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Effectiveness of Stereoscopic Displays for Indirect-Vision Driving and Robot Teleoperation

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14. ABSTRACT

A three-part experiment was conducted to investigate the usefulness of two types of three-dimensional (3-D) stereoscopic displays (SDs) for simulated indirect-vision driving (with various terrains) and live robot teleoperation. Results showed that overall, participants completed their tasks significantly faster when they used an SD in 3-D mode compared to the baseline two-dimensional (2-D)/monoscopic condition. They also navigated more accurately with SDs in 3-D mode. When the effectiveness of the SDs was examined separately, the results showed that the system with active 3-D shutter glasses appeared to be more effective in supporting faster responses and task completion times than did the system using passive polarized 3-D glasses. Participants' self-assessed "simulator sickness" and workload after interacting with the two SD systems did not differ significantly between displays or between the 3-D vs. 2-D modes of operation.

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stereoscopic display, robot teleoperation, human-robot interaction, simulation, operator performance, indirect vision driving

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1. Introduction

The U.S. Army is currently developing future manned ground vehicles that will support indirect-vision driving (IVD), that is, driving via a visual display rather than direct viewing of the environment. The current plans for the future vehicular programs are to use a 360° horizontal/ 90° vertical two-dimensional (2-D) display to provide local situational awareness information to the driver. However, recent field tests of vehicles using these IVD displays showed that drivers tended to drive significantly more slowly than when driving with normal direct view of the environment, showing as much as a 60% increase in time on their driving tasks (Flascher, 2008; GDLS, 2007). It was reported that driving performance decrement may have been linked to the drivers' poor depth perception of the environment due to the loss of binocular depth perception when using the 2-D IVD video displays, resulting in their degraded judgment of the terrain features (GDLS, 2007).

One proposed solution is to investigate the effectiveness of stereoscopic displays (SDs) for improving driving performance in general, and driving speed in particular. Past research has shown that SDs, which rely on various techniques to present binocular images to the user, appear to provide advantages over 2-D/monoscopic displays, such as faster and more accurate perception of the environment, better distance estimation, enhanced detection of terrain hazards (e.g., slopes and depressions), enhanced object recognition and detection, and visual noise filtering (Drasic, 1991; Merritt, CuQlock-Knopp, and Myles, 1997; Scribner and Gombash, 1998; Singer, Ehrlich, Cinq-Mars, and Papin, 1995). Studies have shown that SDs could enhance telerobotic vehicle operators' speed of navigation and distance judgment (Holzhausen, Pitrella, and Wolf, 1993; Spain and Hughes, 1991; Umeda, Martin, and Merritt, 1991).

1.1 Stereoscopic Displays

Stereoscopic displays can provide many advantages over traditional monocular displays in driving, particularly in off-road, military driving. According to Dumbreck, Smith, and Murphy (as cited in Drascic, 1991), remote manipulation tasks that involve "ballistic movement, recognition of unfamiliar scenes, analysis of three dimensionally complex scenes and the accurate placement of manipulators or tools within such scenes" especially benefit from SDs. However, empirical studies examining the utility of SDs generally report that SDs might be useful in only certain circumstances. For example, Drascic (1991) found that the benefits of SDs, while longer lasting for tasks that required binocular depth cues (i.e., using a robot to place an object between two "bombs" separated by 8 cm), did not last as long for tasks that did not require much binocular depth perception (i.e., same task with "bombs" separated by 64 cm). Generally, participants quickly learned how to use the monocular cues available in the monocular displays to accomplish those tasks.

Draper, Handel, and Hood (1991) had participants perform Fitts Law (Fitts, 1954) tapping tasks and reported that SDs were only useful for more difficult tasks and only for inexperienced participants. They suggested that SDs would be useful when the image quality, task structure and predictability, user experience, and manipulator dexterity were suboptimal. Rosenberg (1993) found that SDs helped depth-matching performance and the distances between the two cameras affected the usefulness of the SDs. They reported that the best performance was achieved when the inter-camera distance was less than the interocular distance (i.e., 2–3 cm vs. 6 cm). On the other hand, Green, Dougherty, and Savacool (2003) did not find significant benefits of using SDs for their task, teleoperating shipboard cranes to place cargo, in terms of time and accuracy of task performance and depth perception. As for user preference, a consistent finding from various studies is that teleoperators generally prefer SDs over monocular displays (Drascic and Grodski, 1993; Green Dougherty, and Savacool, 2003). However, as noted in Scribner and Gombash (1998), artificially induced binocular stereovision may increase motion sickness and perceived stress.

More realistic tests were conducted by researchers from the U.S. Army who investigated the ability of humans to detect obstacles in static and moving video terrain with three-dimensional (3-D) and hyperstereo (ocular distance artificially increased to accentuate depth cues) displays. The results indicated improved detection of negative terrain and mobility obstacles for the 3-D conditions vs. 2-D conditions (Merritt, CuQlock-Knopp, Kregel, Smoot, and Monaco, 2005; Merritt, CuQlock-Knopp, and Myles, 1997). Preliminary field demonstrations of actual Army systems suggest the 3-D performance gains will extend to teleoperated systems. The researchers caution that SDs have definite perceptual and physical limitations, as mentioned above; however, SDs should be an optional mode for complex terrain, especially where depth perception is crucial, and for arm manipulations and other tasks where normal 3-D cues are unavailable (B. Vaughan, personal communication, 16 March 2006).

1.2 Current Study

In the current study, we investigated whether an SD could improve the operators' IVD and robot teleoperation performance, and which type of SD supported better performance. We evaluated two types of SD technologies: active shutter glasses (nVIDIA[*]) and passive polarized glasses (Miracube[†]). The experiment had three parts – Perceptual evaluation, Robot Teleoperation, and Virtual (simulated IVD). For the Perceptual part of the experiment, participants viewed still images of terrain using one of the SDs in 3-D and responded about object distance from the camera as well as object height on elevation planes. They also viewed videos of hazardous terrain using one of the SDs in 3-D and responded when they detected a terrain drop-off. For the Robot Teleoperation part of the experiment, participants maneuvered a robot through a course of cones on a grass terrain using one of the SDs in both 2-D and 3-D modes. For the Virtual part of

[*]nVIDIA is a registered trademark of nVIDIA Corp.

