger force feedback and more degrees of freedom can be beneficial to performance when only haptic cues are available, but when haptic and audio cues are combined, there was no difference (between PHANToM and Wingman) (Yu & Brewster, 2002).

Also in: 4.3.2, 4.6.3

4.3.4 Interference

Papers that address the influence of the time difference between haptic media and audio/visual media and the effect of auditory cues on the haptic perception (Harada, Ohno & Sato (1998); as cited in Ishibashi, Kanbara & Tasaka, 2004).

Also in: 2.7.5, 4.2.3, 4.7.1

The sensory modality most affected by sensorimotor discord is the tactile sense (e.g., one can only touch things that are close, so touch is more local and intimate than vision or audition) (Durlach & Slater, 2000; as cited in Allison, Zacher, Wang & Shu, 2004).

Also in: 2.6.1, 2.6.2, 2.6.3

The hand (or other effector) is both a sensor and an end-effector; thus, a haptic device is typically a display and an input device. In a real environment, this input-output pairing implies a lawful synchrony between user actions and sensory feedback. (Allison, Zacher, Wang & Shu, 2004)

Also in: 2.6.4, 2.7.4

Delays (typical of those found in long distance telecollaboration) inhibit the ability of users to collaborate using haptic or visual communication at a distance. Delay can result in dissociation between the state of the system at the two end stations, which can cause differences in the response of operators who are compensating for perceived errors. (Allison, Zacher, Wang & Shu, 2004)

Also in: 2.5.1, 2.5.3, 3.9.1, 3.9.3, 4.1.7

4.3.5 Synchronization

Tactile information is often perceived as single stimulus when two tactile stimuli are presented simultaneously (Tan, 2000).

Also in: 2.7.3

Visual feedback reduced performance times and underforce errors, compared to haptic feedback, at various levels of delay (between presentation of cues); however, visual feedback interacts with delay such that at
200 milliseconds, the modes are equal. Visual feedback can also increase the number of overforce errors committed. (Allison, Zacher, Wang & Shu, 2004)

**4.3.6 Redundant information**

Performance decrements resulting from use of tactile cues (compared to visual cues) may have been caused by difficulties in passively perceiving dynamic tactile stimuli. Redundant information, even of low resolution, aids in the perception of dynamic tactile stimuli. (Van Erp & Verschoor, 2000)

**4.4 AV**

When considering offloading to another modality, determine whether complex information can be presented usefully in an auditory path, and whether auditory and visual cues can be combined to facilitate the processing of information (Brown, Newsome & Glinert, 1989).

**4.4.1 Interference**

Interference is greater when two visual tasks are performed together or when two auditory tasks are performed together, than when a visual task is combined with an auditory task (Treisman & Davies, 1973; Duncan et al., 1997; as cited in Bourke & Duncan, 2005).
Top-down operations, such as voluntarily scanning a visual scene for information, are impaired by the addition of a concurrent auditory task (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 3.6.1, 3.6.4 AV, 6.7

4.4.2 Synchronization
4.4.3 Redundant information

As more distracting voices are added to an audio conversation tracking task, it becomes harder to track target words. Also, as the number of distracting voices goes up, it becomes increasingly beneficial to augment audio cues with a video display of the target speaker. (Rudmann, McCarley & Kramer, 2003)

Also in: 3.9.2, 3.9.4 AV, 4.2.3

Providing a visual display of a speaker that is congruent with the display of speech improves comprehension, especially as background noise increases. (MacLeod & Summerfield, 1987; as cited in Rudmann et al., 2003) Tracking or shadowing the speech of a target speaker while ignoring another distracting speaker is easier when the visual display of the target speaker is displayed away from the sound source rather than near it. (Rudmann et al., 2003)

Also in: 2.1.4 AV, 4.1.9, 4.2.1, 4.2.5, 4.4.1

In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003)

Also in: 2.1.4 AV, 2.1.4 TV, 2.2.4 AV, 2.2.4 TV, 2.6.4, 2.7.4 AV, 2.7.4 TV, 4.5.3

The delivery of both visual and auditory information could provide the best of both worlds – this redundancy gain has been found in the delivery of instructions, though it has been surprisingly absent when investigated in some dual-task contexts (Helleberg & Wickens, 2003; Seagull and Wickens, 2001; as cited in Wickens, et al 2003) as if the combination may produce the “worst of both worlds.”

Also in: 6.7

(Wang et al, 1993; as cited in Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user) Redundant multimodal output using visual display of test and speech restitution of the same text enables faster learning of an interface.

Also in: 5.1.4 AV

4.5 TV

Adding tactile/propriocceptive cues to visual cues can allow users to expand their geometric field of view without significantly distorting distance perception (Yang & Kim, 2004).

Also in: 2.1.1, 2.1.4 TV, 2.7.4 TV

Because vision frequently dominates the integrated visual/haptic percept, caution should be used when combining vision and haptics for tasks involving size, shape, or position judgment (Hale & Stanney, 2004).
Adding haptic location information (e.g., through active position pointing) to a visual display enhances target placement memory (Hale & Stanney, 2004).

\textbf{Also in:} 3.6.4 TV

GP#:1623

Confusion and control instabilities in the multimodal system can be minimized by avoiding time lags between visual and haptic loops (Hale & Stanney, 2004).

\textbf{Also in:} 2.7.4 TV, 6.6.4

4.5.1 Interference

Vision usually dominates the integrated visual-haptic percept; however, in some circumstances like judging an object’s texture, the combined percept is clearly affected by haptics (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

\textbf{Also in:} 2.6.1, 2.6.3

GP#:1571

Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation and vice versa (Ernst, Banks, Wichmann, Maloney, Bulthoff, 2002).

\textbf{Also in:} 2.6.1, 2.6.3

GP#:1572

If touch can be entirely ignored, visual spatial attention tasks won’t affect tactile processing, allowing it to convey additional information (such as a tactile warning) (Hale & Stanney, 2004).

\textbf{Also in:} 3.1.3, 6.3.1

4.5.2 Synchronization

Haptic-audio combination has not been explored to a large extent, studies most focus on visual-auditory (see [10] for concise summary). The temporal thresholds are very high for visual-haptic asynchrony. (Adelstein, Begault, Anderson & Wenzel, 2003)

\textbf{Also in:} 2.7.4 AT, 2.7.4 AV

GP#:1370

The maximum visual-haptic cue asynchrony or delay that participants tolerate was 45 ms (on average). The range in which stimuli were judged to be synchronous was centered around a visual delay of about 7 ms. This point of subjective simultaneity (PSS) was liable to individual differences. (Vogels, 2004)

\textbf{Also in:} 1.4.4 TV, 2.2.1, 2.2.4 TV, 2.7.4 TV

GP#:1765

The point of subjective simultaneity (PSS) shifts towards visual delays when attention is directed to a visual cue, and towards haptic delays when participants direct attention to a haptic stimulus (Vogels, 2001).

\textbf{Also in:} 2.7.1, 2.7.3, 2.7.4 TV, 6.3.1, 6.3.3

4.5.3 Redundant information

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

\textbf{Also in:} 2.6.2, 3.7.4 AT, 3.7.4 TV, 4.6.3, 5.2.2, 6.3.2
In an uncrossed-hands posture, just noticeable differences were lower when stimuli (audio and visual or tactile and visual) were presented from different positions, rather than the same position. However, this spatial redundancy benefit was reduced when participants used a crossed-hands posture. Results demonstrate that people can use redundant spatial cues to facilitate performance on multisensory temporal order judgment tasks. (Spence, Baddeley, Zampini, James, and Shore, 2003).

Also in: 2.1.4 AV, 2.1.4 TV, 2.2.4 AV, 2.2.4 TV, 2.6.4, 2.7.4 AV, 2.7.4 TV, 4.4.3

4.6 AT

4.6.1 Interference

High-bandwidth audio information can attenuate the effects of tactile cues in distributed collaboration situations (Sallnas, Rassmus-Grohn, & Sjostrom, 2000).

Also in: 3.9.4 AT

4.6.2 Synchronization

Manipulating the attention of the participant can influence the perception of simultaneity—the stimulus cued by the experimenter is usually perceived earlier. This was shown for stimuli presented within audio-tactile modalities (Stone, 1926), within the auditory modality (Needham, 1936), and within the visual modality (Stemach & Herdman, 1991; as cited in Vogels, 2004)

Also in: 2.5.1, 2.5.2, 2.5.4 AV, 4.1.8, 4.2.4, 6.3

4.6.3 Redundant information

Sound has a natural role in actions involving mechanical impact and vibration, so auditory display should be used to augment virtual haptic interfaces (Adelstein, Begault, Anderson & Wenzel, 2003).

Also in: 2.6.2, 8.3, 8.4 AT

In the absence of visual cues, multimodal conditions (audio-tactile) led to higher accuracy, lower response time, and less workload compared to unimodal conditions in deciphering a 2d bar graph (Yu & Brewster, 2002).

Also in: 2.5.4 AT, 3.11, 6.6.4 AT

Stronger force feedback and more degrees of freedom can be beneficial to performance when only haptic cues are available, but when haptic and audio cues are combined, there was no difference (between PHANToM and Wingman) (Yu & Brewster, 2002).

Also in: 4.3.2, 4.3.3

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

Also in: 2.6.2, 3.7.4 AT, 3.7.4 TV, 4.5.3, 5.2.2, 6.3.2

4.7 ATV

4.7.1 Interference

Also in: 1219
Audio is not as prevalent as tactile with regards to data analysis and inspection when visual information is absent (Ramloll, Yu, Brewster, Riedel, Burton, & Dimigen, 2000).

Also in: 2.7.1, 2.7.2, 2.7.3, 3.11

GP#:1358

Papers that address the influence of the time difference between haptic media and audio/visual media and the effect of auditory cues on the haptic perception (Harada, Ohno & Sato (1998); as cited in Ishibashi, Kanbara & Tasaka, 2004).

Also in: 2.7.5, 4.2.3, 4.3.4

4.7.2 Synchronization
4.7.3 Redundant information

4.8 General Multimodal

In terms of using multiple modes to convey redundant information, more modes aren’t always better. The modes can interfere with each other or lead to performance decrements (Akamatsu, MacKenzie, & Hasbroucq, 1995; Jeong, 2001; Emery, Edwards, Jacko, Moloney, Barnard, Kongnakorn, Sainfort, & Scott, 2003; Jeong & Gluck, 2003).

GP#:1023

In certain tasks, use of two modes yields performance (and/or reaction time improvements) greater than the sum of their parts. However, this depends on the task. This has been referred to as redundancy gain or bimodal enhancement (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Guest & Spence, 2003).

GP#:1025

Multimodal stimulation is not always better than unimodal stimulation. It may depend on the task or dependent measure. For example, if an operator is extensively trained to perform a task in one modality but then tested on the same task in a different modality or multiple modalities, the operator’s performance may be constrained due to distraction. Also, performance under multimodal conditions may not be significantly different from unimodal performance when viewed from certain dependent variables (i.e., detection accuracy), but may be different for others (i.e., detection speed). (Tannen, 2000)

Also in: 5.1.4, 5.1.5

GP#:1047

Displays using text, pictures, and speech are more effective than a device with any of these components missing (Elting, Zwickel & Malaka, 2002).

GP#:1066

Multimodal interfaces should be able to flex and adapt to handle natural environmental fluctuations like power outages or being damaged (Oviatt et al., 2004).

Also in: 2.7.4, 3.10, 4.9

GP#:1313

Guidelines for handling human errors:
1) Make the action more perceptible (i.e. the possibility of activating the execution of another likely wrong action should be reduced, a given action should provide unambiguous information for the ongoing activity, even before the attainment of the end state);
2) Use multi-sensory feedback;
3) Display messages at a high level but with specific content (i.e. multilevel error messages, error message tells you it can not comply with your request, but there is a “since” or “because” button you can use to receive more info);
4) Provide an activity log (people depend on external memory aids);
5) Allow comparisons (comparisons between outputs is a useful source of information for action evaluation);
6) Make results available to users as soon as possible and allow the user to have control of the format display (suggestions for this include, i) exploiting layout, ii) exaggerating the differences, iii) stressing the aspects relevant to the just performed task);
7) Provide result explanations (i.e. make it extremely easy to determine why an input was not successful. If an input causes an error, indicate the varying factors that may have led to the error and the best way to fix it. (Rizzo et al., 1996, 116-118)

Also in: 4.1.4, 4.9, 5.3.5, 7.1.5

GP#:1469

When task-relevant information is expected primarily in one sensory modality, then performance suffers for events in secondary modalities, even if they appear in isolation (Spence & Driver, 1997).

Also in: 5.2.4

GP#:1587

The direct manipulation of a GUI interface resulted in fewer errors on average, but was not significantly less than when interacting multimodally (e.g., pen/voice map device). Time needed to repair an error was significantly less with a multimodal device. (Cohen, McGee, & Clow, 2000)

Also in: 3.2.4

GP#:1795

Nigay & Coutaz (1993) have a framework dedicated to multimodality: “Fusion” (whether the events from several modalities have to be merged—combination or independence) x “Use of Modality” (sequential or parallel). This results in 4 categories of multimodality: “Alternate” = combination and sequential; “Synergistic” = combination and parallel; “Exclusive” = independence and sequential; and “Concurrent” = independence and parallel. (As cited in Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user)

GP#:1796

A system should use multimodality only if it helps in achieving usability criteria such as: enabling a fast interaction, improving recognition in a noisy (audio, visual or tactile) environment, enabling user to easily link presented information to more global contextual knowledge (interpretation), or translating information from one modality to another. (Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user)

Also in: 7.2.5

GP#:1797

There are five types of cooperation between modalities: “Transfer” (a chunk of information produced in one modality is used by another modality); “Equivalence” (a chunk of info may be processed as an alternative, by either modality. It allows the user to select the fastest modality); “Specialization” (a specific kind of information is always processed by the same modality and can have data-relative, modality-relative, or absolute specialization); “Redundancy” (The information is processed by these modalities); Complementarity (different chunks of information are processed by each modality and have to be merged). (Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user)

Also in: 4.8.3

GP#:1805

(Stanney et. al., 2004)
4.8.1 Interference

Concurrent verbal tasks interfere with manual performance. There is a lateralization of this interference effect that is dependent on the modality of the verbal task, such that the visual modality interferes more with right-hand tapping. (McGowan & Duka, 2000)

Content across multiple medias should be consistent (Maybury, 1995).

When information must be combined from various sources located at different points in space (e.g., information from two maps), or different points in time (e.g., panning), or both, the composite mental picture will be less accurate than when all information is available in a single source (Wickens, Thomas, & Young, 2000).

People are slower to respond to an event in one modality if they have just responded to an event in a different modality (modality-shifting effect) (Spence & Driver, 1997).

Ideally, an adaptive multimodal system would detect, automatically learn, and adapt to a user’s dominant multimodal integration pattern. This could result in a substantial improvement in system processing speed,
accuracy of interpretation, and synchronous interchange with the user. (Oviatt, Lunsford, and Coulston, 2005)

Also in: 5.5.4

GP#:1637

The inherent multi-dimensionality of sound in time, timbre and space often renders it to be the preferred means of transmission of data, information, and alerts in human-computer interfaces. By using auditory displays, numerous streams of data can be presented concurrently, offloading the visual system to perform other tasks. (Roginska, 2004)

Also in: 2.7.1, 2.7.2, 3.1.2, 4.2, 6.7.2

GP#:1771

Tasks that are less automated are more likely to interfere with other activities (Wickens, 2000).

Also in: 6.7

GP#:1772

Two tasks that demand more common resources will show larger dual task decrements than two tasks that demand separate resources (Wickens, 1992; as cited in Wickens, 2000).

Also in: 6.6.5, 6.7.2

4.8.2 Synchronization

When designing multimodal systems, need to consider synchronization factors (when redundancy is involved); if there is too much separation between cues, can create confusion (Di Fillippo & Pai, 2000).

GP#:1275

The temporal relationship of multimodal events (including the response times of input devices) must be considered (Bellik, 1997; as cited in Vo, 1998).

GP#:1369

It has been suggested that the more properties shared between two modalities, the stronger the observer’s unity assumption that information from different sensory channels can be attributed to the same distal event or object [14]. These properties include spatial location, motion, temporal patterning or rate [15], all of which can be impacted by temporal asynchrony in a multimodal display system. (Adelstein, Begault, Anderson & Wenzel, 2003)

Also in: 2.1.4, 2.7.4

GP#:1399

Multimodal feedback enhances presence/performance in VR systems, but only when the feedback from one modality is consistent with another (Oviatt, 2003; as cited in Yang & Kim, 2004) and is configured appropriately for the task at hand (Oviatt, 1999; as cited in Yang & Kim, 2004).

Also in: 8.4

4.8.3 Redundant information

For multitasking where one task is secondary and only requires management at certain times, it is important to have an interruption cue that differs from the dominant resources required of the primary task (generally visual) (Hopp, Smith, Clegg, & Heggestad, 2005; Enriquez, Afonin, Yager, & Maclean, 2001).

GP#:1031

If the information in different modalities has no new content, it only increases the cognitive load experienced by the user (Elting, Zwickel & Malaka, 2002).

Also in: 6.6.4
Content across multiple medias should be consistent (Maybury, 1995).

Also in: 4.8.1

GP#:1156

Many researchers suggest the use of multimodal VR interfaces because they provide the user with more naturalness, expressive power, and flexibility [16].

Multimodal operating systems work more steadily than unimodal systems because they integrate redundant information that is shared between output modalities. (Althoff, McGlaun, Schuller, Morguet & Lang, 2001)

GP#:1231

Users with more expertise tend to choose complementary modes, while beginners tend to choose more redundant modes/devices (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Also in: 1.2.4, 1.2.5, 5.5.4, 5.5.5

GP#:1234

Multimodal interfaces should be able to flex and adapt to handle natural environmental fluctuations like power outages or being damaged (Oviatt et al., 2004).

Also in: 2.7.4, 3.10, 4.9

GP#:1313

Visual in-cockpit technology should be adopted with caution for single-pilot operations, and that adopting other design or training features should be considered to address the attentional implications of that technology (this is true for cockpit displays of traffic information which may not be knowledgeable of all outside traffic). Design and training should be performed in conjunction if redundant display modalities are chosen, so that benefits of redundancy can be realized. (Wickens, Goh, Helleberg, Horrey & Talleur, 2003)

Also in: 3.8.1, 4.1, 5.1.1, 6.3.1

GP#:1793

There are five types of cooperation between modalities: “Transfer” (a chunk of information produced in one modality is used by another modality); “Equivalence” (a chunk of info may be processed as an alternative, by either modality. It allows the user to select the fastest modality); “Specialization” (a specific kind of information is always processed by the same modality and can have data-relative, modality-relative, or absolute specialization); “Redundancy” (The information is processed by these modalities); “Complementarity” (different chunks of information are processed by each modality and have to be merged). (Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user)

Also in: 4.8

4.9 Miscellaneous

Device designers should consider at what point in the information process the device should automatize: (1) information acquisition; (2) information analysis; (3) decision selection; or (4) action implementation (Parasuraman, Sheridan, Wickens, 2000).

GP#:1039

Cognitive overload is a critical issue to consider in user interface design. Presentation planners should adapt their presentation to the cognitive requirements of the communication device used. (Elting, Zwickel & Malaka, 2002)

Also in: 6.6.5

GP#:1062
When designing adaptive communication interfaces it is important to consider the following questions: How would the operator's knowledge states and decision processes be affected by receiving instant messages? When should an adaptive chat management tool interrupt the operator and under what conditions? Is there a principled way for this tool to infer the operator’s workload and his/her ability to cognitively attend to communication messages? How will an adaptive chat management strategy affect overall human performance, situational awareness, and frustration? (Cummings, 2004)

Also in: 3.1.5, 6.4.5, 6.6.5

Some aspects of reality can be captured by using symbols to make a description of it. However, there is a trade-off: any particular representation makes certain information explicit at the expense of other information. Information that is not salient at a given moment is pushed into the background and may be quite hard to recover. (Marr, 1982; as cited in Bennett, Malek & Woods, 2000)

Factors related to instrumentation design and display design should be considered in conjunction (Vicente & Ethier, 2000).

In determining how much information to present a user with, consider that users need sufficient information to adequately perform the task, but too much information can overload a user’s short-term memory and cause frustration (Baca & Picone, 2005).

Also in: 6.6.5

General design principles relevant for sustaining situational awareness include the following: organize information around goals; present level two situational awareness information directly to support comprehension; support global situational awareness; support trade-offs between goal-driven and data-driven processing; make critical cues for schema activation salient; take advantage of parallel processing capabilities; and use information filtering carefully. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 6.4.5, 6.7.2

In designing a device, there are several layers of complexity to consider, including system complexity, operational complexity, cognitive complexity (composed of display complexity and task complexity), apparent complexity (face validity), and as always, the user’s mental model. To manage the complexity of a system, consider the following principles: avoid “feature creep” (adding more and more bells and whistles); map system functions to the goals and mental models of users; provide system transparency and observability; provide consistency and standardization on controls across different displays and systems; and minimize task complexity. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 6.4.5

Secondary-task displays must be selected based on some specification of acceptable primary task performance degradation (Tessendorf, Chewar, Ndiwalana, Pryor, McCrickard & North, 2002).

Also in: 6.7

Use a body-centered frame of reference (as opposed to a device-centered frame of reference) to reduce susceptibility to sensory overload and to allow users to orient themselves to the direction of travel (Traylor & Tan, 2002; as cited in O’Modhrain, 2004).

Also in: 3.2.5, 3.5.5, 6.4.5, 8.5

GP#:1261
When designing user interfaces, determine what user characteristics produce the biggest differences in performance and then design the user interface to maximize the benefits for all groups (Gwizdka & Chignell, 2004).

Also in: 1, 5

GP#:1313

Multimodal interfaces should be able to flex and adapt to handle natural environmental fluctuations like power outages or being damaged (Oviatt et al., 2004).

Also in: 2.7.4, 3.10, 4.8

GP#:1314

Inverted damping allowed the user to select items significantly quicker than using normal damping or no-damping methods (Williams and Michelitsch, 2003).

GP#:1348

Handheld devices: People exert considerable force on handheld objects; The technical aspects of handheld devices (battery life, mechanical functioning, etc) are challenging (Fogg, Cutler, Arnold & Eisbach, 1998).

GP#:1351

Most devices require action on the user’s part-- Driving devices such as GPS navigation systems add an extra element of complexity into the vehicle (Burnett, Summerskill & Porter, 2004).

Also in: 3.11, 3.2.5, 3.3.5

GP#:1379

A critical issue in designing an information display is determining what type of data “best” maps onto which sensory input channel. The nature of the information to be displayed can immediately suggest the sensory channel of choice. (Loftin, 2003)

Also in: 2.7.5

GP#:1383

With the integration of displaying the degree of uncertainty into the presentation format of medical data, it is possible to make computer-produced data more reliable and acceptable by users (discussed here in the context of medical personnel) (Krol, Reich, Pavone & Fuhrman, 2004).

Also in: 5.4.5, 7.1.5

GP#:1386

The best user functions are often the most invisible. For example, highly skilled controllers valued simplicity over functionality. (Mackay, Fayard, Frobert & Medini, 1998)

Also in: 1.4.5, 7.1.5

GP#:1400

Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

Also in: 2.7.1, 2.7.2, 2.7.4, 2.7.4 AV, 3.11, 5.2.5

GP#:1431

Because the appearance (fidelity) of the learning environment is not particularly relevant for some tasks, realism doesn’t need to be the principle focus underlying the development of virtual environment training systems (Waller, Knapp & Hunt, 2001).

Also in: 5.1.5, 8.5

GP#:1452
When information must be combined from various sources located at different points in space (e.g., information from two maps), or different points in time (e.g., panning), or both, the composite mental picture will be less accurate than when all information is available in a single source (Wickens, Thomas, & Young, 2000).

Also in: 2.1.4, 2.7.4, 3.2.1, 4.8.1

Guidelines for handling human errors:
1) Make the action more perceptible (i.e. the possibility of activating the execution of another likely wrong action should be reduced, a given action should provide unambiguous information for the ongoing activity, even before the attainment of the end state);
2) Use multi-sensory feedback;
3) Display messages at a high level but with specific content (i.e. multilevel error messages, error message tells you it can not comply with your request, but there is a “since” or “because” button you can use to receive more info);
4) Provide an activity log (people depend on external memory aids);
5) Allow comparisons (comparisons between outputs is a useful source of information for action evaluation);
6) Make results available to users as soon as possible and allow the user to have control of the format display (suggestions for this include, i) exploiting layout, ii) exaggerating the differences, iii) stressing the aspects relevant to the just performed task);
7) Provide result explanations (i.e. make it extremely easy to determine why an input was not successful. If an input causes an error, indicate the varying factors that may have led to the error and the best way to fix it. (Rizzo et al., 1996, 116-118)

Also in: 4.1.4, 4.8, 5.3.5, 7.1.5

Nyquist theorem states that a signal must be sampled with a rate twice as fast as the maximum frequency in the signal in order to reconstruct it: $\text{nyquist} = 2\times \text{max}$. A method called grouped sampling takes the method of modified fixed sampling a step further. It uses the approach of identifying the minimum sampling rate (in KHz) for different groups of sensors (Shahab et al., 2001).

Also in: 2.7.5

A fully functioning system for navigational aid should incorporate methods of inputting the destination and user preferences in terms of the route to be taken by the user (Sokoler et al., 2002).

