5-2011

Investigating the Usability of a Vibrotactile Torso Display for Improving Simulated Teleoperation Obstacle Avoidance

Lindsay Long
Clemson University, lindsal@clemson.edu

INVESTIGATING THE USABILITY OF A VIBROTACTILE TORSO DISPLAY FOR IMPROVING SIMULATED TELEOPERATION OBSTACLE AVOIDANCE

A Thesis
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Applied Psychology

---

by
Lindsay O'Hara Long
May 2011

Accepted by:
Christopher Pagano, Ph.D., Committee Chair
Eric Muth, Ph.D.
Ian Walker, Ph.D.

ABSTRACT

While unmanned ground vehicle (UGV) teleoperation is advantageous in terms of adaptability and safety, it introduces challenges resulting from the operator's poor perception of the remote environment. Previous literature on the ability of haptic feedback to augment visual displays indicates that UGV obstacle avoidance information may be more meaningfully communicated via vibrotactile torso systems. Presenting this information so that operators can accurately detect the proximity from walls and obstructions could result in a significant reduction in errors, ultimately improving task performance and increasing the usability of teleoperation. The goal of the current study was to determine the degree to which a vibrotactile torso belt could improve UGV teleoperation performance over video feed alone in a simulated environment. Sixty operators controlled a UGV using a simulated video feed, while half also utilized a vibrotactile belt. Results indicated that the vibrotactile display did not improve navigational performance or decrease subjective workload over video feed alone. Possible reasons for this and limitations are discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Investigating the Usability of a Vibrotactile Torso Display for Improving Simulated Teleoperation Obstacle Avoidance

Unmannned ground vehicle (UGV) operation is the control of a ground-based robotic system from a distant location. UGVs are becoming increasingly important because of their ability to remove humans from dangerous and otherwise inaccessible environments. They are currently employed in a number of military and civilian applications and their employment will continue to expand into additional tasks requiring an emphasis on operator safety. These vehicles are controlled by operators in direct line of sight of the UGV, known as remote control operation, or in physically separate environments known as teleoperation (Fong & Thorpe, 2001). Of the two, teleoperation has the potential for a wider range of applications, including the bottom of the ocean, lunar surfaces, urban search and rescue, and combat missions.

While teleoperation is advantageous in terms of adaptability and safety, it introduces challenges resulting from the operator's poor perception of the remote environment (e.g., Smets, 1995, Tittle, Roesler & Woods, 2002). Since the operator is separated from the UGV, feedback about the remote environment must be displayed in the form of camera feeds and graphical displays which, alone, are insufficient for successful operation and navigation (see Chen, Haas & Barnes, 2007). Not only does this poor perceptual feedback lead to increases in cognitive load, but it can also hinder even the most basic and important UGV navigational tasks, such as estimating distances from obstacles and possible collisions (Van Erp & Padmos, 2003). Presenting this information so that operators can accurately detect the proximity from walls and obstructions could result in a significant reduction in errors, ultimately improving task performance and increasing the usability of UGV teleoperation. As a result, a primary area in teleoperation research has been concerned with how to best display information about the remote environment, focusing on visual and tactile feedback.

Visual feedback, the primary source of perceptual information used in traditional teleoperation displays, often fails to transmit all the perceptual information necessary for perceiving obstacle proximities. Much of this visual feedback is in the form of video feed from one or more cameras attached to the remote UGV. Traditional video feeds omit critical properties used in direct visual perception, thereby reducing the perceptual information available about the remote environment. This includes a reduced field of view that gives the appearance of viewing the remote environment through a scope, or "soda straw" (Woods, Tittle, Feil & Roesler, 2004). This limited field of view inhibits performance directly related to obstacle avoidance such as the detection of remote targets (Darken, Kempster & Peterson, 2001) and the detection of time-to-collision (Van Erp & Padmos, 2003). Further, information about depth present in normal binocular viewing of the natural environmant is reduced in teleoperation, contributing to what has been called the "remote perception problem" (Gomer, Dash, Moore & Pagano, 2009; Moore, Gomer, Pagano & Moore, 2009; Tittle et al., 2002). As a result, teleoperators must rely on monocular information that is not coupled to normal head movements, negatively affecting depth perception and, ultimately, obstacle proximity detection by distorting estimates of distance and size (Gomer et al., 2009; Rastogi, 1996).

Within the context of simulated environments, modifying the field of view also affects perceptual cues related to distance perception (Kuhl, Thompson, & Creem-Regehr , 2006; Thompson, & Creem-Regehr , 2006, 2009; Waller, 1999). Geometric field of view (GFOV) is the view of the visual angle depicted in the remote environment. Objects and environmental properties can be altered to appear closer and larger by shrinking the GFOV (magnification), or can be rendered to appear smaller and farther away by increasing the GFOV (minification). More of the remote environment can be displayed to the operator when the GFOV is minimized, and minification has shown to improve distance estimates for both egocentric judgements (distance to an object) (Kuhl, et al., 2006) and exocentric judgements (distance between objects) (Waller, 1999).

The sense of touch has shown to support traditional visual feedback by utilizing sensations of pressure and texture to communicate information about the remote environment (see Chouvardas, Miliou & Hatalis, 2005b). Presenting feedback via touch reduces demands on other senses such as vision, leading to improvements in operational performance. As a result, tactile displays are increasingly being used to augment other sensory systems, especially in situations where there is reduced visual information available (Archaumbault & Burger, 2001), such as teleoperation (Chouvardas, Miliou & Hatalis, 2005a).

