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14. ABSTRACT

Salience has generally been regarded as a property of a stimulus that allows it to stand out and be noticed. Typically, tactile stimuli are defined by dimensions such as the frequency, intensity, force, location, and duration of the signal. However, these definitions and their associated thresholds, in isolation, are of little value if one does not consider interaction characteristics of the user or situational context. In this report we describe a preliminary model for tactile salience composed of 3 core constructs (individual differences, technology, and context) and their interactions. This definition provides an integrated approach to assess effectiveness of tactile displays. We report an initial series of comparative tests using paired comparisons with forced-choice and independent scaled ratings of various multitactor patterns. Results showed significant differences due to tactor design characteristics, patterns of tactile cue arrays, and some differences due to measurement approach. Implications for future research are discussed.

15. SUBJECT TERMS

tactile displays, tactile actuators, tactile salience, multisensory wearable display, Soldier performance

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1. Introduction

1.1 Background: Effectiveness of Tactile Displays in Military Operations

A review of published literature investigating the use of tactile displays in operational settings has shown that this technology, when implemented effectively, can increase performance (e.g., speed, accuracy) and lower cognitive workload in general across a diverse domain of military operational settings, in land, sea, and air (van Erp et al. 2004; Self et al. 2007; Elliott et al. 2009, 2013a, 2013b). Tactile cueing has been shown to provide a particularly intuitive means of conveying direction and orientation information. The contribution and effectiveness of tactile displays for direction and orientation have been demonstrated in adverse, demanding, and distracting situations, such as combat vehicles (e.g., Carlander and Eriksson 2006; Krausman and White 2008), aircrew cockpits (Raj et al. 2000; Rupert 2000a, 2000b, 2004; McGrath et al. 2004; van Erp et al. 2006; van Erp and Self 2008), high-speed watercraft (Dobbins and Samways 2002), unmanned aerial vehicle landings (Calhoun et al. 2004, 2005; Aretz et al. 2006; McKinley et al. 2007), high-acceleration environments (Eriksson et al. 2006, van Erp et al. 2007), underwater environments (Chiasson et al. 2002; Samways 2005; Self et al. 2007), dismount Soldier navigation in rough terrain (Elliott et al. 2006, 2007, 2010b), dismount Soldier robot control (Redden et al. 2009; Elliott et al. 2010a) and during strenuous movements (Elliott and Gilson 2006, Pettitt et al. 2006, Redden et al. 2006). A 2002 report on spatial disorientation countermeasures stated that “The most important advance of recent years with the potential to combat spatial disorientation has been the use of tactile stimuli to give information on spatial disorientation” (Benson 2002). For dismount Soldier navigation, Soldier comments were highly in favor, agreeing that the GPS-driven tactile torso belt system allowed them to navigate “hands-free, eyes-free, and mind-free” (Elliott et al. 2010b).

Tactile alerts have also been effective in decision-making contexts, to better guide attention and manage interruptions. For example, they effectively prompted task switching in high-workload complex decision-making conditions (Ho et al. 2001; Hopp et al. 2005; Hameed et al. 2006, 2007) and simulation-based scenarios for human-robot interaction (Chen et al. 2008) and driving (Davis 2006, 2007; Ho et al. 2007). Krausman and her colleagues (Krausman et al. 2005, 2007) have demonstrated the value of tactile alerts to guide attention in simulations of tank leader communications and within simulated and actual vehicles with high levels of vibrations. Additional studies further support the ability of Soldiers to detect not only single alerts, but also spatio-temporal patterns presented across multiple tactors (i.e., vibrating mechanisms) to represent and communicate different kinds of information (Pettitt et al. 2006).

While preliminary results showed effectiveness of tactile displays for Army tasks, further improvements were indicated. Subsequent development of tactile display technology, funded by the Small Business Innovative Research (SBIR) program, resulted in more user-friendly instantiations of this technology (Elliott et al 2011). One effort integrated a tactile vest with instrumented glove technology that allowed hand and arm signals to be covertly communicated from the glove-equipped sender to the wearer of the tactile vest (Elliott et al. 2014). In that study, Soldiers were able to successfully interpret tactile patterns portrayed on the tactile vest during strenuous movements (e.g., running, crawling, climbing) and during tactical movement through rough terrain.

A second effort, also funded by SBIR, developed a tactile system as a smartphone app for networked communications and ease of use. Alternative tactors were also developed to enable tactile displays to present vibratory sensations that are easily distinguished when integrated within a dual-row tactile belt. Each row had a different type of tactor (also referred as tactile actuators). One type of tactor was used for navigation (direction cues), while another type, having a sharper sensation, was used for incoming alerts (Pomranky-Hartnett et al. In review.). When this dual-row tactile belt was added to a standard chest-mounted flip-down smart tablet display, Soldiers were able to move more quickly and accurately, correctly interpreting incoming messages while on the move. Soldiers were also able to minimize the use of the visual display. When the tactile belt system was off, Soldiers checked their visual map display an average of 17 times while navigating 300 m (during night operations); when the tactile system was on, Soldiers checked their visual display an average of 1.2 times for the same distance. The lower number of checks to the visual display frees the Soldiers' attention to better monitor their surroundings and helps maintain light security during night operations.

There is growing interest in using tactile cue displays for more-complex communications representing operational information and replacing or augmenting verbal (and possibly visual) concepts. Multiple resource theory (MRT) (Wickens 1992, 2002) predicts effectiveness of this approach given high workload through other sensory channels. Prenav theory (van Erp 2007) places more emphasis on ease of comprehension, such that the tactile cue displays would need to be inherently intuitive or trained to automaticity. Prenav explains how tactile cues can affect attention, cognition, and performance, with particular regard for the effects of practice, automaticity, and intuitive response. For example, when tactors are placed around the torso to indicate direction (e.g., turn in the direction of the vibration), the operator response is immediate and without deliberation.

Consideration of both MRT and Prenav theories generates predictions of higher effectiveness when there is 1) already a very high workload, 2) a need for attention management cues (for example, alerts), 3) a need for direction or spatial orientation information, or 4) tactile communication patterns are easily learned and easily identified with little or no attentional effort. When multiple patterns are involved, training through repetition can help achieve a more automatic recognition-based response (Shiffrin and Schneider 1984).

1.2 Tactile Salience

1.2.1 Salience

One of the general problems in all sensory perception is information overload, but humans are adept at using selective attention and quickly prioritizing large amounts of information and thus give attention to that which is the most important. Salience is the property of a stimulus that allows it to stand out and be noticed. Salience is widely used in describing visual system performance of humans and in computational models that drive computer vision (Frintop et al. 2010; Borji et al. 2013) but has not been extensively or systematically applied to the tactile modality.

1.2.2 Tactile Salience

Tactile salience can be simply defined as the probability that the tactile cue will be detected. In controlled laboratory settings, salience can often be modeled as a function of tactor engineering and the vibratory stimuli characteristics (i.e., physical characteristics of the signal itself) when context, or “noise”, is very low. However, as context becomes more complex, additional factors become significant (Mortimer 2011). Here we summarize key findings from a variety of increasingly complex investigations as they relate to salience of tactile signals.

1.2.3 Factors Associated with Tactile Salience

Many questions remain with regard to how best to design tactile arrays for a particular context. Further research in this area should clarify moderating factors and refine guiding principles to determine when, where, why, and how to best employ alternate cues to support operator performance in demanding or complex environments. For example, research should also look at the effects on other levels of performance complexity, from simple reaction times to complex decision making under uncertainty, and particularly on aspects of workload. Very few studies manipulate or measure workload in a systematic manner. A systematic approach is needed to better define, investigate, and predict efficacy of tactile displays. The following section offers one approach to conceptualization and investigation of tactile display effectiveness.

1.2.3.1 Tactor Characteristics

Early studies of tactile signaling focused on psychophysical responses to tactor characteristics (see, for example, the reviews by Verrillo et al. 1969; Cholewiak et al. 1991; Kaczmarek et al. 1991; Cheung et al. 2008; Lederman and Klatzky 2009). Others have also offered a thorough discussion of tactor characteristics in engineering terms such as the transducer force, bandwidth, and duration of signal (Loomis and Lederman 1986; Cholewiak and Wollowitz 1992; Jones and Sarter 2008). Self et al. (2007) provides a discussion of tactile signal properties (i.e., size, shape, orientation, position, moving patterns, frequency, amplitude, rhythm, and waveform) as they can contribute to effectiveness in military operations. Redden et al. (2006) showed significant differences in operational performance (e.g., perception and interpretation of tactile cues during strenuous movements). Many studies have accumulated that demonstrate that tactor characteristics can have significant impacts on tactile perception, localization, and interpretation.

1.2.3.2 Body Location

Sensitivity to touch and the discrimination of tactile cues are highly dependent on the body location. Touch is arranged somatotopically (i.e., point-to-point correspondence of body areas to the nervous system; Penfield and Rasmussen 1950), leading to an intuitive mapping of direction and spatial constructs on the surface of the body (van Erp 2007). The location of touch stimuli is mapped onto a posture percept to provide orientation. Information regarding direction and orientation has usually been portrayed through tactors mounted on the torso due to stability of the location and intuitive nature of the direction mapping (van Erp and Werkhoven 1999; Rupert 2000a, 2000b; Cholewiak and McGrath 2006).

However, other locations have also been proven effective for alerts, attention management, and, to some extent, direction information, including the wrist (Ho et al. 2001; Dobbins and Samways 2002; Calhoun et al. 2004; Brewster and King 2005) fingers (Lathan and Tracey 2002; Hameed et al. 2006), palm of hand (Tang et al. 1997), arm (Bloomfield and Badler 2007), abdomen (Moorhead et al. 2004; Ho et al. 2007), shoulder (Hopp et al. 2005), back (Lindeman et al. 2003; Tan et al. 2003; Jones et al. 2006, Hameed et al. 2007), and head (Myles et al. 2013). For each location, vibration amplitude and spatial sensitivity thresholds differ and affect the ease by which tactile sensations are perceived, discriminated, and understood.

While locations on the body will affect several types of sensitivity per se, they can also affect the intuitive understanding of the message. For example, a tap on the shoulder often evokes not only awareness and attention, but also an automatic response to turn one’s head toward the tap. These intuitive responses can aid the development of effective tactile cues. It is clear that tactile salience can be strongly influenced by body location.

1.2.3.3 Loading

It has also been shown that when holding tactor characteristics and body location constant, the pressure placed against the tactor will also impact perception. Despite what is measured on the benchtop, once tactors are mounted against the body, mechanical loading is introduced that can reduce vibratory output in many types of actuators (Mortimer et al. 2007).