Also in: 3.2.5, 5.5.5

Representing the physical environment (e.g., weather, terrain) and opposing forces (e.g., computer generated forces) in an information display is critical in creating effective military simulations (Oswalt, 1995).

Also in: 3.11, 4.1.4

Distributed and parallel processing of simulation functionality is likely to be an increased requirement, as complex models represent many more aspects of a combat environment (Oswalt, 1995).

Also in: 3.11

Advances in technology do not mitigate the need for thorough design and thoughtful implementation. For example, the design of military simulations still combines science and art (Oswalt, 1995).

Also in: 3.11

GP#:1526
A major factor in display design seems to be the computational demands related to different spatial filtering rather than the perceived location of the sources (MacDonald et al., 2002).

Also in: 2.1.5, 6.6.5

GP#:1529

With mobile devices, keeping interactions minimally demanding of cognitive and visual attention is a core design issue (Hinckley et al., 2005).

Also in: 4.1, 6.3.5, 6.6.5

GP#:1556

Future mobile and educational interfaces should be designed with the goal of supporting the poorer attention span, impulse control, and higher error rates of users with an impulsive profile, especially in the case of mobil, in vehicle, military, and other applications that bear an unacceptably high cost for committing errors (Oviatt, Lunsford, and Coulston, 2005).

Also in: 1.4.5, 3.2.5, 3.3.5, 6.3.5

GP#:1562

Artificial neural networks using physiological signals can be used to provide accurate estimates of operator functional state that can be used to provide adaptive aiding (Wilson & Russell, 2003).

Also in: 6

GP#:1563

Miniaturization of physiological recording equipment and computer hardware will make possible the development of small wearable assessment systems (Wilson & Russell, 2003).

GP#:1566

In designing for integration, displays that show data in relation to one another in a meaningful way supports improved performance (Burns, 2000).

GP#:1722

If the decision-making function is consistently performed by automation, there will come a time when the human operator will not be as skilled in performing that function. It is well documented in the cognitive psychology literature that forgetting and skill decay occur with disuse. (Rose, 1989 as cited in Parasuraman, Sheridan & Wickens, 2000)

Also in: 6.5.5

GP#:1741

Information that can be obtained easily from display must also be semantically meaningful in the context of the domain tasks to be performed (Bennett & Walters, 2001).

GP#:1756

An important consideration in the design of any user interface is the relationship between the displayed information and the mental model that results after interaction with the interface (Eberts, 1988).

GP#:1757

When interacting with displays containing different augmenting cues, the mental models developed by the user after interaction with the interface are different from each other (Eberts, 1988).

Also in: 2.7.5, 6

GP#:1768

Ecological Information Augmentation (EIA) is a process and methodology for the design of information displays. It is of particular use when the task domain is difficult because the information involved may not be particularly salient or may be difficult to process at higher levels. There are four steps to EIA: 1) Identify the key information in a specified perceptual/motor task; 2) Assess the theoretical degree to which the perception or processing of this information might constitute a processing bottleneck; 3) Design and
implement a putative method to increase the saliency or cognitive processing efficiency of that information; and 4) Empirically test the results of the implementation. (Knecht, 2001)

Also in: 5.2.5, 6.6.5, 6.7.1

GP#:1800

(Hale & Stanney, 2004)

Also in: 2.7.1, 2.7.3, 3.11, 4.1, 4.3, 8.3, 8.6, 8.7

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Visual Display (VD)</th>
<th>VD + Tactile Interface</th>
<th>VD + Positional Actuator</th>
<th>VD + Probe-Based (Force Feedback) System</th>
<th>VD + Exoskeleton System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile perception</td>
<td></td>
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</tr>
<tr>
<td>Texture Perception (hard/soft, smooth/rough, and so on)</td>
<td></td>
<td>More accurate judgment of softness and roughness than visual alone</td>
<td>Possible to judge with same accuracy as when using fingertip</td>
<td>If tactile actuators are present in fingertips, possible to judge texture</td>
<td></td>
</tr>
<tr>
<td>2D form perception (spatial acuity, pattern recognition, curvature perception, and so on)</td>
<td>Relative depth in field of view (FOV)</td>
<td>Tactile can be ignored when irrelevant</td>
<td>Not useful</td>
<td>If tactile actuators are present in fingertips, possible to judge 2D form perception</td>
<td></td>
</tr>
<tr>
<td>Kinesthetic perception</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Spatial awareness/position (for example, objects in environment, limb with respect to trunk, body with respect to environment)</td>
<td>Relative depth of objects in FOV</td>
<td>Allow egocentric frame of reference within personal space</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
<td>Force feedback enhances distance judgments within personal space (arm’s reach)</td>
<td></td>
</tr>
<tr>
<td>3D form perception (length discrimination, weight, and shape identification, for example)</td>
<td>Identification and discrimination depend on viewing angle No indication of weight</td>
<td>Deformability through force feedback aid discrimination and identification Adding force to virtual scene increases presence Improved weight discrimination of objects Improved object interaction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Hale & Stanney, 2004)
5. User Considerations

Auditory icons (aurally presented sounds meant to represent a physical event, such as breaking glass, screeching tires, etc) had better response times (a measure of cognitive load) than conventional auditory warnings and no display conditions, but drivers are not used to auditory icons yet (Belz, Robinson, & Casal, 1999).

Also in: 3.1.2, 3.3.2, 4.2.2

A lane assist system (composed of tactile and visual cues meant to help drivers stay within a lateral distance and prevent collisions) may be useful for helping drivers stay within a limited lateral distance, but it also increased stress (possibly because of unfamiliarity with device) (Ward, Shankwitz, Gorgestani, Donath, Boer, & DeWaard, 2003; as cited in Alexander et al 2004).

Also in: 1.2.4, 3.3.4 TV

When designing user interfaces, determine what user characteristics produce the biggest differences in performance and then design the user interface to maximize the benefits for all groups (Gwizdka & Chignell, 2004).

Also in: 1, 4.9

Perceivers are active seekers and processors of information (Kelleher & van Genabith, 2004).

Also in: 6

Wearing multifocal lenses may help the posture of an individual (more so than bifocal lenses), because they allow the user to raise their chin while looking at a computer terminal (Inoue, 2002).

Also in: 2.6.4, 4.1

The following are guidelines for designing tactile displays for comfort: ensure comfort over longer periods of time - tactile displays worn on the body must be unobtrusive and comfortable; electrodes and vibrators can generate heat potentially causing burns; the comfortable stimuli range is 15-20 dB above the absolute threshold; and the vibrations of the hand-arm should always be limited; most critical frequencies are around 12 Hz. (Van Erp, 2002)

Also in: 2.1.3, 2.2.3, 4.3

Changes in the virtual viewing direction resulting in a rotation of the virtual environment makes users uncomfortable. Head-slaved displays let the user perceive a more stable environment (Kappe, van Erp, & Korteling, 1999).

Also in: 4.1.5, 8.1

5.1 Training User on Device

Training operators on how to use a given device, as well as the device’s limitations, is crucial for maintaining situational awareness (Varakin, Levin & Fidler, 2004).

Also in: 3.5.5, 6.4.5

When designing user interfaces, determine what user characteristics produce the biggest differences in performance and then design the user interface to maximize the benefits for all groups (Gwizdka & Chignell, 2004).
5.1.1 Visual

When working with a visual display, visual performance is enhanced when the display is larger, more realistic, less cluttered, well contrasted, and when operators are familiarized and have more control (Wickens & Long, 1995; Yeh, Wickens & Seagull, 1999; Gulliver, Serif & Ghinea, 2004; Yeh & Wickens, 2001; Zhou, Cheok, Yang & Qiu, 2004).

Some researchers have found that change blindness is not affected by practice (Resink, 2000; as cited in Durlach, 2004), but others found that if you are using a limited set of icons and symbols, training may help reduce/avoid change blindness. People still experience change blindness even if their primary task is to watch for changes. (Durlach, 2004)

Most people group types of messages by color pattern. Messages can be kept secret since only the message recipient knows what message the color pattern refers to. It is difficult to associate messages to color patterns, and it is difficult to later recall the association. (Tarasewich et al., 2004)

When training a task in a virtual environment, you see order effects. Training in visual-only first followed by the addition of visual-haptic has better performance than the reverse order. (Basdogan et al., 2000)

Visualizing steps (e.g., screenshots on a computer) is good for procedural learning tasks; task completion time suffers when text is added to visualizations (specifying the steps) (Bradshaw & Johari, 2003).

Proprioceptive feedback (via head-mounted display) was found to have no significant effect on the rate at which participants developed spatial knowledge (contrary to other study findings) (Ruddle & Peruch, 2004).

Global landmarks promote quicker spatial learning of a visual perimeter (Ruddle & Peruch, 2004).

Visual in-cockpit technology should be adopted with caution for single-pilot operations, and that adopting other design or training features should be considered to address the attentional implications of that technology (this is true for cockpit displays of traffic information which may not be knowledgeable of all outside traffic). Design and training should be performed in conjunction if redundant display modalities are chosen, so that benefits of redundancy can be realized. (Wickens, Goh, Helleberg, Horrey & Talleur, 2003)
Wickens, Goh, Helleberg, Horrey & Talleur (2003) provide a model which can be used to diagnose non-optimal patterns and to compare scanning strategies of amateurs. This model also offers potential to assess when design features may, by increasing the effort of information access, lead to serious departures from optimal scan patterns.

Also in: 1.2.1, 3.6.1

5.1.2 Audio

Holding the PDA device like a cell phone to record a memo automatically may require less attention from the user than having to search manually for a button. However, there is a usability problem because users do not expect devices to be able to react in this way; thus, training user on device issues is key. (Hinckley et al., 2005)

Also in: 5.1.3, 5.4.5, 6.3.2, 6.3.3

5.1.3 Tactile

When designing a haptic device, it is important to remember that people can learn haptic skills fairly quickly, and a simple haptic device can support complex interactions (Fogg, Cutler, Arnold, and Eisbach, 1998).

Also in: 4.3

Haptic devices: It is difficult to communicate haptic events in words or pictures, rapid prototyping is more effective than language in conveying haptic ideas. People can learn haptic skills fairly quickly. A simple haptic device can support complex interactions. (Fogg, Cutler, Arnold & Eisbach, 1998)

Also in: 3.9.3, 4.3

Haptic performance is subject to considerable modification through training, or to enhanced or reduced use (Dinse et. al., 2005).

Also in: 5.1.2, 5.4.5, 6.3.2, 6.3.3

Digital value only displays (i.e., no analog configural display) produce the poorest performance for control/fault detection tasks (Bennett & Walters, 2001).

Also in: 4.1.4, 4.1.8, 4.1.9

5.1.4 Multimodal (AV, AT, TV, ATV)

When designing effective displays, include those graphical features that can be decoded most effectively. The way a process is represented can affect the potential for operators to misinterpret a single sensor value as standing for the state of a higher-order process. It is not always an issue of choosing one format or mode over another, but rather a determination of how to combine sources of evidence, develop effective representations, and coordinate multiple representations in the process of representation design. All representations, in making some aspects of the world more salient than others, have the potential to be misleading. (Bennett, Malek & Woods, 2000)

Also in: 4.1.4, 4.1.8, 4.1.9
Multimodal stimulation is not always better than unimodal stimulation. It may depend on the task or dependent measure. For example, if an operator is extensively trained to perform a task in one modality but then tested on the same task in a different modality or multiple modalities, the operator’s performance may be constrained due to distraction. Also, performance under multimodal conditions may not be significantly different from unimodal performance when viewed from certain dependent variables (i.e., detection accuracy), but may be different for others (i.e., detection speed). (Tannen, 2000)

Also in: 4.8, 5.1.5

- AV

Redundant multimodal output using visual display of test and speech restitution of the same text enables faster learning of an interface. (Wang et al, 1993; as cited in Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user)

Also in: 4.4.3

- AT
- TV

When training a task in a virtual environment, you see order effects. Training in visual-only first followed by the addition of visual-haptic has better performance than the reverse order. (Basdogan et al., 2000)

Also in: 5.1.1, 8.1, 8.4 TV

- ATV

5.1.5 Not Specific to a Mode

Multimodal stimulation is not always better than unimodal stimulation. It may depend on the task or dependent measure. For example, if an operator is extensively trained to perform a task in one modality but then tested on the same task in a different modality or multiple modalities, the operator’s performance may be constrained due to distraction. Also, performance under multimodal conditions may not be significantly different from unimodal performance when viewed from certain dependent variables (i.e., detection accuracy), but may be different for others (i.e., detection speed). (Tannen, 2000)

Also in: 4.8, 5.1.4

If a new device is found to be the best choice, it is important to consider the competency levels of the user with the new device (Elting, Zwickel & Malaka, 2002).

Many transfer studies that consider age-related effects on performance only examine initial performance after a transfer in performance conditions. However, in multiple-task studies involving changes in performance conditions, it is important to examine practiced transfer performance because it allows for the stabilization of modified performance emphases. (Sit & Fisk, 1999)

Also in: 1.1.5

It is important to provide product-specific, multiple-task practice before interpreting patterns of age-related differences (sit & Fisk, 1999).

Also in: 1.1.5

Tunnel vision may be reduced with training (Williams, 1995; as cited in Sarter, 2001).

Also in: 6.4.5
Participants learn to match probability of response to an alarm with the probability that the alarm gives true information. (Bliss, Gilson, & Deaton, 1995; as cited in Seagull & Sanderson, 2001)

**Also in:** 3.1.5, 5.4.5

Because the appearance (fidelity) of the learning environment is not particularly relevant for some tasks, realism doesn’t need to be the principle focus underlying the development of virtual environment training systems (Waller, Knapp & Hunt, 2001).

**Also in:** 4.9, 8.5

In enabling knowledge that requires conscious effort to acquire, lower-fidelity (and less nauseogenic) desktop virtual environments may be just as effective as more expensive “immersed” virtual environments. Therefore, realism doesn’t need to be the principle focus underlying the development of virtual environment training systems. (Waller, Knapp & Hunt, 2001)

**Also in:** 8.5

Individual differences have the potential to impact performance in a simulation task more than the appearance of the training system (Waller, Knapp & Hunt, 2001).

**Also in:** 1.4.5

Those interested in training complex cognitive skills should control for differences in user’s cognitive abilities and computer experience (Waller, Knapp & Hunt, 2001).

**Also in:** 1.2.5, 1.4.5

The following errors should be considered with regard to foreground-background interaction: background becomes foreground when it should not (e.g., PDA screen changes from landscape to portrait when resting in user’s lap); background fails to become foreground when it should (e.g., user holds PDA like phone but gesture is not recognized); foreground manipulation is incorrectly interpreted as background activity (e.g., user tips PDA to avoid glare and display changes orientation); foreground burdens user with tasks that could be automated in the background (e.g., user explicitly switches display format, which could have been automated if user knew that sensors supported this function). (Hinckley et al., 2005)

**Also in:** 4.1

Individuals use cognitive styles that are applied consistently across similar tasks. Analytic participants acquire more effective skills during training than holistic participants and are not affected by the difficulty for training when transferring to novel stimuli. Holistic participants are affected by the difficulty of training, and initially perform more accurately in transfer to novel stimuli, if trained using hard comparisons. Easily trained holistic participants are more flexible in their strategies longitudinally than analytic participants are. Holistic participant’s strategies are malleable even after training. This leads to design implications not only for training strategies, but also for computer interface design. (Pratt, 2003)

**Also in:** 1.4.5, 6

There are three major steps in designing a VR training simulation: task analysis/human computer interaction evaluation (what is the goal of training, what tasks to include, what are the requirements for sensory modality integration); iterative evaluation process (evaluate system for system usability and user considerations like motion sickness); and system-wide evaluation (how does device affect performance and does training transfer to natural environment). (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003)
People’s movements are affected by the configuration of their environment, and perimeter edge following is a strategy that is frequently adopted by trained searchers; when perimeter was not clearly defined, participants did not adopt this strategy, and when the perimeter was defined, participants followed the perimeter edge during early stages of spatial learning and then took shortcuts through the environment center to target objects (Ruddle & Peruch, 2004).

When users do not receive any instructions about their attention, they divide their attention between two modalities in their own preferred way (Vogels, 2004).

The design of the task environment or the training program can be altered to bring about greater success in time-sharing through deployment of multiple resources, or through training to develop automaticity and improve attention control (Wickens, 2000).

5.2 Device Salience (user awareness and/or use or device)

5.2.1 Visual

Image panning takes time, and users are even less likely to pan in high-demand, time-critical situations (Wickens, Thomas, & Young, 2000).
5.2.2 Audio

In a task that required users to go through a maze on a screen, providing users with audio cues resulted in many users taking short halting steps until the next audio command was issued. Thus, devices could be enhanced by allowing a user to request audio cues whenever he/she wants them. (Chewar & McCrickard, 2002)

Also in: 3.2.2

GP#:1125

Users tend to rely on a sound’s onset as the cue, rather than other features occurring later in a signal (Adelstein, Begault, Anderson & Wenzel, 2003).

Also in: 2.7.2, 4.2

GP#:1371

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

Also in: 2.6.2, 3.7.4 AT, 3.7.4 TV, 4.5.3, 4.6.3, 6.3.2

GP#:1506
Table 1
Recommendations for various notification systems design objectives, based on significant differences observed in the experiment. “Optimal Trial Only” column indicates result findings for the filtered optimal performance group

<table>
<thead>
<tr>
<th>Ticker vs. Fade vs. Blast animation</th>
<th>Recommended</th>
<th>Not recommended</th>
<th>Optimal trials only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Browse time</td>
<td></td>
<td>No secondary</td>
<td>Recommended—blast</td>
</tr>
<tr>
<td>display</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incorrect answers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceived intrusiveness</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
<tr>
<td><strong>Secondary task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring latency</td>
<td>Blast, then fade</td>
<td>Ticker</td>
<td></td>
</tr>
<tr>
<td>Basic awareness hit rate</td>
<td>Ticker</td>
<td>Fade</td>
<td>Not recommended—blast</td>
</tr>
<tr>
<td>Basic awareness false alarm rate</td>
<td>Fade</td>
<td>Ticker</td>
<td>Recommended—ticker.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Not recommended—blast</td>
</tr>
<tr>
<td>Detailed awareness hit rate</td>
<td>Ticker</td>
<td>Blast</td>
<td>—</td>
</tr>
<tr>
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<tr>
<td><strong>Dual-task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected frequency of use</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
</tbody>
</table>

(McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 3.1.1, 3.1.2, 4.1, 5.2.1, 5.4.1, 5.4.2, 6.7

5.2.3 Tactile

Haptic effects and hapticons used in conjunction with IM: Email and IM primarily use textual messages-extended with audio-visual cues. Hapticons are small, programmed force patterns that can communicate a basic notion similar to regular icons in a graphic interface. These vibration patterns only become hapticons after users start to recognize the patterns and associate them with a particular meaning. (Rovers & van Essen, 2004)

Also in: 3.1.3, 3.9.4 ATV, 4.3.1

5.2.4 Multimodal (AV, AT, TV, ATV)

When task-relevant information is expected primarily in one sensory modality, then performance suffers for events in secondary modalities, even if they appear in isolation (Spence & Driver, 1997).

Also in: 4.8

- AV
- AT
- TV
- ATV

5.2.5 Not Specific to a Mode
When designing a display, it is important to consider whether the user is going to see/pay attention to each element, rather than simply considering how an element could be used by the operator (Varakin, Levin & Fidler, 2004).

When incorporating automation into devices, major challenges include keeping the operator in the loop and maintaining modal awareness (i.e., automation understanding). Thus, consider the following guidelines: automate only if necessary; use automation for routine actions rather than higher level cognitive tasks; keep the operator in control and in the loop; avoid use of information cueing; and provide automation transparency. (Endsley, Bolte, & Jones, 2003)

Also in: 6.4.5

Modality expectation is very important in attention allocation/vigilance tasks (McFarlane, 1999; as cited in Sarter, 2001).

Also in: 3.4.5, 5.4.5

Modality-appropriateness hypothesis: the modality that is most appropriate or reliable with respect to a given task will dominate perception in that task. For example, vision has higher spatial resolution so it dominates in spatial tasks, and audition has higher temporal resolution so it dominates in temporal tasks. (Shimojo & Shams, 2001; as cited in Yang and Kim, 2004)

Also in: 2.7.1, 2.7.2, 2.7.4, 2.7.4 AV, 3.11, 4.9

If a decision aid, expert system, or other type of decision automation consistently and repeatedly selects and executes decision choices in a dynamic environment, the human operator may not be able to sustain a good “picture” of the information sources in the environment, as he or she is not actively engaged in evaluating the information sources leading to a decision (Parasuraman, Sheridan & Wickens, 2000).

Also in: 6.4.5, 6.5.5

Ecological Information Augmentation (EIA) is a process and methodology for the design of information displays. It is of particular use when the task domain is difficult because the information involved may not be particularly salient or may be difficult to process at higher levels. There are four steps to EIA: 1) Identify the key information in a specified perceptual/motor task; 2) Assess the theoretical degree to which the perception or processing of this information might constitute a processing bottleneck; 3) Design and implement a putative method to increase the saliency or cognitive processing efficiency of that information; and 4) Empirically test the results of the implementation. (Knecht, 2001)

Also in: 4.9, 6.6.5, 6.7.1

5.3 Intuitiveness of Device

5.3.1 Visual

Modes should be chosen based on the intuitiveness of information interpretation (i.e., match the purpose of the information with the sense that is best able to handle it). In response to numerous aviation accidents caused by spatial disorientation, engineers added more visual displays for pilots. However, this did not reduce the occurrence of accidents, partially because the visual channels were overloaded (so the new information was not being processed), but also because tactile cues are more naturally interpreted as orientation cues (we use proprioception naturally in real-life), compared to visual cues. (Rupert, 2000)
Most people group types of messages by color pattern. Messages can be kept secret since only the message recipient knows what message the color pattern refers to. It is difficult to associate messages to color patterns, and it is difficult to later recall the association (Tarasewich et al., 2004).

Also in: 3.9.1, 4.1.1, 5.1.1

The following are three guidelines for designers of visual displays: designers should (1) consider how different quantities are encoded within any chosen representational format, (2) consider the full range of alternative varieties of a given task, and (3) balance the cost of familiarization with the computational advantages of less familiar representations (Peebles & Cheng, 2003).

Also in: 4.1

5.3.2 Audio

Advantages of audio displays (compared to visual displays) for alarms: audio alarms are naturally interpreted as a warning signal, have faster neural transmission compared to visual (especially important for time-critical warnings) (Mowbray & Gebhard, 1969; as cited in Simpson, Bolia, & Draper, 2004).

Verbal communication is often the most direct/efficient/unambiguous method of information transfer; it allows information exchange regarding events that are now in the visual field (Simpson, Bolia, & Draper, 2004).

Also in: 2.7.2, 3.1.1, 3.1.2, 3.9.2, 6

5.3.3 Tactile

Modes should be chosen based on the intuitiveness of information interpretation (i.e., match the purpose of the information with the sense that is best able to handle it). In response to numerous aviation accidents caused by spatial disorientation, engineers added more visual displays for pilots. However, this did not reduce the occurrence of accidents, partially because the visual channels were overloaded (so the new information was not being processed), but also because tactile cues are more naturally interpreted as orientation cues (we use proprioception naturally in real-life), compared to visual cues. (Rupert, 2000)

Also in: 3.8.1, 3.8.2, 5.3.1

Textures generally worked better than forces for emphasis and annotation in haptic devices. Power requirements of embedded haptic feedback are the greatest challenge, particularly for portable displays. Continuous interaction through a haptically actuated device rather than discrete button/key presses can produce simple yet powerful tools that leverage physical intuition. (Snibbe, MacLean, Shaw, Roderick, Verplank & Scheeff, 2001)

Also in: 4.3.1

Thirty percent of civil air crashes have been attributed to pilot spatial disorientation, caused by faulty or misleading visual/vestibular system inputs – a problem that can be ameliorated by the use of intuitive tactile inputs (Schrope, 2001).

Also in: 3.8.1, 3.8.4 TV, 6.4.1, 6.4.4 TV

It is important to make tactile messages self-explanatory (Van Erp, 2002).

Also in: 4.3

GP#:1493

GP#:1700

GP#:1752
By using the exact physical properties of the surface, the designer can work with material and dynamics in virtual reality, gaining an intuitive understanding of its malleability (Ix et al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 8.3

5.3.4 Multimodal (AV, AT, TV, ATV)

If a user is uncertain as to the meaning of a new modality or cue, then use of that modality (alone or in conjunction with other modes) could (at least initially) impede performance (Brown, Newsome & Glinert, 1989).

Also in: 5.3.5

• AV
• AT
• TV

In 3D interactions, the direct and physical operations on real objects via a 2D mouse are both unnatural and counter-intuitive (Ix et al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 8.3, 8.6

• ATV

5.3.5 Not Specific to a Mode

If a user is uncertain as to the meaning of a new modality or cue, then use of that modality (alone or in conjunction with other modes) could (at least initially) impede performance (Brown, Newsome & Glinert, 1989).