While some tactile modalities are better suited for particular human-computer interaction tasks than others (see Chouvardas, Miliou & Hatalis, 2007), vibration may be particularly beneficial in teleoperation (Chouvardas, et al., 2007; Kontarinis & Howe, 1995). These vibrotactile displays are the most extensively studied of the tactile modalities (see Chouvardas, et al., 2005b) and they are becoming more widely used in many common consumer electronics (i.e., cellular phones). Physiologically, vibration stimulates the Pacinian corpuscles, which respond rapidly to changing stimuli. This allows operators to perceive real-time stimuli about the remote environment and react quickly (Chouvardas, et al., 2007). Second, vibrotactile feedback has the ability to present a wide range of information to teleoperators that can carry different meanings. Perceptible vibration varies in amplitude, frequency, and rhythm, and can be detected at different locations and during different temporal intervals (Van Erp, 2002). Further, the mechanical vibrating elements of tactors, or haptic motors, can be designed to be small and lightweight with minimal power consumption, making them ideal candidates for integration into wearable garments (Tan & Pentland, 1997). This permits the operator to be mobile and less confined to a single location . As a result, these types of displays have been associated with teleoperation performance improvements in air, land and sea, (see Van Erp & Self, 2008) as well as space (Van Erp & Van Veen, 2006; Van Erp, Van Veen, & Ruijsendaal, 2007).

Vibrotactile feedback can be presented in a variety of forms. While teleoperators have navigated UGVs using gloves (e.g., Lathan & Tracey, 2002), styluses (e.g., Lee, Sukhatme, Kim & Park, 2002), and joysticks (e.g., Rösch, Schilling, & Roth, 2002), this feedback may be more appropriately displayed via devices worn around the torso. These types of displays are typically in the form of vests or belts that not only cover larger skin surfaces, they do not occupy the use of the hands. Encompassing the midsection, vibrotactile torso displays present localized feedback throughout the trunk via multiple tactors, delivering three-dimensional sensory information. Similar to the rooting reflex in infants where babies turn in the direction of a touch to the cheek, vibrotactile stimulation naturally draws attention in the direction of the tactile sensation. Also referred to as the tap-on-the-shoulder principle (Van Erp & Verschoor, 2004), this effect is an intuitive mode of feedback presentation in that it requires little to no training to understand (Tan & Pentland, 1997; Van Erp & Van Veen, 2004). Further, tactile stimulation surrounding the torso is spatially mapped to the users egocentric position, giving these displays a holistic, 360º field of touch that is naturally understood (Van Erp, 2000). These proprioceptive advantages have made vibrotactile torso displays beneficial when used in conjunction with other displays, and have shown to reduce mental workload, improve navigational performance, and augment visual displays.

When task demands are high, incorporating a vibrotactile display along with visual feedback can lead to performance improvements without increasing cognitive workload demands. For example, Van Erp, Veltman, and Van Veen (2003) assessed the effectiveness of a vibrotactile vest to improve altitude error in a simulated helicopter study, under both normal and degraded visual conditions. They found that incorporating a vibrotactile display reduced the error by half without affecting the subjective workload of the pilot. Research also indicates that torso vibrotactile displays can decrease workload associated with understanding position under degraded visual conditions. Using a motion machine, Cheung and Bouck (2009) had participants reorient themselves from various heave, roll, and pitch starting locations by using feedback from twenty-four tactors located throughout their midsection. The researchers assessed the utility of the display by comparing the amount of displacement and workload between participants either receiving or not receiving vibrotactile feedback. Further, participants were unable to see or hear. They found that both displacement and workload, as assessed by the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) were significantly reduced when utilizing the vibrotactile vest.

Vibrotactile torso displays have also been shown to improve cueing and navigational performance in different operational contexts. For example, Ho, Tan, and Spence (2005) demonstrated that automobile drivers utilizing a vibrotactile belt responded more quickly and accurately to driving events. The belt contained two sensors that cued attention to critical events in driving scenarios and the task required participants to correctly respond by braking or accelerating. Those wearing the display reacted faster and more accurately than those not wearing the display. Vibrotactile displays can also reliably present waypoint navigation information to pedestrians. Van Erp, Hendrik, Van Veen, and Jansen (2005) measured the pace of participants as they walked an unknown path only guided by tactile feedback from a vibrotactile display which was a belt containing eight tactors. They determined that all participants were able to complete the routes and increased their pace to acceptable walking speeds within a short time frame. The authors extended this type of navigation with vibrotactile displays to air and maritime environments. Van Erp, Jansen, Dobbins, and Van Veen (2004) demonstrated the ability of a vibrotactile belt to guide operator navigation in a set course for a Gazelle helicopter and a high-speed inflatable boat. Without knowledge of their course and only using vibrotactile feedback cues, the operators were able to successfully guide their vehicles over the navigation path. Furthermore, in both wayfinding navigation studies, participants had little to no familiarity or experience with the display.

Vibrotactile torso displays also improve performance by reducing perceptual challenges resulting from displays that present too much or too little visual information. Many situations require teleoperators to make operational decisions while simultaneously monitoring numerous telemetry displays and one or more video feeds from a remote UGV. Cognitive resources can become increasingly strained, but implementing vibrotactile torso displays has been found to decrease subjective levels of mental workload in navigation (Cheung & Bouck, 2009; Van Erp, et al., 2003; Van Erp & Van Veen, 2004; Van Erp & Werkhovern 2006). In addition, vibrotactile torso displays deliver feedback more efficiently when there is not enough visual information. For example, extreme conditions such as smoke or darkness provide little to no video feed, and teleoperators may be forced to rely solely upon graphical telemetry displays. In these types of visually demanding situations, implementing vibrotactile torso displays have resulted in improved task performance (Cheung & Bouck, 2009; Van Erp, et al., 2003; Van Erp 2005).