[†]Miracube is a registered trademark of Miracube, Inc.

the experiment, participants drove through both 3-D stereo and non-stereo scenarios in a 3-D rendered, simulated driving environment (VBS2*). Different types of terrains were simulated in the virtual scenarios.

2. Method

2.1 Participants

Thirty-two individuals (19 males and 13 females, mean age = 25.8) from the Orlando, FL area participated in the experiment. Participants received payment for their time at the rate of $15/hour.

2.2 Apparatus

2.2.1 Stereoscopic Display Systems

The stereoscopic display systems used were an nVIDIA and a Pavonine Miracube display (figure 1).

Figure 1. Stereoscopic displays used in the virtual tests.

*Virtual Battlespace 2 (VSB2) is a registered trademark of Bohemia Interactive Australia (BIA).

The nVIDIA system used a 22-in 120 Hz display, with a resolution of 1680 × 1050 pixels, viewed with active 3-D shutter glasses synchronized by an infrared (IR) emitter pointing toward the glasses. The stereoscopic video is sent as an alternating series of left eye and right eye frames. Therefore, the frame rate perceived by the user is 60 Hz. All frames have full pixel resolution. To achieve proper depth, convergence, and orthostereo (the ability to produce images in the display that are the same visual size as in the real world), the display had to be calibrated each time the experimental condition changed between 2-D and 3-D. To achieve this, the depth was set, using the scroll bar on the back of the emitter, to a predefined level (3/50 for 2-D, 30/50 for 3-D) and the convergence was set, using Ctrl+F5 or Ctrl+F6 on the keyboard, to a predefined level (0 for 2-D, ~2.5 in for 3-D).

The Pavonine system used a 24-in Miracube display, with a resolution of 1920 × 1200 pixels. The Miracube display uses a filter sheet placed in front of the 60 Hz liquid crystal display. The filter has alternating lines of polarization causing the odd pixel rows of the display to be polarized oppositely from the even rows. Coupled with passive polarized 3-D glasses, this provides the viewer with a stereoscopic signal at nearly full brightness but with half vertical resolution per eye. To achieve proper depth, convergence, and orthostereo, the display had to be calibrated each time the experimental condition changed between 2D and 3D. To achieve this, values were set to a predefined level for 3D (convergence = –0.0306, separation = 562.17%), and they were toggled on and off using the "?" key on the keyboard.

2.2.1.1 Stereoscopic Video Data Processing. The video data path was as follows. Each camera was connected to its own dedicated 1394.b port. Using the synchronized capture feature of the cameras, frames are captured synchronously (measured to be <1/480 of a second difference). The two frame streams are then combined by the Stereoscopic Multiplexer* software program (for more information, please see). The Multiplexer provides two functions. First it compares the time stamps of frames on both incoming streams. If the frames are not in sync, it will drop frames until the streams are in sync. The Multiplexer then merges the two streams into a single, double-wide side-by-side 2048 × 768 video stream, which is then encoded using xvid compression, packetized, and sent over the network using two bridged Linksys† WRT600N routers. The receiving computer then depacketizes the stream and makes it available as a virtual live camera to the system. Any Windows direct-show compatible device can then connect to the virtual camera and receive the video stream. Stereoscopic Player® is then used to connect to the virtual camera, convert the video into the correct format for the display, and play the video.

*Stereoscopic Multiplexer is a registered trademark of 3dtv.at.
†Linksys is a registered trademark of Cisco Systems, Inc.

2.2.2 Stereoscopic Images, Video, and Simulation

Twenty still pictures were used in the experiment. For ten of the pictures, participants were asked to choose which of two objects was closest to the camera. For the other ten pictures, participants were asked to choose between two planes of elevation and identify the object that had a higher elevation. Ten pre-recorded videos of terrain scenes were also used in the experiment, each scene averaging 30 to 45 s long. The 10 scenes were of wooded areas and were collected both locally and remotely by a consultant (Merritt et al., 2005). Participants were asked to respond as soon as they saw a terrain drop-off in the scene.

Bohemia Interactive's VBS2 (U.S. Army version) and the VBS2 VTK Developer Suite v1.23 were used to create the virtual driving simulation. Custom 3-D models that were needed to create the virtual scenarios were modeled in 3ds Max9[*]. Custom textures were created with Adobe[†] Photoshop[‡] CS3. The models and textures were then converted to VBS2 native formats (.paa and .p3d) using Oxygen2 and the Tex Viewer. All terrain models larger than 50 m had to be imported into VBS2 as separate models and then reassembled to appear seamless.

For the Negative Terrain tracks, it was important to minimize the visual cues that are typically present in realistically-rendered 2-D simulations (e.g., high contrast lighting, realistic textures which give the illusion of added depth). The Negative Terrain tracks incorporated both positive terrain features, such as trees and rocks, and negative terrain features, such as cliffs and ditches. An attempt was made to eliminate all visual hints, such as changes in texture type or shadows that would be a cue to the participant that a drop-off in elevation was ahead. Flatly-rendered textures with random repeating patterns (e.g., sand with weeds and plain grass) were used to eliminate visual cues caused by the textures. A script was created to change the time of day in VBS2 to dusk to eliminate high contrast lighting (e.g., sharp highlights and shadows in negative terrain areas).