1.2.3.4 Multitactor Cues

Perception of tactile cues can be enhanced through use of a multitactor array. These arrays may be as simple as using 2 or more tactors together to boost the tactile sensation. Multiple tactors can be used separately to convey meaning. For example, a 2-tactor array, with one tactor placed on each wrist, may be used to convey a direction cue (i.e., turn left, turn right). More-sophisticated arrays can be constructed, with both simultaneous and sequential activations, such that the tactor cues can be likened to melodies (Brewster and Brown 2004). Brewster and Brown referred to these tactile melodies as tactons (TACTile icONS). Similarly, multitactor cues developed to cue different operator actions have been referred to as tactions or tactile actions (Mortimer et al. 2011). Tactions have been defined in terms of broad dimensional variables and have also been linked to recognition/discriminability and importance (i.e., salience). Characteristics of tactions (e.g., simplicity, intuitiveness, meaningfulness, distinctiveness) can also affect salience.

1.2.3.5 Task Demands/Environmental Context

Published reviews of tactor characteristics discuss how the physical stimulus characteristics can affect perception and localization under controlled conditions (Jones and Sarter 2008). However, it is evident that situational factors and task demands also play a part in tactile perception. Theory-based discussions of multisensory tactile integration, such as MRT (Wickens 2008) and the Prenav theory of preattentive processing (van Erp 2007) emphasize the role of task characteristics in design of multisensory tactile designs. In addition, tactile cues have been found to be preferentially processed compared with other modalities under conditions of divided attention (Hanson et al. 2009).

The importance of task characteristics was demonstrated in a meta-analysis comparing tactile displays, visual displays, and tactile-visual displays. In a review of over 600 initial publications regarding these displays, over 60 studies provided empirical data meeting criteria for meta-analytic investigation (Elliott et al. 2009; Prewett et al. 2012). These analyses identified several moderating effects including workload, type of integration with visual display, and type of information cue (e.g., alert, direction, spatial orientation, semantic communication). Results were consistent with MRT, which predicts that distribution of information across sensory channels can result in better performance when one channel is overloaded. Tactile cues were associated with higher performance when they were added to an existing system. Results were also consistent with Prenav theory, which posits that an advantage of the tactile sensory channel is that they can be processed in an intuitive precognitive manner. Tactile cues were associated with higher performance when applied to tasks such as cueing direction or orientation.

The moderating impact of task demands has been clearly demonstrated in military applications. Pettitt et al. (2006) showed that tactile localization and perception can be affected by strenuous movements depending on the stimulus parameters of tactor actuation. Self et al. (2007) describes various issues with regard to spatial acuity, localization, and perception of tactile cues in military applications use. They note that while there are limits and biases associated with vibrotactile localization on the torso (as described by Cholewiak et al 2004; van Erp 2005a, 2005b), they often do not impact operational effectiveness, where information regarding general direction (e.g., left, right, front, back, up, down) are usually critical and sufficient. On the other hand, Self et al. (2007) noted that situations that require more-precise localization can benefit from tactile characteristics such as burst duration, stimuli onset asynchrony, and, in some instances, use of apparent motion and other tactile illusions. While single location tactile cues and multitactor patterns can be perceived during strenuous movements, care must be taken in the selection of tactor stimulus parameters (Redden et al. 2006) to avoid the effects of loading (Mortimer et al. 2007) during practical testing conditions.

1.2.3.6 Multisensory Considerations

In addition to consideration of the engineering aspects of tactile, there has also been a stream of research that focuses on cognitive aspects of multisensory integration—studying the effects of tactile signals as they are presented with information from other sensory channels. With the exception of tactile devices developed to aid persons with sensory impairments (sensory substitution), tactile displays function primarily in multisensory situations (sensory augmentation). Much support has amassed for the use of the tactile channel as an additional means of information processing. The ability of the operator to integrate multisensory information can, under some circumstances, create cross-modal interactions resulting in outcomes such as sensory illusions. Several hypotheses have been offered to explain the relative dominance of sensory modalities (Andersen et al. 2004, 2005; Spence and Ho 2008). However, the variety of predictions and outcomes show the complexity associated with this research, indicating that dominance can be a function of the user's chosen focus of attention.

While interesting effects have been noted as arising from multisensory incongruence, more practical conclusions can be made in terms of how tactile, along with other sensory channels, can enhance operator perception and response. A meta-analysis of 24 studies showed advantages to visual-audio multisensory displays compared with visual-only displays (Burke et al. 2006). Similarly, meta-analyses of tactile and visual displays showed advantages when tactile cues were added to visual display cues (Elliott et al. 2009). Effectiveness of tactile displays has also been shown to be a function of intuitive design in multisensory context for more-automated functions such as driving (van Erp and van Veen 2004) and spatial orientation (van Erp et al. 2006).

The study of human factors in multisensory integration research is ongoing; however, there is some convergence (Spence and Driver 1997). Specifically, in the majority of situations, a combination of stimuli across modalities that present correlated information will likely be more powerful and effective than that from a single sensory modality (Coovert et al. 2006). The addition of tactile cues has been associated with faster reaction times. Faster vehicle braking responses occurred in reaction to tactile rear-end collision warnings compared with when visual cues were used (Scott and Gray 2008; Spence and Ho 2008). Operators fired more quickly in outdoor target practice using targets to the left, right, and center when using torso-mounted tactile direction cues than with visual cues (Gilson et al. 2007). Tactile cues added to visual cues also yielded faster reaction times in simulation-based studies of operator decision making and performance (Forster et al. 2002; Calhoun et al. 2004, 2005,). van Erp and his colleagues found that adding tactile cues improved performance in visually demanding situations such as navigating a car through unfamiliar urban terrain (van Erp et al. 2004) and maintaining helicopter altitude in low visibility (van Erp et al. 2003). Similarly, Chiasson et al. (2002) reported faster navigation in air (high-altitude parachute environment), ground, and underwater using tactile direction cues. Tactile cues were found to be particularly helpful when added to provide additional information, such as alerts, direction cues, and spatial information. Redundancy of both visual and tactile cues was also associated with better performance. Overall results showed a consistent positive result for tactile cues, particularly when tactile cues were added to support an existing task rather than replace a visual information cue. Results show overwhelming evidence for the effectiveness of tactile cues when added to a task situation to guide direction, manage attention, or support spatial orientation.

However, meta-analytic results also showed a great deal of variation, particularly when tactile cues were used for communication, as opposed to their use as alerts, or for direction or orientation. Results were more consistently positive when tactile cues were used for direction, orientation, or alerts, particularly when the tactile cues were augmenting visual cues as compared with when they were used to replace visual cues (Elliott et al. 2009). When tactors are signaling direction, orientation, or just a general "alert", results regarding performance (e.g., speed, accuracy) were consistently positive depending more on tactor characteristics that affect perception and localization. Outcomes regarding speed and accuracy for more complex and nonintuitive information were moderated by the level and type of workload. In addition, remaining variance, after consideration of information type and workload level, indicates the presence of other factors that significantly affect perception and performance.

1.3 A Systematic Framework

It is clear that tactile salience is affected or moderated by many factors in addition to engineering characteristics of the tactors. While issues of tactor engineering are clearly important to the concept of salience, the salience of any tactile cue or taction will be affected, perhaps to a great extent, by many factors, including body location, characteristics of the user, task demands, and the environment in general.

Perhaps even more important, these core factors interact with each other such that the interactions may be more highly predictive than particular characteristics per se. Predictions of operator performance in naturalistic settings require the consideration of these characteristics as they interact in a particular setting. To better emphasize the interplay of these factors, Fig. 1 shows the construct of tactile salience as mediated by 3 core factors—characteristics pertaining to the user, the technology, and the environment—and their interactions. The effect of any one characteristic cannot be precisely predicted without consideration and/or control of other core factors.

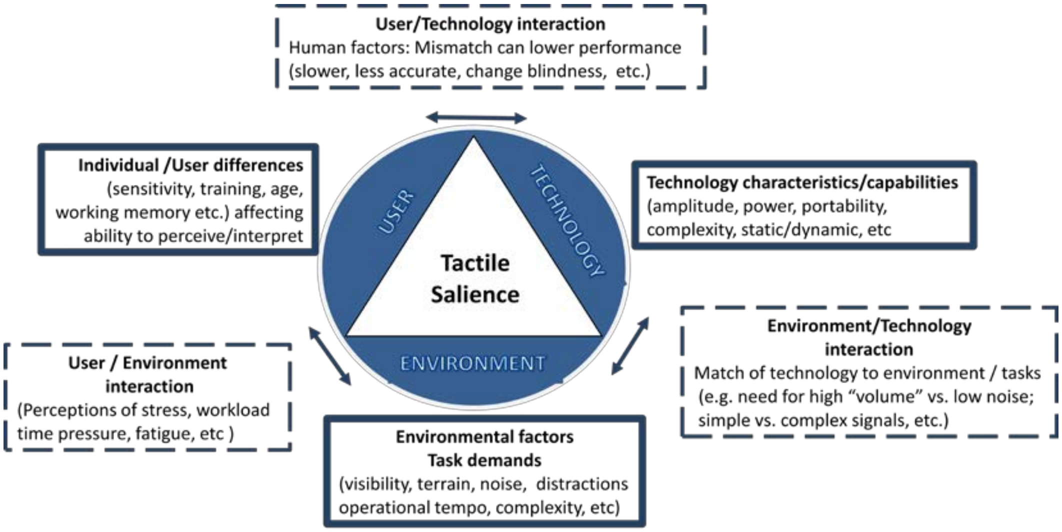

Fig. 1 Core factors and interactions affecting tactile salience

A description of the 3 main sources of influences on tactile salience, as shown in Fig. 1, follows.

1.3.1 Technology Characteristics/Capabilities

Many studies have addressed a multitude of features related to the design of tactile stimulators and the construction of the stimulus signal. There is no doubt that these factors affect salience and can predict user perception, localization, and interpretation in controlled settings. For example, abrupt onset (or changes) in stimuli and high-frequency (200–300 Hz) tone-burst vibrations are known to be naturally salient. Effects of characteristics such as amplitude, frequency, and interstimulus interval are well summarized in a number of publications (Cholewiak and Wollowitz 1992; Mortimer et al. 2007; Jones and Sarter 2008).