Even though vibrotactile torso displays have been shown to improve performance by augmenting visual feedback, they have yet to be employed to aid operators' ability to detect and avoid environmental obstructions. Obstacle avoidance, which includes accurately identifying and then circumventing collisions with walls, barriers, obstructions, and other UGVs, can result in robot damage or damage to environmental surfaces. Avoiding collisions is heavily dependent on the perception of the remote environment as operators must be able to accurately estimate distances to obstructions, correctly judge aperture widths, and maintain safe distances from walls. Improving these abilities would not only result in a significant increase in overall UGV teleoperation usability but would reduce the costs associated with damaged and potentially irretrievable UGVs.

Previous literature on the ability of haptic feedback to augment visual displays indicates that obstacle avoidance information may be more meaningfully communicated via vibrotactile torso systems, though there is no empirical evidence to support this. Entities such as the NATO Research & Technology Organization have recognized the importance of obstacle avoidance in teleoperation, as well as the potential of tactile displays to enhance obstacle detection and avoidance (Van Erp & Self, 2008). Even though tactile torso display systems deliver feedback more intuitively than visual and graphical displays, they have not been incorporated into UGV teleoperation displays to improve obstacle avoidance. The goal of the proposed study was to determine the degree to which a vibrotactile torso belt could improve efficient teleoperation navigational performance over a video feed alone.

Specifically, the present study investigated two hypotheses in the context of a simulated environment. First, it was hypothesized that a vibrotactile torso display would improve obstacle avoidance performance over a video feed alone. Vibrotactile torso feedback can intuitively direct attention of operators (Van Erp & Verschoor, 2004), it has shown to improve navigational performance (Van Erp, Hendrik, Van Veen, & Jansen, 2005) and it can augment visual displays when communicating information about the remote environment (Chouvardas, et al., 2005b). Therefore, operators wearing the vibrotactile torso display would hit fewer obstacles and have faster course completion times. Second, subjective workload would be lower for teleoperators using the torso display than those utilizing visual feed alone. Incorporating vibrotactile torso displays have shown to reduce subjective cognitive load in operators in previous research (Cheung & Bouck, 2009; Van Erp, et al., 2003), and it is hypothesized that subjective workload scores will be lower for those utilizing a vibrotactile display in the current study.

Methods

Participants

Sixty students attending Clemson University (Clemson, SC) participated in this study (24 males, 36 females; age, *M* = 19.03 *SD* = 1.09) and were awarded course credit for their participation. All participants had normal or corrected to normal vision, and self-reported full use of their arms, neck, and hands.

Materials and Apparatus

Performance was evaluated in the context of a simulated environment. A simulated video feed of a remote environment was created using a Joint Architecture for Unmanned Systems (JAUS)-compliant unmanned vehicle simulator developed by AnthroTronix (AnthroTronix, Silver Springs, MD). The simulated video feed emulated a remote environment and UGV from the point of view of a camera placed on the top rear of the vehicle. The two courses were maze-like passageways, with constricted corridors and numerous turns (see Figure 1 for representative screen shots).

Figure 1. Representative images of simulated video feed and virtual course.

The simulated video feed was presented to participants through a 19” Acer LCD monitor. The image of the simulated video feed appeared in a 9 x 7” frame in the center of the screen. Participants used a Logitech Dual Action Gamepad remote controller to navigate the simulated environment (see Figure 2).

Figure 2. Remote controller used for operating the simulated UGV.

Vibrotactile feedback was supplied by a tactile feedback belt system developed by Anthrotronix, Inc. under an Army Research Laboratory effort (see Figure 3). The system is a military field belt comprised of eight rotary vibration tactors which are contained underneath heavy fabric. Each sensor is approximately 1.9 cm in diameter and 1 cm in thickness, and vibrates with a tactile intensity of 1 g nominal. The belt weighs approximately 1.3 lbs and is adjustable to fit snuggly around the torso. Each tactor is individually powered and can vary in amplitude of vibration, allowing the belt to provide feedback at different locations and intensities around the torso. The tactile belt communicates with the computer and JAUS simulator via Bluetooth.

Figure 3. The vibrotactile feedback belt.

Subjective workload was assessed using the NASA Task Load Index (NASA-TLX) mental workload questionnaire (Hart & Staveland, 1988). The NASA-TLX evaluates the magnitude of six separate subscales associated with mental demand in a given task. Participants assign weights and ratings to the six separate factors and magnitudes of each factor are reported. Only Overall Workload, a weighted average of the subscales, was utilized in the present study and ranges from 0 (low) to 100 (high).

Design

The present study utilized a between-subjects design to assess any navigational performance differences for operators utilizing a vibrotactile feedback display.

Participants were randomly divided into two conditions: one group navigated the course using only simulated video feed while the second group utilized simulated video feed in addition to a vibrotactile display. Performance was measured by the time it took to complete the course and the number of collisions within the course.

The number of participants was determined after conducting a power analysis based on the effect sizes summarized by Elliott, Coovert, and Redden (2009). The range of applicable effect sizes, in the form of Hedge's g, for the current study ranged from .597 to .911. Using power=.80, condition sizes were calculated to range from n=35 to n=15, respectively. A conservative midrange value of n=30 per group was chosen.