Also in: 5.3.4

Guidelines for handling human errors:
1) Make the action more perceptible (i.e. the possibility of activating the execution of another likely wrong action should be reduced, a given action should provide unambiguous information for the ongoing activity, even before the attainment of the end state);
2) Use multi-sensory feedback;
3) Display messages at a high level but with specific content (i.e. multilevel error messages, error message tells you it can not comply with your request, but there is a “since” or “because” button you can use to receive more info);
4) Provide an activity log (people depend on external memory aids);
5) Allow comparisons (comparisons between outputs is a useful source of information for action evaluation);
6) Make results available to users as soon as possible and allow the user to have control of the format display (Suggestions for this include, i) exploiting layout, ii) exaggerating the differences, iii) stressing the aspects relevant to the just performed task);
7) Provide result explanations (i.e. make it extremely easy to determine why an input was not successful. If an input causes an error, indicate the varying factors that may have led to the error and the best way to fix it. (Rizzo et al., 1996, 116-118)

Also in: 4.1.4, 4.8, 4.9, 7.1.5

5.4 Trust in Device/Reliability

5.4.1 Visual

GP#:1546
Practical implications for design of helmet-mounted displays:
Designers should consider the potential consequences of attention guidance presented on an HUD. Cuing benefits decrease as cue precision is degraded, but imprecise cuing is better than no cuing at all. Trust in the automated cuing information influences attention allocation strategies. It may help to widen attentional breadth by signaling cue precision, when presenting cues of low spatial resolution. Operators need to be informed about the spatial resolution of the displayed guidance information and to balance this knowledge with the information provided by an automated system. The use of a simulated HMD does not alter the pattern of behavior relative to an actual HMD. The presentation of information on an HMD combined with the real world or any noisy environment may be intrusive to the operator’s task. Ground soldiers need to search and filter through multiple sources of information, and as task demands increase, reliance on any automated system may increase as well. (Yeh, Merlo, Wickens, & Brandenburg, 2003)

Also in: 4.1.5, 6.6.1

GP#:1730

The following are guiding objectives to building ambient varieties of peripheral displays: (1) personalized – information source and representation should be customized to user preference; (2) flexible – variety of info sources should be available for display; (3) consolidated – moderate number (5-15) of information sources should be consolidated and presented in one location; (4) accurate – system should accurately communicate the current state of monitored information; (5) appealing – the system should be fun to use and an aesthetically pleasing addition to the user environment. (Stasko et. al., 2004)

Also in: 4.1.4, 4.1.6, 5.5.1

GP#:1801

D.S. McCrickard et al. / Int. J. Human-Computer Studies 58 (2003) 547–582 567

5.4.2 Audio
Auditory icons (aurally presented sounds meant to represent a physical event, such as breaking glass, screeching tires, etc) are more accurately identified than conventional auditory warning signals (beeps/tones), but respondents are skeptical of the new technology (Belz, Robinson, & Casal, 1999).

Also in: 3.1.2, 4.2.2

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Table 1

<table>
<thead>
<tr>
<th>Ticker vs. Fade vs. Blast animation</th>
<th>Recommended</th>
<th>Not recommended</th>
<th>Optimal trials only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Browse time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No secondary display</td>
<td>—</td>
<td></td>
<td>Recommended—blast</td>
</tr>
<tr>
<td>Incorrect answers</td>
<td>—</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>Perceived intrusiveness</td>
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<td><strong>Secondary task</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Monitoring latency</td>
<td>Blast, then fade</td>
<td>Ticker</td>
<td></td>
</tr>
<tr>
<td>Basic awareness hit rate</td>
<td>Ticker</td>
<td>Fade</td>
<td>Not recommended—blast</td>
</tr>
<tr>
<td>Basic awareness false alarm rate</td>
<td>Fade</td>
<td>Ticker</td>
<td>Recommended—ticker. Not recommended—blast</td>
</tr>
<tr>
<td>Detailed awareness hit rate</td>
<td>Ticker</td>
<td>Blast</td>
<td>—</td>
</tr>
<tr>
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<tr>
<td><strong>Dual-task</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Expected frequency of use</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
</tbody>
</table>

(McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 3.1.1, 3.1.2, 4.1, 5.2.1, 5.2.2, 5.4.1, 6.7

5.4.3 Tactile

When tactile in-car displays were utilized in an automobile driving task, drivers had to learn to trust the tactile device (Van Erp & Van Veen, 2004).

Also in: 3.3.3

5.4.4 Multimodal (AV, AT, TV, ATV)

- AV
- AT
- TV
- ATV

5.4.5 Not Specific to a Mode
When evaluating a device, one should consider the following: (1) mental workload; (2) situation awareness (how much the automation of decisions reduces the operator's situation awareness); (3) complacency (operator may not trust the automation and may eventually not monitor the device); and (4) skill degradation (operator may be out of practice due to the function being consistently performed by automation). (Parasuraman, Sheridan, Wickens, 2000)

Also in: 6.4.5, 6.6.5, 7.2.5

GP#:1189

Levels of uncertainty correspond to levels of situational awareness: you can have uncertainty in perception (data uncertainty), comprehension uncertainty, projection uncertainty, and decision uncertainty. Strategies for reducing uncertainty include searching for more information, relying on defaults, conflict resolution, thresholding, bet-hedging and contingency planning, and narrowing options. When designing a device, explicitly define missing information, support sensor reliability assessment, use data salience in support of certainty, and represent information timeliness. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 6.4.5

GP#:1191

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

Also in: 1.2.5, 3.1.1, 3.1.2, 3.1.4, 3.1.5, 3.5.5, 6.4.5

GP#:1227

Interpretations of the behavior of an interrupting application can turn users away from future application use [16, 27] and influence attitude towards the info the application provides [31] (Adamczyk & Bailey, 2004).

Also in: 3.1.5

GP#:1239

An operator’s reliance on and compliance with a warning system are strongly situational. It might be beneficial to place warnings close to other relevant info (Meyer, 2001).

Also in: 2.1.5, 3.1.5

GP#:1249

Modality expectation is very important in attention allocation/vigilance tasks (McFarlane, 1999; as cited in Sarter, 2001).

Also in: 3.4.5, 5.2.5

GP#:1322

The “cry-wolf effect” refers to the fact that people often cease to respond to warnings if the frequency of nonvalid warnings is high (Sorkin, 1988; as cited in Maltz & Meyer, 2001).

Also in: 3.1.5

GP#:1323

Automation bias occurs when we rely too strongly on warnings (at expense of other indicators of problems) (Mosier, Skitka, Heers, & Burdick, 1998; as cited in Maltz & Meyer, 2001).

Also in: 3.1.5

GP#:1324
Both the cry-wolf effect and automation bias are more likely to occur under high workload conditions (Parasuraman, Molloy, & Singh, 1993; as cited in Maltz & Meyer, 2001).

Also in: 3.1.5, 6.6.5

GP#:1325

Participants adjust their reliance on warnings according to their diagnostic value (so modes that are less reliable won’t be interpreted) but not completely (so unreliable cues can be more detrimental than no cues) (Maltz & Meyer, 2001).

Also in: 3.1.5

GP#:1326

Participants learn to match probability of response to an alarm with the probability that the alarm gives true information (Bliss, Gilson, & Deaton, 1995; as cited in Seagull & Sanderson, 2001).

Also in: 3.1.5, 5.1.5

GP#:1383

With the integration of displaying the degree of uncertainty into the presentation format of medical data, it is possible to make computer-produced data more reliable and acceptable by users (discussed here in the context of medical personnel) (Krol, Reich, Pavone & Fuhrman, 2004).

Also in: 4.9, 7.1.5

GP#:1384

Data from studies on target context support the use of allocentric coding of information because it improves performance. Performance also increased when the context is familiar. Target context led to a better awareness of perturbation. (Ferrel, Orliguet, Leiffen, Bard & Fleury, 2001)

Also in: 1.2.5, 3.6.5

GP#:1393

When multiple alarms go off simultaneously, and the alarm of interest is known to be unreliable (50-60% reliability), the likelihood that a user will perceive the alarm as important (in need of a response) increases as number of other alarms going off goes up (especially in proportion to number of alarms in array), as the spatial/temporal proximity of the alarms increases, and according to whether the other alarms going off are “related” to the alarm of interest (e.g., Two engine lights). (Gilson, Mouloua, Graft, & McDonald, 2001)

Also in: 3.1.5, 6.3.5

GP#:1504

Automated systems aren’t always accurate (e.g., automated systems reporting weather conditions were rarely accurate) (Freeman, 2002).

GP#:1532

Holding the PDA device like a cell phone to record a memo automatically may require less attention from the user than having to search manually for a button. However, there is a usability problem because users do not expect devices to be able to react in this way; thus, training user on device issues is key. (Hinckley et al., 2005)

Also in: 5.1.2, 5.1.3, 6.3.2, 6.3.3

GP#:1721

If automation is highly, but not perfectly, reliable in executing decision choices, then the operator may not monitor the automation and its information sources and hence will fail to detect the occasional times when the automation fails (Wiener, 1981 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 6.5.5

GP#:1723

Automation reliability is an important determinant of human use of automated systems because of its influence on human trust (Lee & Moray, 1992 as cited in Parasuraman, Sheridan & Wickens, 2000).
5.5 User Preferences

It could be practical to design systems that are able to quickly and accurately determine user perceptual and processing preferences, using this information to adapt the display accordingly (e.g., determine what kind of route description/display to use) (Chewar & McCrickard, 2002).

Also in: 3.2.5

5.5.1 Visual

Whether a participant generally prefers visual information or audio information can have implications for performance. Specifically, visual-preference participants went fastest when graphic route descriptions were provided, while audio-preference participants did best with audio cues. (Chewar & McCrickard, 2002)

Also in: 3.2.1, 3.2.2, 5.5.2

Users vary widely in their preferences for a given modality. For example, there was a lot of variability in user preferences between light and heat as the preferred interruption cue (40% versus 60%), though user preferences had no affect on performance or effectiveness of the interruption cue. (Arroyo & Selker, 2003)

Also in: 5.5.3, 7.3

Graphics and haptic update rates should be maintained at least around 30 Hz and 1000 HZ respectively to have satisfying experience interacting with a virtual environment (Basdogan et al., 2000).

Also in: 8.1, 8.3, 2.2.1, 2.2.3, 5.5.3

In a comparison of 3 different visual displays (ranging from very graphical to very text-based), overall preference didn’t match recall performance (WebPortal, which was in the middle in terms of graphics/text, was preferred most, but InfoCanvas had the best recall) (Plaue, Miller, & Stasko, 2004).

Also in: 4.1.4, 7.3

Clutter or sparsity in visual representations can have negative effects ranging from decreased user performance to diminished visual appeal. Clutter can result in over-plotting (certain objects aren’t visible because they are occluded by other objects). Sparsity can result in inefficient use of available display space. Non-linear magnification schemes can be used to minimize clutter in a display. (Woodruff, Landay & Stonebraker, 1999)

Also in: 4.1.4

When choosing a graphical representation, one shouldn’t always choose the most familiar to the target user, but should instead balance the cost of familiarization with computational advantages of less familiar representations (Peebles & Cheng, 2003).

Also in: 4.1.4

Operators are not comfortable driving a Jeep with a 40° field of view, but were more confident with a 120° field of view (McGovern, 1993; van Erp, 1997; as cited in Reingold, Loschky, McConkie & Stampe, 2003).

Also in: 3.3.1, 4.1.6
Users are willing to permanently give up a portion of their computer screen space for a peripheral awareness application if the information presented is easily customized and individually relevant (Cadiz, Venolia, Jancke, & Gupta, 2002).

Also in: 4.1.4, 4.1.6

The following are guiding objectives to building ambient varieties of peripheral displays: (1) personalized – information source and representation should be customized to user preference; (2) flexible – variety of info sources should be available for display; (3) consolidated – moderate number (5-15) of information sources should be consolidated and presented in one location; (4) accurate – system should accurately communicate the current state of monitored information; (5) appealing – the system should be fun to use and an aesthetically pleasing addition to the user environment. (Stasko et. al., 2004)

Also in: 4.1.4, 4.1.6, 5.4.1

5.5.2 Audio

Whether a participant generally prefers visual information or audio information can have implications for performance. Specifically, visual-preference participants went fastest when graphic route descriptions were provided, while audio-preference participants did best with audio cues. (Chewar & McCrickard, 2002)

Also in: 3.2.1, 3.2.2, 5.5.1

Some participants have a clear preference toward the right ear or left ear in terms of receiving auditory information (Lipschutz, Kelinsky, Damhaut, Wikler, & Goldman, 2002).

Also in: 2.1.2

5.5.3 Tactile

Users vary widely in their preferences for a given modality. For example, there was a lot of variability in user preferences between light and heat as the preferred interruption cue (40% versus 60%), though user preferences had no affect on performance or effectiveness of the interruption cue. (Arroyo & Selker, 2003)

Also in: 5.5.1, 7.3

Modeling a task/process with a dynamic physical metaphor and then haptically rendering this metaphor as the process controller promises to give users functional integration together with simplification. Hand-crafting and quality of haptic experience essential to acceptance - many users simply enjoy the feel of the tools. (Snibbe, MacLean, Shaw, Roderick, Verplank & Scheeff, 2001)

Also in: 3.7.3, 8.3, 8.7

Graphics and haptic update rates should be maintained at least around 30 Hz and 1000 HZ respectively to have satisfying experience interacting with a virtual environment (Basdogan et al., 2000).

Also in: 2.2.1, 2.2.3, 5.5.1, 8.1, 8.3

Soldiers appreciate tactile navigation system for its ease of use and enabling of eyes-free and hands-free navigation (Elliott et. al., 1997).

Also in: 2.7.3, 3.2.3, 7.1.3

5.5.4 Multimodal (AV, AT, TV, ATV)
Several studies have shown that performance is enhanced using multiple modes. However, preference lies with unimodal work. Conversely, there is either a detriment or no difference using multimodal, but the operators prefer it. Therefore, operator preference is important to consider (Ho, Nikolic, Water & Sarter, 2004; McGrath, Estrada, Braithwaite, Raj & Rupert, 2004).

Also in: 5.5.5, 7.3

GP#:1186

Expert users prefer to interact with multimodal interfaces, whereas naïve users have no preference between unimodal or multimodal displays (De Angeli, Gerbino, Cassano, & Petrelli, 1998).

Also in: 1.2.4, 1.2.5, 5.5.5

GP#:1233

If given the choice, users might choose more ultimodal devices as task/scenarios become more complex (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Also in: 6.6.5

GP#:1234

Users with more expertise tend to choose complementary modes, while beginners tend to choose more redundant modes/devices (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Also in: 1.2.4, 1.2.5, 4.8.3, 5.5.5

GP#:1555

Ideally, an adaptive multimodal system would detect, automatically learn, and adapt to a user’s dominant multimodal integration pattern. This could result in a substantial improvement in system processing speed, accuracy of interpretation, and synchronous interchange with the user. (Oviatt, Lunsford, and Coulston, 2005)

Also in: 4.8.1

- AV
- AT

GP#:1569

Users relish the chance to use gestures and speech in combination with computing tasks (Czerwinski & Larson, 1998).

- TV
- ATV

5.5.5 Not Specific to a Mode

GP#:1026

Determining whether a given mode is better than another mode, or whether multimodal is better than unimodal feedback very much depends on the criterion of interest. For example, user preference and perceived ease of use do not always coincide with performance data. User preference may be more a function of what is typically used (users prefer the familiar) and biases in expectations (expectation that multiple modes must be better than a single mode) (Akamatsu, MacKenzie, & Hasbroucq, 1995; Jeong & Gluck, 2003; Kaster, Pfieffer, & Bauckhage, 2003).

Also in: 1.2.5, 7.3

GP#:1048

Several studies have shown that performance is enhanced using multiple modes. However, preference lies with unimodal work. Conversely, there is either a detriment or no difference using multimodal, but the operators prefer it. Therefore, operator preference is important to consider. (Ho, Nikolic, Water & Sarter, 2004; McGrath, Estrada, Braithwaite, Raj & Rupert, 2004)

Also in: 5.5.4, 7.3
Different types of representations work better for different people, with differences occurring across left and right lateralization users and by information display preferences (e.g., a user may prefer to receive information visually or aurally) (Chewar & McCrickard, 2002).

Also in: 1

Tasks that involve communicating information should be evaluated in terms of whether the information must be remembered or used to simply inform the user. If the information must be remembered, it is important to use the most effective means possible (i.e., combination of modes); however, if it is used to inform the user, subjective appeal should be considered most important. (Elting, Zwickel, and Malaka, 2002)

Also in: 3.9.4, 3.9.5, 6.6.5

Expert users prefer to interact with multimodal interfaces, whereas naïve users have no preference between unimodal or multimodal displays (De Angeli, Gerbino, Cassano, & Petrelli, 1998).

Also in: 1.2.4, 1.2.5, 5.5.4

If users have preferences for output devices and modalities they would probably have preferences for inputs devices and modalities (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Users with more expertise tend to choose complementary modes, while beginners tend to choose more redundant modes/devices (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Also in: 1.2.4, 1.2.5, 4.8.3, 5.5.4

Self-report of device/modality preference may not be as valid of a predictor of future use/ease of use/performance as observation of user’s past choices (Wenzel, 1994; as cited in Althoff et al., 2003).

Also in: 7.3

Data displayed in browsers should be available, easily accessible, up-to-date, and should consolidate info from a variety of sources. Representation should be calm and “refined”, not demanding attention from the user. The user should be allowed to personalize the graphics browser display. Displays should hide sensitive data from public view. (Miller & Stasko, 2002)

Also in: 4.1.4, 4.1.6

Few people (less than 3% of those surveyed) felt that it wasn’t dangerous to use an in-vehicle navigation system while driving, yet there are an increasing number of crashes associated with the use of vehicle navigation systems (Burnett, Summerskill & Porter, 2004).

Also in: 3.2.5, 3.3.5, 7.3

A fully functioning system for navigational aid should incorporate methods of inputting the destination and user preferences in terms of the route to be taken by the user (Sokoler et al., 2002).

Also in: 3.2.5, 4.9
Users of mobile sensing devices should be afforded a customization feature to compensate for usage contexts that are not anticipated (Hinckley et al., 2005).

**GP#:1568**

Users appreciate automated suggestions for browsing and categorizing their information/data (Czerwinski & Larson, 1998).

**GP#:1764**

When users do not receive any instructions about their attention, they divide their attention between two modalities in their own preferred way (Vogels, 2004).

**Also in: 5.1.5, 6.3.5**
6. Cognitive Factors

There are cognitive biases relevant to vision. For example, we cannot “unsee” a pattern once it has been recognized. Automated fusion methods supporting human analysis may provide aids to reduce cognitive biases, improve the understanding of heterogeneous, multi-source data, and provide increased opportunities for data discovery. (Hall & Shaw 2002)

Also in: 2.6.1

GP#:1135

Results suggest that the posterior portion of the intraparietal sulcus (IPS), close to the parieto-occipital sulcus, is involved in the integration of visual and tactile sensory information (Saito, Okada, Morita, Yonekura, and Sadato, 2003).

Also in: 2.7.4 AT

GP#:1197

There is little conflict between memory in different domains (Morey & Cowen, 2004).

GP#:1240

The capacity of working memory is equal to seven plus or minus two (Miller, 1956; as cited in Gwizdka & Chignell, 2004).

GP#:1259

Visual attention is known to be influenced by cognitive (top-down, bottom-up) factors. Looking at neural systems with an fMRI showed that even during relatively simple simulated driving task, visual, motor and cognitive processes interacted in complex ways. (Graydon et al., 2004)

Also in: 2.6.1, 3.3.1

GP#:1281

Expertise may moderate a person’s ability to process information efficiently, perhaps affecting ability to process information from multiple modes (Bellenkes, Wickens & Kramer, 1997).

Also in: 1.2.4

GP#:1285

People construct mobile contexts (interactional view), which is contrary to the traditional representational view in which contexts are regarded as observer-independent entities. (Oulasvirta, Tamminen, Roto & Kuorelahti, 2005)

GP#:1286

In mobility, the cognitive and social are intertwined – social, physical, and artifactual resources that lead to enjoyment of mobility also cause cognitive resource depletion, thereby restricting interaction with mobile devices (Oulasvirta, Tamminen, Roto & Kuorelahti, 2005).

GP#:1287

Spatial and object working memory differ fundamentally in that only object working memory depends on verbal mediation (Postle, D’Esposito & Corkin, 2005).

GP#:1293

The representation of knowledge about objects overlaps with mechanisms responsible for sensory perception (Postle, D’Esposito & Corkin, 2005).

GP#:1294

Visual perception of objects automatically recruits semantic knowledge about related objects (Postle, D’Esposito & Corkin, 2005).

Also in: 2.6.1, 2.7.1

GP#:1295
Advantages of audio displays (compared to visual displays) for alarms: audio alarms are naturally interpreted as a warning signal, have faster neural transmission compared to visual (especially important for time-critical warnings) (Mowbray & Gebhard, 1969; as cited in Simpson, Bolia, & Draper, 2004). Verbal communication is often the most direct/efficient/unambiguous method of information transfer; it allows information exchange regarding events that are now in the visual field (Simpson, Bolia, & Draper, 2004).

Also in: 2.7.2, 3.1.1, 3.1.2, 3.9.2, 5.3.2

Perceivers are active seekers and processors of information (Kelleher & van Genabith, 2004).

Also in: 5

A lot of our cognitive information is derived from a small portion of our visual field of view (FOV). The foveal region of the eye (< 2º of our total FOV) contains most of our photoreceptors. Eye and head motion allow us to take in more information. Head displacement and navigation create optic flow and motion parallax, which is sensed by our peripheral vision and used to judge motion. (Lantz, 1997)

Also in: 2.3.1, 2.6.1, 3.2.1, 4.1.6

The span of absolute judgment and span of immediate memory impose severe limitations on the amount of information that humans are able to receive/process/remember. Miller (1956) thought people should use only one sensory channel at a time, but he also concluded that humans can usefully perceive about 7 different variables presented in a single sensory modality. Considering the latter conclusion, using only visual displays would not optimal because it would limit human information perception bandwidth. (Miller, 1956; as cited in Loftin, 2003)

Also in: 4.1, 6.7.2

Synesthesia occurs when a person receives stimuli via one sensory channel, but he/she perceives it along another sensory channel (e.g., A person may see objects of a particular shape, but perceive the shapes as tasting differently) (Loftin, 2003).

Also in: 2.7.4

Observers have an imperfect memory for distractors they have recently rejected in the course of search (Horowitz & Wolfe, 2001; as cited in Haimson & Anderson, 2002).

Also in: 3.6.5

Users may experience difficulty integrating (comparing) objects in a scene when panning is required (Wickens, Thomas, & Young, 2000).

Also in: 4.1.4, 7.1

Computational models (grounded in cognitive theory) enable one to incorporate and test relevant cognitive factors (e.g., declarative and procedural knowledge) as well as perceptual-motor factors, such as mouse movements and shifts in visual attention (Peebles & Cheng, 2003).

Also in: 6.3.1

Artificial neural networks using physiological signals can be used to provide accurate estimates of operator functional state that can be used to provide adaptive aiding (Wilson & Russell, 2003).
Maximal integration in space and time along means-end links should improve problem solving (Burns, 2000).

Some pre-attentive features, such as blinking, can be distracting and can interfere with the gestalt perception process (Kim & Hoffmann, 2003).

Individuals use cognitive styles that are applied consistently across similar tasks. Analytic participants acquire more effective skills during training than holistic participants and are not affected by the difficulty for training when transferring to novel stimuli. Holistic participants are affected by the difficulty of training, and initially perform more accurately in transfer to novel stimuli, if trained using hard comparisons. Easily trained holistic participants are more flexible in their strategies longitudinally than analytic participants are. Holistic participant’s strategies are malleable even after training. This leads to design implications not only for training strategies, but also for computer interface design. (Pratt, 2003)

Stimuli perceived inside the head result in a more accurate and faster response than externalized stimuli (Roginska, 2004).

Response time does not change linearly with presentation speed; rather, there is an optimal presentation rate at which the response time is fastest and accuracy is highest. (Roginska, 2004)

Stimuli presented in the frontal hemisphere are attended to faster than those in the back hemisphere (Roginska, 2004).

The nervous system combines visual and haptic information similar to a minimum likelihood integrator. Visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation. (Ernst & Banks, 2002)

The encoding of emotional stimuli facilitates affectively congruent motor actions, such that positive stimuli lead to spontaneous motor actions of approach whereas negative stimuli lead to spontaneous motor actions of avoidance (Gawronski et. al., 2005).

Human visual search performance can be explained largely in terms of the cognitive strategy that is used to coordinate the relevant perceptual and motor processes. A clear and useful visual hierarchy triggers a fundamentally different visual search strategy and effectively gives the user greater control over the visual navigation. Cognitive strategies will be an important component of a predictive visual search tool. (Hornof, 2004)
Memory is susceptible to interference by irrelevant sound, especially in maintenance of order in short-term memory (Banbury et al., 2001).

Also in: 4.2.3

GP#:1757

When interacting with displays containing different augmenting cues, the mental models developed by the user after interaction with the interface are different from each other (Eberts, 1988).

Also in: 2.7.5, 4.9

GP#:1758

For a task to be consistent, the operator must be able to determine lawful relationships between the input and the output (Eberts, 1988).