1.3.2 Individual/User Differences

Salience can also be affected by characteristics of the user. These include sensory and perceptual characteristics common to all operators, such as sensory processing limitations that limit tactile discrimination and body location (Cholewiak and Collins 1991). These can also include individual differences in cognitive abilities, personality, training, experience, age, or posture. Differences can always occur with regard to user motivation or focus of attention.

1.3.3 Environmental Factors and Task Demands

It has been shown that factors such as physical demands and workload can significantly affect tactile cue perception. In addition, a variety of contextual aspects, such as operational tempo, physical demands, nature and type of distracters, level of threat, and consequences of failure should be considered. Features such as environmental noise can certainly impact the perception, recognition and thus effectiveness of tactile signals.

While each category can act as a main effect on tactile salience, interactions among the categories are also important. Interactions between the user and the environment/task context produce factors such as perceptions of stress, workload, or fatigue that are likely to affect attention, the need for alerts, and/or the ability of the user to attend to alerts. As an example, individuals with higher levels of neuroticism, emotional reactivity, and/or lower stress tolerance are likely to experience work situations more intensely (Hogan 1991). While simple direction cues may prove valuable when the user is stressed or fatigued, more complex cues may be less likely to be attended to. Thus, map-based visual information and complex audio information (e.g., turn north after the second street on your left) can become much less effective than tactile direction cues (e.g., go this way). One can see that issues regarding multisensory integration would fit here.

Interactions between environmental/task context and technology include the degree of match between the operational context and technology features or capabilities. Basic examples include situations that require tactors that are very quiet (e.g., covert communications), or that augment attention management (complex decision making), or that are very easily perceived (e.g., during strenuous movements).

Interactions between the user and technology basically address the traditional domain of human factors engineering. The mismatch between user and technology characteristics can result in poor performance when technology does not address operator norms that affect their ability to perceive and easily interpret tactile signals. Thus, it is reasonable to posit that tactile salience depends on main effects and interactions among characteristics of the user, the technology, and the environment.

The identification of these core factors is not new. Many human factors approaches list similar or comparable factors (Hollnagel 2003; Crandall et al. 2006; Hall et al 2012) as do theories of decision making (Hollenbeck et al. 1995). The triangular framework resembles that of Hollenbeck’s decision-making theory, with regard to implications that can be tested using hierarchical regression analysis, to test for and distinguish mediating versus moderating effects. The framework emphasizes the interactions among the 3 core constructs, the importance of situation factors, and discourages the generation of principles that posit universal effects.

The framework allows for systematic identification of factors that are relevant to tactile salience in a particular operational context. It also can serve to organize and guide research through systematic hypothesis generation. As an example of a variable relating to technology, some tactors have been found to be effective under strenuous conditions while others have not, depending on the engineering specifications of the tactor used for the display. Another set of variables includes those relating to the type, degree, and distribution of task demands/workload. For example, waypoint land navigation is now relatively easy with a handheld device that has a visual map display. Many cars have such a device, often augmented by audio cues. For the driving task, this visual-audio display is usually sufficient for task performance. It can also be sufficient for a hiker, assuming the hiker is on a mapped trail. However, if the hiker goes off-trail, task demands increase. There may be more incentive to put the device away and pay attention to surrounding landmarks or threat (e.g., flora, fauna) and have hands free for other tasks (e.g., making one's way, drinking water). When attentional and physical task demands increase, the usefulness of tactile information that is intuitive and hands-/eyes-free is also likely to increase. Similarly, tactile alerts can help manage and focus attention in a complex high-tempo multitasked environment.

Figure 1, while simple, can serve to organize the variety of predictive factors (e.g., main effects and core mediating variables) and moderating interrelationships and guide systematic investigations for research. In addition, it can be a useful guide for tactile system development, using cognitive task analytic techniques (e.g., observation, interview) to identify characteristics of the naïve and expert users, along with characteristics of the task demands and environment context. This systematic approach allows consideration of the extent to which experiment findings will generalize from one situation to another.

1.4 Study Experimental Design

After reviewing important issues such as tactile limitations and advantages, multimodal combinations, and possible interactions, it is clear that a core characteristic of a tactile cue array in a given situation would be the degree to which the tactile cues are salient. In this study, we completed a preliminary exploration of the nature of tactile salience to collect baseline measures: when the cues occur in a more controlled situation and when the participant is stationary.

We operationally defined tactile salience through operator self-reports regarding their perceptions of various tactions. Tactile salience was explained as the degree to which a taction was "noticeable, distinct, strong". It was measured in 2 ways. In one set of paired cues, for each pair, the participant was asked to choose which one was more salient. In another set of paired cues, the participant was asked to rate each taction separately, on a 5-point scale, ranging from 1 = “weak, blurred, faint, vague” to 5 = “noticeable, distinct, strong, salient”. They then indicated which taction of the pair was stronger. For each pair of tactions, we systematically varied the tactor type within and across the 6 different taction cues. These baseline measures were evaluated for reliability and discriminability with regard to the different tactile cue signals.

2. Method

In this study, we examined the effect on salience of 2 tactor types as they were used on 6 different tactions. Differences were also expected among the tactions as a second main effect.

2.1 Type of Tactor

In this study, we compared perceptions of salience associated with 2 types of specialized tactors. In other common tactor types, frequency and intensity of the delivered stimulus may be less well controlled (limited more by the mechanical construction and skin coupling of the device than the electrical driving signal) and may be inseparably linked to one another. In one commonly used version of such a tactor (e.g., eccentric mass devices like pager motors), these qualities vary simultaneously and have complex multimodal skin stimulation that make precise definition of the stimulus signal more difficult. For this effort, we used 2 tactors developed to avoid these problems and optimized for human tactile perception, the EAI C-2/C-3 tactor and the EAI EMR tactor, as shown in Fig. 2.

Fig. 2 EAI EMR, C-2, and C-3 tactor transducers (left to right)

2.1.1 EAI C-3 Tactors

The EAI C-3 tactor is a smaller variant of the EAI C-2 tactor, which has been proven effective in previous experiments (Redden et al. 2006) The C-2 and C-3 are almost equivalent in vibratory output. The C-3 (6 g) is substantially lighter than the C-2 (18 g). In this study, we used the C-3 tactor, which has the same engineering approach as the C-2, shown in Fig. 2. The contact with the skin is from the predominant moving mass (Fig. 3), driving the skin with perpendicular sinusoidal movement that is independent of the loading on the housing (Mortimer et al. 2007). Only the “inner circle” vibrates, while the outer ring is still, thus stopping the “spread” of vibrations. In this study, the C-3 tactors were programmed at the frequency that is optimal for human perception on the torso (250 Hz). The sensation is particularly “sharp” with this type of tactor due to its structure and designed resonance. These linear actuator tactors provide a strong, point-like sensation that is easily felt and localized. The C-3 tactors have a rise time of less than 2 ms.

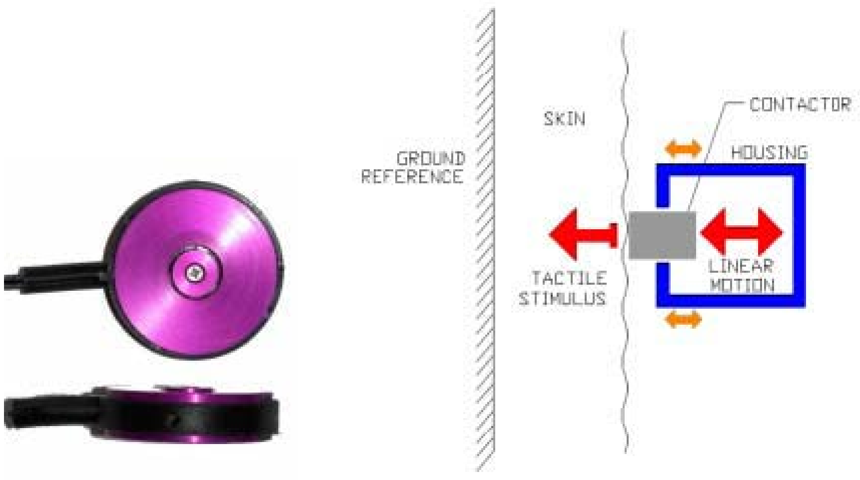

Fig. 3 C-3 linear actuator: photograph (left) and operational schematic (right)

2.1.2 EAI EMR Tactors

The EMR is a new, potentially low-cost design that produces the highest displacement amplitudes reported thus far, with an operating frequency around 80–100 Hz. The EMR has a rise time of about 12 ms. The C-3 tactors are considered to be moving magnet linear motors, while the EMR uses rotational motors that are suspended in a unique linear actuator configuration. The rotational motor is mounted on the moving “contactor”, which is lightly preloaded against the skin. When an electrical signal is applied, the “contactor” oscillates perpendicular to the skin.

Table 1 provides a description of characteristics of each type of tactor. Figs. 4 and 5 show the EMR and C-3 tactors as they are embedded within the prototype dual-row belt used in this study.

Table 1 Characteristics of C2, C-3, and EMR tactors

Characteristic	C-2 and C-3 Tactors	EMR Tactors
Mechanism	Moving magnet linear actuator	Motor-based actuator
Diameter	C-2: 1.17 inches; C-3: 0.74 inch	1.00 inch
Thickness	C-2: 0.30 inch; C-3: 0.24 inch	0.4 inch
Main frequency	200–300 Hz (but can operate at lower frequencies	50–140 Hz (but can operate at lower frequencies)
Peak displacement	0.04 inch	0.047 inch
Material	Anodized aluminum, polyurethane	Polycarbonate and ABS plastic

Note: ABS = acrylonitrile butadiene styrene.

Fig. 4 EMR and C-3 tactors in a prototype dual-row belt

Fig. 5 Prototype dual-row belt. Each belt contained a row of 8 C-3 tactors and a row of 8 EMR tactors.

2.2 Tactions

Tactile actions, or “tactions”, are a type of tactile communication where the activation of more than one tactor is used to communicate a single unique meaning. A taction can also be developed through multiple activations of a single tactor, where the timing can vary to communicate different meanings, similar to how Morse code can represent different letters. Tactions should be developed such that the user easily recognizes and distinguishes each taction. While the engineering characteristics of a particular tactor can affect tactile salience, so can characteristics of tactions with regard to the number of tactors used, their placement, and their sequencing.

The tactions used in this study are described in detail with the following figures. Tactions were created through software using visual graphics to easily create, save, and modify taction characteristics. Tactors 1–8 correspond to a lower row of EMR tactors and tactors 9–16 correspond to a higher row of C-3 tactors. Each tactor was separated by 3 inches. Some of the tactions (e.g., the ones with names, as opposed to “circle” or “x”) were developed and used in previous studies using Soldier subjects and were found to be easy to perceive and interpret (Gilson et al. 2007).