A demographics questionnaire included open-ended questions regarding videogame experience. Participant responses were coded on a 1 to 5 Likert scale in terms of experience.

All participants completed a brief training course to become comfortable with the simulated environment and controller (and vibrotactile display for the display condition). Following successful completion of the training course, all participants completed two experimental courses. Completion entailed controlling the simulated vehicle from a starting point A to a finish point. After completion of both courses, mental workload was assessed using the NASA-TLX mental workload questionnaire. The number of collisions and course completion time were each combined over both experimental courses because both experimental courses were similar in design. Differences in performance and workload between the two conditions were used to evaluate the overall effectiveness of the vibrotactile display.

Procedure

All participants provided informed consent and completed a short demographics questionnaire, which included questions regarding video game experience. A brief explanation of the study was given, which included an explanation of UGVs using a small model robot that emulated the simulated vehicle. Participants were then familiarized with the controller and simulated environment. For those participants in the display condition, the features and functionality of the vibrotactile belt system were described and the belt was then comfortably fitted to their waist.

All participants then completed a brief training course which mimicked the experimental courses in terms of design, but was significantly shorter. This allowed participants to become familiar with the technology and to also demonstrate a level of minimal proficiency. The training course required participants to navigate the vehicle from starting point A to finish point B in less than 90 seconds while making fewer than ten collisions. If participants exceed either criterion, they completed the same training course until they were able to meet both limits. An experimenter recorded time while the simulator recorded the number of collisions, which were defined as any point the vehicle came into contact with any entity in the course (walls, corners, obstacles). Those in the display condition completed the training course while wearing the vibrotactile display.

Following successful completion of training, participants completed two trial courses in the same order. Both experimental courses were longer than the training course and contained obstacles. Those in the display condition also completed the courses while wearing the vibrotactile display. Participants were instructed to control the simulated UGV from start to finish as quickly as they could while avoiding collisions to the best of their ability.

Once participants were finished, they completed the NASA-TLX and a qualitative survey regarding task difficulty.

Results

Data Analysis

Performance was recorded in two experimental courses. Because both experimental courses were qualitatively similar in terms of design, both the number of collisions and the course completion time were summed between Course 1 and Course 2 to represent a single score for each measure of performance. NASA-TLX subjective workload data are represented as Overall Workload and range from 0 (low) to 100 (high).

Overall Performance and Workload

Means for each performance measure by both display type and gender are listed in Table 1. Performance was significantly correlated with workload, such that those with fewer collisions and faster course completion times experienced less workload (see Table 2). Videogame experience was also correlated with both measures of performance, such that more experience resulted in less collisions and faster completion times. Three independent samples t-tests concluded there was no effect of display type on the number of collisions ($t(58)=.90$, $p=.37$), course completion time ($t(58)=-1.34$, $p=.19$) or overall subjective workload ($t(58)=.32$, $p=.75$).

Table 1.

Means and standard deviations for performance measures by display condition and gender.

			Collisions		Completion Time (s)		NASA TLX Score (0-100)		Videogame Experience (Likert, 1-5)	
	Gender	N	M	SD	M	SD	M	SD	M	SD
No Display	F	20	78.4	48.87	614.05	93.24	46.27	18.10	2.3	1.08
	M	10	39.9	16.56	537.5	58.87	39.40	12.63	3.4	1.08
	Total	30	65.57	44.62	588.53	90.12	43.97	16.58	2.67	1.18
Vibrotactile Display	F	16	74.81	48.50	684.5	138.87	49.42	11.13	1.94	1.06
	M	14	33.43	15.24	559.14	54.18	34.77	19.56	3.64	1.28
	Total	30	55.5	41.97	626.0	123.84	42.58	17.05	2.73	1.44

Table 2

Overall Pearson correlation coefficients for performance and demographic variables.

	Number of Collisions	Completion Time	NASA-TLX Score
Completion Time (s)	.73**	--	
NASA-TLX Score	.47**	.45**	--
Videogame experience	-.39**	-.42**	-.23

**p<.01

Three two-way between groups analyses of covariance were conducted to assess the effect of display type and gender on each dependent variable while controlling for videogame experience, which has shown to be related to teleoperational ability (Chen, 2010). For number of collisions, there was no main effect of display type (F (1,55)= .28, p=.60, η^2= .01), although males made significantly fewer collisions than females (F (1,55)= 6.01, p=.02, η^2= .10). There was no significant interaction (F (1,55)= .00, p=.95, η^2= .00). For course completion time, while those in the vibrotactile display condition had a trend towards longer times than those without the vibrotactile display, the difference was not significant (F (1,55)= 3.14, p=.08, η^2= .05). Males completed the course significantly faster than females (F (1,55)= 6.00, p=.02, η^2= .10), though there was no interaction (F (1,55)= .52, p=.47, η^2= .01). Lastly, there was no significant difference between display conditions for subjective workload (F (1,55)= .03, p=.86, η^2= .00). Males tended to report lower workload scores than females, though the difference was not significant (F (1,55)= 3.9, p=.06, η^2= .06). There was no interaction between workload and gender (F (1,55)= .70, p=.41, η^2= .01).