VBS2 is a very robust 3-D game engine that can render very high polygon environments, high resolution textures, and many dynamic and static objects in real-time. Due to the unique requirements of the Negative Terrain condition, these tracks featured a higher polygon count and higher resolution textures than the other virtual conditions. Computer performance varies in 3-D simulations depending on the polygon count and the size and number of textures being rendered in real-time. A drop in computer performance is magnified to a greater extent when the environment is being rendered in 3-D stereo in real-time, since the 3-D engine must render two images per frame instead of one. A slight drop in hardware performance was discovered on the Negative Terrain tracks due to the reasons above. When in 3-D stereo mode, at times the vehicle appeared to move slightly more slowly than when in 2-D mode while maintaining smooth driving conditions with no lag.

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[*]3ds Max9 is a registered trademark of Autodesk, Inc.

[†]Adobe is a registered trademark of Adobe Systems, Inc.

[‡]Photoshop is a registered trademark of Adobe Systems, Inc.

2.2.3 Talon Robot

The small unmanned ground vehicle (SUGV) was a TALON* robot (figure 2), which was controlled remotely. The TALON used in the experiment was the small, mobile version. It has been used in military operations since 2000, and armed TALONs began to serve as battle buddies for Soldiers in 2005. The two cameras used in the experiment, Sony† XCD-SX90CR cameras with a resolution of 1024 × 768 pixels, were mounted on the main platform of the TALON, with an inter-camera distance of 2.25 in, along with other processing equipment for the SD systems. The combined field of view for the cameras was 44.5°. The distance between the cameras and the ground was 30.5 in.

Figure 2. TALON robot with stereoscopic cameras.

*Talon is a registered trademark of Foster-Miller, Inc.
†Sony is a registered trademark of Sony Corp.

2.2.4 Surveys and Tests

A demographics questionnaire (appendix A) was administered at the beginning of the training session. Participants' perceived workload was evaluated using the computerized version of the National Aeronautics and Space Administration-Task Load Index (NASA-TLX) questionnaire (appendix B), which includes a pairwise comparison weighting procedure (Hart and Staveland, 1988). The NASA-TLX is a self-reported questionnaire of perceived demands in six areas: mental, physical, temporal, effort (mental and physical), frustration, and performance. Participants evaluated their perceived workload level in these areas on 10-point scales as well as completed pairwise comparisons for each subscale.

The Simulator Sickness Questionnaire (SSQ; see appendix C) was used to evaluate participants simulator sickness symptoms (Kennedy, Lane, Berbaum, and Lilienthal, 1993). The SSQ consists of a checklist of 16 symptoms. Each symptom is related in terms of degrees of severity (none, slight, moderate, severe). A total severity score can be derived by a weighted scoring procedure (see appendix D) and reflects overall discomfort level.

2.2.5 Stereoscopic Test

The stereoscopic test used was a Randot Stereo Test[*] that had four parts, three of which were used for this experiment. The stereo test uses polarized glasses worn by the participant and is held perpendicular to the ground 16 in from the participant. The first part of the test was identification of shapes in four boxes that required a stereoacuity of 500 s of arc, and this was the point at which participants were either included or excluded from the study. The second part of the test was identification of shapes in four boxes that required a stereoacuity of 250 s of arc. The third part of the test was identification of which of three circles stood out to the participant, and these required varying levels of stereoacuity from 200 to 20 s of arc. Participants' scores (i.e., seconds of arc) were used as a covariate, stereoacuity, for the analyses.

2.3 Experimental Design

The overall design of the study was a 2 × 2 mixed-subjects design. The between-subject factor was Display type (nVIDIA v Miracube) and the within-subject factor was Stereovision (2-D v 3-D). However, for the first part of the experiment, participants did not evaluate the pictures and videos in 2-D, as Merritt et al. (2005) have demonstrated that terrain hazards could be detected sooner with a 3-D display than with a 2-D display.

2.4 Procedure

After being briefed on the purpose of the study and signing an informed consent form, participants completed the demographics questionnaire. The experimenter explained the experiment to participants and answered any questions they had at the time. Not all participants

[*] Randot stereo tests are produced by Precision Vision.

completed the three parts of the experiment sequentially due to equipment delays. The participants then went through the calibration process as described in section 2.2.1. The distance between the participant and the SD was 23 in for nVIDIA and 25 in for Miracube.

2.4.1 Perceptual Tests

For the Perceptual tests, participants viewed 20 still pictures; for 10 of the pictures they identified the closer object, and for the other 10 they identified which object was on a higher elevation plane. Participants then watched 10 pre-recorded video clips of hazardous terrain in 3-D (with his/her assigned SD system) and responded as soon as they detected a drop-off in terrain. Each video was ~30–45 s long, and after completing this portion, participants assessed their workload and sickness symptoms.

2.4.2 Robot Teleoperation Tests

Participants practiced teleoperating the robot (without line-of-sight) for one course in 2-D and one course in 3-D. They were then asked to drive a robot through four courses marked by traffic cones (figure 3), twice with 3-D and twice with 2-D (the same display with 3-D turned off). If participants drove the robot completely out of the course (i.e., the entire robot was outside the course), the trial was restarted, and each participant was allowed to restart each trial twice. If participants went outside the course more than three times (the original trial plus two restarts), they were moved to the next course. The performance data from the last successful trial was used with a restart value reflecting that participants had to be restarted. Trials were counterbalanced (Williams Square) to avoid order effects. Each trial took approximately one minute and after completing this portion, participants assessed their workload and sickness symptoms.

Figure 3. Robot teleoperation tests.

2.4.3 Virtual Tests

Participants were asked to drive through three types of courses, and each type of course featured two unique tracks (figure 4). One type of course was a "Floating Objects Course" in which participants drove on an enclosed, pavement course toward six sets of object pairs (figure 4a). Participants were instructed to drive as quickly as possible around the objects on the side (left or right) of the closer object. Another type of course was an "Obstacle Course," in which participants drove as quickly as possible around obstacles, such as rocks and shrubs (figure 4b). The third type of course was a "Negative Terrain Course" in which participants drove on an enclosed course of varying negative and positive terrain features (i.e., holes in the ground, drop-offs, and hills; figure 4c). Participants were instructed to drive as quickly as possible through the course while avoiding the positive and negative terrain obstacles. Each participant was given a practice course for each type of trial in 2-D and 3-D prior to starting the experimental trials, and each participant completed each type of experimental course twice, once in 2-D and once in 3-D. Trials were counterbalanced (Williams Square) to avoid order effects. Each trial took approximately three minutes and after completing all trials, participants assessed their workload and sickness symptoms.