While each taction is given a label, such as “rally”, these labels were not communicated to the Soldier, as we wanted impressions of salience independent of assigned meaning. Further investigations will pursue taction characteristics associated with meaning (e.g., ease of learning, ease of recall).

Rally

The Rally taction comprises a dynamic sequence of pulses starting in the center (belly) and moving clockwise around the body. It was implemented on both rows (EMR, tactions 1–8, C-3, tactions 9–16), as portrayed in Fig. 6. Note that in these experiments, only one type of tactor was used in particular taction.

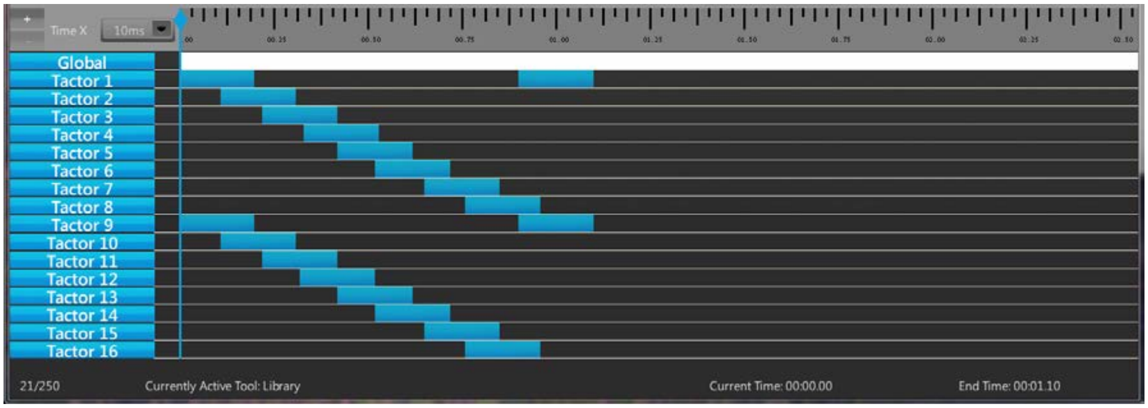

Fig. 6 Rally taction for EMR (tactions 1–8) and C-3 (tactions 9–16)

NBC

The NBC (nuclear biological chemical threat) taction comprises a dynamic sequence of alternating pulses (between the back left front right). It was implemented on both rows (EMR, tactions 1–8, C-3, tactions 9–16), as portrayed in Fig. 7. Note that in these experiments, only one type of tactor was used in a particular taction.

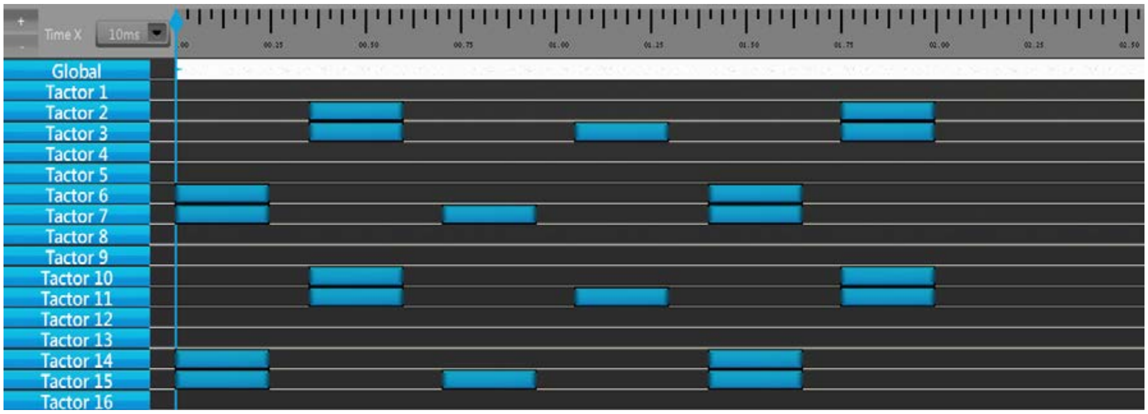

Fig. 7 **NBC taction for EMR (tactions 1–8) and C-3 (tactions 9–16)**

Halt

The Halt taction comprises of 4 repeated pulses (front, left, right, and back on simultaneously). It was implemented on both rows (EMR, tactions 1–8, C-3, tactions 9–16), as portrayed in Fig. 8.

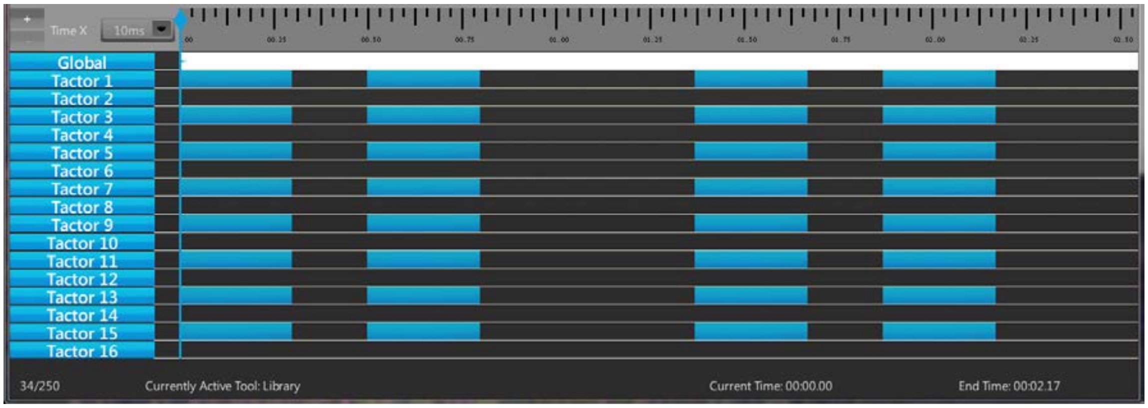

Fig. 8 **Halt taction for EMR (tactions 1–8) and C-3 (tactions 9–16)**

X

The X taction comprises 9 simultaneous pulses. It uses both the EMR and C-3 tactors in the taction. This taction was "static" in the sense that the pulse stimuli were presented on fixed tactors in the belt array. However, each tactor pulse was "complex" in that the amplitude or gain was ramped linearly. Specifically, each tactor was pulsed on for a 1,500-ms tone-burst duration while the gain was linearly varied from maximum to zero (254-1 gain) (see Fig. 9).

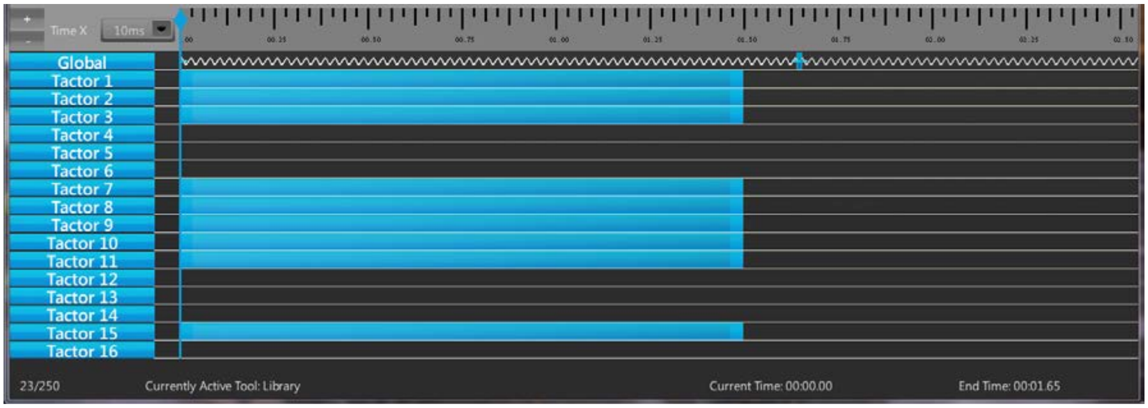

Fig. 9 X taction for EMR (tactions 1–8) and C-3 (tactions 9–16)

Circle

The Circle taction comprises 8 dynamic pulses on both the EMR and C-3 tactors. Each tactor pulse was "complex" in that the amplitude or gain was ramped linearly (see Fig. 10).

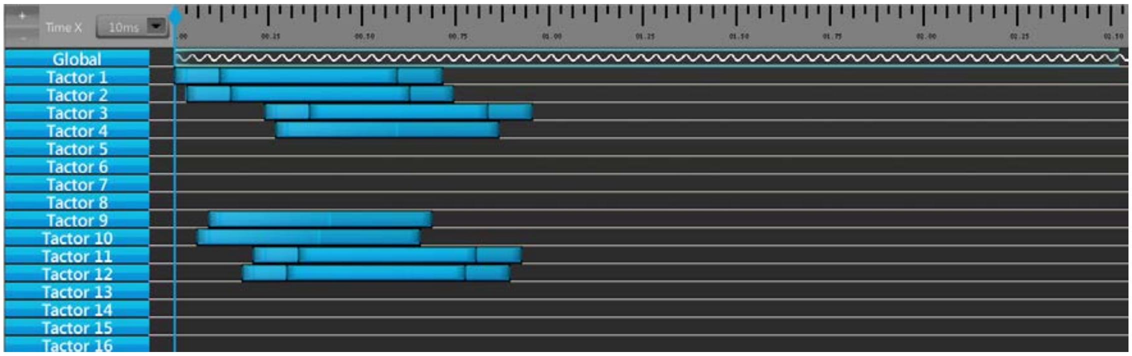

Fig. 10 Circle taction for EMR (tactions 1–8) and C-3 (tactions 9–16)

The effect of the circle taction was to produce the illusion of a circle being drawn on the front right torso.

2.3 Participants

Twenty-six Soldiers volunteered to participate in this data collection. They were drawn among Soldier participants who volunteered for a study on tactile support for Soldier navigation and covert communications. These Soldiers were recruited from active-duty units located at Fort Benning, GA (2-69 Armor Battalion). The Soldiers ranged in age from 18 to 31 (mean = 23), ranged in height from 60 to 74 inches (mean = 70), and weighed between 123 and 240 lb (mean = 175). They averaged 31 months of military service and ranged in rank from PVT to SGT. Their occupational specialties centered on infantry/armor and support operations. Twelve Soldiers listed deployments in combat operations such as Iraq and Afghanistan. Very few reported being ticklish in the chest/waist area (mean = 1.94, where 1 = not at all ticklish and 5 = very ticklish).