To further assess the contributions of gender and videogame experience on navigational performance, standard multiple regression analyses were conducted for each dependent variable. For number of collisions the multiple regression resulted in r^2 (60) = .25 with only gender significant. Partial t-values were t (57) =-2.62 (p=.01) and t(57) = -1.52 (p=.13) for gender and videogame experience, respectively. When the regression was repeated with videogame experience removed from the model the r^2 dropped to .22, indicating that once gender was in the model videogame experience only accounted for an additional 3% of the variance in the number of collisions. For course completion time, the multiple regression resulted in r^2 (60) = .21. Gender was a significant predictor with a partial t-value of *t*(57) =-2.13 (*p*=.04), while videogame experience was close to significant, with a partial *t*-value of *t*(57) = -1.94 (*p*=.06). The model r^2 lowered to .19 when the regression was repeated with videogame experience removed, indicating when including gender videogame experience contributed only an additional 2% of the variance in course completion times. For total workload, a simple regression was conducted to assess the contribution of gender and omitted videogame experience because of the lack of a significant correlation (see Table 2). Gender was a significant predictor (*t*(59)=-2.62, *p*=.01).and had a r^2 (60) = .11, indicating that approximately 11% of the variation in workload scores was due to gender.

Performance by Individual Course

Because there was no effect of display type on overall trial performance, subsequent analyses were conducted to further explore performance during the two trial courses individually. Means and standard deviations for both Course 1 and 2 by display type are presented in Table 3. Irrespective of display type, Course 1 contained more collisions while Course 2 contained a higher course completion time, though the first course contained more obstacles while the second course was longer. To assess whether there was any effect of display type on performance in either course, independent samples t-tests were performed for each performance variable. In Course 1, there was no effect of display type on collisions (*t*(58) = .90, *p*= .37) or course completion time (*t*(58)

= -1.15, *p*= .26). Findings were similar for Course 2 as there was no effect of display type on collisions (*t*(58) = .46, *p*= .65) or completion time (*t*(58) = -1.34, *p*= .17).

Table 3.

Means and standard deviations for performance measures in each trial course by display condition and gender.

	Course 1				Course 2			
	Collisions		Completion time (s)		Collisions		Completion time (s)	
	M	SD	M	SD	M	SD	M	SD
No Display	58.47	37.88	211.43	45.08	7.1	10.13	377.10	51.62
Vibrotactile Display	49.80	36.60	226.30	54.93	5.7	13.12	399.70	74.34
Total	54.13	37.19	218.87	50.38	6.4	11.64	388.4	64.47

Performance during Training

Performance during training was also explored and descriptive statistics are listed by display type and gender in Table 4. If participants failed to meet criterion by completing the training course in under 90 seconds while making fewer than 10 collisions, they were required to complete the same course again. Three participants failed to complete the training course on the first try, though these participants met both requirements during their second time through the training course. They were all females in the Vibrotactile Display condition and exceeded the collision limit by having 11, 13, and 83 collisions. Because 83 was an extreme outlier compared to the performance of other participants, this participant's performance data was omitted from the data presented in Tables 3 and 4.

Table 4.

Means and standard deviations for performance measures during training by display condition and gender.

			Training Collisions				Training Completion Time (s)			
	Gender	N	M	SD	Min	Max	M	SD	Min	Max
No Display	F	20	2.85	2.32	0	8	55.9	5.9	48	67
	M	10	.60	.70	0	2	53.0	6.6	41	65
	Total	30	2.10	2.20	0	8	54.9	6.2	41	67
Vibrotactile Display	F	15*	3.33	4.01	0	13	59.73	9.45	48	90
	M	14	.93	1.27	0	4	53.71	5.15	43	63
	Total	29	2.17	3.21	0	13	56.8	8.14	43	90

**One participant was removed due to an extremely high number of collisions.*

Both number of collisions and course completion time during training was assessed to determine any main effect of the vibrotactile display or gender. A two-way between groups analyses of variance was conducted, while omitting the single participant with 83 collisions. There was no main effect for display type for either collisions (F (1,55)= .356, p=.55, η^2= .01) or course completion time (F (1,55)= .1.53, p=.22, η^2= .03). There was a main effect of gender for both number of collisions (F (1,55)= .11.71, p=.00, η^2= .18) and for completion time (F (1,55)= .5.69, p=.02, η^2= .09), indicating that males performed significantly better than females during training. However, the interaction was not significant for either collisions (F (1,55)= .01, p=.91, η^2= .00) or completion time (F (1,55)= .73, p=.39, η^2= .01).

Discussion

This study investigated the ability of a vibrotactile display to improve simulated teleoperation performance over a video feed alone. It was hypothesized that operators wearing the vibrotactile belt would make fewer collisions and have faster course completion times, as well as report lower ratings of subjective workload. However, these hypotheses were not supported in the present study. There was no effect of the vibrotactile display on either the number of collisions or the course completion times. These findings are contrary to recent navigational research with vibrotactile displays, which have generally found that these types of interfaces improve navigational and operational performance. The belt also had no effect on subjective cognitive workload as assessed by the NASA-TLX. Previous research has found reduced workload ratings when incorporating tactile feedback along with a visual display (Cheung & Bouck, 2009; Van Erp, et al., 2003; Van Erp & Van Veen, 2004; Van Erp & Werkhovern 2006). Specifically, the vibrotactile display used in the current study did not supplement teleoperational performance over video feed alone in the given simulated context. Reasons for this include potential problems associated with the experimental tasks, concerns related to training and learning effects, and issues with the vibrotactile feedback.