Following completion of the three parts of the experiment, participants were fully debriefed, and their information was taken for payment. The entire experiment lasted ~1 1/2 h.

2.5 Dependent Measures

The dependent measures for the Perceptual tests of the experiment were response time and accuracy. The dependent measures for the Robot Teleoperation tests were course completion time and number of cones hit. The dependent measures for the Virtual tests were course completion time and accuracy of completing the simulated driving tasks (i.e., how many terrain hazards they failed to avoid). Subjective measures included participants' assessments of their workload (i.e., NASA-TLX scores) and sickness (i.e., SSQ) scores, which were assessed after each part of the experiment. Mixed-design Analyses of Covariance (ANCOVAs) with Display (nVIDIA v Miracube) as the between-subject factor and Stereovision (2-D v 3-D) as the within-subject factor were used to evaluate the performance measures. Participants' stereovision was used as the covariate. All tests were performed using SPSS 18.0 with an alpha level of 0.05.

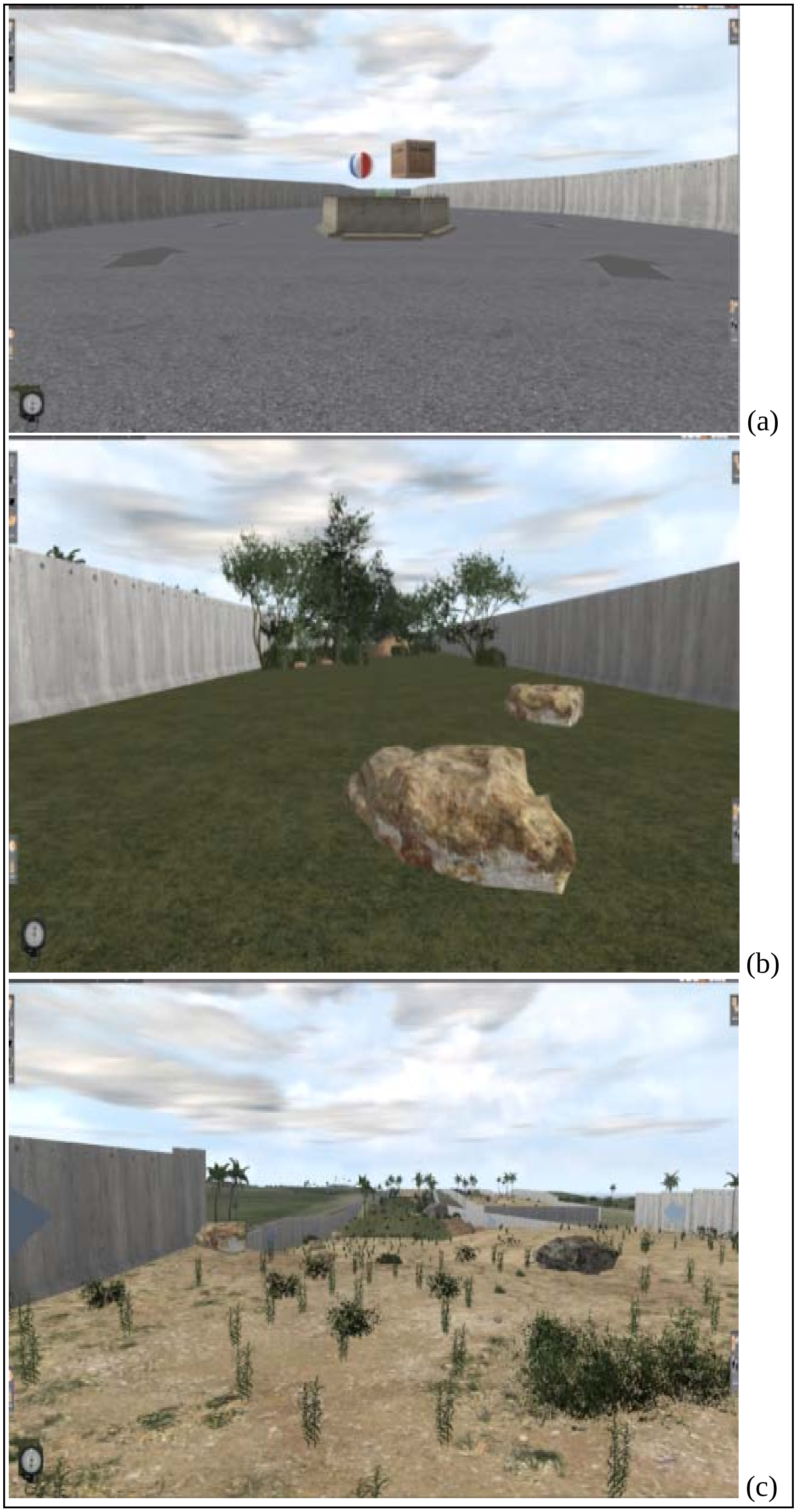

Figure 4. (a) Floating objects course; (b) obstacle course; and (c) negative terrain course.

3. Results

3.1 Overall Effects of Stereovision and Display Type

Table 1 lists several measures relating to participants' performance. The effects of Stereovision on course completion times for the Robot Teleoperation and the three Virtual tests were evaluated. The analysis revealed that there was a significant main effect for Stereovision, $F(4,26) = 5.53$, $p < 0.005$, with 2-D being longer/slower than 3-D. The effect of Display in the 3-D conditions was investigated separately to examine the effect of different display types on times (i.e., response times for Video viewing, course completion times for Robot Teleoperation and the Virtual tests). The analysis showed that there was a significant main effect for Display, $F(1,29) = 4.46$, $p < 0.05$, with nVIDIA being better (i.e., faster) than Miracube. The following segments report the results of each task.