2.4 Procedures

2.4.1 Orientation

Upon arrival, each Soldier was briefed on the purpose of the investigation, the procedures to be followed during the study, and any risks involved in their participation. While Soldiers volunteered to be part of this study, they were given a more formal opportunity to reconsider. Copies of the informed consent form were provided to all participants, and the investigator explained the contents. They were informed that the nature of the experiment focused on their perceptions and rankings with regard to single tactile cues and pairs of tactile cues. All cues were presented while the Soldier was sitting and stationary. They understood they would wear the tactile belt and headphones delivering white noise to mask audio cues. Soldiers were given an opportunity to review the experiment objectives, have any questions answered by the investigators, and sign the consent form indicating their informed voluntary consent to participate if they were still willing. The participants were informed that if they chose not to participate, they could convey that choice privately to the experimenter. All Soldiers agreed to participate. A demographic questionnaire was then administered to obtain pertinent information on their backgrounds.

2.4.2 Training

Soldiers donned the belt system and responded with a yes or no (e.g., felt or not felt) each time a tactor was activated, during the fitting procedure, to ensure proper functioning of the belt. No problems with belt functioning were noted during the course of the study. Training consisted of familiarizing each Soldier with the rating scale used to assess salience. The tactions were previously developed to be associated with meaning (i.e., “rally”); however, in this study they were not associated with any meaning. The Soldiers did not need to be trained to recognize or distinguish them. This was to attain a rating of salience per se, as opposed to interpretability.

2.4.3 Data Collection

Two blocks of paired tactions were presented to each participant. Each block consisted of pairs of tactions, which were counterbalanced to enable systematic comparisons. For example, some pairs of tactions allowed for systematic comparisons of C-3 versus EMR tactors where the pair consisted of the same taction: the first taction was presented with C-3 tactors and the second with EMR tactors (and vice versa). Similarly, some tactions were paired to compare the relative salience of 2 different tactions when presented with the same tactor type. In this way, main effects due to tactor type and taction characteristics can be identified.

The first block of paired tactile signals were presented in pairs that crossed tactor type (EMR vs. C-3) and 3 different tactions named Rally, Halt, and NBC. The participants did not need to learn these tactions, as we were only interested in their perceptions of salience. Each Soldier was presented with a taction, followed by the second taction of the pair. Each Soldier was asked to indicate whether the first or second cue was more salient using the definition that was explained previously. A poster having this definition of salience was within sight. After the Soldier experienced both tactions, he/she indicated which one was more salient. Soldiers responded with either “first” or “second”. Figure 11 shows a row from the data collection sheet.

	First Presentation	**Second Presentation**	**Selection**	
1	HaltC-3	HaltEMR	1st	2nd

Fig. 11 First row of block 1 data collection sheet where the experimenter circles either the first or second taction as more salient

The order of pairings in block one crossed each tactor type and taction. For example, HALTC-3 was followed either by HaltEMR or HaltC-3. Similarly, RallyEMR was followed by either RallyEMR or RallyC-3. The ordered pairs can be seen in Appendix A. This order enables a 2 × 3 analysis of variance (ANOVA) to disentangle the effects of tactor type, taction, and their interaction.

For the second block of cues, tactile signals were also presented in pairs; however, each cue was rated independently for the degree to which the cue was salient according to the 5-point rating scale. The experimenter would present the first taction and the participant would respond with a rating from 1 (very low salience) to 5 (very high salience). The experimenter then presented the second taction, which the participant would also rate. The participant would then indicate which taction of the pair was more salient. The experimenter recorded each response on an observer form (see Appendix B for the complete form). Figure 12 shows the organization of the answer sheet filled out by the researcher.

First taction	Second taction	Rating for first (top row) and second (bottom row) tactions				
		1	2	3	4	5
RallyC-3	HaltC-3	1	2	3	4	5

Fig. 12 Data collection answer sheet for block 2 pairings; preferred taction was circled

The tactions used in block 2 included 4 tactions used in block 1 (RallyC-3, RallyEMR, HaltC-3, and HaltEMR) and 2 additional ones (X and circle). Each taction was presented first 5 times so that each taction was followed by each of the other tactions. There were no repeated pairs in this block and the presentation order of the pairs were randomized. The data collection sheet is provided in Appendix B.

3. Results

The following section provides descriptive statistics (means, standard deviations [SDs]) and inferential tests of significance based on repeated measures general linear model (GLM). In addition to the F and p statistic associated with hypothesis testing, we also provide a measure of effect size, partial eta square ($\eta\rho^2$), to better interpret the practical significance of differences between conditions. In addition, we provide visual representation of the 95% confidence intervals within the bar graphs, which indicate the precision of the mean as it generalizes to the population (i.e., the range estimated, with 95% confidence, to include the “true” mean).

3.1 Block 1: Paired-Comparison Forced-Choice Responses

Analysis of this dataset was based on the mean number of times the signal, when presented first, was chosen to be more salient. Given the forced choice nature of the variable, this mirrors the number of times the signal, when presented second, was chosen to be more salient. Data were separated with regard to pairs that contrasted different taction/types versus those that repeated the same taction/type. Descriptive data for the comparison pairs are presented in Table 2. The first commands are listed in the first left-most column followed by the second command. Some signal pairings were of the same signal (e.g., HaltC-3 followed by HaltC-3). Such “same” pairings are used to determine if an order bias exists (e.g., the first in the pair is always rated as “best”). Each pairing was presented 4 times. The pairings of interest are those that compared different tactions. Thus, for the first pairing, HaltC-3, when followed by HaltEMR, was chosen to be more salient an average of 20 times by the 26 Soldiers. When HaltEMR was presented first, it was chosen to be more salient an average of 3.25 times. Consideration of these comparisons leads to reliable estimates of the relative salience of each pairing. When averaged across all presentations, the mean number of times a particular signal was chosen as more salient ranged from 11.63 to 13.25, which is approximately half the time. This suggests no significant trend due to order bias.

Table 2 Descriptive results for block 1 dataset (without repeats), which indicates the mean number of times the first cue was chosen as more salient in a forced choice pairing

Tactor Type	Taction	Mean No. Times Chosen More Salient	SD	N
C-3	Halt	20.00	2.160	4
	NBC	24.50	0.577	4
	Rally	23.00	1.414	4
	Total	22.50	2.393	12
EMR	Halt	3.25	1.500	4
	NBC	2.00	2.000	4
	Rally	1.00	0.816	4
	Total	2.08	1.676	12
Total	Halt	11.63	9.117	8
	NBC	13.25	12.104	8
	Rally	12.00	11.808	8
	Total	12.29	10.622	24

Table 3 presents ANOVA results for the 2 main factors of tactor type (C3; EMR) and taction (Halt; NBC; Rally) and the interaction term.

Table 3 ANOVA results for tactor type, taction, and interaction term for the prediction of forced-choice preference

Factor	df	F value	P value	$\eta\rho^2$
Tactor type	1, 18	1,078.293	<0.001	0.984
Taction	2, 18	2.497	0.110	0.217
Type × taction	2, 18	8.749	0.002	0.493

Results indicate a significant and strong effect due to the type of tactor used, with the C-3 tactor being chosen much more frequently as more salient in the forced-choice pairing. In this context, the differences among tactions used did not reach the significance criterion of 0.05; however, the effect size showed a small to moderate effect. The effect size measures the actual difference between the means, controlling for factors such as sample size. For example, when one has a very large sample size, small effects can be found to be significant. However, in small samples, large effects can be found to be not significant because there is not enough statistical power to reach significance. When the sample size is small and significance is not found, larger effect sizes indicate a possibility that differences would have been significant given a larger sample size. There was a significant interaction among type and taction; that is, the effect of tactor type was somewhat moderated by the taction used.

Figure 13 shows the mean number of times each taction was preferred as more salient, divided by tactor type. It should be noted that, given the forced-choice format, that the higher the mean preference for one taction, the mean for the other taction will likely be correspondingly lower. In addition, the consistency of preference is not a direct measure of the difference in degree of salience. A tactor type might be somewhat more noticeable, as opposed to very much more noticeable, and still have high consistency of preference. For each taction, and for the average across all tactions, there are significant differences in salience due to tactor type.

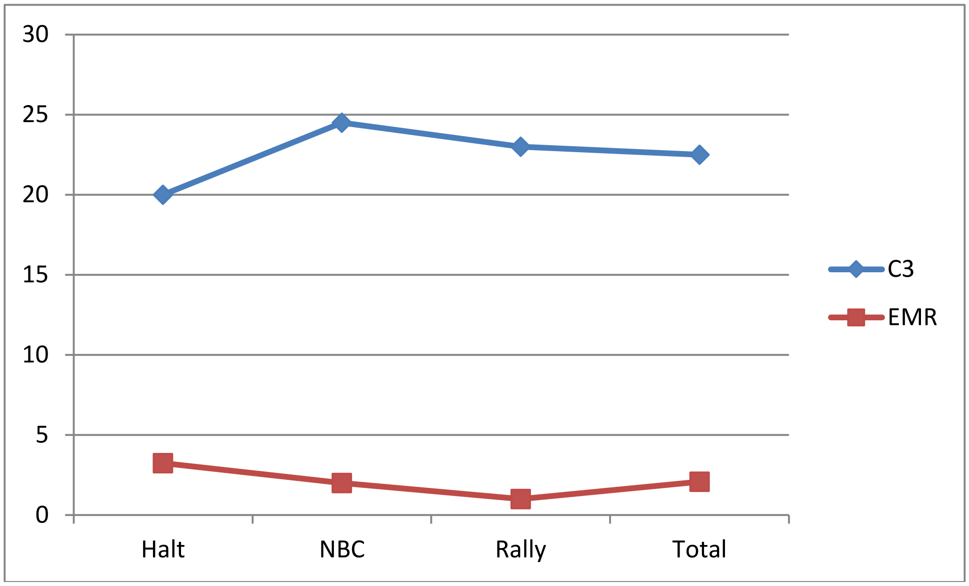

Fig. 13 Mean number of times each taction was identified as more salient by tactor type; data shown in Table 2

This forced choice data was also analyzed separately with regard to the pairs that presented identical taction/types. These were the pairs where the same taction was presented twice. Table 4 provides descriptive results. It should be noted that, given the forced-choice format, for all pairings the second mean will mirror the first such that the sum of the first and second means will always be 24. For example, the mean for HaltC3 is 12.50 for the first presentation; therefore, the mean for the second presentation would be 11.50.