It is possible that the perception of the course via the video feed alone was not challanging enough in the present study to elicit performance differences. Van Erp and Van Veen (2004) demonstrated differences in performance and subjective ratings of mental load between three different display types during a perceptual driving task that was explicitly designed to require a high workload. They assessed reaction time and workload within both normal and high workload conditions for a visual display, a tactile display, and a combined multimodal display. Under normal workload conditions there were no performance differences between the three displays, but significant performance differences were revealed when workload was high. Perceived workload remained unchanged for the tactile and multimodal display groups between workload conditions, but for the visual modality there was a large difference between the normal and high conditions. In the present experiment the ability of the subjects to perceive the simulated course may not have been difficult enough to elicit performance differences between the two display modalities and future studies with this vibrotactile display should increase the cognitive demand of operators and degrade the video feed. For example, additional monitoring tasks could be applied, the video could be degraded, or consequences for trial errors could be implemented.

Participants were required to demonstrate a minimum level of proficiency during a training scenario, and it is possible that the criteria of the training task were not rigorous enough. Simulated navigational tasks such as these are susceptible to many factors, including spatial ability and prior experience, and this training task was to ensure that participants could perform at a specific level before being required to complete the experimental courses. Because there were no performance differences in the experimental trial, post hoc analyses were conducted to assess performance during training. Only three participants were required to complete the training course a second time due to an exceeded number of collisions (one was very extreme), though all were able to meet the performance criteria when completing the course a second time. Further, the means for number of collisions (M=2.2) and completion time (M=56.8 seconds) were well below the set criteria (10 collisions and 90 seconds, respectively). Future study design using the display and simulator in this study should ensure that training requirements are more stringent.

Minor differences in the design of the two simulated experimental courses made it impossible to asses any learning effects, which may have partially shadowed any performance effects of the vibrotactile display. Post hoc analyses assessing the courses individually revealed a higher number of collisions in the first course. However, the first course contained more difficult obstacles and required the participant to make more complicated navigational maneuvers. The second course was also much longer than the first, which resulted in a longer mean completion time. Had these experimental scenarios been more similar in terms of number of obstacles and length, comparative analyses could have been conducted. It would have been possible to assess interactions between display type and rate of improvement and to determine how much variance in performance was due to experience with the simulated courses. Simulated courses evaluated with the vibrotactile display will be designed to be similar in terms of collisions and distance for future studies.

In the present study participants had a clear, unobstructed view of the remote environment and it is possible that the tactile display did not present any additional information about the environment that could not be easily obtained through vision. Performance differences have been found between visual and multimodal (visual + tactile) displays in situations with degraded visual conditions (Van Erp, 2005). Adding a scenario where visual conditions were impaired may have resulted in performance differences between display conditions. Future studies assessing the practicality of vibrotactile displays should assess its ability to improve performance when visual feedback is poor.

The vibrotactile display used in the current study was highly sensitive and it may not have delivered feedback that was specific enough to be informative. Vibration was emitted when the vehicle came within a specific proximity of an obstacle and perhaps this distance was too large, resulting in an overabundance of vibratory feedback. Post experimental comments revealed that many participants considered the vibration excessive, with the display vibrating when the participants felt that they were in no danger of hitting an obstacle. Several comments from participants indicated that the vibration was so prolonged that they attempted to ignore the feedback altogether. Modifying the time of feedback presentation by reducing the distance between the vehicle and the obstacle before operators are notified vibrotactilly may result in a more practical display.

Besides the timing of vibratory feedback presentation, the varying amplitudes of feedback may also have resulted in a display that was not informative about obstacle proximities in the simulated environment. The vibrotactile display used in the present study delivered varying intensities of localized vibration through each of the eight tactors in the belt to alert operators of changing obstacle proximities from the vehicle, though the difference between intensities was small. The different vibrotactile intensities that operators felt may have been too similar and, perceptually, the difference between the mildest sensation may not have differed greatly from the most intense vibration. Operators may have interpreted vibration from each of the tactors as only a single alert and not as a dynamic feedback system providing differing degrees of warnings. As a result, operators may not have found the vibration to be of much informational value. Research has shown that vibrotactile feedback is limited in terms of conveying information through intensity differences because humans are sensitive to only a small number of discernable differences in vibration frequencies (Van Erp; 2002). Future studies with this display should investigate more meaningful methods of presenting remote environments through vibrotactile feedback, or at least ensure that fluctuating feedback meant to alert operators is reliably discernable.

Similarly, the vibrotactile display also failed to reliably inform operators when they had collided with an obstacle. While the intensity of vibration increased as the vehicle came in closer contact with an obstacle, there was no change in vibration from when the vehicle was directly beside an object to when the vehicle was in contact with an object. The tactor presented a constant, static buzz, to where post-experimental feedback revealed that several participants were somewhat unaware whether they had actually collided with an obstacle or merely come very close to it. Incorporating feedback that adequately informs participants of a collision is crucial for a display that is meant to help prevent impact with obstacles. Future studies should seek to understand what type of collision feedback would be most informative, including varying the types of vibrotactile stimulation or incorporating other displays, such as visual telemetry displays.

While there was no effect of a vibrotactile display on teleoperation performance, gender was a strong predictor of navigational ability in the present study. Generally, gender differences in virtual navigation have been thought to be the result of differences in spatial ability and strategy (Lawton & Morrin, 1999; Prestopnik & Roskos-Ewoldsen, 2000). Teleoperation performance has also shown to be affected by videogame usage (Chen, 2010), of which men tend to have more experience (Philips, Rolls, Rousse, & Griffiths, 1995). However, gender was a stronger predictor than videogame experience when both were placed into multiple regression models together, and videogame experience was not significant when gender was placed into the model first. While both spatial ability and videogame experience certainly may have played a role in contributing to a considerable gender effect in the current study, other studies have found that visual displays can affect performance differences between males and females and future studies should consider the type of visual display. For instance, visual displays with larger and wider fields of view have reduced performance differences between males and females typically observed in virtual navigation tasks (Tan, Czerwinski, & Robertson, 2006).