Table 1. Summary of performance measure means and standard deviations.

		Measures	2-D		3-D	
			nVIDIA	**Miracube**	**nVIDIA**	**Miracube**
Perceptual	Stills	Response time (s)	—	—	8.14 (6.35)	6.43 (5.14)
		Percent correct	—	—	73 (44)	78 (42)
	Video	Response time (s)	—	—	8.25 (6.21)	11.22 (4.21)
Robot Teleoperation	—	Completion time (s)	65.03 (14.71)	74.78 (20.52)	62.63 (14.54)	67.94 (19.87)
		No. of cones hit	3.88 (1.69)	4.56 (1.79)	3.38 (1.40)	4.19 (1.31)
Virtual	Floating	Completion time (s)	15.01 (3.84)	15.66 (4.66)	16.74 (5.13)	17.43 (6.07)
		No. of trials correct	3.69 (1.01)	4.44 (1.03)	4.44 (1.21)	5.19 (1.11)
	Obstacle	Completion time (s)	152.6 (33.4)	149.2 (30.4)	160.3 (41.0)	157.7 (40.2)
		Time off course (s)	16.73 (13.52)	16.92 (10.14)	14.84 (14.09)	13.85\(9.69)
	Negative	Completion time (s)	209.8 (48.7)	217.6 (50.0)	189.2 (45.0)	217.2 (47.7)
		Time off course (s)	17.44 (14.29)	10.11 (13.93)	11.23 (6.12)	11.13 (11.39)

Note: Standard deviations are presented in parentheses.

3.2 Perceptual Tests

For the still images, the Closer task and the Elevation task were merged for the analyses. Additionally, trials that less than 60% of participants got correct were not included in the analyses, as that performance level was just higher than chance level. The effect of Display on participants' response times and accuracy (number correct out of 8 trials) was analyzed. Display did not have a significant effect on either response times or accuracy. For the Video viewing part of the tests, the effect of Display on response times for the 10 video clips was analyzed. The analysis revealed that there was a significant main effect for Display, $F(1,26) = 5.47$, $p < 0.05$, with nVIDIA ($M = 7.33$ sec) being better (i.e., faster) than Miracube ($M = 11.87$ s) (figure 5).

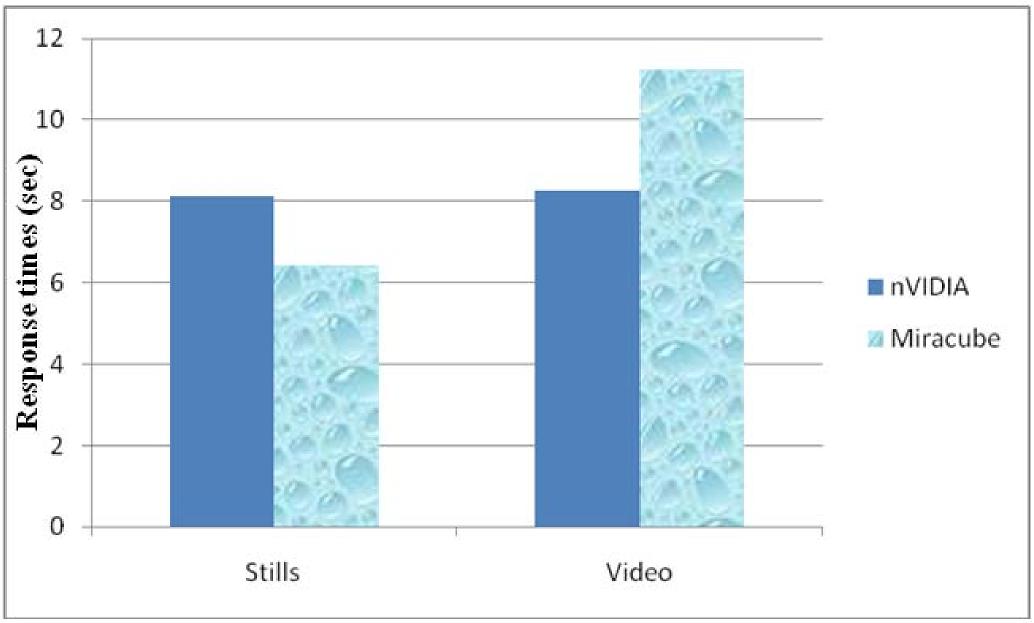

Figure 5. Response times (s) for the perceptual tests.

3.3 Robot Teleoperation

The effects of Display and Stereovision on participants' course completion times and number of cones hit were analyzed. There was a marginally significant main effect of Display for course completion times, $F(1,28) = 3.024$, $p = 0.093$, with the nVIDIA display ($M = 62.89$ s) resulting in faster completion times than the Miracube display ($M = 73.59$ s) by more than 10 s, which is an ~15% reduction in completion times. While the difference in completion times between stereo conditions failed to reach statistical significance, the 3-D condition ($M = 65.8$ s) produced faster operating times than the 2-D condition ($M = 70.6$ s) by almost 5 s (figure 6). In terms of accuracy (number of cones hit), participants hit less cones in 3-D and with the nVIDIA display. However, the differences failed to reach statistical significance.