GP#:1786

Left hemisphere specializations have been found for the perception of speech (Kimura, 1961, 1967), and for the temporal resolution of brief auditory stimuli (Brown & Nicholls, 1997). Right hemisphere specializations have been reported for pitch discrimination (Sidtis, 1981) and auditory space perception. (Altman, 1983; Altman, Balonov, & Deglin, 1979; Bisiach et al, 1984; Burke et al, 1994; as cited in Bolia, Nelson & Morley, 2001)

Also in: 2.6.2

6.1 Automaticity

6.1.1 Visual

Visual scanning and target detection tasks seem to be facilitated with tactile stimulation in terms of effectiveness and operator affinity. Several studies have indicated that when tactile is used along with visual, response times are faster and accuracy is more precise. Often the explanation stems from the idea that participants react before they fully process the situation (they avoid overthinking) (Akamatsu & Sato, 1994; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; He & Agah, 2001).

Also in: 3.4.4 TV, 3.6.4 TV

GP#:1046

Visual work processing is not strongly automatic (although this is disputed by much research). Reading-specific cognitive machinery appears to be time-shared with other cognitive operations like response selection. (McCann, Remington & Van Selst, 2000)

GP#:1053

Target cuing is one form of stage one automation, which is automation that implicitly or explicitly guides attention to areas of the world that the automation infers are important for the human user (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 3.6.1, 6.3.1

GP#:1537

6.1.2 Audio

Experience/automaticity of a task interacts with what mode of feedback is most helpful (audio, visual, haptic, bimodal, unimodal, or trimodal) on a computer drag and drop task. Trimodal was best for most experienced users. Auditory was best for all users. (Jacko et al, 2004)

Also in: 1.2.2, 1.2.4 ATV, 3.7.2, 3.7.4 ATV, 6.1.4 ATV

GP#:1002

People tend to code messages auditorily: rapidly successive data are to be resolved, where the recipient is preoccupied with other tasks or in a condition of reduced alertness, and one wishes to break in with unexpected messages or warnings, when highly meaningful materials are to be apprehended and remembered, where flexibility of message transmission is important, where out of a large mass of data we
wish to present information germane to the issue at hand, and where visual reception is less available. (Geldard, 1960)

Also in: 3.1.2, 4.2, 6.3.2, 6.6.2

6.1.3 Tactile

6.1.4 Multimodal (AV, AT, TV, ATV)

- AV
- AT
- TV
- ATV

Experience/automaticity of a task interacts with what mode of feedback is most helpful (audio, visual, haptic, bimodal, unimodal, or trimodal) on a computer drag and drop task. Trimodal was best for most experienced users. Auditory was best for all users. (Jacko et al, 2004).

Also in: 1.2.2, 1.2.4 ATV, 3.7.2, 3.7.4 ATV, 6.1.2

6.1.5 Not Specific to a Mode

When attentional requirements are too low, there is danger that driver awareness might be reduced because of monotony. In this case there may be too much automaticity. Arousal/stimulation or higher attentional requirements could be more effective. When attentional requirements are too high, the user will be forced to prioritize competing tasks. (Liu, 2003)

Also in: 3.3.5, 6.3.5

In a comparison of the behaviors/performance of novice and expert automobile drivers, novices had more lateral lane deviations and struggled in their performance of secondary tasks (e.g., putting in a cassette). Additionally, they glanced at the car’s instrument panel more often than the experts. These findings have implications for automaticity: once users have sufficient driving experience, they are more able to successfully dual task while driving. (Landsdown, 2002)

Also in: 1.2.5, 3.3.5

Expertise may allow a person to become proficient at the most difficult tasks that one must face, presumably due to automaticity (Bellenkes, Wickens & Kramer, 1997).

Also in: 1.2.5

When a task’s control demand becomes low (e.g., automatic performance), information processing becomes more parallel (Beilock et al. 2004; as cited in Luria & Meiran, 2005).

Also in: 6.6.5, 6.7

Response selection is parallel when tasks are repeated (because control demands are low) than when they are switched (Luria & Meiran, 2005). In other words, when tasks are repeated or practiced, then the next time the task is performed, it is more likely to be performed in parallel (versus serially), possibly because of practice effects. Furthermore, if one is switching from one task to a new task, control demands are higher and less likely to be performed in parallel.

Also in: 6.6.5, 6.7

GP#:1643
Found no individual differences in the number of trials from a point of mastery to an automaticity criterion or from initial learning to the mastery criterion of a novel task (Sax, 1996).

Also in: 1.2.5

Three factors that influence the ease/difficulty of dual-tasking are automaticity, multiple resources, and task similarity (Wickens, 1992; as cited in Wickens, 2000).

Also in: 6.7

Automaticity is closely and reciprocally related to the difficulty, mental effort, and attention resource demands of a member of a time-shared task pair (Kahneman, 1973; as cited in Wickens, 2000).

Also in: 6.3.5, 6.6.5, 6.7

The design of the task environment or the training program can be altered to bring about greater success in time-sharing through deployment of multiple resources, or through training to develop automaticity and improve attention control (Wickens, 2000).

Also in: 5.1.5, 6.3.5, 6.7.2

### 6.2 Cross-modal

Compared to visual warning signals, auditory and tactile signals are more effective at drawing cross-modal attention to particular positions (Spence & Driver, 1997).

Also in: 3.1.1, 3.1.2, 3.1.3

#### 6.2.1 Visual

There is evidence that auditory and visual spatial attention are separate but linked systems for information processing. Therefore, since audio and visual are linked, it may be better to offload overly taxed audio or visual information to the tactile modality to reduce workload. (Spence & Driver, 1996)

Also in: 6.2.2, 6.2.3, 6.2.4

The visual part of the brain is more stimulated by aural presentation than by visual presentation, though it is unclear why (Medvedev, Rudas, Pakhomov, Ivanitskii, Il'yuchenok, & Ivanitskii, 2003).

Also in: 2.6.1, 6.2.2, 6.3.1

After experience in tool-use, visual stimuli in the opposite hemifield to the stimulated hand could produce stronger crossmodal interactions than visual stimuli in the same anatomical hemifield, when the tools are crossed (Maravita, Spence, Kennett & Driver, 2002).

Also in: 1.2, 3.7.1

The quality of one mode (e.g., audio or visual) affects the perceived quality of another mode, and a single mode should not be considered in isolation (e.g., regarding cross-modal interaction of Audio/Visual quality perception) (Rimell & Hollier, 1999).

Also in: 6.2.2, 6.2.4 AV

#### 6.2.2 Audio

GP#:1018
There is evidence that auditory and visual spatial attention are separate but linked systems for information processing. Therefore, since audio and visual are linked, it may be better to offload overly taxed audio or visual information to the tactile modality to reduce workload. (Spence & Driver, 1996)

Also in: 6.2.1, 6.2.3, 6.2.4

GP#:1196

The visual part of the brain is more stimulated by aural presentation than by visual presentation, though it is unclear why (Medvedev, Rudas, Pakhomov, Ivanitskii, Il'yuchenok, & Ivanitskii, 2003).

Also in: 2.6.1, 6.2.1, 6.3.1

GP#:1205

In a target detection task, audio and tactile modes were found to be interdependent (Davenport, 1969).

Also in: 3.6.2, 3.6.3, 6.2.3, 6.2.4 AT

GP#:1340

Sense of touch may actually be dependent on diverse cognitive resources (high level knowledge), availability of cues for object identification, perceptual bias by other modalities (4, 5, 6) and cross modal attention. (Interacting cognitive subsystems theory; Booth & Schmidt-Tjørksen, 2001)

Also in: 2.7.3, 3.6.3, 6.3.3

6.2.3 Tactile

GP#:1018

There is evidence that auditory and visual spatial attention are separate but linked systems for information processing. Therefore, since audio and visual are linked, it may be better to offload overly taxed audio or visual information to the tactile modality to reduce workload. (Spence & Driver, 1996)

Also in: 6.2.1, 6.2.2, 6.2.4

GP#:1205

In a target detection task, audio and tactile modes were found to be interdependent (Davenport, 1969).

Also in: 3.6.2, 3.6.3, 6.2.2, 6.2.4 AT

GP#:1417

Interference is greater when two visual tasks are performed together or when two auditory tasks are performed together, than when a visual task is combined with an auditory task (Treisman & Davies, 1973; Duncan et al., 1997; as cited in Bourke & Duncan, 2005).

Also in: 4.1.7, 4.2.3, 4.4.1, 6.7

GP#:1466

Cross-modal links apply to spatial aspects of attention (e.g., people attend more effectively to concurrent auditory and visual channels when presented from a common spatial location) (Spence & Driver, 1997).
Cross-modal links for attentional levels of processing can substantially limit multimodal performance (Spence & Driver, 1997).

Cross-modal links are problematic for multiple resource theory, because evidence may exist that offloading visual to audio may not reduce cognitive workload (Spence & Read, 2003).

Tactile-auditory cross-modal effects may be less significant than visual-auditory cross-modal effects (McGuirl & Sarter, 2001).

There are cross-modal links in spatial attention between vision and audition and between vision and touch (Eimer, 2001).

In dual task situations, as the complexity of one task increases, performance on a different task (performed simultaneously) decreases. Although this was especially true when both tasks utilized visual resources (as Wickens would suggest), it was also true when the tasks used different modalities (visual and audio), suggesting that common resources may be used for both. (Jamson & Merat, 2005)

The cortical fields activated by the auditory go/no-go task overlapped with the fields activated by the visual go/no-go task in 6 locations of the brain (Klingberg and Roland, 1997).

The McGurk effect is a perceptual phenomenon in which vision alters speech perception (McGurk & MacDonald, 1976; as cited in Yang & Kim, 2004).

Cross-modal links apply to spatial aspects of attention (e.g., people attend more effectively to concurrent auditory and visual channels when presented from a common spatial location) (Spence & Driver, 1997).

The quality of one mode (e.g., audio or visual) affects the perceived quality of another mode, and a single mode should not be considered in isolation (e.g., regarding cross-modal interaction of Audio/Visual quality perception) (Rimell & Hollier, 1999).
Tactile-auditory cross-modal effects may be less significant than visual-auditory cross-modal effects (McGuirl & Sarter, 2001).

Also in: 6.2.4 AV

GP#:1205

In a target detection task, audio and tactile modes were found to be interdependent (Davenport, 1969).

Also in: 3.6.2, 3.6.3, 6.2.2, 6.2.3

• TV

Crossmodal effects may occur between visual and tactile stimuli when presented on the same side, leading to enhanced visual cortex activity (Lindeman, Sibert, Mendez, Patil, & Phifer, 2005).

GP#:1034

There are cross-modal links in spatial attention between vision and audition and between vision and touch. (Eimer, 2001).

Also in: 6.2.4 AV

GP#:1187

Performance on tasks using Visual Visual with tactile input (VVt) was significantly better than Tactile Visual (TV), Tactile Tactile with visual input (TTv), and Tactile Tactile (TT). The results suggest that bilateral posterior portion of the intraparietal sulcus is involved in the integration of visual and tactile sensory information. (Saito et al., 2003)

Also in: 2.7.1, 2.7.3, 2.7.4 TV

GP#:1269

Prolonged active use of tools (over several minutes) can modify visual-tactile spatial integration, so that visual stimuli located at the current position of the tool’s far end now interact most with tactile stimuli on whichever hand wields the connecting tool (Maravita, Spence, Kennett & Driver, 2002).

Also in: 3.7.4 TV

GP#:1300

Tactile hallucinations (though less prevalent in manifestation) of size often accompany stronger visual hallucinations of size (Halpern, 1959).

Also in: 2.7.1, 2.7.3, 2.7.4 TV

GP#:1498

Cross-modal cueing effects used within multimodal displays should follow an external spatial frame-of-reference (posture-independent) model rather than a hemispheric (anatomical) model (Hale & Stanney, 2004).

Also in: 2.7.4 TV

GP#:1625

If touch is potentially response-relevant, vision and touch stimuli can become cognitively linked, which may hinder the effectiveness of conveying additional information tactually (Hale & Stanney, 2004).

Also in: 2.7.4 TV

GP#:1627

There is evidence that visual cortical areas are active during some tactile tasks; tactile tasks requiring analyses of macrospatial features seemed more likely to recruit activity in visual areas than tactile tasks requiring analyses of microspatial features. Both visual and tactile texture analyses activated the cortex around the intraparietal sulcus, cross-modal or multimodal processing occurs frequently during both tactile and visual sensory perception in the normal sighted, and aid in the interpretation of cross-modal changes occurring in the blind. (Prather, 2003)
6.2.5 Not Specific to a Mode

As workload increases, cross modal links in spatial attention become more pronounced (Spence & Read, 2003).

Also in: 6.6.5

GP#:1006

Modes are not localized in the brain. Rather, they are more generalized such that input from one modality can activate “brain space” typically devoted to another modality. So, modes may share brain space. (Macaluso, Frith, & Driver, 2000)

GP#:1041

Take into account the particular relationships between cognitive resources and choose those that would induce least cognitive load [30] (Adamczyk & Bailey, 2004).

GP#:1230

Performance efficiency may be improved by hemispheric integrity. This may be because the hemispheres of the brain are cross-linked and one side (i.e right) controls the other side (i.e. left) side of the body and vice-versa. (Shub et al., 1997)

GP#:1316

6.3 Attention/Arousal

Manipulating the attention of the participant can influence the perception of simultaneity—the stimulus cued by the experimenter is usually perceived earlier. This was shown for stimuli presented within audio-tactile modalities (Stone, 1926), within the auditory modality (Needham, 1936), and within the visual modality (Stemach & Herdman, 1991; as cited in Vogels, 2004).

Also in: 2.5.1, 2.5.2, 2.5.4 AV, 4.1.8, 4.2.4, 4.6.2

GP#:1766

6.3.1 Visual

The visual part of the brain is more stimulated by aural presentation than by visual presentation, though it is unclear why (Medvedev, Rudas, Pakhomov, Ivanitskii, Il'yuchenok, & Ivanitskii, 2003).

Also in: 2.6.1, 6.2.1, 6.2.2

GP#:1196

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.1, 3.4.3, 4.16, 6.3.3, 6.6.1, 6.6.3, 6.7

GP#:1243

Attention-directing signals should be designed to be picked up in parallel to ongoing tasks, provide information on the significance of the interruption, and allow for evaluation that doesn’t require foveal attention (Woods, 1995; as cited in Sarter, 2001).

Also in: 3.1.1, 3.1.5

GP#:1244

GP#:1265
Higher contrast on a visual display leads to better detection. Caffeine may enhance detection on a short term target detection vigilance task when administered at 1.1mg/kg. (Temple et al., 2000)

Also in: 3.4.1, 3.6.1, 4.1.1

Peripheral displays must address two sets of user attention issues: (1) context about the user (e.g., interruptibility, primary task, focus of attention; and (2) attention management (e.g., abstraction and transitions, which are independent of context) (Matthews, Dey, Mankoff, Carter & Rattenbury, 2004).

Also in: 3.1.5, 4.1.6

Peripheral displays must support three characteristics to manage connection between information importance and user attention: (1) abstraction (extracting features/reducing fidelity of info to make it easier to read at a glance than raw input); (2) notification levels (differences in information importance); and (3) transitions (effects on a display that attract appropriate amount of attention from user based on new notification level) (Matthews, Dey, Mankoff, Carter & Rattenbury, 2004).

Also in: 3.1.5, 4.1.6

Objects that are created by combining color and shape or size do not create emergent features.

Combining spatial and non spatial dimensions like colors or shapes into a single object facilitates initial parallel processing of both dimensions in a way that will support both focused attention and information integration.

Using separate colors for each indicator disrupted information integration. Using common colors disrupted focused attention relative to performance with monochrome display.

Using unique color borders compensated for the loss of distinctiveness of individual dimensions and lead to in improvement in both attentional and integrational performance.

Current data suggest that the extra time (200-400ms) needed to process color information is probably worthwhile given the increase in the accuracy of check reading and given that the accuracy of integrations was not disrupted by color. (Wickens and Andre, 1990)

Also in: 4.1.1, 4.1.2, 6.7

The visual environment presents more information than we can process, so our brain selects regions in a “visual buffer” for detailed processing. Attention is greatest at a single point in the visual buffer and diminishes gradually from that point. (Kelleher & van Genabith, 2004)

Also in: 2.6.1

Even with the filtering of information from passive attention processes, there still remains more information in the visual field than can be processed by the brain (Chum & Wolfe, 2001; as cited in Kelleher & van Genabith, 2004).

Without a perceptual border indicating region to be attended to, the user’s attention may actually spread to the entire visual hemifield in which the attended position is located (Hughes & Zimba, 1985; as cited in Haimson &Anderson, 2002).

Also in: 2.7.1, 4.1.4, 8.1
Range rings or the partitioning of a display allows more focused attention and limits the repeated analysis of distractors (Haimson & Anderson, 2002).

**Also in:** 3.6.1, 4.1.4

**GP#:**1496

Visual scanning is adversely affected by divided attention (e.g., dual task context) (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

**Also in:** 3.6.1, 6.7

**GP#:**1497

The flicker-induced change-blindness paradigm can be used as a measure of where observers tend to direct their attention in a visual scene (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

**Also in:** 2.4.1

**GP#:**1536

In general, sensing techniques in mobile devices should provide the following: eliminate/reduce user frustration by making it easier for the user to get at functionality while engaged in an auxiliary task (e.g., dual tasking); mitigate attentional demands by using techniques that enable eyes-free use (e.g., offloading visual channels) (Hinckley et al., 2005).

**Also in:** 6.6.1, 6.7.1

**GP#:**1537

Target cuing is one form of stage one automation, which is automation that implicitly or explicitly guides attention to areas of the world that the automation infers are important for the human user (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 3.6.1, 6.1.1

**GP#:**1540

Helmet-mounted displays amplified a form of attentional tunneling (Yeh, Merlo, Wickens, & Brandenburg, 2003).

**Also in:** 4.1.5

**GP#:**1561

Computational models (grounded in cognitive theory) enable one to incorporate and test relevant cognitive factors (e.g., declarative and procedural knowledge) as well as perceptual-motor factors, such as mouse movements and shifts in visual attention (Peebles & Cheng, 2003).

**Also in:** 6

**GP#:**1579

Expertise is another factor that may affect how attention is deployed and how objects in a scene are represented (Varakin, Levin, & Fidler, 2004).

**Also in:** 1.2.1

**GP#:**1581

Head-up displays may paradoxically make pilots less aware to unexpected and potentially dangerous events that can happen outside of the aircraft; this is known as cognitive capture or cognitive tunneling (Tufano, 1997; Wickens & Long, 1995, as cited in Varakin, Levin, & Fidler, 2004).

**Also in:** 3.5.1, 3.8.1, 4.1.5, 6.4.1

**GP#:**1583

The following hypotheses have been posited on the Illusions of Visual Bandwith: people might overestimate how much visual information can be attended to simultaneously; designers overestimate the number of locations that a user will typically attend to; and people may overestimate the representational consequences for having attended to an object or location. (Varakin, Levin, & Fidler, 2004)
Dynamic tactile information (e.g., five tactors placed on the forearm vibrating sequentially) can be used to accurately reorient visual attention or vice versa (Hale & Stanney, 2004).

If touch can be entirely ignored, visual spatial attention tasks won’t affect tactile processing, allowing it to convey additional information (such as a tactile warning) (Hale & Stanney, 2004).

Dynamic objects in peripheral vision tend to be very distracting (Cadiz, Venolia, Jancke, & Gupta, 2002).

Better task-map coherence resulted in better attention switching strategies, reduced navigation errors, and better performance (Prabhu, 1996).

Spoken words are more powerful distracters than either pictures or printed words (Goolkasian and Foos, 2005).

A common assumption related to visual attention is that parallel processing occurs without attention (preattentive), and that serial processing requires attention. There are examples that refute this assumption; specifically, targets that are processed serially and do not trigger “pop-out” can actually be discriminated from distracters in a dual-task situation. Moreover, targets that are processed in parallel cannot be discriminated from distracters when attention is occupied by some other concurrent task. Preattentive (preattentive) processing implies parallel processing. In practice, this is constrained by the size of the receptive fields. (VanRullen et al., 2004)

Two independent dimensions are needed to account for the variety of visual discrimination tasks: one with respect to visual search performance (parallel versus serial dimension) and the other with respect to dual-task performance (the preattentive versus attentive dimension) (VanRullen et al., 2004).

Role of visual attention is twofold: (1) to dynamically generate neuronal selectivity that are not explicitly implemented in the visual system at the level of single neurons and (2) to resolve spatial ambiguities that arise when multiple stimuli fall in the same receptive field. (VanRullen et al., 2004)

The point of subjective simultaneity (PSS) shifts towards visual delays when attention is directed to a visual cue, and towards haptic delays when participants direct attention to a haptic stimulus (Vogels, 2001).
In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

Also in: 3.1.1, 3.1.2, 3.2.1, 3.8.1, 4.1, 4.2, 6.3.2, 6.3.4 AV, 6.7

GP#:1793

Visual in-cockpit technology should be adopted with caution for single-pilot operations, and that adopting other design or training features should be considered to address the attentional implications of that technology (this is true for cockpit displays of traffic information which may not be knowledgeable of all outside traffic). Design and training should be performed in conjunction if redundant display modalities are chosen, so that benefits of redundancy can be realized. (Wickens, Goh, Helleberg, Horrey & Talleur, 2003)

Also in: 3.8.1, 4.1, 5.1.1, 4.8.3

6.3.2 Audio

GP#:1235

Auditory system is extremely sensitive to change, even when outside focus of attention (Wenzel, 1994).

Also in: 2.4.2

GP#:1335

The auditory system is extremely sensitive to change, even when it is not being attended to (Wenzel, 1994).

Also in: 2.4.2

GP#:1506

For object manipulation tasks, augmenting natural haptic cues with auditory cues (tone sounded when object was contacted or placed) was more helpful than augmenting with graphic cues (change in object color) – this may be due to the “attention-grabbing” properties of audio (though natural visual resources did help); augmenting natural haptic cues with auditory or graphical cues was only beneficial in the reaching phase, not the place/acquire phase. (Zahariev & MacKenzie, 2003)

Also in: 2.6.2, 3.7.4 AT, 3.7.4 TV, 4.5.3, 4.6.3, 5.2.2

GP#:1532

Holding the PDA device like a cell phone to record a memo automatically may require less attention from the user than having to search manually for a button. However, there is a usability problem because users do not expect devices to be able to react in this way; thus, training user on device issues is key. (Hinckley et al., 2005)

Also in: 5.1.2, 5.1.3., 5.4.5, 6.3.3

GP#:1547

Spoken words like “deadly, danger and lethal” are rated as more arousing than words like “warning or caution” (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 3.1.2, 4.2

GP#:1548

Female voices seem to connote more urgency than male voices for conveying warnings. If a male or female voice is synthesized, the gender effect of the speaker seems to disappear (Hellier, Edworth, Weedon, Walters, Adams, 2002).

Also in: 2.7.2, 3.1.2, 4.2

GP#:1609
People tend to code messages auditorily: rapidly successive data are to be resolved, where the recipient is preoccupied with other tasks or in a condition of reduced alertness, and one wishes to break in with unexpected messages or warnings, when highly meaningful materials are to be apprehended and remembered, where flexibility of message transmission is important, where out of a large mass of data we wish to present information germane to the issue at hand, and where visual reception is less available. (Geldard, 1960)

**Also in:** 3.1.2, 4.2, 6.1.2, 6.6.2

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Spoken words are more powerful distracters than either pictures or printed words (Goolkasian and Foos, 2005).

**Also in:** 6.3.1

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Sound appears to have obligatory access to memory; even when attention is directed elsewhere, sound is recorded and processed by the brain. Nonspeech sounds, such as tones, can be as disruptive to performance as speech. (Banbury et. al., 2001)

**Also in:** 4.2

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In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damros, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

**Also in:** 3.1.1, 3.1.2, 3.2.1, 3.8.1, 4.1, 4.2, 6.3.1, 6.3.4 AV, 6.7

### 6.3.3 Tactile

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

**Also in:** 2.4.1, 2.4.3, 4.1.6, 3.4.1, 3.4.3, 6.3.1, 6.6.1, 6.6.3, 6.7

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Sense of touch may actually be dependent on diverse cognitive resources (high level knowledge), availability of cues for object identification, perceptual bias by other modalities (4, 5.6) and cross modal attention. (Interacting cognitive subsystems theory; Booth & Schmidt-Tjzrksen, 2001).

**Also in:** 2.7.3, 3.6.3, 6.2.3

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Holding the PDA device like a cell phone to record a memo automatically may require less attention from the user than having to search manually for a button. However, there is a usability problem because users do not expect devices to be able to react in this way; thus, training user on device issues is key. (Hinckley et al., 2005)

**Also in:** 5.1.2, 5.1.3., 5.4.5., 6.3.2

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Tactition is a good break in sense; cutaneous sensations are highly attention demanding, thus they may be good for emergency messages (Geldard, 1960).

**Also in:** 2.7.3, 3.1.3
The point of subjective simultaneity (PSS) shifts towards visual delays when attention is directed to a
visual cue, and towards haptic delays when participants direct attention to a haptic stimulus (Vogels, 2001).

Also in: 2.7.1, 2.7.3, 2.7.4 TV, 4.5.2, 6.3.1

6.3.4 Multimodal (AV, AT, TV, ATV)

Cross-modal links apply to spatial aspects of attention (e.g., people attend more effectively to concurrent
auditory and visual channels when presented from a common spatial location) (Spence & Driver, 1997).