The perception of remote environments during teleoperation is fraught with difficulties (e.g., ; Casper & Murphy, 2003; Gomer et al., 2009; Moore et al., 2009; Murphy, 2004; Smets, 1995; Tittle, Roesler, & Woods, 2002), and future studies should continue to explore different displays for improving various types of operator performance. While the present study failed to find any obstacle avoidance improvements from the vibrotactile display, knowledge from these findings will contribute to designing the next prototype and inform future studies of display limitations.

References

Archaumbault, D. & Burger, D. (2001). From multimodality to multimodalities: The need for independent models. Proceedings of the UACHI 2001 conference, Universal Access in HCI –Towards an Information society for All, 2001, 227-231.

Casper, J. & Murphy, R.R. (2003). Human-robot interactions during the robot-assisted urban search and rescue response at the world Trade Center. *IEEE Transactions on Systems, Man, and Cybernetics – Part B: Cybernetics, 33*, 367-385.

Chen, J.Y.C. (2010). UAV-guided navigation for ground robot tele-operation in a military reconnaissance environment. *Ergonomics, 53*(8), 940-950.

Chen, J.Y.C., Haas, E.C., & Barnes, M.J. (2007). Human performance issues and user interface design for teleoperated robots. *IEEE Transactions on Systems, Man, and Cubernetics , 37*(6), 1231-1245.

Cheung, B. & Bouak, F. (2009) Using tactile cueing to enhance spatial awareness under degraded visual environment. Proceedings of NATO RTO Symposium Human Performance Enhancement for NATO Military Operations (Science, Technology and Ethics). Sofia, Bulgaria. NATO RTO RTO-MP-HFM-181.

Chouvardas, V.G., Miliou, A.N., & Hatalis, M.K. (2005a). Tactile display applications: A state of the art survey. Proceedings of the 2nd Balkan Conference in Information, 2005, 290-303.

Chouvardas. V.G., Miliou, A.N., & Hatalis, M.K. (2005b). Tactile displays: A short overview and recent developments. Proceedings of the 5th Conference on Technology and Automation- 2005, 246-251.

Chouvardas. V.G., Miliou, A.N., & Hatalis, M.K. (2007). Tactile displays: Overview and recent advances. *Displays*, *29*, 185-194.

Darken, R.P., Kempster, K., & Peterson, B. Effect of streaming video quality of service on spatial comprehension in a reconnaissance task. Proceedings of the 23rd Army Science Conference, 391-400.

Dobbins, T. & Samways, S. (2002). The use of tactile navigation displays for the reduction of disorientation in maritime environments. In *Proceedings of the RINA Conference on High Speed Craft: Technology and Operation* (pp.13-20). London: Royal Institution of Naval Architects.

Elliott, L.R., Coovert, M.D., & Redden, E.S. (2009). Overview of meta-analyses investigating vibrotactile versus visual display options. Proceedings of the *13th International Conference of Human-Computer Interaction*, 2009.

Fong, T. & Thorpe, C. (2001). Vehicle teleoperation interfaces. *Autonomous Robots, 11*, 9-18.

Gomer, J. A., Dash, C., Moore, K. S., & Pagano, C. C. (2009). Using radial outflow to provide depth information during teleoperation. *Presence: Teleoperators and Virtual Environments, 18*, 304-320.

Grierson, L.E.M., Zelek, J., & Carnahan, H. (2009). The application of a tactile way-finding belt to facilitate navigation in older persons. *Ageing International,34*(4), 0163-5158.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N Meshkati (Eds), *Human mental workload* (pp. 139Ð183). Amsterdam: North Holland.

Ho, C., Tan, H.Z., & Spence, C. (2005). Using spatial vibrotactile cues to direct visual attention in driving scenes. *Transportation Research, 8*, 397-412.

Kanduri, A.K., Thomas, G., Cabrol, N., Grin, E., & Anderson, R.C. (2005). The (in)accuracy of novice rover operators' perception of obstacle height from monoscopic images. *IEEE Transactions on Systems, Man, and Cybernetics 35(4), 505-512.*

Kontarinis, D.A. & Howe, R.D. (1995). Tactile display of vibratory information in teleoperation and virtual environments. *Presence, 4*(4), 387-402.

Kuhl, S.A., Thompson, W. B., & Creem-Regehr, S. H. (2006). Minification influences spatial judgments in virtual environments. In *Proceedings of the Symposium on Applied Perception in Graphics and Visualization*. ACM, New York, 15–19.

Kuhl, S.A., Thompson, W. B., & Creem-Regehr, S. H. (2009). HMD Calibration and its effect on distance judgements. *ACM Transactions on Applied Perception*, *6*(3), 19.

Lathan, C. & Tracey, M. (2002). The effects of operator spatial perception and sensory feedback on human-robot teleoperation performance. *Presence, 11*(4), 368-377.

Lawton, C.A. & Morrin, K.A. (1999). Gender differences in pointing accuracy in computer-simulated 3D mazes. *Sex Roles, 40*(12), 73-92.