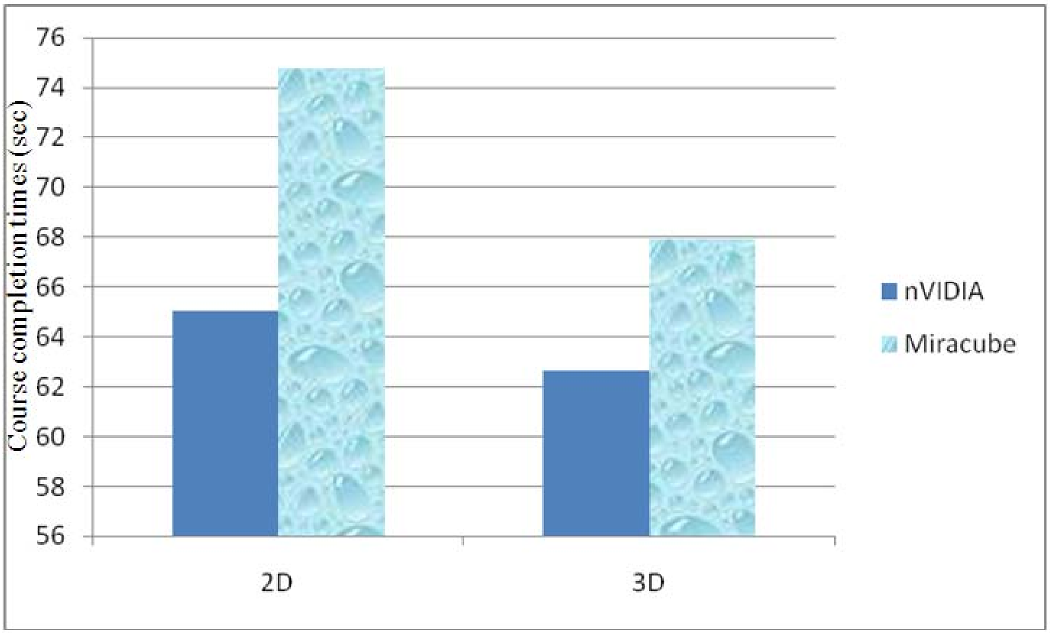

Figure 6. Robot teleoperation completion times.

3.4 Virtual Scenarios

3.4.1 Floating Object Course

The effects of Display and Stereovision on participants' course completion times and accuracy (i.e., number of trials correct) were analyzed. For course completion times, there was a marginally significant interaction effect of Display x Stereoacuity, $F(1,29) = 3.65$, $p = 0.066$, indicating that completion times were more affected by Stereoacuity in the Miracube than the nVIDIA display (the Miracube display had a greater disparity in completion time over trials than the nVIDIA display) and that completion times were faster for those who had a better stereoacuity (69 or below). Those participants using nVIDIA who had better stereoacuity were ~1 s faster than those with worse stereoacuity; those using Miracube who had better stereoacuity and were ~4 s faster than those with worse stereoacuity. For accuracy, 3-D ($M = 4.81$) provided significantly more accurate results than 2-D ($M = 4.06$), $F(1,29) = 4.37$, $p < 0.05$. Additionally, the Miracube display ($M = 4.79$) provided significantly more accurate results than the nVIDIA display ($M = 4.09$), $F(1,29) = 5.00$, $p < 0.05$. Participants' average speed (miles per hour) for the virtual tests in the 3-D condition is depicted in figure 7.

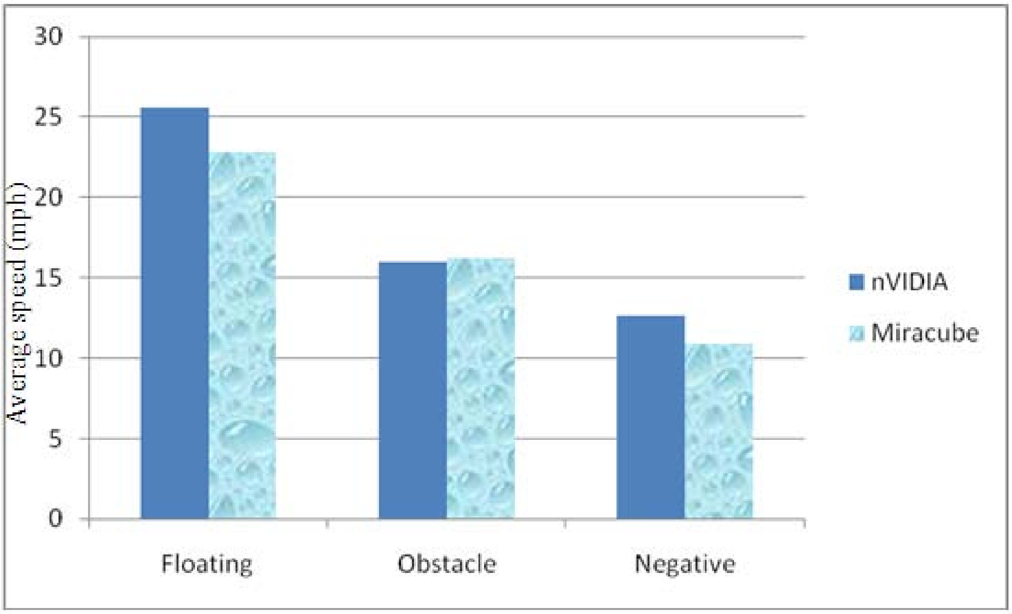

Figure 7. Average speed (miles per hour) for the virtual tests in 3-D condition.

3.4.2 Obstacle Course

The effects of Display and Stereovision on participants' course completion times and accuracy (i.e., time off course) were analyzed. For accuracy, there was a marginally significant effect of Stereovision in that 3-D (M = 14.15 s) produced more accurate performance than 2-D (M = 16.25 s), $F(1,27) = 3.59$, $p = 0.069$. The percentage of time participants' were off-course for the obstacle and the negative terrain courses are depicted in figure 8.