Also in: 6.2.4, 6.2.4 AV, 6.3.4 AV

Cross-modal links for attentional levels of processing can substantially limit multimodal performance
(Spence & Driver, 1997).

Also in: 6.2.4

• AV

Multi-sensory binding processes are subject to attentional demands. Specifically, high attentional demands
may impact the understanding of information from audio-visual presentations. (Alsius, Navarra, Campbell,
& Soto-Faraco, 2005)

Also in: 6.6.4 AV

Cross-modal links apply to spatial aspects of attention (e.g., people attend more effectively to concurrent
auditory and visual channels when presented from a common spatial location) (Spence & Driver, 1997).

Also in: 6.2.4, 6.2.4 AV, 6.3.4

In contrast to MRT, auditory presentation of side task information can be detrimental because of the
phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in
Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a
visual message to attract attention away from the ongoing visual tasks of higher priority (aviating,
navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver,
2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from
working memory and hence must be attended to immediately.

Also in: 3.1.1, 3.1.2, 3.2.1, 3.8.1, 4.1, 4.2, 6.3.1, 6.3.2, 6.7

• AT
• TV
• ATV

6.3.5 Not Specific to a Mode

When attentional requirements are too low, there is danger that driver awareness might be reduced because
of monotony. In this case there may be too much automaticity. Arousal/stimulation or higher attentional
requirements could be more effective. When attentional requirements are too high, the user will be forced
to prioritize competing tasks. (Liu, 2003)

Also in: 3.3.5, 6.1.5

GP#:1010
Tombu supports capacity sharing. He may be suggesting that performance could be better or at least of same quality when dual-tasking than when single tasking because a person's level of arousal is higher. When tasks are more difficult, more effort is put forth. This idea is subject to the law of diminishing returns, though. If the dual task becomes too difficult then the same concept no longer applies. So, perhaps there is an optimal difficulty. (Tombu & Jolicœur, 2003)

Also in: 6.6.5, 6.7.2

GP#:1081

Attention is required to perceive change. Attention can only be focused on one object, or a small group of objects, at a time. (Divita, Obermayer, Nugent, Linvilleu, 2004)

Also in: 2.4.5

GP#:1095

Situational awareness can decrease under high workload situations because of competition for attention; it can also decrease under low workload conditions due to boredom and complacency (Cummings, 2004).

Also in: 3.5.5, 6.4.5, 6.6.5

GP#:1255

Older participants (age 60 and older) have difficulty in dividing attention; this is due to actual difficulties in dual tasking, not just the additive effects of lower performance in each individual task (Ponds, Brouwer, & van Wolffelaar, 1988).

Also in: 1.1.5, 6.7

GP#:1257

Performance decreases over time in vigilance tasks (the “vigilance decrement”); this appears to be due to limitations in the amount of effortful control that we can exert rather than the simple withdrawal of attention (mindlessness). Devices should be designed for vigilance tasks in a way that reduces the need for effortful attention (e.g., offload to audio). (Grier, Warm, Dember, Matthews, Galinsky, Szalma, & Parasuraman, 2003)

Also in: 3.4.2, 3.4.5

GP#:1262

Individuals need to be actively engaged (actually driving) in the navigation/driving task to increase their sense of situation awareness (Gugerty, 1997).

Also in: 3.2.5, 3.3.5, 3.5.5, 6.4.5

GP#:1277

Performance in dual-task situations can be better than in single-task situations because subjects find the situations more challenging and thus increase the amount of effort they expend (Weinstein & Wickens, 1992).

Also in: 6.6.5, 6.7

GP#:1315

Results show that balancing may be more attentionally demanding for older adults than young adults (Swan et al., 2004).

Also in: 1.1.5

GP#:1393

When multiple alarms go off simultaneously, and the alarm of interest is known to be unreliable (50-60% reliability), the likelihood that a user will perceive the alarm as important (in need of a response) increases as number of other alarms going off goes up (especially in proportion to number of alarms in array), as the spatial/temporal proximity of the alarms increases, and according to whether the other alarms going off are “related” to the alarm of interest (e.g., two engine lights). (Gilson, Mouloua, Graft, & McDonald, 2001)
It is important to control for single-task performance when measuring between-group differences in divided attention ability (e.g., differences in dual task ability) (Somberg & Salthouse, 1982).

Contrary to previous research, Somberg & Salthouse (1982) suggest that there are no age-related differences in divided attention (i.e., dual tasking). Instead, other processes (e.g., memory, perceptual impairments) are responsible for the poorer performance of older individuals on individual tasks. Performance on individual tasks is worse to begin with, subsequently causing decrements in dual task contexts.

Vigilance decrements often occur after 20-30 minutes on a vigilance task; thus, vigilance tasks should be designed for short segments, or have some sort of change every so often to increase arousal/attention (Singleton, 1989; as cited in Young & Stanton, 2002).

With mobile devices, keeping interactions minimally demanding of cognitive and visual attention is a core design issue (Hinckley et al., 2005).

It is important to preserve user’s focus of attention by minimizing disruptions to the ground, as this may cause an untimely interruption that requires the user to attend to some aspect of the system when they otherwise would not have had to do so (Hinckley et al., 2005).

Future mobile and educational interfaces should be designed with the goal of supporting the poorer attention span, impulse control, and higher error rates of users with an impulsive profile, especially in the case of mobil, in vehicle, military, and other applications that bear an unacceptably high cost for committing errors (Oviatt, Lunsford, and Coulston, 2005).

Better task-map coherence resulted in better attention switching strategies, reduced navigation errors, and better performance (Prabhu, 1996).

Under conditions that control for age differences in single-task performance, age-related deficits in dividing attention are minimal unless the task possesses substantial memory demands (Salthouse, Rogan & Prill, 1984; Somberg & Salthouse, 1982).

Calm technology will move easily from the periphery of our attention, to the center, and back. The following are differences between ambient and peripheral displays: ambient displays typically communicate one (or few at most) pieces of information and aesthetics and visual appeal of the display is paramount; peripheral displays refer to systems out of a person’s primary focus of attention and may
communicate one or more pieces of information (thus, ambient displays are a proper subset of peripheral displays). (Stasko et. al., 2004)

Also in: 4.1.6

GP#:1743

The crucial variable connecting attention and encoding is attentional capacity, such that stimuli that are difficult to encode require more attentional capacity, which in turn leads to stronger attention grabbing power. Obtained influence on attention seems to be relatively automatic, processes of attention allocation may regulate behavior even before deliberation and executive control come into play. (Gawronski et. al., 2005)

GP#:1764

When users do not receive any instructions about their attention, they divide their attention between two modalities in their own preferred way (Vogels, 2004).

Also in: 5.1.5, 5.5.5

GP#:1770

Automaticity is closely and reciprocally related to the difficulty, mental effort, and attention resource demands of a member of a time-shared task pair (Kahneman, 1973; as cited in Wickens, 2000).

Also in: 6.1.5, 6.6.5, 6.7

GP#:1775

When humans get overloaded in a dual task situation (e.g., when demands exceed capacity), they can adopt various strategies of attention control (e.g., one might protect the more important task and allow decrement to less important task, could postpone one task completely). This illustrates how multiple task performance can move between concurrent performance and sequential performance (Adams, Tenney & Pew, 1991; as cited in Wickens, 2000).

Also in: 6.6.5, 6.7

GP#:1777

Optimal attention control is an important feature that distinguishes better and more practiced dual task performers from those who are less skilled (Damos, 1991; as cited in Wickens, 2000).

Also in: 1.4.5, 6.7

GP#:1778

The design of the task environment or the training program can be altered to bring about greater success in time-sharing through deployment of multiple resources, or through training to develop automaticity and improve attention control (Wickens, 2000).

Also in: 5.1.5, 6.1.5, 6.7.2

6.4 Situational Awareness

6.4.1 Visual

When instant messaging systems are used concurrently with a primary task, users may fixate on instant messages rather than the primary task. This may result in a loss of situational awareness and a performance decrement. (Cummings, 2004)

Also in: 3.1.1, 3.5.1

GP#:1094

Peripheral visual cues are good for detecting “dynamic discontinuities” (example, motion or luminance change) and require few resources, but tunnel vision may be a problem under conditions of stress and/or cognitive load (Leibowitz & Appelle, 1969; as cited in Sarter, 2001).

Also in: 2.4.1, 3.4.1, 4.1.6, 6.6.5

GP#:1246
78% of pilots said it was easier to find the aircraft navigation pathway using goalpost vs. paving-stone display. Effects of type of symbology used could be nullified through practice. Some pilots had trouble interpreting a 2-D display to represent 3-D space. Situational Awareness outside of cockpit decreased from 44% to 14% from baseline to Highway in the Sky (HITS) condition. Pilots flying conventional instruments were significantly better at estimating heading and altitude than pilots using HITS display. 2 additions to the HITs display that might prove effective are the inclusion of air traffic on the display and inclusion of the synthetic terrain indicator. (Williams, 2002)

Also in: 1.2.1, 3.5.1, 3.8.1

HMDs often degrade performance and lower presence because of their narrow field of view (FOV). The visual FOV of the [naked] human eye spans more than 180 degrees (Seay, Krum, Hodges, & Ribarsky, 2001; Waller, 1999; as cited in Yang & Kim, 2004).

Also in: 2.1.1, 2.6.1, 4.1.5, 8.1

A smaller map with a wide field of view (FOV) displayed in the corner of a 3D map display can reduce tunnel vision (Wickens, Thomas, & Young, 2000).

Also in: 2.7.1, 3.2.1, 4.1.2, 4.1.4

Thirty percent of civil air crashes have been attributed to pilot spatial disorientation, caused by faulty or misleading visual/vestibular system inputs – a problem that can be ameliorated by the use of intuitive tactile inputs (Schrope, 2001).

Also in: 3.8.1, 3.8.4 TV, 5.3.3, 6.4.4 TV

Head-up displays may paradoxically make pilots less aware to unexpected and potentially dangerous events that can happen outside of the aircraft; this is known as cognitive capture or cognitive tunneling (Tufano, 1997; Wickens & Long, 1995, as cited in Varakin, Levin, & Fidler, 2004).

Also in: 3.5.1, 3.8.1, 4.1.5, 6.3.1

The use of density on maps is an important tool for enhancing situation awareness; displaying different saturations to represent troop movement allows users to achieve higher levels of situational awareness rapidly (Kim & Hoffmann, 2003).

Also in: 3.2.1, 3.5.1, 3.6.1, 4.1

Three visual tools (density, clustering, and lethality assessment) can enhance the situational awareness of a military commander on the battlefield. They can provide visual abstractions of an actual battle, not just terrain visualization. (Kim & Hoffmann, 2003)

Also in: 3.2.1, 3.5.1, 4.1

Guidelines for displays exhibiting high compatibility between display and mental task:
1. Integrate and collate related relevant information in a manner that allows visual comoparisons that make use of quick glances
2. Allow allocators to manage incidents rather than just calls.
3. Indicate the level of certainty in the information received.
4. Allow a spiral visual search pattern to locate the next nearest ambulance available to an incident (location).
5. Allow for assigning of temporary intermediate planning states and intentions. (Blandford & Wong, 2004)
Motion-based displays such as a ticker are better than in-place animations for comprehension and memorability, except when a cue is provided. While in-place displays aid rapid identification, participants who used the ticker obtained better detailed awareness than those who used the blast and the fade. This suggests that if it is essential to remember specific details of monitored information, and application of detailed awareness relies on first demonstrating basic awareness (rather than being cued), a motion-based display should be used. (McCrickard, Catrambone, Chewar & Stasko, 2003)

Situational awareness has been shown to diminish with a field of view less than 100 degrees (Reingold et al., 2003).

6.4.2 Audio

Spatial audio has potential to enhance SA at all three of Endsley’s levels: (1) Recognizing the relevant elements in a situation, (2) Comprehending the meaning of these elements, and, on the basis of this understanding, (3) Predicting the system status into the immediate future (Simpson, Bolia, & Draper, 2004).

Auditory cues are considered essential for maintaining a strong sense of presence (the world seems “dead” without sound) (Simpson, Bolia, & Draper, 2004).

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in–vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

The presentation of information via auditory displays can lead to increased situational awareness (Roginska, 2004).

6.4.3 Tactile

Perceptions of presence increases in virtual realities as frame rate increases. Frame rates below 15 frames/sec produce anomalous results. Presence in a virtual environment can be measured using physiological measures. Change in heart rate is a more accurate measure than change in skin conductance or change in skin temperature. Adding simple passive haptic cues (such as a small platform users stand on so they can feel edges with their feet) increases presence in virtual environments. (Meehan, Insko, Whitton, & Brooks, 2002)

6.4.4 Multimodal (AV, AT, TV, ATV)
   • AV
Crossmodal links are problematic for multiple resource theory, because evidence may exist that offloading visual to audio may not reduce cognitive workload (Spence & Read, 2003).

Also in: 6.2.4 AV

GP#:1395

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.2, 3.3.4 AV, 6.4.2, 6.6.2, 6.6.4 AV, 6.7, 7.1.2, 7.1.4 AV

- AT
- TV

Thirty percent of civil air crashes have been attributed to pilot spatial disorientation, caused by faulty or misleading visual/vestibular system inputs – a problem that can be ameliorated by the use of intuitive tactile inputs (Schrope, 2001).

Also in: 3.8.1, 3.8.4 TV, 5.3.3, 6.4.1

- ATV

6.4.5 Not Specific to a Mode

When evaluating a device, one should consider the following: (1) mental workload; (2) situation awareness (how much the automation of decisions reduces the operator's situation awareness); (3) complacency (operator may not trust the automation and may eventually not monitor the device); and (4) skill degradation (operator may be out of practice due to the function being consistently performed by automation) (Parasuraman, Sheridan, Wickens, 2000).

Also in: 5.4.5, 6.6.5, 7.2.5

GP#:1093

Training operators on how to use a given device, as well as the device’s limitations, is crucial for maintaining situational awareness (Varakin, Levin & Fidler, 2004).

Also in: 3.5.5, 5.1

GP#:1092

Even though automated mediation could lower user workload, a loss of situational awareness could result since not all messages deemed significant would be seen by the controller (Cummings, 2004).

Also in: 3.5.5, 6.6.5

GP#:1093

When designing adaptive communication interfaces it is important to consider the following questions: How would the operator’s knowledge states and decision processes be affected by receiving instant messages? When should an adaptive chat management tool interrupt the operator and under what conditions? Is there a principled way for this tool to infer the operator’s workload and his/her ability to cognitively attend to communication messages? How will an adaptive chat management strategy affect overall human performance, situational awareness, and frustration? (Cummings, 2004)

Also in: 3.1.5, 4.9, 6.6.5

GP#:1095

Situational awareness can decrease under high workload situations because of competition for attention; it can also decrease under low workload conditions due to boredom and complacency (Cummings, 2004).

Also in: 3.5.5, 6.3.5, 6.6.5
General design principles relevant for sustaining situational awareness include the following: organize information around goals; present level two situational awareness information directly to support comprehension; support global situational awareness; support trade-offs between goal-driven and data-driven processing; make critical cues for schema activation salient; take advantage of parallel processing capabilities; and use information filtering carefully. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 4.9, 6.7.2

Levels of uncertainty correspond to levels of situational awareness: you can have uncertainty in perception (data uncertainty), comprehension uncertainty, projection uncertainty, and decision uncertainty. Strategies for reducing uncertainty include searching for more information, relying on defaults, conflict resolution, thresholding, bet-hedging and contingency planning, and narrowing options. When designing a device, explicitly define missing information, support sensor reliability assessment, use data salience in support of certainty, and represent information timeliness. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 5.4.5

In designing a device, there are several layers of complexity to consider, including system complexity, operational complexity, cognitive complexity (composed of display complexity and task complexity), apparent complexity (face validity), and as always, the user’s mental model. To manage the complexity of a system, consider the following principles: avoid “feature creep” (adding more and more bells and whistles); map system functions to the goals and mental models of users; provide system transparency and observability; provide consistency and standardization on controls across different displays and systems; and minimize task complexity. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 4.9

Use of alarms to support situational awareness is complex, as operators view audio/video alarms through a filter of their own expectancies, schemas, mental models of systems and situations, and past experiences of the system’s reliability. In designing alarms to facilitate situational awareness: do not make people rely on alarms but rather provide projection support; support alarm confirmation activities; make alarms unambiguous; reduce false alarms; use multiple modalities to alarm, but make sure that they are consistent; minimize alarm disruptions to ongoing activities; and support rapid development of global situational awareness of systems in an alarm state. (Endsley, Bolte, & Jones, 2003)

Also in: 1.2.5, 3.1.1, 3.1.2, 3.1.4, 3.1.5, 3.5.5, 5.4.5

When incorporating automation into devices, major challenges include keeping the operator in the loop and maintaining modal awareness (i.e., automation understanding). Thus, consider the following guidelines: automate only if necessary; use automation for routine actions rather than higher level cognitive tasks; keep the operator in control and in the loop; avoid use of information cueing; and provide automation transparency. (Endsley, Bolte, & Jones, 2003)

Also in: 5.2.5

Use a body-centered frame of reference (as opposed to a device-centered frame of reference) to reduce susceptibility to sensory overload and to allow users to orient themselves to the direction of travel (Traylor & Tan, 2002; as cited in O’Modhrain, 2004).

Also in: 3.2.5, 3.5.5, 4.9, 8.5

Tunnel vision may be reduced with training (Williams, 1995; as cited in Sarter, 2001).
Individuals need to be actively engaged (actually driving) in the navigation/driving task to increase their sense of situation awareness (Gugerty, 1997).

Also in: 3.2.5, 3.3.5, 3.5.5, 6.3.5

Automation of decision-making may reduce the operator’s awareness of the system and of certain dynamic features of the work environment. Humans tend to be less aware of changes that are under control of another agent (whether that agent is automated or another human). (Kaber, Omal, & Endsley, 1999 as cited in Parasuraman, Sheridan & Wickens, 2000)

Also in: 2.4.5

If a decision aid, expert system, or other type of decision automation consistently and repeatedly selects and executes decision choices in a dynamic environment, the human operator may not be able to sustain a good “picture” of the information sources in the environment, as he or she is not actively engaged in evaluating the information sources leading to a decision. (Parasuraman, Sheridan & Wickens, 2000)

Also in: 5.2.5, 6.5.5

6.5 Decision Making Heuristics

6.5.1 Visual

Human visual search performance can be explained largely in terms of the cognitive strategy that is used to coordinate the relevant perceptual and motor processes. A clear and useful visual hierarchy triggers a fundamentally different visual search strategy and effectively gives the user greater control over the visual navigation. Cognitive strategies will be an important component of a predictive visual search tool. (Hornof, 2004)

Also in: 3.6.1, 6

6.5.2 Audio

6.5.3 Tactile

6.5.4 Multimodal (AV, AT, TV, ATV)

• AV
• AT
• TV
• ATV

6.5.5 Not Specific to a Mode

Methods of data presentation and extraction greatly affect people’s decision-making abilities [5], suggesting the use of information to illustrate uncertainty of data (discussed here in a medical context). (as cited in Krol, Reich, Pavone & Fuhrman, 2004)

Maximal integration in space and time along means-end links should improve problem solving.(Burns, 2000).

Also in: 6

Highly integrated ecological displays result in fast and accurate problem solving performance (Burns, 2000).
If a decision aid, expert system, or other type of decision automation consistently and repeatedly selects and executes decision choices in a dynamic environment, the human operator may not be able to sustain a good “picture” of the information sources in the environment, as he or she is not actively engaged in evaluating the information sources leading to a decision. (Parasuraman, Sheridan & Wickens, 2000)

Also in: 5.2.5, 6.4.5

If automation is highly, but not perfectly, reliable in executing decision choices, then the operator may not monitor the automation and its information sources and hence will fail to detect the occasional times when the automation fails (Wiener, 1981 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 5.4.5

If the decision-making function is consistently performed by automation, there will come a time when the human operator will not be as skilled in performing that function. It is well documented in the cognitive psychology literature that forgetting and skill decay occur with disuse. (Rose, 1989 as cited in Parasuraman, Sheridan & Wickens, 2000)

Also in: 4.9

6.6 Workload

Device designers need to consider what happens to performance and to a user’s cognitive load when there are discrepancies between the information provided between two modes. Devices should be designed to aid in the comprehension of information, rather than providing conditions that could degrade comprehension. (suggested by Multimodal project team)

The “Index of Cognitive Activity” is a new approach to measuring cognitive effort based on eye movements and pupil dilation. Dilation reveals when cognitive effort is highest, and eye movements provide evidence of why. Especially during critical events, one wants to know whether the operator is confused by the presentation or location of specific information, whether he is attending to key information when necessary, or whether he is distracted by irrelevant features of the display. (Marshall, 2003)

6.6.1 Visual

It is difficult for users to maintain a sense of compass directions when displayless interfaces are used. If it is not feasible to provide users with a map for navigation, augmenting verbal directions with non-speech audio cues may reduce workload (Baca & Picone, 2005).

Also in: 3.2.1, 3.2.2, 6.6.2

A multimodal condition (visual and audio) especially improved performance on a secondary task for older participants. Potential explanations for these findings include the following: visual abilities decrease with age (so users need audio to compensate for visual loss), older participants may experience higher workload while driving; or older users may be less equipped to deal with the same level of workload (older participants reported more stress in general when driving). (Liu, 2001)

Also in: 1.1.1, 1.1.4AV, 6.7

Offloading alerts from the visual to the tactile mode was especially beneficial as cognitive load increased; there were fewer differences between conditions (visual, tactile, and visual/tactile) at lower states of cognitive workload (Sklar & Sarter, 1999).

Also in: 3.1.1, 3.1.3, 3.1.4 TV, 6.6.3, 6.6.4 TV
In dual task situations, as the complexity of one task increases, performance on a different task (performed simultaneously) decreases. Although this was especially true when both tasks utilized visual resources (as Wickens would suggest), it was also true when the tasks used different modalities (visual and audio), suggesting that common resources may be used for both. (Jamson & Merat, 2005)

Also in: 6.2.4 AV, 6.6.4 AV

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.1, 3.4.3, 4.1.6, 6.3.1, 6.3.3, 6.6.3, 6.7

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)

Also in: 2.7.1, 2.7.3, 6.6.2, 6.6.3, 6.6.4 ATV, 7.3

By presenting information multimodally (A-V) with a visual distraction did better than expected vs. Visual only. (A-V) presentation of text based and picture based learning materials induced less cognitive load than visual only presentation of the same materials (Brünken et al., 2004).

Also in: 2.7.1, 2.7.4 AV, 6.6.4 AV

A reduction in visual load (e.g., full screen layout with a single event log) is more supportive of a supervisory task that requires focused attention on one event type. In contrast, a reduction in operational load (e.g., full screen layout with five event logs) is more supportive of supervisory tasks that require divided attention across different event types of different handling priority. (Parush, 2004)

Also in: 4.1.4, 6.7

Stereoscopic viewing becomes especially useful in a virtual reality environment when the data load is light (Fujimoto & Ishibashi, 2004).

Also in: 8.1

Middle-aged workers may incur a heavier visual load resulting from VDT (visual display terminal) use than that experienced by younger workers (Inoue, 2002).

Also in: 1.1.1

Image panning takes time, and users are even less likely to pan in high-demand, time-critical situations (Wickens, Thomas, & Young, 2000).

Also in: 4.1.4, 5.2.1

In general, sensing techniques in mobile devices should provide the following: eliminate/reduce user frustration by making it easier for the user to get at functionality while engaged in an auxiliary task (e.g., dual tasking); mitigate attentional demands by using techniques that enable eyes-free use (e.g., offloading visual channels) (Hinckley et al., 2005).

Also in: 6.3.1, 6.7.1
The amount of data presented on a helmet-mounted display represents only a small subset of information that will be displayed to ground soldiers in the future, and there are already detrimental clutter effects (Yeh, Merlo, Wickens, & Brandenburg, 2003).

Also in: 4.1.5

Practical implications for design of helmet-mounted displays:
Designers should consider the potential consequences of attention guidance presented on an HUD. Cuing benefits decrease as cue precision is degraded, but imprecise cuing is better than no cuing at all. Trust in the automated cuing information influences attention allocation strategies. It may help to widen attentional breadth by signaling cue precision, when presenting cues of low spatial resolution. Operators need to be informed about the spatial resolution of the displayed guidance information and to balance this knowledge with the information provided by an automated system. The use of a simulated HMD does not alter the pattern of behavior relative to an actual HMD. The presentation of information on an HMD combined with the real world or any noisy environment may be intrusive to the operator’s task. Ground soldiers need to search and filter through multiple sources of information, and as task demands increase, reliance on any automated system may increase as well. (Yeh, Merlo, Wickens, & Brandenburg, 2003)

Also in: 4.1.5, 5.4.1

The following hypotheses have been posited on the Illusions of Visual Bandwith: people might overestimate how much visual information can be attended to simultaneously; designers overestimate the number of locations that a user will typically attend to; and people may overestimate the representational consequences for having attended to an object or location (Varakin, Levin, & Fidler, 2004).

Also in: 2.7.1, 4.1, 6.3.1

People tend to code messages visually: where messages involve spatial orientation or guidance, where fine discrimination is needed, where complex or unfamiliar material is to be comprehended, where reference data have to be immediately available or when simultaneous comparisons need to be made, where a recipient of information has to make relatively prompt selection of data from larger stocks of information, and where auditory reception is hampered by unfavorable environmental conditions (Geldard, 1960).

