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Effects of Vibrotactile Display Position and Shape on Extrapersonal Localization

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EFFECTS OF VIBROTACTILE DISPLAY POSITION AND SHAPE ON EXTRAPERSONAL LOCALIZATION

by

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ABSTRACT

EFFECTS OF VIBROTACTILE DISPLAY POSITION AND SHAPE ON EXTRAPERSONAL LOCALIZATION

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Vibrotactile displays are capable of conveying extrapersonal spatial information to users navigating or operating within a three-dimensional environment (e.g., aircraft pilots). Although vibrotactile displays can be applied to many parts of the body, recent applications have focused on torso-based displays that egocentrically reference distal targets. However, these displays may be poorly suited to convey elevation because of the generally cylindrical shape of the human torso. The purpose of the present study was to evaluate the relative effectiveness of handheld vibrotactile displays configured either in a cylindrical or spherical-shape as compared to a torso-based display. Due to its shape, the spherical display was predicted to facilitate superior elevation discernment; however, it was anticipated users must employ an object-centered reference point independent of the body when perceiving directionality via a handheld display. Hypothesis testing indicated participants' perception of extrapersonal elevation was improved by the spherical handheld display. Evidence was not conclusive regarding participants use of an object-centered egocenter. The use of a handheld vibrotactile display resulted in increased subjective workload scores, regardless of shape. Results from the present study suggest a spherical handheld display may be advantageous for three-dimensional tasks; however, specific applications should be evaluated on a case-by-case basis.

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CHAPTER I

INTRODUCTION

The sense of touch facilitates the exploration of one's immediate peripersonal space through bodily contact; however, touch can also direct attention towards people and objects located in extrapersonal space. For example, a tap on the shoulder immediately draws one's attention in the apparent direction of the person who initiated the shoulder tap, not to the actual shoulder where the finger tap was detected (Van Erp, 2005a). The "tap-on-the-shoulder" metaphor is the basis for many tactile displays designed to cue users' spatial attention. Notable examples include Rupert's (2000) Tactile Situation Awareness System (TSAS) and Brill and colleagues' TACTile Information Communication System (TACTICS; Brill, Terrence, Downs, Gilson, Hancock, & Mouloua, 2004; Brill, Terrence, Stafford, & Gilson, 2006). These and other related efforts (see Van Erp, 2005a) have focused on mapping distal targets to the torso using discrete vibrotactile stimuli. However, the generally cylindrical shape of the human torso likely limits users' ability to attribute proximal stimuli to specific distal targets, especially in terms of elevation. Torso-centered vibrotactile displays have also been shown to distort spatial information presented along the azimuth as a result of anchor point bias (Cholewiak, Brill, & Schwab, 2004; Van Erp, 2005a) and internal kinesthetic egocenter placement (Van Erp, 2005a). The purpose of the present study was to evaluate the relative effectiveness of a torso-based vibrotactile display as compared to cylindrical and spherical-shaped handheld display, respectively, which were anticipated to require an object-centered egocenter independent of the body.

Spatial Displays and Touch

The sense of touch has been previously discussed as a means of conveying spatial sensory information to the visually impaired. For example, Collins (1970) suggested the sense of touch as a practical substitute for vision because of similarities between somatosensory receptors in the skin and the structure of the retina. Additional researchers (e.g., Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969; White, 1970) explored creating a tactile vision-substitution system. In this context, two-dimensional images and video were physically recreated on participants' chest and back using arrays of *tactors* (i.e., individual vibrating stimulators). Participants were able to recognize some complex object forms, such as a human face, but only after experiencing multiple viewing angles of the same target (Lenay et al., 2003). Additionally, reports from blindfolded sighted participants suggest these displays in no way replicate the experience of vision, regardless of tactor array size or density. Lenay et al. (2003) clarify vibrotactile displays facilitate *perceptual substitution* rather than true *sensory substitution*. Recreating images on participants' torsos using vibrotactile stimuli conveys some spatial information about the surrounding environment, but cannot replace the sensory information conveyed by vision. Ultimately, torso-based tactile vision-substitution displays were deemed largely ineffective due to the non-intuitive nature of attempting to "feel" two-dimensional images presented on the surface of the skin (Rupert, 2000).

Subsequent vibrotactile research within the field of aviation investigated incorporating vibrotactile displays in the cockpit to reduce pilot error in high-workload contexts (e.g., poor weather-related visibility and military combat situations). Instead of trying to replace pilots' visual experience, aviation-oriented vibrotactile displays focused on improving pilot performance by offloading display information from the often overwhelmed visual (and sometimes auditory) modality. For example, Hirsch (1974) presented error rate information for single-axis altitude control to the thumb and index finger and found improved operator performance compared to an analogous visual condition. Additionally proposed aviation displays such as the Cutaneous Tactile Communicator (CTC; Zlotnik, 1988) strove to completely eliminate the need to check cockpit flight instruments by providing pilots with sufficient in-flight information (e.g., airspeed and angle-of-attack information) through vibrotactile stimulation.