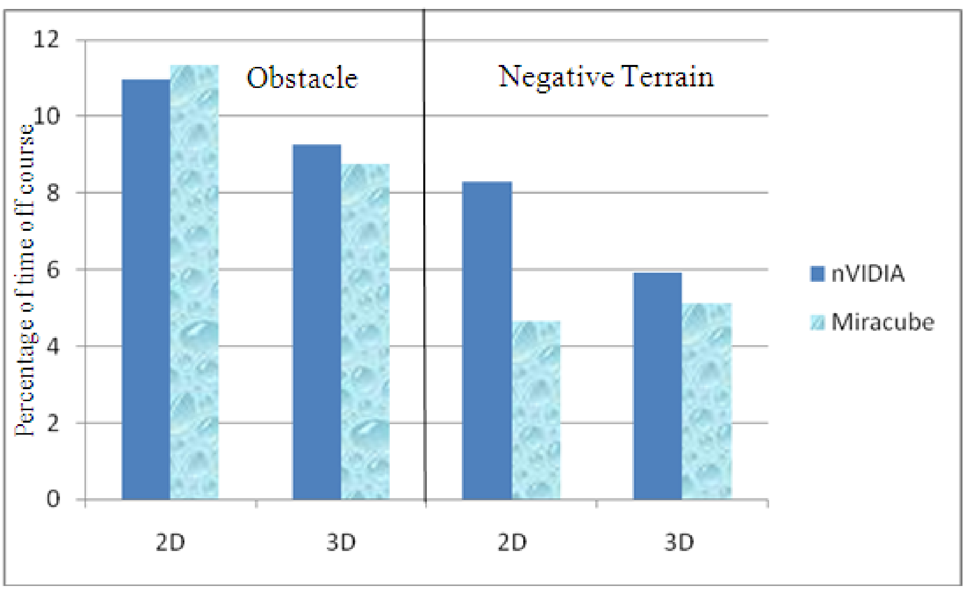

Figure 8. Percentage of time off-course for the obstacle and negative terrain courses.

3.4.3 Negative Terrain Course

The effects of Display and Stereovision on participants' course completion times and accuracy (i.e., time off-course) were analyzed. None of the factors were significant.

3.5 Sickness and Perceived Workload

Participants' SSQ scores and perceived workload were both slightly higher with nVIDIA than with Miracube. However, the difference was not statistically significant. Additionally, the nVIDIA display ($M = 6.31$) resulted in higher workload scores than the Miracube display ($M = 4.44$) for the Perceptual tests.

4. Discussion

In this experiment, we evaluated two SD systems in three different types of tasks: Perceptual evaluation with still pictures and pre-recorded videos, live Robot Teleoperation, and simulated indirect driving in Virtual environments with different types of terrain. Overall, participants completed their tasks significantly faster when they used an SD in 3-D mode compared to the baseline 2-D mode. When the effectiveness of the SDs were examined separately, the analysis showed that the nVIDIA system appeared to be more effective than the Miracube in supporting faster response times and course completion times.

For the Perceptual tests, participants perceived hazardous terrains in videos significantly faster using nVIDIA than Miracube. Similarly, for the Robot Teleoperation tests, participants navigated the robot significantly faster using nVIDIA than Miracube, saving ~15% of navigation time per trial. Participants also operated the robot slightly faster with the 3-D mode than with the 2-D mode, although the 3-D/2-D difference failed to reach statistical significance.

For the Floating course of the Virtual tests, the results showed that participants' accuracy was significantly better with 3-D than with 2-D. In contrast to the results of the Robot Teleoperation tests, participants' accuracy was significantly better with Miracube than with nVIDIA. For the Obstacle course of the Virtual tests, the results showed that participants performed slightly better with 3-D than with 2-D, although the difference failed to reach statistical significance. For the Negative Terrain course of the Virtual tests, none of the factors were found to be significant. The lack of difference in operator performance for the Miracube display may be due to the fact that the Negative Terrain tracks had a very large amount of graphics that had to be rendered (as opposed to the Floating tracks and Obstacle tracks) and, for the Miracube display, two image streams needed to be rendered for the 3-D condition but only one image stream for the 2-D condition. Therefore, images in the 3-D Miracube condition could have been slightly slower or "sluggish" compared to 2-D, and this could account for why 3-D did not result in better performance than 2-D for the Miracube display. For the nVIDIA display, on the other hand, there was no difference in the amount of image streams that had to be rendered in the 2-D v 3-D conditions. In other words, there was no additional "cost" associated with rendering 3-D images for the nVIDIA display compared to the 2-D condition. As a result, participants drove faster in the 3-D condition (about 10% reduction in course completion time) and also more accurately (42% reduction in time off-course).

The data did not indicate a significant effect of Display type on sickness or workload for any of the tasks. This suggests that the two displays are comparable in their workload and sickness-inducing characteristics. Display type also did not have an effect on self-rated performance for the Robot Teleoperation or the Virtual scenarios. However, people using the nVIDIA display thought they performed better on the Perceptual tasks than people using the Miracube display. This could be due to the difficulty of the tasks combined with the viewing-position constraints of the Miracube display (i.e., if participants moved out of the "ideal" viewing eye height, the stereo was not as clear [less L/R channel separation, thus more ghosting, with consequent reduction in binocular depth perception], whereas the nVIDIA uses shutter glasses, which are not adversely affected by changes in user eye position relative to the display screen).

In conclusion, the results of this study indicate that stereoscopic displays do have advantages over tradition 2-D displays with respect to depth perception, specifically on driving and robot teleoperation tasks. Furthermore, the results show that the nVIDIA system is a superior system for these tasks than the Miracube system. Thus, it is recommended that the U.S. Army employ these systems in robot operator controls and indirect-vision driving displays. This should result in better performance, and potentially less loss of life and equipment.