Table 4 Descriptive results for forced choice dataset consisting of only identical pairs. Values greater than 12 indicate varying levels of preference for the first cue presentation.

Tactor Type	Taction	Mean No. of Times Chosen as More Salient	SD (1st)	N
C-3	Halt	12.50	3.109	4
	NBC	16.75	2.630	4
	Rally	13.00	1.633	4
	Total	14.08	3.029	12
EMR	Halt	14.50	2.082	4
	NBC	17.75	2.363	4
	Rally	15.25	1.500	4
	Total	15.83	2.329	12
Total	Halt	13.50	2.673	8
	NBC	17.25	2.375	8
	Rally	14.13	1.885	8
	Total	14.96	2.789	24

In Table 4, values lower than 12 indicate the second presentations were more frequently indicated as salient, while values higher than 12 indicate the first presentation was more frequently indicated as salient. It can be seen that NBC taction had a tendency to be more likely chosen as more salient for both C3 and EMR tactors. Further descriptive data providing means for each taction, as followed by each of the other tactions, are provided in Appendix C.

Within these identical pairings, there was a slight tendency overall to choose the first signal. Observation of raw data showed that some Soldiers had a tendency to consistently choose the first signal when both were perceived as “same”. However, there was also some variance due to the taction signal. The NBC taction was more likely to have the first presentation chosen as more salient, regardless of tactor type. ANOVA results, presented in Table 5, showed a significant difference due to taction. Results are portrayed in Fig. 14.

Table 5 ANOVA results for forced choice identical pairs (NBC, Rally, Halt) (repeated pairs only)

Factor	df	F value	P value	$\eta\rho^2$
Tactor type	1, 18	3.509	0.077	0.163
Taction	2, 18	6.167	0.009	0.407
Type × taction	2, 18	0.167	0.847	0.018

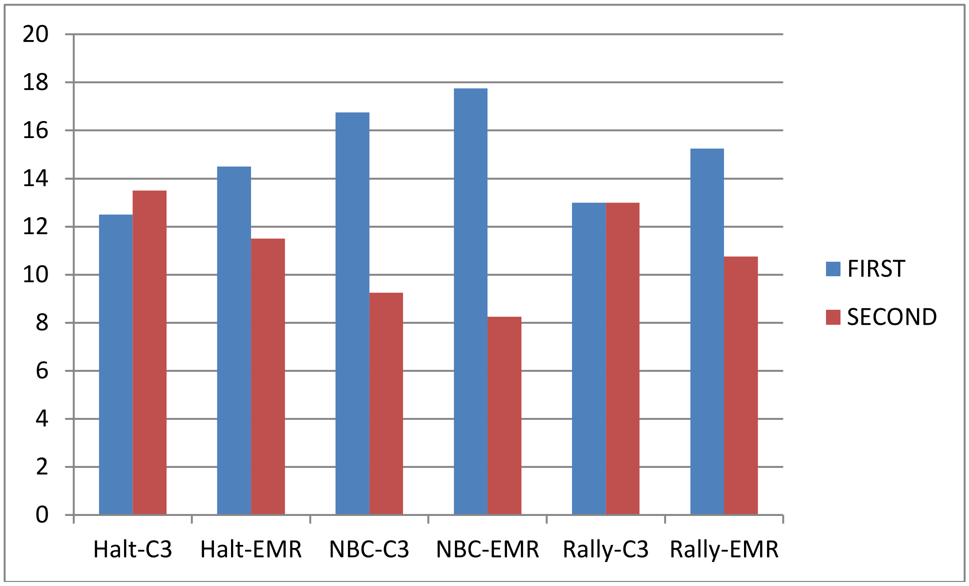

Fig. 14 Comparison of first vs. second presentations of identical pairs. Blue bars indicate the number of times that the first presentation of the identical pair was chosen as more salient. Red bars indicate the average number of times the second presentation of the identical pair was chosen as most salient.

3.2 Block 2: Independent Ratings in Paired Presentations

Block 2 data consisted of pairings presented to each Soldier. However, each Soldier rated the salience of each taction as it was presented using a 1–5 scale indicating strength of salience. They then indicated which of the tactions was more salient. This provides both forced choice data, as collected in block 1, and independent ratings. Use of independent ratings allows one to directly assess strength of differences in salience. For example, taction “A” may have consistently been chosen over taction “B”; however, the preference may be weak or strong. Independent ratings of the salience of “A” and “B” can be consistent with forced-choice analyses and better assess strength of differences in salience.

Analysis of this block 2 dataset was based on the mean rating assigned to each signal. Ratings ranged from 1–5, with 5 being the most salient rating. Table 6 provides the mean rating assigned to each signal when it was presented first in the pair. Results of ANOVA showed the differences among the mean ratings were statistically significant and large ($F, 5, 125 = 87.09$, $p < 0.001$, $\eta\rho^2 = 0.78$). Results are shown in Fig. 15. More descriptive data are provided in Appendix D, Table 1.

Table 6 Mean ratings for first presentation for each taction in block 2 where each signal was individually rated for salience on a scale from 1 to 5

Tactor Type	Taction	Mean	SD	Mean	SD	N
C-3	Rally	3.64	0.637	3.86	0.596	26
	Halt	4.17	0.559			26
EMR	Rally	2.66	0.534	2.95	0.500	26
	Halt	3.24	0.546			26
C-3 and EMR combined	Circle	1.90	0.731	2.99	0.482	26
	X	4.09	0.613			26

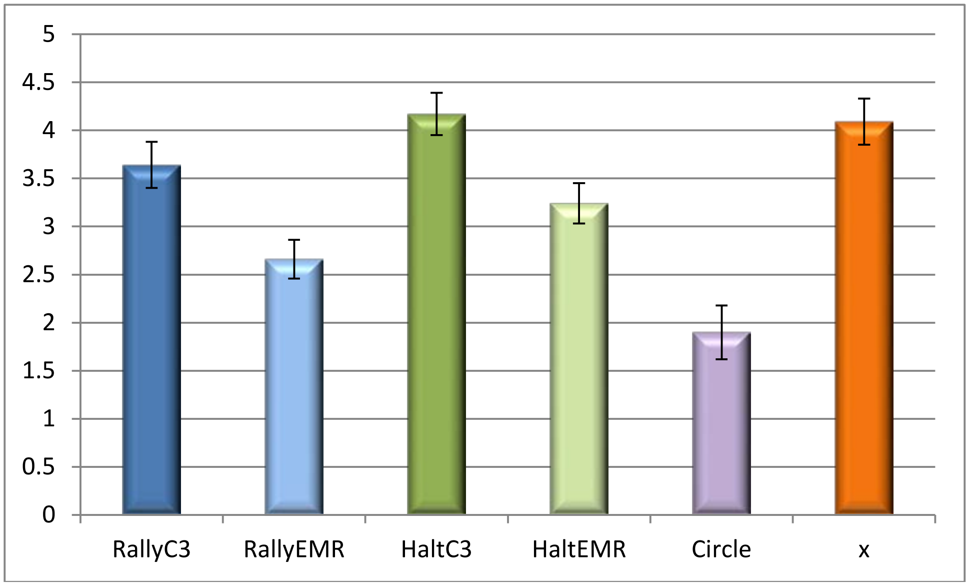

Fig. 15 Mean ratings for signals as they were presented first. Circle and X tactions used both C3 and EMR tactors. Error bars represent 95% confidence intervals.

Data were also analyzed for interaction between tactor type and taction among 4 tactions (RallyEMR, RallyC-3, HaltEMR, and HaltC-3C-3). Results are shown in Table 7 and indicate a significant and large effect for both tactor type and taction; their interaction was not significant. Results are displayed in Fig. 16.

Table 7 ANOVA results for tactor type, taction, and interaction term for the prediction of block 2 rating

Factor	df	F value	P value	$\eta\rho^2$
Tactor type	1, 25	70.74	<0.001	0.74
Taction	1, 25	57.79	<0.001	0.70
Type × taction	1, 25	0.375	0.546	0.015

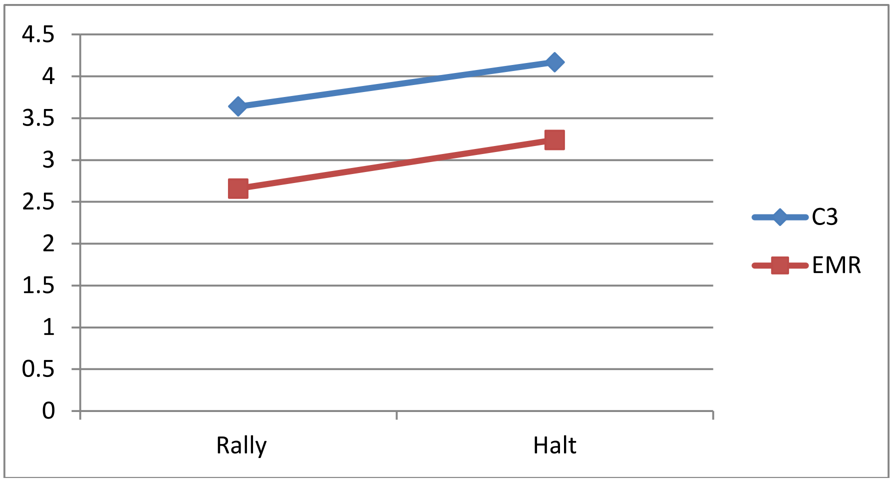

Fig. 16 **Mean ratings for block 2 Rally and Halt tactions by tactor type**

3.2.1 First Versus Second Presentation: Effect of Order

Table 8 presents mean ratings for each taction when the pairs are identical. Results indicate the ratings are equivalent regardless of being presented first or second when the user is not forced to choose. This is in contrast to results from the forced choice analysis that showed differences between the first and second presentations, particularly with the NBC taction (Table 4). Thus, while the forced choice format can be more sensitive to consistent differences, those differences may be quite small.

Table 8 **Mean ratings for each taction when presented first or second**

First presentation Taction	Mean (SD)	Second Presentation Taction	Mean (SD)
Circle	1.866 (0.107)	Circle	1.863 (0.052)
RallyEMR	2.600 (0.209)	RallyEMR	2.744 (0.187)
HaltEMR	3.159 (0.083)	HaltEMR	3.329 (0.099)
RallyC-3	3.692 (0.151)	RallyC-3	3.825 (0.123)
X	4.122 (0.098)	X	4.292 (0.103)
HaltC-3	4.200 (0.109)	HaltC-3	4.266 (o.130)

3.2.2 Influence of First Taction on Perception of Second Taction

Analyses were conducted on the mean ratings of the second taction as they differed as a function of the first taction. Means are included in Appendix D Table D-2. Results indicated no significant effect (F 1, 5 = 0.48, p = 0.80, = 0.071).