Lee, S., Sukhatme, G.S., Kim, G.J., & Park, C. (2002). Haptic control of a mobile robot: A user study. IEEE Conference on Intelligent Robots and Systems – 2002.

Merlo, J.L., Stafford, S., Gilson, R., & Hancock, P.A. (2006). The effects of physiological stress on tactile communication. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting - 2006, 1562-1566.

Moore, K. S., Gomer, J. A., Pagano, C. C., & Moore, D. D. (2009). Perception of robot passability during direct line of sight and teleoperation. *Human Factors, 51*, 557-570.

Murphy, R. R. (2004). *Humans, robots, rubble, and research. Interactions, 12*(2), 37-39.

Philips, C.A., Rolls, S., Rouse, A. & Griffiths, M.D. (1995). Home video game playing in schoolchildren: A study of incidence and pattern of play. *Journal of Adolescence, 18*, 687-691.

Prestopnik, J.L. & Roskos-Ewoldsen, B. (1999). The relations among wayfinding strategy use, sense of direction, sex, familiarity, and wayfinding ability. *Journal of Environmental Psychology, 20*(2), 177-191.

Rastogi, A. (1996). Design of an interface for teleoperation in unstructured environments using augmented reality displays. M.S. thesis, University of Toronto, Toronot, ON, Canada.

RÖsch, O.J., Schilling, K., & Roth, H. (2002). Haptic interfaces for the remote control of mobile robots. Control Engineering Practice, 10, 1309-1313.

Smets, G. (1995). Designing for Telepresence: The Delft Virtual Window System. *Local Applications of the Ecological Approach to Human-Machine Systems, 2*, 182-207.

Tan, H.Z. & Pentland, A. (1997). Tactual displays for wearable computing. *Proceedings of the* First International Symposium on Wearable Computers, 84-89.

Thomas, L.C. & Wickens, C.D. (2000). Effects of display frames of reference on spatial judgments and change detection. University of Illinois, Institute of Aviation Final Technical Report (ARL-00-14/ARMY-FED-LAB-00-4). Savoy, IL: Aviation Research Lab.

Tittle, J.S., Roesler, A., & Woods, D.D. (2002). The remote perception problem. *Proceedings of* the Human Factors and Ergonomics Society 46th Annual Meeting, 260-264.

Van Erp, J.B.F. (2000). Tactile Navigation Display. In S. Brewster & R. Murray-Smith (Eds.) Haptic human computer interaction. Lecture notes in computer science (vol. 2058, 165-173). Berlin: Springer Verlag.

Van Erp, J. B. F. (2002). Guidelines for the use of vibro-tactile displays in human computer interaction. In *Proceedings Eurohaptics 2002,* Edinburgh, S. A. Wall et al., Eds. 18–22.

Van Erp, J.B.F. (2005). Presenting directions with a vibrotactile torso display. *Ergonomics*, *48*(3), 302-313.

Van Erp, J.B.F., Groen, E.L., Bos, J.E., & Van Veen, H.A.H.C. (2006). A tactile cockpit instrument supports the control of self-motion during spatial disorientation. *Human Factors*, *48*(2), 219-228.

Van Erp, J.B.F., Jansen, C., Dobbins, T. & Van Veen, H.A.H.C. (2004). Vibrotactile waypoint navigation at sea and in the air: Two case studies. In *Eurohaptics 2004 conference*. Munchen, Germany.

Van Erp, J.B.F. & Padmos, P. (2003). Image parameters for driving with indirect viewing systems. *Ergonomics*, 46, 1471-1499.

Van Erp, J.B.F. & Self, B.P. (2008). Tactile displays for orientation, navigation, and communication in air, sea, and land environments. NATO Research and Technology Organization.

Van Erp, J.B.F. & Van Veen, H.A.H.C. (2004). Vibrotactile in-vehicle navigation sysem. Transportation Research Part F-. *Traffic Psychology and Behaviour, 7*(4-5), 247-256.

Van Erp, J.B.F. & Van Veen, H.A. (2006). Touch down: The effect of artificial touch cues on orientation of microgravity. *NeuroScience Letters, 404,* 78-82.

Van Erp, J.B.F., Van Veen, H.A.H.C., Jansen, C., & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. *Transactions on Applied Perception, 2*(2), 106-117.

Van Erp, J.B.F., Van Veen, H.A.H.C., & Ruijsendaal, M. (2008). More than a feeling: Bringing touch into astronauts' spatial orientation. *Microgravity Science and Technology*,

Van Erp, JB.F. Veltman, J.A., & Van Veen, H.A.H.C. (2003). A tactile cockpit instrument to support altitude control. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, 114-118.

Van Erp, J.B.F. & Verschoor, M.H. (2004). Cross-modeal visual and vibrotactile tracking. *Applied Ergonomics, 35*, 105-112.

Van Erp, J.B.F. & Werkhoven, P. (2006). Validation of principles for tactile navigation displays. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, 1687-1691.

Waller, D. (1999). Factors affecting the preception of interobject distances in virtual environments. *Presence, 8*(6), 657-670.

Woods, D.D., Tittle, J., Feil, M., & Roesler, A. (2004). Envisioning human-robot coordination in future operations. *IEEE Transactions on Systems, Man, and Cybernetics, Appl. Review, 34*(2), 210-218.

Zijlstra, F.R.H. & Van Doorn, L. (1985). *The construction of a scale to measure perceived effort*. ISN 6105/6107, NABS N10. University of Technology, Delft, The Netherlands.