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Appendix A. Demographic Survey and Summary of Results

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

Participant # _______ Age ______ Major ________________ Date ___________ Gender ___

1. What is the <u>highest</u> level of education you have had?
Less than 4 yrs of college ____ Completed 4 yrs of college ____ Other ____

2. When did you use computers in your education? (*<u>Circle all that apply</u>*)

Grade School	Jr. High	High School
Technical School	College	Did Not Use

3. Where do you currently use a computer? (*<u>Circle all that apply</u>*)

Home Work Library Other________ Do Not Use

4. For each of the following questions, <u>circle</u> the response that best describes you.

How often do you:	
Use a mouse?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use a joystick?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use a touch screen?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use icon-based programs/software?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use programs/software with pull-down menus?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use graphics/drawing features in software packages?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Use E-mail?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Operate a radio controlled vehicle (car, boat, or plane)?	Daily, Weekly, Monthly, Once every few months, Rarely, Never
Play computer/video games?	Daily, Weekly, Monthly, Once every few months, Rarely, Never

5. Which type(s) of computer/video games do you most often play if you play at least once every few months?

6. Which of the following best describes your expertise with computer? (check √ one)
_____ Novice
_____ Good with one type of software package (such as word processing or slides)
_____ Good with several software packages
_____ Can program in one language and use several software packages
_____ Can program in several languages and use several software packages

7. Are you in your usual state of health physically? YES NO
If NO, please briefly explain:

8. How many hours of sleep did you get last night? ______ hours

9. Do you have normal color vision? YES NO

10. Do you have prior military service? YES NO If Yes, how long __________

Summary of Demographic Survey Results

Age: Ranged from 18-40 Mean = 25.8 Standard Deviation = 6.2

Gender: 19 Males 13 Females

How often do you:

- Drive a car? Never = 1 Rarely = 0 Once every few months = 0 Monthly = 0 Weekly = 1 Daily = 30
- Use a joystick? Never = 6 Rarely = 17 Once every few months = 3 Monthly = 1 Weekly = 2 Daily = 3
- Operate a radio-controlled vehicle? Never = 15 Rarely = 12 Once every few months = 2 Monthly = 1 Weekly = 1 Daily = 1
- Play computer/video games? Never = 2 Rarely = 7 Once every few months = 5 Monthly = 5 Weekly = 4 Daily = 9

Which types of computer/video games do you most often play if you play at least once every few months? Driving games = 5 Other/None = 27

Which of the following best describes your expertise with computer/video games?

- Novice = 6
- Good with one type of software package = 8
- Good with several software packages = 14
- Can program in one language and use several software packages = 2
- Can program in several languages and use several software packages = 2

What type(s) of radio-controlled vehicle do you use most often if you use one at least every few months? Ground vehicles = 6 Other/None = 26

Which of the following best describes your expertise with radio-controlled vehicles?

- Novice = 26
- Good with one type of software package = 4
- Good with several software packages = 2
- Can program in one language and use several software packages = 0
- Can program in several languages and use several software packages = 0

Are you in your good/comfortable state of health physically? Yes = 31 No = 1

Do you have normal/corrected-to-normal vision? Yes = 30 No = 2

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Appendix B. NASA-TLX Questionnaire

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

Please rate your <u>overall</u> impression of demands imposed on you during the exercise.

1. Mental Demand: How much mental and perceptual activity was required (e.g., thinking, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

LOW |---|---|---|---|---|---|---|---|---|---| HIGH
1 2 3 4 5 6 7 8 9 10

2. Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

LOW |---|---|---|---|---|---|---|---|---|---| HIGH
1 2 3 4 5 6 7 8 9 10

3. Temporal Demand: How much time pressure did you feel due to the rate or pace at which the task or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

LOW |---|---|---|---|---|---|---|---|---|---| HIGH
1 2 3 4 5 6 7 8 9 10

4. Level of Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

LOW |---|---|---|---|---|---|---|---|---|---| HIGH
1 2 3 4 5 6 7 8 9 10

5. Level of Frustration: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

LOW |---|---|---|---|---|---|---|---|---|---| HIGH
1 2 3 4 5 6 7 8 9 10

6. Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

LOW |---|---|---|---|---|---|---|---|---|---| HIGH
1 2 3 4 5 6 7 8 9 10

Appendix C. Simulator Sickness Questionnaire

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

Instructions: Please indicate how you feel **right now** in the following areas, by **circling** the word that applies.

1.	General Discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye Strain	None	Slight	Moderate	Severe
5.	Difficulty Focusing	None	Slight	Moderate	Severe
6.	Increased Salivation	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty Concentrating	None	Slight	Moderate	Severe
10.	Fullness of Head	None	Slight	Moderate	Severe
11.	Blurred vision	None	Slight	Moderate	Severe
12.	Dizzy (Eyes Open)	None	Slight	Moderate	Severe
13.	Dizzy (Eyes Closed)	None	Slight	Moderate	Severe
14.	Vertigo*	None	Slight	Moderate	Severe
15.	Stomach Awareness**	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe

*Vertigo is a disordered state in which the person or his/her surroundings seem to whirl dizzily: giddiness.
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.
Are there any other symptoms you are experiencing right now? If so, please describe the symptom(s) and rate its/their severity below. Use the other side if necessary.

Appendix D. Scoring Procedure for the Simulator Sickness Questionnaire

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

Symptoms scored 0 (None) - 3 (Severe)

Nausea (Raw) - Sum of General discomfort, increased salivation, sweating, nausea, diff concentrating, stomach awareness, burping

Nausea sub scale = Nausea (Raw) x 9.54

Oculomotor - Sum of general discomfort, fatigue, headache, eye strain, diff focusing, diff concentrating, blurred vision

Oculomotor sub scale = Nausea (Raw) x 7.58

Disorientation - Sum of diff focusing, nausea, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), vertigo

Disorientation sub scale = Nausea (Raw) x 13.92

TSS = [Nausea (Raw) + Oculomotor (Raw) + Disorientation (Raw)] x 3.74

List of Symbols, Abbreviations and Acronyms

2-D	two dimensional
3-D	three dimensional
ANCOVA	analysis of covariance
IR	infrared
IVD	indirect-vision driving
NASA-TLX	National Aeronautics and Space Administration - Task Load Index
SD	stereoscopic display
SSQ	Simulator Sickness Questionnaire
SUGV	small unmanned ground vehicle

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