4. Discussion

4.1 Overview

This report summarizes published research regarding the effectiveness of tactile displays in tactical operational environments. These findings show that this technology, when implemented effectively, can increase performance (e.g., speed, accuracy) and lower cognitive workload in general across a diverse domain of operational settings, from underwater navigation to orientation in space environments. They have been found effective during strenuous movements and within heavily vibrating vehicles. Results also show effectiveness for different tasks, depending on the nature of the tactile cue (e.g., alert, direction, spatial orientation, communication), and whether the tactile cue is an independent source of information or whether it augments, in consistent fashion, information from other sensory channels. Tactile cues have been effectively perceived and localized across a variety of body locations. The effectiveness of a particular location will be affected by the purpose of the display.

While these findings are optimistic, further guidance is needed for the system developer to understand how best to design a tactile display for a particular purpose. While many research results show positive effect, results also indicate many moderating variables that affect whether, and to what degree, a tactile display would impact performance, such as operator training, tactor characteristics, level of workload, and operational context. These factors were organized in a framework that acknowledges 3 core main factors that mediate the salience of a tactile cue or taction—those relating to technology, operational context (task demands and environmental factors), and characteristics of the user. Perhaps more important are the interactions among these core factors. The main factors and their interactions affect the salience of the taction and the ability of the user to perceive, localize, and interpret the tactions.

- User characteristics (training, sensitivity, stress tolerance, ability)
- Operational context (task demands, environmental factors, noise, visibility, threat, etc.)
- Technology characteristics (tactor characteristics such as amplitude, power, etc., and system characteristics such as wearability, portability, weight loading, etc.)

4.2 Summary of Results

The experiment described in the report addressed some baseline issues with regard to relative salience of a small set of tactions varying in taction characteristics, such as whether they are static (simultaneous presentation of multiple tactors), dynamic (sequential activation of tactors), or complex (activation of multiple tactors using ramp modulations in vibrational amplitude). These tactions also varied with regard to the type of tactor used in the presentation. Two tactor types were used that varied in presentation characteristics. In the first block of paired presentations, tactile salience was measured by the user indicating which taction was stronger in each pair. In a second block of paired presentations, users provided forced-choice ratings and were asked to provide independent ratings of the salience of each taction using a 5-point scale ranging from 1 = "weak, blurred, faint, vague" to 5 = "noticeable, distinct, strong, salient". This allows comparison of measurement approaches.

The first block of taction pairs presented 2 types of tactors, each presenting 3 different tactions, using forced-choice paired comparisons, where the Soldier indicated which of 2 tactions were more salient. Summation of these preference scores indicate the relative salience of each taction compared with every other taction. ANOVA results indicated a strong and significant effect due to type of tactor, with the C-3 tactor being more salient as expected (due to its higher operational frequency). It also indicated a significant interaction effect, in that the difference due to tactor type was different for different tactions, such that the NBC-C3 taction was associated with the highest degree of salience. There were also noticeable differences in salience among the tactions, as indicated by their effect size; however, these differences did not meet the statistical criterion for significance. These differences will be further investigated in a follow-up study.

Block 1 data also included identical pairs, where one taction was followed by the same taction, with the intention of evaluating the presence of any order bias in the data. There was a slight tendency to choose the first signal; examination of raw data showed some Soldiers consistently chose the first signal given an identical pair. Results also indicated a significant order effect due to taction. Respondents were more likely to indicate the first taction as more salient if the taction was NBC regardless of whether the NBC was presented with C-3 or EMR tactors. The NBC taction was also associated with higher salience scores in general. This may be due to the simultaneous firing of multiple tactions or to body location. A follow-up investigation will investigate taction characteristics more fully.

In block 1, the differences due to tactor type were quite large. However, the large effect size may be due to the nature of forced-choice data: the higher the mean preference for one taction, the mean for the other taction will be correspondingly lower. The consistency of preference in a forced choice format is not a direct measure of the difference in degree of salience. A tactor type might be somewhat more noticeable, as opposed to very much more noticeable, and still be associated with high consistency of preference.

For the second block of paired presentations, we augmented the forced-choice response by also collecting subjective responses based on independent ratings of each taction based on a 5-point scale. This allows more quantitative analysis of the degree of preference. It also introduced 2 more tactions based on combinations of C-3 and EMR tactors. Results were consisted with the block 1 forced-choice data with regard to the effect of tactor characteristics: the differences among the mean ratings were statistically significant and large in favor of C-3 tactors.

A subset of block 2 data was also analyzed for interaction between tactor type and taction, among 4 tactions (RallyEMR, RallyC-3, HaltEMR, and HaltC-3). Results show a significant and large effect for tactor type, consistent with block 1 data. Unlike block 1 data, block 2 data also resulted in significant differences among the tactions, with lowest ratings for the circle taction and highest for the Halt and X tactions. Block 2 data did not find a significant interaction effect as was found in block 1. This may be because block 2 data did not include the NBC taction.

Block 2 data were also examined for order effects among identical pairs. Results did not find the order effect found in block 1 data: Results indicated the differences among the rankings were not significant. Analysis also compared the mean ranking of each taction with the mean of all other tactions averaged together; for example, the mean rating of the Circle taction compared with the average rating assigned to all other tactions presented second was analyzed. If there were no effect of the first taction on the second taction, one would expect the average of all tactions presented second would be similar, regardless of the first taction. However, the average of the second presentations varied, such that the mean was higher when the first taction had a low rating of salience and lower when the first taction had a high rating of salience. This indicates a contrast effect consistent with other subjective data involving rank order decisions (Tversky et al. 1982). Thus, it is important in experiment design to control for both order and contrast effects by using a counterbalanced approach such as Williams's squares. (Williams 1949).

Comparison of block 1 and block 2 analysis shows some difference due to measurement approach. The forced-choice approach appears to be more sensitive to differences in perception effects such as order even when these differences may be small. When respondents were able to indicate that a given pair was perceived as “same” (e.g., assigning the same rank) through the ratings procedure in block 2, the differences were minimized. The appropriate measure to be used in analysis will depend on the context and nature of the research question.

5. Conclusions

Findings from these analyses demonstrated significant effects due to tactor characteristics, with the C-3 tactor consistently associated with higher measures of salience using 2 approaches to measurement. This was expected, as the C-3 tactor was engineered with specifications similar to the C-2 tactor, which has been demonstrated in previous studies to be more effective than traditional tactors. The C-3 tactor is much smaller and lighter than the C-2, and thus these results have practical significance for the design of wearable tactile displays.

While C-3 tactors were more salient, Soldiers also had no problem perceiving the EMR tactors. The EMR tactors have the following advantages: It produces low-frequency stimuli, very-low acoustic signature, and high efficiency (with regard to power use). This experiment was performed with the Soldier stationary in a sitting position. Further investigation is planned for comparisons while on the move.

Significant effects were also found for differences among tactions and for interactions between tactor type and taction. Given these baseline findings, further research is indicated to investigate taction characteristics to better explain how some tactions are perceived as more salient. Further research is also indicated to better delineate the moderating effects of user characteristics and operational context as discussed within the conceptual framework of factors affecting tactile salience. Additional research is planned to investigate moderating variables on tactile salience. In addition, other cognitive performance constructs will also be examined with regard to ease of learning and recognition.

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Appendix A. Block 1 Data Collection Sheet

This appendix appears in its original form, without editorial change.

Soldier ID: 　　 **Date:** 　　 **Time:**

TEST BLOCK1

	First Presentation	Second Presentation	Selection	
1	HaltC-3	HaltEMR	1st	2nd
2	NBCEMR	NBCC-3	1st	2nd
3	RallyC-3	RallyC-3	1st	2nd
4	HaltC-3	HaltC-3	1st	2nd
5	HaltEMR	HaltC-3	1st	2nd
6	RallyEMR	RallyC-3	1st	2nd
7	NBCC-3	NBCEMR	1st	2nd
8	NBCC-3	NBCC-3	1st	2nd
9	HaltEMR	HaltEMR	1st	2nd
10	NBCEMR	NBCEMR	1st	2nd
11	RallyC-3	RallyEMR	1st	2nd
12	RallyEMR	RallyEMR	1st	2nd
13	NBCEMR	NBCC-3	1st	2nd
14	RallyC-3	RallyC-3	1st	2nd
15	HaltEMR	HaltEMR	1st	2nd
16	NBCC-3	NBCC-3	1st	2nd
17	RallyC-3	RallyEMR	1st	2nd
18	RallyEMR	RallyC-3	1st	2nd
19	HaltEMR	HaltC-3	1st	2nd
20	NBCC-3	NBCEMR	1st	2nd
21	NBCEMR	NBCEMR	1st	2nd
22	HaltC-3	HaltC-3	1st	2nd
23	RallyEMR	RallyEMR	1st	2nd
24	HaltC-3	HaltEMR	1st	2nd
25	HaltEMR	HaltEMR	1st	2nd
26	HaltEMR	HaltC-3	1st	2nd
27	NBCEMR	NBCEMR	1st	2nd
28	NBCC-3	NBCEMR	1st	2nd
29	RallyC-3	RallyC-3	1st	2nd
30	HaltC-3	HaltC-3	1st	2nd
31	NBCEMR	NBCC-3	1st	2nd
32	HaltC-3	HaltEMR	1st	2nd

33	NBCC-3	NBCC-3	1st	2nd
34	RallyC-3	RallyEMR	1st	2nd
35	RallyEMR	RallyEMR	1st	2nd
36	RallyEMR	RallyC-3	1st	2nd
37	NBCEMR	NBCEMR	1st	2nd
38	NBCC-3	NBCC-3	1st	2nd
39	HaltC-3	HaltEMR	1st	2nd
40	RallyC-3	RallyEMR	1st	2nd
41	HaltEMR	HaltC-3	1st	2nd
42	NBCC-3	NBCEMR	1st	2nd
43	HaltC-3	HaltC-3	1st	2nd
44	RallyC-3	RallyC-3	1st	2nd
45	NBCEMR	NBCC-3	1st	2nd
46	RallyEMR	RallyEMR	1st	2nd
47	HaltEMR	HaltEMR	1st	2nd
48	RallyEMR	RallyC-3	1st	2nd

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Appendix B. Block 2 Data Collection Sheet

This appendix appears in its original form, without editorial change.