Also in: 2.6.1, 3.10, 4.1

Auditory alarm problems include high rates of false alarms, interruptive, uninformative, stress-inducing acoustic profiles for alarm sounds, and alarms that are acoustically indistinguishable from one-another (Seagull, 2002).

Also in: 4.2.5, 6.6.4 AV

Auditory displays can communicate information redundant to or independent of visual displays, potentially offloading some visual workload to the auditory channel (Seagull, 2002).

Also in: 4.2.5, 6.6.4 AV

Spatialized audio cueing can lead to increased target detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman & Breda, 1998; Nelson et al, 1998, as cited in Tannen, 2000).

Also in: 2.1.2, 3.6.2, 6.6.2, 6.6.4 AV
Pilots scan near-domain information about system functions (presented by cockpit instrumentation) and far-domain information about local airspace and terrain features (out the window). Pilots have tried to develop efficient scanning methods to cope with these demands, but switching between domains is challenging because it requires rapid changes in line-of-sight (LOS) and optical focus, often under adverse physical conditions. Switching is also cognitively demanding because pilots have to pick-up and synthesize information across domains, thus creating a high potential for error (Weinstein & Wickens, 1992; as cited in Tannen, 2000).

Also in: 3.8.1, 6.7

GP#:1669

Single-seat cockpits have limited space for information display, and there is already a high display load in cockpits. Too many displays may contribute to information overload, increasing the probability of pilot error. (Reising, Liggett & Munns, 1999; Weinstein & Wickens, 1992; as cited in Tannen, 2000)

Also in: 3.8.1, 4.1.4

GP#:1679

Results suggest that there is a resource competition between working memory demands of information storage, and the perceptual cognitive demand of reading each menu screen and deciding the appropriate option to select (Wickens and Seidler, 1997).

Also in: 4.1.4

GP#:1681

Configural displays are more effective than separable displays for the performance of high-level property tasks. The pattern is less clear for low-level data tasks - participants had greater difficulty completing the low-level data probes than they did completing the high-level probes. Performance was significantly faster and more accurate with composite visual displays than with baseline displays. (Bennett et. al., 2000)

Also in: 4.1.4

GP#:1685

Animation can be used in secondary displays with minimal negative impact on certain primary tasks. While other work (Maglio and Campbell, 2000) seems to suggest otherwise, both experiments supported this claim. The difference may result from a primary task that is less cognitively demanding and uses smoother, slower animations. (As cited in McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 4.1.4

GP#:1692

A large amount of text presented in a dense or complex format will tax working memory, and complex symbols that are small, or that are accompanied by explanatory text that is too small to read, will be difficult for older adults and others with visual impairments to interpret (Hancock, Rogers, & Fisk, 2001).

Also in: 1.1.1, 4.1.2, 4.1.4

GP#:1717

Cockpit predictor displays have shown that pilot workload decreases and hazard detection performance improves with the addition of predictive information concerning the flight path of neighboring aircraft (Morphew & Wickens, 1998 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 3.8.1

GP#:1718

The horizontal situation indicator in the cockpit provides the pilot with a graphic display of the projected flight plan and the current position of the aircraft; this, more than any other automated system in the cockpit, has been credited with reducing the workload of the pilot (Wiener, 1988 as cited in Parasuraman, Sheridan & Wickens, 2000).

Also in: 3.8.1, 4.1.4

GP#:1737
Reducing the visual processing load by decreasing resolution in the periphery is important in the development of artificial vision systems (Reingold et. al., 2003).

**Also in:** 4.1.3, 4.1.6

### 6.6.2 Audio

GP#:1100

Tactile displays that present driving behavior feedback result in lower user workload than auditory displays (Van Erp & Van Veen, 2004).

**Also in:** 3.3.2, 3.3.3, 6.6.3

GP#:1115

It is difficult for users to maintain a sense of compass directions when displayless interfaces are used. If it is not feasible to provide users with a map for navigation, augmenting verbal directions with non-speech audio cues may reduce workload. (Baca & Picone, 2005)

**Also in:** 3.2.1, 3.2.2, 6.6.1

GP#:1268

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)

**Also in:** 2.7.1, 2.7.3, 6.6.1, 6.6.3, 6.6.4 ATV, 7.3

GP#:1282

Search performance was decreased when participants simultaneously heard and responded to questions about prose passages while driving. For dual-task condition, participants are less accurate in identifying signs, took longer to do searches and showed more prolonged fixations indicating more effortful processing. Subjective measures of workload supported these findings. (McPhee et al., 2004)

**Also in:** 3.3.2, 6.7

GP#:1395

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in–vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

**Also in:** 3.3.2, 3.3.4 AV, 6.4.2, 6.4.4 AV, 6.6.4 AV, 6.7, 7.1.2, 7.1.4 AV

GP#:1609

People tend to code messages auditorily: rapidly successive data are to be resolved, where the recipient is preoccupied with other tasks or in a condition of reduced alertness, and one wishes to break in with unexpected messages or warnings, when highly meaningful materials are to be apprehended and remembered, where flexibility of message transmission is important, where out of a large mass of data we wish to present information germane to the issue at hand, and where visual reception is less available. (Geldard, 1960)

**Also in:** 3.1.2, 4.2, 6.1.2, 6.3.2

GP#:1654

Spatialized audio cueing can lead to increased target detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman & Breda, 1998; Nelson et al, 1998, as cited in Tannen, 2000).

**Also in:** 2.1.2, 3.6.2, 6.6.1, 6.6.4 AV

GP#:1668

Without supplementary visual cueing, virtual auditory cueing led to increased detection rates and decreased detection times, and to reductions in subjective workload. It also improved the efficiency of search patterns. (Cunningham et. al., 1995; Cunningham et. al., 1998; as cited in Tannen, 2000)
6.6.3 Tactile

Ability to sense tactile cues may decrease when the user is experiencing cognitive load. In particular, the efficacy of tactile cues decreased when participants were in a zero-gravity situation, as is often experienced by pilots and astronauts. (Bhargava, Scott, Traylor, Chung, Mrozek, Water & Tan, 2005)

Also in: 2.2.3

GP#:1100

Tactile displays that present driving behavior feedback result in lower user workload than auditory displays (Van Erp & Van Veen, 2004).

Also in: 3.3.2, 3.3.3, 6.6.2

GP#:1116

Adding force/haptic characteristics to a joystick improved several performance measures (as assessed in an F16 landing simulator), particularly in turbulent conditions. Specifically, it reduced error in landing near a desired touchdown point, led to lower subjective workload, and reduced the joystick activity necessary for handling the aircraft. (Repperger, 1997; as cited in Repperger, Gilkey, Green, LaFleur & Haas, 2001)

Also in: 3.8.3

GP#:1166

Offloading alerts from the visual to the tactile mode was especially beneficial as cognitive load increased; there were fewer differences between conditions (visual, tactile, and visual/tactile) at lower states of cognitive workload (Sklar & Sarter, 1999).

Also in: 3.1.1, 3.1.3, 3.1.4 TV, 6.6.1, 6.6.4 TV

GP#:1243

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.1, 3.4.3, 4.1.6, 6.3.1, 6.3.3, 6.6.1, 6.7

GP#:1268

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)

Also in: 2.7.1, 2.7.3, 6.6.1, 6.6.2, 6.6.4 ATV, 7.3

GP#:1701

Simultaneous or sequential presentation of multiple tactile messages on the same display can result in tactile clutter and reduced comprehension (Van Erp, 2002).

Also in: 2.7.3, 4.3

6.6.4 Multimodal (AV, AT, TV, ATV)

A multimodal presentation of information may only become useful if task demands are especially high (Wickens, Goh, Helleberg, Horrey, & Talleur, 2003).

GP#:1042

If the information in different modalities has no new content, it only increases the cognitive load experienced by the user (Elting, Zwickel & Malaka, 2002).

Also in: 4.8.3
Confusion and control instabilities in the multimodal system can be minimized by avoiding time lags between visual and haptic loops (Hale & Stanney, 2004).

Also in: 2.7.4 TV, 4.5

- AV

Crossmodal links are problematic for multiple resource theory, because evidence may exist that offloading visual to audio may not reduce cognitive workload (Spence & Read, 2003).

Also in: 6.2.4 AV

Multi-sensory binding processes are subject to attentional demands. Specifically, high attentional demands may impact the understanding of information from audio-visual presentations. (Alsius, Navarra, Campbell, & Soto-Faraco, 2005)

Also in: 6.3.4 AV

In dual task situations, as the complexity of one task increases, performance on a different task (performed simultaneously) decreases. Although this was especially true when both tasks utilized visual resources (as Wickens would suggest), it was also true when the tasks used different modalities (visual and audio), suggesting that common resources may be used for both. (Jamson & Merat, 2005)

Also in: 6.2.4 AV, 6.6.1

By presenting information multimodally (A-V) with a visual distraction did better than expected vs. Visual only. (A-V) presentation of text based and picture based learning materials induced less cognitive load than visual only presentation of the same materials (Brünken et al., 2004).

Also in: 2.7.1, 2.7.4 AV, 6.6.1

AIM is a good example of adding audio to reduce visual load—the sound of a door opening accompanied by little icon next to name that pops up on list (Rovers & van Essen, 2004).

Also in: 3.1.1, 3.1.4 AV, 6.6.5

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.2, 3.3.4 AV, 6.4.2, 6.4.4 AV, 6.6.2, 6.7, 7.1.2, 7.1.4 AV

Auditory alarm problems include high rates of false alarms, interruptive, uninformative, stress-inducing acoustic profiles for alarm sounds, and alarms that are acoustically indistinguishable from one-another (Seagull, 2002).

Also in: 4.2.5, 6.6.1

Auditory displays can communicate information redundant to or independent of visual displays, potentially offloading some visual workload to the auditory channel (Seagull, 2002).

Also in: 4.2.5, 6.6.1
Spatialized audio cueing can lead to increased target detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman & Breda, 1998; Nelson et al, 1998, as cited in Tannen, 2000).

Also in: 2.1.2, 3.6.2, 6.6.1, 6.6.2

Multimodal cueing (e.g., spatialized audio and visual) also reduced excessive head motion and lowered pilots’ workload by about 30%, as compared to conditions with no cues (Tannen, 2000).

Also in: 2.1.4 AV, 3.8.4 AV

When more than three items had to be stored in memory, spoken words that appeared with pictures faired the best (Goolkasian and Foos, 2005).

- AT

In the absence of visual cues, multimodal conditions (audio-tactile) led to higher accuracy, lower response time, and less workload compared to unimodal conditions in deciphering a 2d bar graph (Yu & Brewster, 2002).

Also in: 2.5.4 AT, 3.11, 4.6.3

- TV

Offloading alerts from the visual to the tactile mode was especially beneficial as cognitive load increased; there were fewer differences between conditions (visual, tactile, and visual/tactile) at lower states of cognitive workload (Sklar & Sarter, 1999).

Also in: 3.1.1, 3.1.3, 3.1.4 TV, 6.6.1, 6.6.3

If the visual system is overloaded, object identification information can be provided haptically without adding significant cognitive load (Hale & Stanney, 2004).

Also in: 3.6.4 TV

- ATV

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)

Also in: 2.7.1, 2.7.3, 6.6.1, 6.6.2, 6.6.3, 7.3

6.6.5 Not Specific to a Mode

As workload increases, cross modal links in spatial attention become more pronounced (Spence & Read, 2003).

Also in: 6.2.5

Tombu supports capacity sharing. He may be suggesting that performance could be better or at least of same quality when dual-tasking than when single tasking because a person's level of arousal is higher. When tasks are more difficult, more effort is put forth. This idea is subject to the law of diminishing
returns, though. If the dual task becomes too difficult then the same concept no longer applies. So, perhaps there is an optimal difficulty (Tombu & Jolicœur, 2003).

Also in: 6.3.5, 6.7.2

When evaluating a device, one should consider the following: (1) mental workload; (2) situation awareness (how much the automation of decisions reduces the operator's situation awareness); (3) complacency (operator may not trust the automation and may eventually not monitor the device); and (4) skill degradation (operator may be out of practice due to the function being consistently performed by automation) (Parasuraman, Sheridan, Wickens, 2000).

Also in: 5.4.5, 6.4.5, 7.2.5

Cognitive overload is a critical issue to consider in user interface design. Presentation planners should adapt their presentation to the cognitive requirements of the communication device used. (Elting, Zwickel & Malaka, 2002)

Also in: 4.9

Drawbacks of instant messaging systems are that they can be disruptive and the flow of conversation can be awkward in the absence of non-verbal cues. These limitations are especially bad in time-pressured scenarios because interrupting the primary task (with the instant messages) increases mental processing time and leads to errors on the primary task. (Cummings, 2004)

Also in: 3.1.1, 3.9.1, 4.1.7, 6.7

Even though automated mediation could lower user workload, a loss of situational awareness could result since not all messages deemed significant would be seen by the controller (Cummings, 2004).

Also in: 3.5.5, 6.4.5

When designing adaptive communication interfaces it is important to consider the following questions: How would the operator’s knowledge states and decision processes be affected by receiving instant messages? When should an adaptive chat management tool interrupt the operator and under what conditions? Is there a principled way for this tool to infer the operator’s workload and his/her ability to cognitively attend to communication messages? How will an adaptive chat management strategy affect overall human performance, situational awareness, and frustration? (Cummings, 2004)

Also in: 3.1.5, 4.9, 6.4.5

Situational awareness can decrease under high workload situations because of competition for attention; it can also decrease under low workload conditions due to boredom and complacency (Cummings, 2004).

Also in: 3.5.5, 6.3.5, 6.4.5

In determining how much information to present a user with, consider that users need sufficient information to adequately perform the task, but too much information can overload a user’s short-term memory and cause frustration (Baca & Picone, 2005).

Also in: 4.9

Tasks that involve communicating information should be evaluated in terms of whether the information must be remembered or used to simply inform the user. If the information must be remembered, it is important to use the most effective means possible (i.e., combination of modes); however, if it is used to
inform the user, subjective appeal should be considered most important. (Elting, Zwickel, and Malaka, 2002)

Also in: 3.9.4, 3.9.5, 5.5.5

GP#:1198

High cognitive load is not always detrimental to task performance, and in some cases it can be helpful (Swan, Otani, Loubert, Sheffert, and Dunbar, 2004).

GP#:1230

Take into account the particular relationships between cognitive resources and choose those that would induce least cognitive load [30] Adamczyk & Bailey (2004).

Also in: 6.2.5

GP#:1233

If given the choice, users might choose more ultimodal devices as task/scenarios become more complex (Althoff, McGlaun, Schuller, Morguet & Lang, 2001).

Also in: 5.5.4

GP#:1245

Alarms that distinguish whether system failure is possible, probable, or certain (likelihood alarm displays) are better than traditional alarms (that just signal that some sort of attention is needed) when workload is high (Sorkin, Kantrowitz, & Kantrowitz, 1988; as cited in Sarter, 2001).

Also in: 3.1.5

GP#:1246

Peripheral visual cues are good for detecting “dynamic discontinuities” (example, motion or luminance change) and require few resources, but tunnel vision may be a problem under conditions of stress and/or cognitive load (Leibowitz & Appelle, 1969; as cited in Sarter, 2001).

Also in: 2.4.1, 3.4.1, 4.1.6, 6.4.1

GP#:1263

To compensate for increases in working memory load when driving, drivers will focus on a subset of cars (cars located in close proximity) instead of each individual car (Gugerty, 1997).

Also in: 2.1.5, 3.3.5

GP#:1277

Performance in dual-task situations can be better than in single-task situations because subjects find the situations more challenging and thus increase the amount of effort they expend (Weinstein & Wickens, 1992).

Also in: 6.3.5, 6.7

GP#:1324

Both the cry-wolf effect and automation bias are more likely to occur under high workload conditions (Parasuraman, Molloy, & Singh, 1993; as cited in Maltz & Meyer, 2001).

Also in: 3.1.5, 5.4.5

GP#:1327

Alarms often increase operator workload rather than decrease it because of so many false alarms (Cook & Woods, 1996; as cited in Seagull & Sanderson, 2001).

Also in: 3.1.5

GP#:1361
AIM is a good example of adding audio to reduce visual load—the sound of a door opening accompanied by little icon next to name that pops up on list (Rovers & van Essen, 2004).

Also in: 3.1.1, 3.1.4 AV, 6.6.4 AV

GP#:1392

When workload is high, operators tend to rely mainly on surface cues of displays, so it’s especially important to use cues consistently (e.g., colors) (Gilson, Mouloua, Graft, & McDonald, 2001).

Also in: 2.1.1, 4.1.1

GP#:1414

When a task’s control demand becomes low (e.g., automatic performance), information processing becomes more parallel (Beilock et al. 2004; as cited in Luria & Meiran, 2005).

Also in: 6.1.5, 6.7

GP#:1415

Response selection is parallel when tasks are repeated (because control demands are low) than when they are switched (Luria & Meiran, 2005). In other words, when tasks are repeated or practiced, then the next time the task is performed, it is more likely to be performed in parallel (versus serially), possibly because of practice effects. Furthermore, if one is switching from one task to a new task, control demands are higher and less likely to be performed in parallel.

Also in: 6.1.5, 6.7

GP#:1507

In-driver support systems (rather than automation systems) should be used to help increase driving performance; automation is generally meant to improve performance by reducing workload, but excessively low mental demands can be detrimental to performance – possibly worse than overload (Hancock & Parasuraman, 1992; Hancock & Verwey, 1997; as cited in Young and Stanton).

Also in: 3.3.5

GP#:1508

Although most researchers tend to assume that our “resource size” is fixed, there is some support that it may change with long-term fluctuations in mood or age (Hasher & Zacks, 1979; Humphreys & Revelle, 1992); also, this study provides support that it can also change in the short-term in response to task demands (e.g., resources “shrink” to accommodate demand reduction) (Young & Stanton, 2002).

Also in: 1.1.5, 2.6

GP#:1509

Automating longitudinal control may be better than automating lateral control (or both) in a driving task, as the typical negative effects of underload with automation were not different between this condition and manual condition (no automation) (Young & Stanton, 2002).

Also in: 3.3.5

GP#:1526

A major factor in display design seems to be the computational demands related to different spatial filtering rather than the perceived location of the sources (MacDonald et al., 2002).

Also in: 2.1.5, 4.9

GP#:1529

With mobile devices, keeping interactions minimally demanding of cognitive and visual attention is a core design issue (Hinckley et al., 2005).

Also in: 4.1, 4.9, 6.3.5

GP#:1557
Event-related potentials (ERPs) are sensitive to workload manipulations, thus making the ERP a useful workload assessment index (Isreal, Wickens, Chesney & Donchin, 1980).

Workload itself must be disaggregated into dimensions such as display load, response load, and memory load (Isreal, Wickens, Chesney & Donchin, 1980).

No single secondary task is uniquely suited to assess all variations in workload; instead, secondary tasks should be selected in accordance with the dimensions of task load that are of greatest concern in the system under evaluation (Isreal, Wickens, Chesney & Donchin, 1980).

Under conditions that control for age differences in single-task performance, age-related deficits in dividing attention are minimal unless the task possesses substantial memory demands (Salthouse, Rogan & Prill, 1984; Somberg & Salthouse, 1982).

Ecological Information Augmentation (EIA) is a process and methodology for the design of information displays. It is of particular use when the task domain is difficult because the information involved may not be particularly salient or may be difficult to process at higher levels. There are four steps to EIA: 1) Identify the key information in a specified perceptual/motor task; 2) Assess the theoretical degree to which the perception or processing of this information might constitute a processing bottleneck; 3) Design and implement a putative method to increase the saliency or cognitive processing efficiency of that information; and 4) Empirically test the results of the implementation. (Knecht, 2001)

Automaticity is closely and reciprocally related to the difficulty, mental effort, and attention resource demands of a member of a time-shared task pair (Kahneman, 1973; as cited in Wickens, 2000).

Two tasks that demand more common resources will show larger dual task decrements than two tasks that demand separate resources (Wickens, 1992; as cited in Wickens, 2000).

When humans get overloaded in a dual task situation (e.g., when demands exceed capacity), they can adopt various strategies of attention control (e.g., one might protect the more important task and allow decrement to less important task, could postpone one task completely). This illustrates how multiple task performance can move between concurrent performance and sequential performance (Adams, Tenney & Pew, 1991; as cited in Wickens, 2000).

Tombu supports capacity sharing. He may be suggesting that performance could be better or at least of same quality when dual-tasking than when single tasking because a person's level of arousal is higher. When tasks are more difficult, more effort is put forth. This idea is subject to the law of diminishing returns, though. If the dual task becomes too difficult then the same concept no longer applies. So, perhaps there is an optimal difficulty (Tombu & Jolicœur, 2003).
Visual guidelines for focal images cannot be extended to images displayed as a secondary task in a dual task situation. The difference in an image’s ability to convey meaning decreases when it moves from focal to secondary task situation. Display attributes for secondary tasks should be based on acceptable amounts of primary task performance degradation (Chewar, McCrickard, Ndiwalana, North, Pryor, Tessendorf, 2002).

Also in: 4.1.6

A secondary simultaneous task can slow change detection even if the distracting task requires different modalities from the primary task (Durlach, 2004).

Also in: 2.4.5

When users are faced with dual task situations, it is important to consider that a diversion of attention creates an opportunity for changes to occur on an unattended display. Because interruption to any task is a possibility, it has been suggested that all devices should draw the user’s attention to changed information when the operator resumes viewing a given display. (Divita, Obermayer, Nugent, Linvilleu, 2004)

Also in: 2.4.1, 3.1.1

Drawbacks of instant messaging systems are that they can be disruptive and the flow of conversation can be awkward in the absence of non-verbal cues. These limitations are especially bad in time-pressured scenarios because interrupting the primary task (with the instant messages) increases mental processing time and leads to errors on the primary task. (Cummings, 2004)

Also in: 3.1.1, 3.9.1, 4.1.7, 6.6.5

A multimodal condition (visual and audio) especially improved performance on a secondary task for older participants. Potential explanations for these findings include the following: visual abilities decrease with age (so users need audio to compensate for visual loss), older participants may experience higher workload while driving; or older users may be less equipped to deal with the same level of workload (older participants reported more stress in general when driving). (Liu, 2001)

Also in: 1.1.1, 1.1.4 AV, 6.6.1

Although warnings aided automobile driving performance, it decreased performance on a secondary task (peripheral detection). Thus, offloading from visual to audio or tactile for the primary task still did not help free enough visual resources for a secondary task (and actually made it worse for secondary task performance). (Martens & van Winsum, 2001)

Also in: 3.1.1, 3.1.2, 3.1.3, 3.3.1, 3.3.2, 3.3.3

The efficacy of three-dimensional audio cues in aiding target acquisition may be reduced when there is a secondary visual task (Pierno, Caria, Glover, & Castiello, 2005).

Also in: 3.6.1, 3.6.2, 3.6.4 AV

In a dual task situation, visual information should be conveyed in terms of relative position whenever possible to allow for optimal probability of accurate communication and primary task sustainability (Tessendorf, Chewar, Ndiwalana, Pryor, McCrickard & North, 2002).

Also in: 3.9.1, 4.1
Secondary-task displays must be selected based on some specification of acceptable primary task performance degradation (Tessendorf, Chewar, Ndiwalana, Pryor, McCrickard & North, 2002).

Also in: 4.9

Foveal visual cues are not supportive of task-sharing and attention allocation, particularly for noticing unexpected changes. Peripheral visual or tactile cues are better. Tactile cues are particularly good when workload is high. (Sarter, 2001)

Also in: 2.4.1, 2.4.3, 3.4.1, 3.4.3, 4.1.6, 6.3.1, 6.3.3, 6.6.1, 6.6.3

Tactile and audio cues can be processed in parallel (Sarter, 2000).

Also in: 2.73, 2.74 AT

Older participants (age 60 and older) have difficulty in dividing attention; this is due to actual difficulties in dual tasking, not just the additive effects of lower performance in each individual task (Ponds, Brouwer, & van Wolffelaar, 1988).

Also in: 1.1.5, 6.3.5

Spatial arrangements are used to represent temporal relationships among multiple tasks (Malone, 1983; as cited in Gwizdka & Chignell, 2004).

Adaptive audio display technology will require the following: 1) intelligent prioritization and novel presentation algorithms, 2) computational auditory scene analysis techniques for evaluating external auditory constraints in real-time and 3) automated multidimensional sound processing techniques.

The use of properly designed, spatialized alerts can significantly reduce effort and improve response times in a highly demanding, dual-task setting with no effect on decision accuracy or other measures of performance. (Brock et al., 2003)

Also in: 2.1.2, 3.1.2, 4.2

Performance in dual-task situations can be better than in single-task situations because subjects find the situations more challenging and thus increase the amount of effort they expend (Weinstein & Wickens, 1992).

Also in: 6.3.5, 6.6.5

Search performance was decreased when participants simultaneously heard and responded to questions about prose passages while driving. For dual-task condition, participants are less accurate in identifying signs, took longer to do searches and showed more prolonged fixations indicating more effortful processing. Subjective measures of workload supported these findings. (McPhee et al., 2004)

Also in: 3.3.2, 6.6.2

There is empirical support for the serial processing theory of attention (Eriksen & Yeh, 1985).