	First Presentation	**Second Presentation**	**Response**				
1	RallyC-3	HaltC-3	1 1	2 2	3 3	4 4	5 5
2	RallyEMR	RallyC-3	1 1	2 2	3 3	4 4	5 5
3	X	RallyEMR	1 1	2 2	3 3	4 4	5 5
4	X	HaltC-3	1 1	2 2	3 3	4 4	5 5
5	RallyEMR	X	1 1	2 2	3 3	4 4	5 5
6	X	RallyC-3	1 1	2 2	3 3	4 4	5 5
7	RallyC-3	RallyEMR	1 1	2 2	3 3	4 4	5 5
8	HaltC-3	X	1 1	2 2	3 3	4 4	5 5
9	Circle	HaltC-3	1 1	2 2	3 3	4 4	5 5
10	HaltEMR	RallyC-3	1 1	2 2	3 3	4 4	5 5
11	Circle	HaltEMR	1 1	2 2	3 3	4 4	5 5
12	X	RallyEMR	1 1	2 2	3 3	4 4	5 5
13	HaltEMR	HaltC-3	1 1	2 2	3 3	4 4	5 5
14	RallyC-3	Circle	1 1	2 2	3 3	4 4	5 5
15	RallyEMR	HaltEMR	1 1	2 2	3 3	4 4	5 5
16	HaltC-3	RallyC-3	1 1	2 2	3 3	4 4	5 5
17	Circle	HaltC-3	1 1	2 2	3 3	4 4	5 5
18	Circle	RallyC-3	1 1	2 2	3 3	4 4	5 5
19	Circle	X	1 1	2 2	3 3	4 4	5 5
20	HaltC-3	HaltEMR	1 1	2 2	3 3	4 4	5 5
21	HaltEMR	X	1 1	2 2	3 3	4 4	5 5

22	X	HaltEMR	1 1	2 2	3 3	4 4	5 5
23	RallyEMR	HaltEMR	1 1	2 2	3 3	4 4	5 5
24	X	Circle	1 1	2 2	3 3	4 4	5 5
25	Circle	RallyEMR	1 1	2 2	3 3	4 4	5 5
26	HaltC-3	RallyC-3	1 1	2 2	3 3	4 4	5 5
27	HaltC-3	Circle	1 1	2 2	3 3	4 4	5 5
28	RallyEMR	RallyC-3	1 1	2 2	3 3	4 4	5 5
29	HaltC-3	RallyEMR	1 1	2 2	3 3	4 4	5 5
30	HaltEMR	Circle	1 1	2 2	3 3	4 4	5 5
31	Circle	X	1 1	2 2	3 3	4 4	5 5
32	RallyC-3	HaltEMR	1 1	2 2	3 3	4 4	5 5
33	RallyC-3	RallyEMR	1 1	2 2	3 3	4 4	5 5
34	RallyEMR	HaltC-3	1 1	2 2	3 3	4 4	5 5
35	HaltEMR	RallyEMR	1 1	2 2	3 3	4 4	5 5
36	RallyEMR	Circle	1 1	2 2	3 3	4 4	5 5
37	HaltC-3	HaltEMR	1 1	2 2	3 3	4 4	5 5
38	X	HaltEMR	1 1	2 2	3 3	4 4	5 5
39	Circle	RallyC-3	1 1	2 2	3 3	4 4	5 5
40	HaltEMR	X	1 1	2 2	3 3	4 4	5 5
41	X	RallyC-3	1 1	2 2	3 3	4 4	5 5
42	HaltC-3	X	1 1	2 2	3 3	4 4	5 5

43	Circle	HaltEMR	1 1	2 2	3 3	4 4	5 5
44	RallyC-3	X	1 1	2 2	3 3	4 4	5 5
45	HaltEMR	RallyC-3	1 1	2 2	3 3	4 4	5 5
46	HaltEMR	Circle	1 1	2 2	3 3	4 4	5 5
47	RallyC-3	Circle	1 1	2 2	3 3	4 4	5 5
48	HaltC-3	Circle	1 1	2 2	3 3	4 4	5 5
49	RallyC-3	HaltEMR	1 1	2 2	3 3	4 4	5 5
50	RallyC-3	HaltC-3	1 1	2 2	3 3	4 4	5 5
51	RallyEMR	Circle	1 1	2 2	3 3	4 4	5 5
52	HaltC-3	RallyEMR	1 1	2 2	3 3	4 4	5 5
53	HaltEMR	HaltC-3	1 1	2 2	3 3	4 4	5 5
54	RallyEMR	X	1 1	2 2	3 3	4 4	5 5
55	Circle	RallyEMR	1 1	2 2	3 3	4 4	5 5
56	HaltEMR	RallyEMR	1 1	2 2	3 3	4 4	5 5
57	RallyEMR	HaltC-3	1 1	2 2	3 3	4 4	5 5
58	X	Circle	1 1	2 2	3 3	4 4	5 5
59	X	HaltC-3	1 1	2 2	3 3	4 4	5 5
60	RallyC-3	X	1 1	2 2	3 3	4 4	5 5

Appendix C. Descriptive Results, Block 1 Variables

In the following table, the first column shows the taction command that was presented first. The second column shows the taction that followed the first. The third column (First Count) is the summation of preferences for the first taction. The fourth column presents the mean of the counts included for each specific pair. The fifth column presents the mean for all pairings starting with the first taction (e.g., HaltC-3). The sixth column presents the mean for all pairings beginning with the same command regardless of tactor (e.g., across HaltC-3 and HaltEMR).

First Command	Second Command	First Count[a]	Mean	Mean (SD)	Mean (SD)
HaltC-3	HaltC-3	16	12.5	16.25 (4.713)	12.56 (6.562)
		11			
		14			
		9			
	HaltEMR	22	20.0		
		20			
		21			
		17			
HaltEMR	HaltC-3	4	3.25	8.88 (6.244)	
		2			
		2			
		5			
	HaltEMR	17	14.5		
		14			
		15			
		12			
NBCC-3	NBCC-3	18	16.75	20.62 (4.502)	15.25 (8.676)
		13			
		17			
		19			
	NBCEMR	24	24.5		
		24			
		25			
		25			
NBCEMR	NBCC-3	1	2.0	9.88 (8.659)	
		1			
		5			
		1			
	NBCEMR	21	17.75		
		16			
		16			
		18			
RallyC-3	RallyC-3	13	13.0	18.0 (5.529)	13.63 (7.800)
		13			
		11			
		15			
	RallyEMR	25	23.0		
		23			
		22			
		22			
RallyEMR	RallyC-3	2	1.0	8.96 (7.298)	
		1			
		0			
		1			
	RallyEMR	16	15.25		
		14			
		17			
		14			

[a] Each pair was presented 4 times.

Appendix D. Descriptive Results, Block 2 Dataset

This appendix appears in its original form, without editorial change.

Table D-1 The following table shows the mean for the *first* taction, total and by each pairing

First Taction	Second Taction	Mean First Taction	Std. Deviation
RallyC-3	haltC-3	3.4808	.68528
	rallyemr	3.5962	.73511
	circle	3.6538	.74524
	haltemr_mean	3.7500	.69642
	X	3.7308	.81524
	RallyC-3	3.6423	0.636
Rallyemr	rallyC-3	2.4615	.59872
	x	2.5769	.50383
	haltemr	2.5769	.75753
	haltC-3	2.8846	.63730
	circle	2.8077	.61769
	Rallyemr	2.6615	0.534
x	rallyemr	4.0192	.69973
	haltC-3	4.1154	.65280
	rallyC-3	4.1538	.57912
	haltemr	4.0385	.89357
	circle	4.1154	.76561
	X	4.0885	0.631
HaltC-3	x_mean	4.0769	.67368
	rallyC-3	4.2308	.60383
	haltemr	4.1154	.55331
	circle	4.2692	.71036
	rallyemr	4.1538	.56159
	HaltC-3	4.1692	0.559
Circle	haltc	1.8269	.73406
	haltemr	1.9231	.74421
	rallyC-3	1.9038	.83689
	x	1.9615	.77360
	rallyemr	1.8846	.76561
	Circle	1.9000	0.731
Haltemr	rallyC-3	3.2308	.68163
	haltC-3	3.2115	.61924
	x	3.1923	.56704
	circle	3.2500	.63640
	rallyemr	3.3269	.52806
	Haltemr	3.2423	0.546

Table D-2 Mean rating of block two *second* tactions, ordered by preceding taction

First Presentation	Second Presentation	Mean 2nd Presentation	Std. Deviation	N
Circle	HaltC3	4.0370	.05238	2
	HaltEMR	3.3889	.02619	2
	RallyC3	3.8519	.10476	2
	RallyEMR	2.8333	.13095	2
	X	4.2593	.10476	2
	Total	3.6741	.54062	10
HaltC3	Circle	1.8889	.00000	2
	HaltEMR	3.3519	.02619	2
	RallyC3	3.9815	.13095	2
	RallyEMR	2.7222	.18332	2
	X	4.2963	.20951	2
	Total	3.2481	.92123	10
HaltEMR	Circle	1.8704	.02619	2
	HaltC3	4.3333	.00000	2
	RallyC3	3.7593	.07857	2
	RallyEMR	2.8148	.36665	2
	X	4.3704	.05238	2
	Total	3.4296	1.02107	10
RallyC3	Circle	1.9074	.02619	2
	HaltC3	4.2778	.07857	2
	HaltEMR	3.3148	.02619	2
	RallyEMR	2.6667	.26189	2
	X	4.2963	.05238	2
	Total	3.2926	.98076	10
RallyEMR	Circle	1.8333	.02619	2
	HaltC3	4.3148	.02619	2
	HaltEMR	3.3333	.15713	2
	RallyC3	3.7778	.15713	2
	X	4.2407	.13095	2
	Total	3.5000	.95792	10
X	Circle	1.8148	.10476	2
	HaltC3	4.3704	.05238	2
	HaltEMR	3.2593	.20951	2
	RallyC3	3.7593	.07857	2
	RallyEMR	2.6852	.13095	2
	Total	3.1778	.93188	10
Total	Circle	1.8630	.05252	10
	HaltC3	4.2667	.13042	10
	HaltEMR	3.3296	.09946	10
	RallyC3	3.8259	.12352	10
	RallyEMR	2.7444	.18760	10
	X	4.2926	.10395	10
	Total	3.3870	.88368	60

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List of Symbols, Abbreviations, and Acronyms

ANOVA	analysis of variance
GLM	general linear model
MRT	multiple resource theory
NBC	nuclear biological chemical
SBIR	Small Business Innovative Research
SD	standard deviation

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