High priority events were handled faster and more accurately than low priority events (Parush, 2004).
The impact of display layout on performance depends on the event type: high priority events handled quicker and more accurately in full screen layout (Parush, 2004).

Also in: 4.1.4

A reduction in visual load (e.g., full screen layout with a single event log) is more supportive of a supervisory task that requires focused attention on one event type. In contrast, a reduction in operational load (e.g., full screen layout with five event logs) is more supportive of supervisory tasks that require divided attention across different event types of different handling priority. (Parush, 2004)

Also in: 4.1.4, 6.6.1

Objects that are created by combining color and shape or size do not create emergent features. Combining spatial and non spatial dimensions like colors or shapes into a single object facilitates initial parallel processing of both dimensions in a way that will support both focused attention and information integration.

Using separate colors for each indicator disrupted information integration. Using common colors disrupted focused attention relative to performance with monochrome display.

Using unique color borders compensated for the loss of distinctiveness of individual dimensions and lead to improvement in both attentional and integrational performance.

Current data suggest that the extra time (200-400ms) needed to process color information is probably worthwhile given the increase in the accuracy of check reading and given that the accuracy of integrations was not disrupted by color. (Wickens and Andre, 1990)

Also in: 4.1.1, 4.1.2, 6.3.1

Interacting cognitive subsystems (ICS) theory suggests that information flows in a highly parallel and modular architecture of distributed cognitive resources. It takes into account cognition and affect simultaneously.

Haptic info can access the level of meaning in a relatively direct manner (within the framework of ICS). Representations can be related to the active aims and goals of the perceiver. (Booth & Schmidt-Tjørksen, 2001)

Also in: 2.7.3

Haptic processing is dependent on stored representations at each of various subsystems—this could be relevant to any set of resources: if incoming information matches or activates representations within a system, the result may be faster and more detailed representations. If stored representations are unavailable or irrelevant, then processing will be constrained to work on sensory input alone. This will affect processing time because receptors have limited parallel processing capacity. This usually results in longer processing times. (Booth & Schmidt-Tjørksen, 2001)

Also in: 2.5.3

Speech-based interactions (e.g., Cell phone use) that occur while a user is driving have dire effects on driving performance, resulting in up to a 4-fold increase in crash risk (Redelmeier & Tibshirani, 1997; Violanti, 1997 as cited in Lee, Caven, Haake & Brown, 2001).

Also in: 3.3.2, 3.3.4 AV
Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.2, 3.3.4 AV, 6.4.2, 6.4.4 AV, 6.6.2, 6.6.4 AV, 7.1.2, 7.1.4 AV

Advantages/disadvantages of displays: Visual displays are good for presenting a large amount of information, but they prevent visual attention to other tasks; Auditory displays can be used with other tasks, but they may be obscured by environmental noise; Tactile displays are easy to use while other tasks are being performed, but they can only transmit a limited amount of information. (Tsukada & Yasumura, 2004)

Also in: 2.7.1, 2.7.2, 2.7.3, 3.11, 4.1, 4.2, 4.3

When a task’s control demand becomes low (e.g., automatic performance), information processing becomes more parallel (Beilock et al. 2004; as cited in Luria & Meiran, 2005).

Also in: 6.1.5, 6.6.5

Response selection is parallel when tasks are repeated (because control demands are low) than when they are switched (Luria & Meiran, 2005). In other words, when tasks are repeated or practiced, then the next time the task is performed, it is more likely to be performed in parallel (versus serially), possibly because of practice effects. Furthermore, if one is switching from one task to a new task, control demands are higher and less likely to be performed in parallel.

Also in: 6.1.5, 6.6.5

Perceptual operations are processed in parallel, while response selection stages are processed serially (Pashler, 1994; as cited in Luria & Meiran, 2005).

Interference is greater when two visual tasks are performed together or when two auditory tasks are performed together, than when a visual task is combined with an auditory task (Treisman & Davies, 1973; Duncan et al., 1997; as cited in Bourke & Duncan, 2005).

Also in: 4.1.7, 4.2.3, 4.4.1, 6.2.4

When engaging in two dissimilar tasks (e.g., visual and verbal), it is visual template complexity, not display size that affects the level of interference resulting from the dual task (Bourke & Duncan, 2005).

Also in: 4.1.2, 4.1.4, 4.4.1

It is critical to first measure a baseline performance level across all participants, in order to more accurately determine the effect that a secondary task has on primary performance. If one is to determine the degree of effect upon performance that a stressor may exert, be it task- or environmentally-determined, individual differences in performance must be considered (Chase et al, 2004).

Also in: 1.4.5, 7.2.5

It is important to control for single-task performance when measuring between-group differences in divided attention ability (e.g., differences in dual task ability) (Somberg & Salthouse, 1982).

Also in: 1.4.5, 6.3.5
Contrary to previous research, Somberg & Salthouse (1982) suggest that there are no age-related differences in divided attention (i.e., dual tasking). Instead, other processes (e.g., memory, perceptual impairments) are responsible for the poorer performance of older individuals on individual tasks. Performance on individual tasks is worse to begin with, subsequently causing decrements in dual task contexts. 

Also in: 1.1.5, 6.3.5

GP#:1495

Top-down operations, such as voluntarily scanning a visual scene for information, are impaired by the addition of a concurrent auditory task (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 3.6.1, 3.6.4 AV, 4.4.1

GP#:1496

Visual scanning is adversely affected by divided attention (e.g., dual task context) (Richard, Wright, Ee, Prime, Shimizu & Vavrik, 2002).

Also in: 6.3.1, 3.6.1

GP#:1559

No single secondary task is uniquely suited to assess all variations in workload; instead, secondary tasks should be selected in accordance with the dimensions of task load that are of greatest concern in the system under evaluation (Isreal, Wickens, Chesney & Donchin, 1980).

Also in: 6.6.5

GP#:1661

Pilots scan near-domain information about system functions (presented by cockpit instrumentation) and far-domain information about local airspace and terrain features (out the window). Pilots have tried to develop efficient scanning methods to cope with these demands, but switching between domains is challenging because it requires rapid changes in line-of-sight (LOS) and optical focus, often under adverse physical conditions. Switching is also cognitively demanding because pilots have to pick-up and synthesize information across domains, thus creating a high potential for error (cites Weinstein & Wickens, 1992). (Tannen, 2000)

Also in: 3.8.1, 6.6.1

GP#:1672

Better task-map coherence resulted in better attention switching strategies, reduced navigation errors, and better performance (Prabhu, 1996).

Also in: 3.2.5, 6.3.5

GP#:1724

Under conditions that control for age differences in single-task performance, age-related deficits in dividing attention are minimal unless the task possesses substantial memory demands (Salthouse, Rogan & Prill, 1984; Somberg & Salthouse, 1982).

Also in: 1.1.5, 6.3.5, 6.6.5

GP#:1725

A common assumption related to visual attention is that parallel processing occurs without attention (preattentive), and that serial processing requires attention. There are examples that refute this assumption; specifically, targets that are processed serially and do not trigger “pop-out” can actually be discriminated from distractors in a dual-task situation. Moreover, targets that are processed in parallel cannot be discriminated from distractors when attention is occupied by some other concurrent task. Preattentive (preattentive) processing implies parallel processing. In practice, this is constrained by the size of the receptive fields. (VanRullen et al., 2004)

Also in: 2.6.1, 3.6.1, 6.3.1

GP#:1726
Preattentive tasks that result in parallel visual search rely on neuronal selectivity present in early visual areas (e.g., orientation, color), whereas preattentive tasks that result in serial visual search rely on higher level neuronal selectivity (e.g., color-orientation conjunctions, animals, faces). Differences are typically accompanied by size of receptive fields. (VanRullen et al., 2004)

Also in: 2.6.1, 3.6.1

GP#:1727

Two independent dimensions are needed to account for the variety of visual discrimination tasks: one with respect to visual search performance (parallel versus serial dimension) and the other with respect to dual-task performance (the preattentive versus attentive dimension) (VanRullen et al., 2004).

Also in: 3.6.1, 6.3.1

GP#:1748

Disruption by irrelevant sound is caused by conflict between two concurrent processes of seriation: one stemming from the rehearsal of material in memory, and the other arising from the obligatory processing of auditory information (Banbury et. al., 2001).

GP#:1751

Tactile navigation system shows promise for operational effectiveness, particularly in situations where there is a need for soldiers to attend to other task demand (e.g., target detection) or to deviate from the planned route (e.g., obstacles, enemy invasion) (Elliott et. al. 1997).

Also in: 3.2.3, 3.6.5

GP#:1760

People develop route and survey knowledge in parallel rather than in sequence (Ruddle & Peruch, 2004).

GP#:1769

Three factors that influence the ease/difficulty of dual-tasking are automaticity, multiple resources, and task similarity (Wickens, 1992; as cited in Wickens, 2000).

Also in: 6.1.5

GP#:1770

Automaticity is closely and reciprocally related to the difficulty, mental effort, and attention resource demands of a member of a time-shared task pair (Kahneman, 1973; as cited in Wickens, 2000).

Also in: 6.1.5, 6.3.5, 6.6.5

GP#:1771

Tasks that are less automated are more likely to interfere with other activities (Wickens, 2000).

Also in: 4.8.1

GP#:1773

When performing two reaction time tasks simultaneously, one can’t select responses for both simultaneously, even though response selection may be able to proceed in parallel with perceptual processing (Pashler, 1998; as cited in Wickens, 2000).

GP#:1774

Access to foveal vision is very limited and can’t be easily shared in dual task situations (e.g., one can’t read two things at once); auditory processing is similar (e.g., one can’t listen to two speakers at once) (Wickens, 2000).

Also in: 2.6.1, 2.6.2, 4.1.6, 4.2

GP#:1775

When humans get overloaded in a dual task situation (e.g., when demands exceed capacity), they can adopt various strategies of attention control (e.g., one might protect the more important task and allow decrement to less important task, could postpone one task completely). This illustrates how multiple task performance...

**Also in: 6.3.5, 6.6.5**

**GP#:1776**

It’s more difficult and more time-consuming to switch between two very different tasks than between two similar ones (Wickens, 2000).

**GP#:1777**

Optimal attention control is an important feature that distinguishes better and more practiced dual task performers from those who are less skilled (Damos, 1991; as cited in Wickens, 2000).

**Also in: 6.3.5, 1.4.5**

**GP#:1791**

In contrast to MRT, auditory presentation of side task information can be detrimental because of the phenomenon of “preemption” (Damos, 1997; Latorella, 1998, Wickens, Dixon, & Seppelt, 2002; as cited in Wickens, Goh, Helleberg, Horrey & Talleur, 2003). A discrete auditory message is more likely than a visual message to attract attention away from the ongoing visual tasks of higher priority (aviating, navigating) because the auditory channel has inherent attention-capturing properties (Spence & Driver, 2000; as cited in Wickens, et al., 2003); and if the message is long, it will be rapidly forgotten from working memory and hence must be attended to immediately.

**Also in: 3.1.1, 3.1.2, 3.2.1, 3.8.1, 4.1, 4.2, 6.3.1, 6.3.2, 6.3.4 AV**

**GP#:1792**

The delivery of both visual and auditory information could provide the best of both worlds – this redundancy gain has been found in the delivery of instructions, though it has been surprisingly absent when investigated in some dual-task contexts (Helleberg & Wickens, 2003; Seagull and Wickens, 2001; as cited in Wickens, et al 2003) as if the combination may produce the “worst of both worlds.”

**Also in: 4.4.3**

**GP#:1801**
Table 1
Recommendations for various notification systems design objectives, based on significant differences observed in the experiment. “Optimal Trial Only” column indicates result findings for the filtered optimal performance group.

<table>
<thead>
<tr>
<th>Ticker vs. Fade vs. Blast animation</th>
<th>Recommended</th>
<th>Not recommended</th>
<th>Optimal trials only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Browse time</td>
<td>No secondary display</td>
<td>—</td>
<td>Recommended—blast</td>
</tr>
<tr>
<td>Incorrect answers</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Perceived intrusiveness</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
<tr>
<td><strong>Secondary task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring latency</td>
<td>Blast, then fade</td>
<td>Ticker</td>
<td>—</td>
</tr>
<tr>
<td>Basic awareness hit rate</td>
<td>Ticker</td>
<td>Fade</td>
<td>Not recommended—blast</td>
</tr>
<tr>
<td>Basic awareness false alarm rate</td>
<td>Fade</td>
<td>Ticker</td>
<td>Recommended—ticker. Not recommended—blast</td>
</tr>
<tr>
<td>Detailed awareness hit rate</td>
<td>Ticker</td>
<td>Blast</td>
<td>—</td>
</tr>
<tr>
<td>Detailed awareness false alarm rate</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
<tr>
<td>Perceived ease of awareness</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
<tr>
<td><strong>Dual-task</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected frequency of use</td>
<td>Ticker</td>
<td>Blast</td>
<td>(Same)</td>
</tr>
</tbody>
</table>

(McCrickard, Catrambone, Chewar & Stasko, 2003)

Also in: 3.1.1, 3.1.2, 4.1, 5.2.1, 5.2.2, 5.4.1, 5.4.2

### 6.7.1 Bottlenecks

Capacity limits and bottlenecks may occur at three stages: (1) encoding visual information in working memory, (2) maintaining and monitoring that information, and (3) selecting an appropriate response (Marois & Ivanoff, 2005).

There is evidence that dual-task situations are processed serially (one task is done first, followed by another), rather than simultaneously (Klingberg and Roland, 1997).

When multiple information is presented visually, it must be processed serially, rather than in parallel (Sarter, 2000).

Gradual transitions between visual displays (3D and 2D) aids response time/accuracy for task switching compared to discrete (sequential) transitions (Hollands, Ivanovic, & Enomoto, 2003).

In general, sensing techniques in mobile devices should provide the following: eliminate/reduce user frustration by making it easier for the user to get at functionality while engaged in an auxiliary task (e.g.,...
dual tasking); mitigate attentional demands by using techniques that enable eyes-free use (e.g., offloading visual channels) (Hinckley et al., 2005).

Also in: 6.3.1, 6.6.1

Ecological Information Augmentation (EIA) is a process and methodology for the design of information displays. It is of particular use when the task domain is difficult because the information involved may not be particularly salient or may be difficult to process at higher levels. There are four steps to EIA: 1) Identify the key information in a specified perceptual/motor task; 2) Assess the theoretical degree to which the perception or processing of this information might constitute a processing bottleneck; 3) Design and implement a putative method to increase the saliency or cognitive processing efficiency of that information; and 4) Empirically test the results of the implementation. (Knecht, 2001)

Also in: 4.9, 5.2.5, 6.6.5

6.7.2 MRT

Tombu supports capacity sharing. He may be suggesting that performance could be better or at least of same quality when dual-tasking than when single tasking because a person's level of arousal is higher. When tasks are more difficult, more effort is put forth. This idea is subject to the law of diminishing returns, though. If the dual task becomes too difficult then the same concept no longer applies. So, perhaps there is an optimal difficulty (Tombu & Jolicœur, 2003).

Also in: 6.3.5, 6.6.5

There may be a performance decrement when two tasks both require the auditory mode (Brucken, Plass & Leutner, 2004).

Also in: 2.6.2, 4.2.3

General design principles relevant for sustaining situational awareness include the following: organize information around goals; present level two situational awareness information directly to support comprehension; support global situational awareness; support trade-offs between goal-driven and data-driven processing; make critical cues for schema activation salient; take advantage of parallel processing capabilities; and use information filtering carefully. (Endsley, Bolte, & Jones, 2003)

Also in: 3.5.5, 4.9, 6.4.5

The span of absolute judgment and span of immediate memory impose severe limitations on the amount of information that humans are able to receive/process/remember. Miller (1956) thought people should use only one sensory channel at a time, but he also concluded that humans can usefully perceive about 7 different variables presented in a single sensory modality. Considering the latter conclusion, using only visual displays would not optimal because it would limit human information perception bandwidth. (Miller, 1956; as cited in Loftin, 2003)

Also in: 4.1, 6

There is evidence for shared resources in driving and navigation (Prabhu, 1996).

Also in: 3.2.5, 3.3.5

The inherent multi-dimensionality of sound in time, timbre and space often renders it to be the preferred means of transmission of data, information, and alerts in human-computer interfaces. By using auditory displays, numerous streams of data can be presented concurrently, offloading the visual system to perform other tasks. (Roginska, 2004)
Time-sharing/dual task performance was found to be most efficient in a multimodal condition (e.g., visual in one ear, computer screen on opposite side), which is consistent with Wickens (1980). The finding is complicated because visual intramodal task performance was nearly as good as intermodal task performance, and auditory intramodal task performance was relatively poor compared to the other two conditions. Support was also found for parallel processing. (Rojas, 1996)

Two tasks that demand more common resources will show larger dual task decrements than two tasks that demand separate resources (Wickens, 1992; as cited in Wickens, 2000).

The design of the task environment or the training program can be altered to bring about greater success in time-sharing through deployment of multiple resources, or through training to develop automaticity and improve attention control (Wickens, 2000).
7. Evaluation of Device

7.1 User Evaluations (includes ease of use)

Users may experience difficulty integrating (comparing) objects in a scene when panning is required (Wickens, Thomas, & Young, 2000).

Also in: 4.1.4, 6

7.1.1 Visual

Observers find it difficult to follow a prescribed path of saccades through dense arrays of symbols (Hooge & Erkelens, 1998; as cited in Haimson & Anderson, 2002).

Also in: 2.7.1, 4.1.4

Increased contrast, in a visual display, is known to increase visual acuity (Heath 1956, Legge et al. 1987), image clarity (Poynter 1992), saccadic length (Roufs et al 1988) and comfort (Roufs et al 1991; as cited in Sheedy et al., 2003).

Also in: 2.7.1, 4.1.1, 4.1.3

Contrast enhancing filters (CEFs) in a visual display have not been found to increase legibility, user reading speed, letter counting or user comfort. In fact, CEFs have been found to increase user discomfort for CRTs (Cathode Ray Tubes), although the researchers note that this finding was counterintuitive because the purpose CEFs were designed to reduce glare and enhance readability of a screen, etc. (Sheedy et al, 2003)

Also in: 4.1.1, 4.1.4

7.1.2 Audio

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.2, 3.3.4 AV, 6.4.2, 6.4.4 AV, 6.6.2, 6.6.4 AV, 6.7, 7.1.4 AV

7.1.3 Tactile

Soldiers appreciate tactile navigation system for its ease of use and enabling of eyes-free and hands-free navigation (Elliott et. al., 1997).

Also in: 2.7.3, 3.2.3, 5.5.3

7.1.4 Multimodal (AV, AT, TV, ATV)

• AV

Speech-based interactions with an in-vehicle computer impaired driving performance (reaction time to the braking of lead car), increased subjective workload, and perceived distraction, especially when the in-vehicle system was more complex (Lee, Caven, Haake, & Brown, 2001).

Also in: 3.3.2, 3.3.4 AV, 6.4.2, 6.4.4 AV, 6.6.2, 6.6.4 AV, 6.7, 7.1.2

• AT
• TV
• ATV
7.1.5 Not Specific to a Mode

With the integration of displaying the degree of uncertainty into the presentation format of medical data, it is possible to make computer-produced data more reliable and acceptable by users (discussed here in the context of medical personnel) (Krol, Reich, Pavone & Fuhrman, 2004).

Also in: 4.9, 5.4.5

GP#:1386

The best user functions are often the most invisible. For example, highly skilled controllers valued simplicity over functionality. (Mackay, Fayard, Frobert & Medini, 1998)

Also in: 1.4.5, 4.9

GP#:1387

Ideas generated by persons outside of a particular job may not be as useful as those generated by the actual operator (Mackay, Fayard, Frobert & Medini, 1998).

Also in: 1.2.5

Participants may be unaware of the loss of accuracy caused by particular display-task combinations (Wickens, Thomas, & Young, 2000).

Also in: 7.3

GP#:1444

Guidelines for handling human errors:
1) Make the action more perceptible (i.e. the possibility of activating the execution of another likely wrong action should be reduced, a given action should provide unambiguous information for the ongoing activity, even before the attainment of the end state);
2) Use multi-sensory feedback;
3) Display messages at a high level but with specific content (i.e. multilevel error messages, error message tells you it can not comply with your request, but there is a “since” or “because” button you can use to receive more info);
4) Provide an activity log (people depend on external memory aids);
5) Allow comparisons (comparisons between outputs is a useful source of information for action evaluation);
6) Make results available to users as soon as possible and allow the user to have control of the format display (suggestions for this include, i) exploiting layout, ii) exaggerating the differences, iii) stressing the aspects relevant to the just performed task);
7) Provide result explanations (i.e. make it extremely easy to determine why an input was not successful. If an input causes an error, indicate the varying factors that may have led to the error and the best way to fix it. (Rizzo et al., 1996, 116-118)

Also in: 4.1.4, 4.8, 4.9, 5.3.5

7.2 Evaluation of Device

7.2.1 Visual

One of the reasons Sideshow, a peripheral awareness system, was so successful was because user input was integrated from the beginning of the design process (Cadiz, Venolia, Jancke, & Gupta, 2002).

Also in: 4.1.6

GP#:1680

The CAVE system outperformed head-mounted displays; however, the CAVE system requires 3 fixed projectors oriented at 270° and is not portable (Werkhoven and Bakker, 1998).

Also in: 4.1.4, 4.1.5
7.2.2 Audio
7.2.3 Tactile
7.2.4 Multimodal (AV, AT, TV, ATV)
  • AV
  • AT
  • TV
  • ATV

7.2.5 Not Specific to a Mode

When evaluating a device, one should consider the following: (1) mental workload; (2) situation awareness (how much the automation of decisions reduces the operator's situation awareness); (3) complacency (operator may not trust the automation and may eventually not monitor the device); and (4) skill degradation (operator may be out of practice due to the function being consistently performed by automation) (Parasuraman, Sheridan, Wickens, 2000).

Also in: 5.4.5, 6.4.5, 6.6.5

When performing usability tests on products that require task coordination, it is important to examine age-related performance after users have had sufficient experience to stabilize performance. (This principle could be applied to anyone (young or old) who is working a new task.) (Sit & Fisk, 1999)

Also in: 1.1.5

Perceptions of presence increases in virtual realities as frame rate increases. Frame rates below 15 frames/sec produce anomalous results. Presence in a virtual environment can be measured using physiological measures. Change in heart rate is a more accurate measure than change in skin conductance or change in skin temperature. Adding simple passive haptic cues (such as a small platform users stand on so they can feel edges with their feet) increases presence in virtual environments. (Meehan, Insko, Whitton, & Brooks, 2002)

Also in: 2.2.3, 6.4.3, 8.1, 8.3

Several researchers are developing methodologies for predicting how safe a design for an in-vehicle information or communications system is likely to be and the potential for excessive visual distraction when carrying out specific tasks (Green, 1999; Noy et al, in press; as cited in Burnett, Summerskill & Porter, 2004).

Also in: 3.3.1, 3.3.5

It is critical to first measure a baseline performance level across all participants, in order to more accurately determine the effect that a secondary task has on primary performance. If one is to determine the degree of effect upon performance that a stressor may exert, be it task- or environmentally-determined, individual differences in performance must be considered (Chase et al, 2004).

Also in: 1.4.5, 6.7

A system should use multimodality only if it helps in achieving usability criteria such as: enabling a fast interaction, improving recognition in a noisy (audio, visual or tactile) environment, enabling user to easily link presented information to more global contextual knowledge (interpretation), or translating information from one modality to another. (Martin, Veldman & Berouli, 1995; NOTE: this article deals primarily with user input, but the notes here are relevant to input from OR to user)
7.3 Between User Evaluation and Performance

Determining whether a given mode is better than another mode, or whether multimodal is better than unimodal feedback very much depends on the criterion of interest. For example, user preference and perceived ease of use do not always coincide with performance data. User preference may be more a function of what is typically used (users prefer the familiar) and biases in expectations (expectation that multiple modes must be better than a single mode). (Akamatsu, MacKenzie, & Hasbroucq, 1995; Jeong & Gluck, 2003; Kaster, Pfeiffer, & Bauckhage, 2003)

Also in: 1.2.5, 5.5.5

Several studies have shown that performance is enhanced using multiple modes. However, preference lies with unimodal work. Conversely, there is either a detriment or no difference using multimodal, but the operators prefer it. Therefore, operator preference is important to consider. (Ho, Nikolic, Water & Sarter, 2004; McGrath, Estrada, Braithwaite, Raj & Rupert, 2004)

Also in: 5.5.4, 5.5.5

Users vary widely in their preferences for a given modality. For example, there was a lot of variability in user preferences between light and heat as the preferred interruption cue (40% versus 60%), though user preferences had no affect on performance or effectiveness of the interruption cue (Arroyo & Selker, 2003).

Also in: 5.5.1, 5.5.3

Self-report of device/modality preference may not be as valid of a predictor of future use/ease of use/performance as observation of user’s past choices (proposition from Multimodal project team).

Also in: 5.5.5

Subjective ratings of mental demand show haptic and audio were low and good alternatives to visual, but according to pupil diameter, trimodal lead to reduced workload even though participants did not perceive it this way. Vibration of haptic feedback was processed as quickly as visual feedback. (Vitense et al., 2002)

Also in: 2.7.1, 2.7.3, 6.6.1, 6.6.2, 6.6.3, 6.6.4 ATV

In a comparison of 3 different visual displays (ranging from very graphical to very text-based), overall preference didn’t match recall performance (WebPortal, which was in the middle in terms of graphics/text, was preferred most, but InfoCanvas had the best recall) (Plaue, Miller, & Stasko, 2004).

Also in: 4.1.4, 5.5.1

Few people (less than 3% of those surveyed) felt that it wasn’t dangerous to use an in-vehicle navigation system while driving, yet there are an increasing number of crashes associated with the use of vehicle navigation systems (Burnett, Summerskill & Porter, 2004).

Also in: 3.2.5, 3.3.5, 5.5.5

Participants may be unaware of the loss of accuracy caused by particular display-task combinations (Wickens, Thomas, & Young, 2000).

Also in: 7.1.5
8. Virtual Reality

8.1 Visual

Tactile feedback in virtual reality systems results in an approximate two-fold performance improvement over visual-only feedback; audio feedback has less of an impact on performance (Gupta, Sheridan, & Whitney, 1997).

Also in: 8.2, 8.3, 8.4 TV

Despite improved performance with multimodal feedback (visual, audio, and tactile versus visual-only), completion times in virtual reality tasks (peg-in-hole) are still significantly slower than their real-life counterpart tasks (Gupta, Sheridan, & Whitney, 1997).

Also in: 2.7.4 ATV, 3.2.4 ATV, 8.4, 8.4 ATV, 8.6

When designing haptic virtual environments, consider the following principles: provide easy-to-find waypoints; do not remove buttons but rather gray them out and provide a different texture so they will still serve as waypoints; use enlarged interaction points so they are easier to see; the texture of the manipulandum (the object the user manipulates) impacts how the user interacts with the haptic device; the characteristics of the manipulandum transfer to the represented object; use rounded edges when representing an image haptically, as users have difficulty tracking sharp edges; and users perceive angles to be more acute in haptic images. (Sjostrom, 2001)

Also in: 4.3.1, 8.3

Perceptions of presence increases in virtual realities as frame rate increases. Frame rates below 15 frames/sec produce anomalous results.

Presence in a virtual environment can be measured using physiological measures. Change in heart rate is a more accurate measure than change in skin conductance or change in skin temperature.

Adding simple passive haptic cues (such as a small platform users stand on so they can feel edges with their feet) increases presence in virtual environments. (Meehan, Insko, Whitton, & Brooks, 2002)

Also in: 2.2.3, 6.4.3, 7.2.5, 8.3

Individuals with low spatial ability had significantly lower performance when searching for information in a desktop virtual reality environment (Modjeska & Chignell, 2003; as cited in Gwizdka & Chignell, 2004).

Also in: 1.4.1

In order for humans to work effectively in virtual environments, some form of haptic and visual feedback should be included in these systems (Mason, Walji, Lee & MacKenzie, 2001).

Also in: 8.3, 8.4 VT

In a head mounted display (HMD)-based virtual environment (VE) system with head tracker, if overall latency is longer than 200ms it will result in motion sickness. Motion parallax can help people perceive depth better than just wearing stereo glasses. Latency compensation aids in the accurate location of 3-D sound by at least 50%. (Wu et al., 1997)

Also in: 2.5.1, 4.1.5

Graphics and haptic update rates should be maintained at least around 30 Hz and 1000 HZ respectively to have satisfying experience interacting with a virtual environment (Basdogan et al., 2000).
When training a task in a virtual environment, you see order effects. Training in visual-only first followed by the addition of visual-haptic has better performance than the reverse order. (Basdogan et al., 2000)

Haptic feedback is better than visual feedback in establishing a sense of togetherness in a shared virtual environment. This may have implications of remote virtual displays for various area of the military collaborating remotely on a task. (Basdogan et al., 2000)

The field of view of the human eye is 200° horizontally, and 125° vertically—this has implications for HMDs (Iwata, 2004).

Stereoscopic viewing becomes especially useful in a virtual reality environment when the data load is light (Fujimoto & Ishibashi, 2004).

HMDs often degrade performance and lower presence because of their narrow field of view (FOV). The visual FOV of the [naked] human eye spans more than 180 degrees (Seay, Krum, Hodges, & Ribarsky, 2001; Waller, 1999; as cited in Yang & Kim, 2004).

Large time delays between control input and visual scene update adversely influence task performance in virtual environments (Ebenholtz, 1992; Kennedy et al., 1990; as cited in Draper et al., 2001).

Image scale factor (the degree to which the image is magnified or minimized compared to actual image) is a major factor in the inducement of simulator sickness (Draper et al., 2001).

Fixed time delays of up to 250 ms are not major contributors to simulator sickness (Draper et al., 2001).

To reduce simulator sickness incidences, avoid image scale deviations from 1.0 magnification when designing virtual interfaces (Draper et al., 2001).

Without a perceptual border indicating region to be attended to, the user’s attention may actually spread to the entire visual hemifield in which the attended position is located (Hughes & Zimba, 1985; as cited in Haimson & Anderson, 2002).
Navigating is best supported by an immersive viewpoint display, in part because this frame of reference is similar to the view that a navigator has when traveling through real space (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 4.1.4

GP#:1441

Users have a more difficult time estimating distances in immersed and exocentric 3D displays as compared with 2D displays (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 4.1.4

GP#:1445

Immersed displays yield reduced accuracy, relative to 3D exocentric displays, on tasks that require information located behind or beside the user. This effect exists even when the information is available by panning or by referring to an inset map (Wickens, Thomas, & Young, 2000).

Also in: 2.1.1, 3.2.1, 4.1.4

GP#:1447

Subjects using immersive displays “anchor” their judgments based on what is visible directly in front of them, rather than panning to see what is beside or behind them (Wickens, Thomas, & Young, 2000).

Also in: 4.1.6

GP#:1448

Immersive displays are best for assessing line-of-sight visibility, and provide better guidance than 2D displays when used in aviation settings (Wickens, Thomas, & Young, 2000).

Also in: 3.2.1, 3.8.1, 4.1

GP#:1449

The best visual display for global-understanding tasks (e.g., battlefield command) is one which offers an initial view of the battlefield in exocentric perspective, allowing the user to zoom in to an immersive view, but which also then pops back to an exocentric position (Wickens, Thomas, & Young, 2000).

Also in: 3.11, 4.1.4

GP#:1450

The space “hidden” from the user in an exocentric 3D environment is larger to the extent that the “tether” of the exocentric display is shorter (i.e. the viewpoint is closer to the point of interest or “anchor”) (Wickens, Thomas, & Young, 2000).

Also in: 3.11, 4.1.4

GP#:1588

As the field of view increases in a virtual reality environment, so will the user’s performance on spatial tasks and sense of “presence” (Reingold, Loschky, McConkie & Stampe, 2003).

GP#:1675

Modalities required for VR simulation varies by task (piloting task requires tactile and visual cues, while visual alone is okay for navigation/monitoring tasks) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

Also in: 3.2.1, 3.8.4, 8.4 TV

GP#:1676

Motion sickness in VR settings is particularly problematic when a sensory decoupling arises (e.g., visual indicated motion reference frame differs from physically indicated motion reference frame) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

Also in: 4.1.8, 8.5
Changes in the virtual viewing direction resulting in a rotation of the virtual environment makes users uncomfortable. Head-slaved displays let the user perceive a more stable environment. (Kappe, van Erp, & Korteling, 1999)

Also in: 4.1.5, 5

In immersive VR environments, greater importance should be given to the speed of updating than to display resolution (Reingold et. al., 2003).

Also in: 4.1.3

Visual feedback reduced performance times and underforce errors, compared to haptic feedback, at various levels of delay (between presentation of cues); however, visual feedback interacts with delay such that at 200 milliseconds, the modes are equal. Visual feedback can also increase the number of overforce errors committed. (Allison, Zacher, Wang & Shu, 2004)

Also in: 4.1.8, 4.3.5, 8.4 TV

8.2 Audio

Tactile feedback in virtual reality systems results in an approximate two-fold performance improvement over visual-only feedback; audio feedback has less of an impact on performance (Gupta, Sheridan, & Whitney, 1997).

Also in: 8.1, 8.3, 8.4 TV

Audio displays must be head-coupled to provide a stable acoustic environment with dynamic cues correlated with head motion (Wourms, Mansfield, & Cunningham, 2001).

Also in: 4.2.4

Subjects are capable of judging roughness (texture) in VR on the basis of sound alone (Lederman, 1979; as cited in Peeva, 2004). There is expected to be a significant negative correlation between texture roughness and pitch with rougher texture being associated with lower pitch (Peeva, 2004).

Also in: 4.2

3-D auditory displays of virtual reality can be used as a way to facilitate multi-channel listening processes (MacDonald et al., 2002).

Also in: 4.2

Separating sounds in both real and virtual spaces has been shown to increase the intelligibility of speech paired with a noise masker (Doll & Hanna as cited in MacDonald et al., 2002).

Also in: 2.7.2

Virtual audio may be particularly useful in assisting the localization of targets under non-optimal visual conditions, such as ground target detection (Tannen, 2000).

Also in: 3.6.2

8.3 Tactile

Tactile feedback in virtual reality systems results in an approximate two-fold performance improvement over visual-only feedback; audio feedback has less of an impact on performance (Gupta, Sheridan, & Whitney, 1997).

Also in: 8.1, 8.3, 8.4 TV

Audio displays must be head-coupled to provide a stable acoustic environment with dynamic cues correlated with head motion (Wourms, Mansfield, & Cunningham, 2001).

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Also in: 2.7.2

Virtual audio may be particularly useful in assisting the localization of targets under non-optimal visual conditions, such as ground target detection (Tannen, 2000).

Also in: 3.6.2

Also in: 3.1.3, 3.2.3

Interface designers need to consider the range of textural information available. Simulating large textures can inhibit the user’s movements so much that their ability to stay on the textured surface is negatively affected. (McGee, Gray & Brewster, 2001)

Also in: 2.7.3, 3.7.3

As frequency of texture increases, perceived roughness of the surface increases. In tasks that require users to discriminate between two surfaces in terms of levels of roughness, frequency differences between the two surfaces must be more than 5 Hz. (McGee, Gray & Brewster, 2001)

Also in: 2.2.3

The texture of a real/virtual surface can increase the sense of realism of an object and convey information about the object’s identity, type, location, function, etc. (McGee, Gray & Brewster, 2001).

Tactile feedback in virtual reality systems results in an approximate two-fold performance improvement over visual-only feedback; audio feedback has less of an impact on performance (Gupta, Sheridan, & Whitney, 1997).

Also in: 8.1, 8.2, 8.4 TV

Design considerations for a haptic virtual reality device include the following: keep the PHANToM device outside of the virtual environment; do not position the stand in the user’s line of sight; and do not make the virtual volume excessively large, as this reduces the quality of the force feedback (Fischer & Vance, 2003).

Also in: 8.7

When designing haptic virtual environments, consider the following principles: provide easy-to-find waypoints; do not remove buttons but rather gray them out and provide a different texture so they will still serve as waypoints; use enlarged interaction points so they are easier to see; the texture of the manipulandum (the object the user manipulates) impacts how the user interacts with the haptic device; the characteristics of the manipulandum transfer to the represented object; use rounded edges when representing an image haptically, as users have difficulty tracking sharp edges; and users perceive angles to be more acute in haptic images. (Sjostrom, 2001)

Also in: 4.3.1, 8.1

The addition of force-feedback decreases errors in a simple virtual reality dexterity task (Arsenault & Ware, 2000).

Also in: 8.7

When designing a haptic interface, use a familiar-shaped tool handle (as opposed to a multipurpose, generic handle) to allow a skill acquired in the real world to transfer to a virtual environment (O’Modhrain, 2004).
Perceptions of presence increases in virtual realities as frame rate increases. Frame rates below 15 frames/sec produce anomalous results. Presence in a virtual environment can be measured using physiological measures. Change in heart rate is a more accurate measure than change in skin conductance or change in skin temperature. Adding simple passive haptic cues (such as a small platform users stand on so they can feel edges with their feet) increases presence in virtual environments. (Meehan, Insko, Whitton, & Brooks, 2002)

Also in: 2.2.3, 6.4.3, 7.2.5, 8.1

Modeling a task/process with a dynamic physical metaphor and then haptically rendering this metaphor as the process controller promises to give users functional integration together with simplification. Hand-crafting and quality of haptic experience essential to acceptance - many users simply enjoy the feel of the tools. (Snibbe, MacLean, Shaw, Roderick, Verplank & Scheeff, 2001)

Also in: 3.7.3, 5.5.3, 8.7

In order for humans to work effectively in virtual environments, some form of haptic and visual feedback should be included in these systems (Mason, Walji, Lee & MacKenzie, 2001).

Also in: 8.1, 8.4 VT

Haptic feedback, especially with respect to object contact, is crucial for optimal performance in virtual environments (Mason, Walji, Lee & MacKenzie, 2001).

Also in: 8.6

Graphics and haptic update rates should be maintained at least around 30 Hz and 1000 HZ respectively to have satisfying experience interacting with a virtual environment (Basdogan et al., 2000).

Also in: 2.2.1, 2.2.3, 5.5.1, 5.5.3, 8.1

Haptic feedback is better than visual feedback in establishing a sense of togetherness in a shared virtual environment. This may have implications of remote virtual displays for various area of the military collaborating remotely on a task (Basdogan et al., 2000).

Also in: 3.9.1, 3.9.3, 8.1

Sound has a natural role in actions involving mechanical impact and vibration, so auditory display should be used to augment virtual haptic interfaces (Adelstein, Begault, Anderson & Wenzel, 2003).

Also in: 2.6.2, 4.6.3, 8.4 AT

The sensation of sustained contact with a virtual surface requires that the user be able to push into the virtual surface and experience compressive contact forces of sufficient magnitude, to make it feel solid (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.7.3, 4.3

Imposing tangential forces on users while they stroke a virtual surface adds an important sense of realness to perception of objects (Salisbury, Brock, Massie, Swarup & Zilles, 1995).

Also in: 2.7.3, 4.3
The major requirements for a haptic visualization method are constant haptic refresh rate, fast force calculations, fast incremental rendering, fast data modification, and consistent haptic and volume rendering (Avila & Sobierajski, 1996).

Also in: 4.3

By using the exact physical properties of the surface, the designer can work with material and dynamics in virtual reality, gaining an intuitive understanding of its malleability (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 5.3.3

The integration of haptics with traditional geometric modeling will increase the bandwidth of HCI, thus shortening the time-consuming design cycle (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 4.3

In 3D interactions, the direct and physical operations on real objects via a 2D mouse are both unnatural and counter-intuitive (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 5.3.4 TV, 8.6

Haptic rendering requires (1) sensing the position of user’s finger, (2) locating the nearest point of the surface, and (3) appropriately generating a force to be applied to the finger (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 4.3
### 8.4 Multimodal (AV, AT, TV, ATV)

Despite improved performance with multimodal feedback (visual, audio, and tactile versus visual-only), completion times in virtual reality tasks (peg-in-hole) are still significantly slower than their real-life counterpart tasks (Gupta, Sheridan, & Whitney, 1997).

Also in: 2.7.4 ATV, 3.7.4 ATV, 8.1, 8.4 ATV, 8.6

The number of senses stimulated directly affects the degree of immersion experienced in a virtual reality environment (Burdea, 1996; as cited in Fischer & Vance, 2003).

Also in: 8.5

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(Hale & Stanney, 2004)

Also in: 2.7.1, 2.7.3, 3.11, 4.1, 4.3, 4.9, 8.6, 8.7

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<table>
<thead>
<tr>
<th>Benefit</th>
<th>Visual Display (VD)</th>
<th>VD + Tactile Interface</th>
<th>VD + Positional Actuator</th>
<th>VD + Probe-Based (Force Feedback) System</th>
<th>VD + Exoskeleton System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile perception</td>
<td></td>
<td>More accurate judgment of softness and roughness than visual alone</td>
<td>Possible to judge with same accuracy as when using fingertip</td>
<td>If tactile actuators are present in fingertips, possible to judge texture</td>
<td></td>
</tr>
<tr>
<td>2D form perception (spatial acuity, pattern recognition, curvature perception, and so on)</td>
<td>Relative depth in field of view (FOV)</td>
<td>Tactile can be ignored when irrelevant</td>
<td>Cross-modal cueing effects useful</td>
<td>Not useful</td>
<td>If tactile actuators are present in fingertips, possible to judge 2D form perception</td>
</tr>
<tr>
<td>Spatial awareness/position (for example, objects in environment, limb with respect to trunk, body with respect to environment)</td>
<td>Relative depth of objects in FOV</td>
<td>Visual proprioception</td>
<td></td>
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<tr>
<td>3D form perception (length discrimination, weight, and shape identification, for example)</td>
<td>Identification and discrimination depend on viewing angle</td>
<td>Deformability through force feedback aid</td>
<td></td>
<td></td>
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</tbody>
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(GP#:1180)

(GP#:1201)

(GP#:1399)
Multimodal feedback enhances presence/performance in VR systems, but only when the feedback from one modality is consistent with another (Oviatt, 2003; as cited in Yang & Kim, 2004) and is configured appropriately for the task at hand (Oviatt, 1999; as cited in Yang & Kim, 2004).

Also in: 4.8.2

- AV
- AT

Sound has a natural role in actions involving mechanical impact and vibration, so auditory display should be used to augment virtual haptic interfaces (Adelstein, Begault, Anderson & Wenzel, 2003).

Also in: 2.6.2, 4.6.3, 8.3

- TV

Tactile feedback in virtual reality systems results in an approximate two-fold performance improvement over visual-only feedback; audio feedback has less of an impact on performance (Gupta, Sheridan, & Whitney, 1997).

Also in: 8.1, 8.2, 8.3

In order for humans to work effectively in virtual environments, some form of haptic and visual feedback should be included in these systems (Mason, Walji, Lee & MacKenzie, 2001).

Also in: 8.1, 8.3

When training a task in a virtual environment, you see order effects. Training in visual-only first followed by the addition of visual-haptic has better performance than the reverse order. (Basdogan et al., 2000)

Also in: 5.1.1, 5.1.4 TV, 8.1

Modalities required for VR simulation varies by task (piloting task requires tactile and visual cues, while visual alone is okay for navigation/monitoring tasks) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

Also in: 3.2.1, 3.8.4, 8.1

Visual feedback reduced performance times and underforce errors, compared to haptic feedback, at various levels of delay (between presentation of cues); however, visual feedback interacts with delay such that at 200 milliseconds, the modes are equal. Visual feedback can also increase the number of overforce errors committed. (Allison, Zacher, Wang & Shu, 2004)

Also in: 4.1.8, 4.3.5, 8.1

- ATV

Despite improved performance with multimodal feedback (visual, audio, and tactile versus visual-only), completion times in virtual reality tasks (peg-in-hole) are still significantly slower than their real-life counterpart tasks (Gupta, Sheridan, & Whitney, 1997).

Also in: 2.7.4 ATV, 3.7.4 ATV, 8.1, 8.4, 8.6

8.5 Not Specific to a Mode (fidelity consideration)
Make sure that what is presented in the virtual world corresponds to objects in the real world (Alhalabi & Horiguchi, 2001).

The number of senses stimulated directly affects the degree of immersion experienced in a virtual reality environment (Burdea, 1996; as cited in Fischer & Vance, 2003).

Use a body-centered frame of reference (as opposed to a device-centered frame of reference) to reduce susceptibility to sensory overload and to allow users to orient themselves to the direction of travel (Traylor & Tan, 2002; as cited in O’Modhrain, 2004).

Many researchers suggest the use of multimodal VR interfaces because they provide the user with more naturalness, expressive power, and flexibility [16].

Multimodal operating systems work more steadily than unimodal systems because they integrate redundant information that is shared between output modalities. (Althoff, McGlaun, Schuller, Morguet & Lang, 2001)

To minimize simulator sickness, limit initial virtual environment exposures to 10 minutes or less (Draper et al., 2001).

Because the appearance (fidelity) of the learning environment is not particularly relevant for some tasks, realism doesn’t need to be the principle focus underlying the development of virtual environment training systems (Waller, Knapp & Hunt, 2001).

In enabling knowledge that requires conscious effort to acquire, lower-fidelity (and less nauseogenic) desktop virtual environments may be just as effective as more expensive “immersed” virtual environments. Therefore, realism doesn’t need to be the principle focus underlying the development of virtual environment training systems. (Waller, Knapp & Hunt, 2001)

Investigators should account for gender differences and user interface proficiency before using measurements acquired in a virtual environment to draw conclusions about people’s knowledge of a real-world place (Waller, Knapp & Hunt, 2001).

Update rates in virtual reality environments should be as high as possible to avoid motion sickness (Reingold, Loschky, McConkie & Stampe, 2003).

Change in heart rate was the most sensitive physiological measure, and more sensitive than most, of the self-reported measures of presence (note: presence is a virtual reality term, it is “the sense of being there” in a virtual environment) (Meehan, 2001).
There are three major steps in designing a VR training simulation: task analysis/human computer interaction evaluation (what is the goal of training, what tasks to include, what are the requirements for sensory modality integration); iterative evaluation process (evaluate system for system usability and user considerations like motion sickness); and system-wide evaluation (how does device affect performance and does training transfer to natural environment). (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003)

Also in: 5.1.5

Motion sickness in VR settings is particularly problematic when a sensory decoupling arises (e.g., visual indicated motion reference frame differs from physically indicated motion reference frame) (Cohn, Schmorrow, Lyons, Templeman, & Muller, 2003).

Also in: 4.1.8, 8.1

One way to present spatial information in a virtual setting is by using a “room metaphor,” by which objects are located inside of 3D rooms; this allows for rapid learning of spatial knowledge within each room but not between rooms (called the “room effect”). This occurs even when walls between rooms are removed; thus, it’s not just a function of local viewing that is provided in each room. (Colle & Reid, 2003)

In virtual environments using tele-operators, latency is universally detrimental because it results in a mismatch between motor action and simulated sensory feedback. Delay can interfere with coordination and planning of motor actions. (Ellis et al, 1997; Park & Kenyon, 1999; as cited in Allison, Zacher, Wang & Shu, 2004)

Also in: 2.5.5

8.6 Object Manipulation

Despite improved performance with multimodal feedback (visual, audio, and tactile versus visual-only), completion times in virtual reality tasks (peg-in-hole) are still significantly slower than their real-life counterpart tasks (Gupta, Sheridan, & Whitney, 1997).

Also in: 2.7.4 ATV, 3.7.4 ATV, 8.1, 8.4, 8.4 ATV

Haptic feedback, especially with respect to object contact, is crucial for optimal performance in virtual environments (Mason, Walji, Lee & MacKenzie, 2001).

Also in: 8.3

In 3D interactions, the direct and physical operations on real objects via a 2D mouse are both unnatural and counter-intuitive (Ix et. al.; as cited in Dachille, Qin, Kaufman & El-Sana, 1999).

Also in: 5.3.4 TV, 8.3
8.7 Force Feedback

It is possible to “feel” a fabric through the internet using tactile cues (Huang, Metaxas, and Govindaraj, 2003).

Design considerations for a haptic virtual reality device include the following: keep the PHANToM device outside of the virtual environment; do not position the stand in the user’s line of sight; and do not make the virtual volume excessively large, as this reduces the quality of the force feedback (Fischer & Vance, 2003).

The addition of force-feedback decreases errors in a simple virtual reality dexterity task (Arsenault & Ware, 2000).
Modeling a task/process with a dynamic physical metaphor and then haptically rendering this metaphor as the process controller promises to give users functional integration together with simplification. Hand-crafting and quality of haptic experience essential to acceptance - many users simply enjoy the feel of the tools. (Snibbe, MacLean, Shaw, Roderick, Verplank & Scheeff, 2001)

Also in: 3.7.3, 5.5.3, 8.3

(Hale & Stanney, 2004)

Also in: 2.7.1, 2.7.3, 3.11, 4.1, 4.3, 4.9, 8.3, 8.6
9. Deleted Guiding Principles

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-- Speech-based control works best in tasks of speed and accuracy when complex information must be entered in conjunction with other manual or visual tasks.
-- When designing the vocabulary for speech-based control, use terms familiar to users, and avoid acoustically similar words.
-- Users can be trained to improve their microphone usage and pronunciation, and should be when possible
-- The use of voice commands as a consent response in heads-up-displays (HUDs) might be slower than an “OK” button owing to delays in the speech recognition process.
Wourms, Mansfield, & Cunningham (2001)

Pentland (2000) addresses “smart clothes”. Devices implemented in clothing that aid the user. Some examples given are a GPS navigation system in a belt that tells users through an earpiece which way to go. Eyeglasses with a 3-D map overlay giving terrain information. The article also mentioned audio sensors that will not alert you to something if it detects voices in the vicinity.

Xiao et al. (2003) Children have a predilection to integrate pen and speech simultaneously (77%) vs. sequentially for 64% of adults. “Self talk” helped people w/Down’s Syndrome increase their memory spans significantly. Even newer audio-video approaches could not distinguish self talk from intentional input into system while speaking. It is possible to circumvent self talk problem with a click to speak function.


Burnett, Summerskill & Porter (2004) A lot of work is being done in this area in speech recognition—offloading user output from touch to speech—non visual, non manual. People tend to look at a microphone when speaking to the system—want to look at who they are talking to (Graham & Carter, 1998).


Realism need not be the principle motivation underlying the development of VE training systems. – (Waller, Knapp & Hunt)

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