Incorporating components from both vision-substitution and aviation display research, Rupert (2000) proposed a new type of vibrotactile spatial display, dubbed the Tactile Situation Awareness System (TSAS), in a joint collaboration with the National Aeronautical Space Administration's Johnson Space Center (NASA JSC; Houston, Texas) and the Naval Aerospace Medical Research Laboratory (NAMRL; Pensacola, Florida). Similar to the chest and back vibrotactile arrays employed by Bach-y-Rita et al. (1969) and White (1970), TSAS consisted of tactor arrays mapped onto users' torsos. However, unlike previous sensory substitution displays, Rupert (2000) did not attempt to use tactor arrays to present visually transduced images or video. Instead, TSAS provided vibrotactile gravity vector cues to combat the spatially disorienting effects of flight sometimes experienced by pilots and astronauts. From the perspective of a pilot, TSAS presented vibrotactile pulses to indicate the direction of the ground when aircraft orientation deviated from straight and level flight. For example, when rolling an aircraft to the right, a TSAS-equipped pilot would feel a vibrating tactor on the lower right side of his or her torso. If the aircraft were to continue to roll to the right, additional tactors would be sequentially activated such that the vibrotactile stimulus would be perceived as moving up the right side of the pilot's torso towards the right shoulder (Rupert, 2000). Pilots using TSAS reported reduced workload during demanding flight conditions because they were more able to focus on visual displays and mission tasks (McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004). Rupert's (2000) novel approach to the applied problem of pilot disorientation succeeded where other countermeasures had failed because TSAS supplemented vision instead of trying to replace it.

TSAS was also an intuitive innovation among preexisting vibrotactile aviation displays because it utilized users' torsos as a reference point from which a rough set of extrapersonal coordinates could be derived. In principle, the use of tactors on the body to outwardly orient pilots' attention is similar to the tap-on-the-shoulder phenomenon, whereby a person tapped on the shoulder turns to look in the direction from which the tap seems to have originated. TSAS was the first vibrotactile display to incorporate this metaphor. However, the original purpose of TSAS necessitated the tap-on-the-shoulder metaphor only convey a relatively large angular region (i.e., capable of orienting pilots towards the Earth). This suggests TSAS could have limited spatial resolution in contexts requiring users to pinpoint specific extrapersonal targets (e.g., discrete localization tasks in low gravity, undersea, or aviation situations). Subsequent to the introduction of TSAS, a great deal of research has been performed involving the use of torso-based tactor arrays to outwardly orient users towards more specific angular regions (e.g., Brill et al., 2004; Brill, Terrence, Stafford, & Gilson, 2006; Garcia et al., 2012; Van Erp, 2005a).

Conveying Lateral Torso Cues

Vibrotactile discriminability along the azimuth of the torso is between 10 and 40 mm (Cholewiak et al., 2004; Van Erp, 2005b). Although not as sensitive as some other parts of the body, these findings indicate discrete vibrotactile stimuli can be sufficiently distinguished on the torso, potentially for the purposes of extrapersonal localization using the tap-on-the-shoulder metaphor. However, additional factors such as anchor point bias and internal kinesthetic egocenter placement have been found to significantly affect participants' perception of vibrotactile stimuli presented horizontally along the torso.

Anchor Point Bias. Anchor points refer to bodily areas associated with highly accurate tactile localization abilities. Originally thought to only coincide with joint position (see Boring, 1942), additional anchor points have been reported on the torso aligned with the navel and spine (Cholewiak et al., 2004). These torso-based anchor points have been shown to reduce azimuth dispersion for external localizations corresponding to vibrotactile stimuli aligned with the midsagittal plane ($SD = 4°$) as compared to laterally positioned stimuli ($SD = 14°$; Van Erp, 2005a). However, this localization difference along the azimuth of the torso may also skew spatial information conveyed by vibrotactile cues. Cholewiak et al. (2004) found that when participants made azimuthal localization errors, they were more likely to occur in a direction away from the midsagittal plane. Conversely, Van Erp (2005a) found a perceived directional bias in the opposite direction as reported by Cholewiak et al. (2004); participants were more likely to err towards the frontal or dorsal anchor points. Van Erp (2008) speculates the skewing of vibrotactile localization towards the midline may be a consequence of an absolute localization bias on the torso towards the midsagittal plane. However, methodological differences between Van Erp (2005a) and Cholewiak et al. (2004) could be responsible for these seemingly contradictory findings. Van Erp (2005a) instructed participants to specify the *distal* positions indicated by vibrotactile stimuli on a large circular response field surrounding participants. In contrast, Cholewiak et al (2004) used a cylindrical response pad with buttons corresponding to *proximal* tactor positions. This difference (distal versus proximal localization) could account for the contrasting findings reported by Cholewiak et al (2004) and Van Erp (2005a), possibly due to the positioning of participants' internal kinesthetic egocenter(s).

Kinesthetic Egocenter Placement. The use of torso-based vibrotactile stimuli to convey the relative position of corresponding distal targets suggests the existence of an internal kinesthetic egocenter (i.e., perceived spatial point of origin). Additional factors, such as local body curvature, have not been found to affect the externally-projected directionality conveyed by discrete vibrotactile stimuli (Van Erp, 2005a). Instead of relying on torso curvature to accurately perceive directions conveyed by torso-based vibrotactile displays, users seem to extrapolate directionality from the linear relationship between one's internal egocenter position and the relative position of a vibrotactile stimulus on the skin. However, localizing participants' kinesthetic egocenter has proven difficult because experimental response methods can significantly affect the evaluation of egocenter location (Shimono, Higashiyama, & Tam, 2001). For example, using an arm to point in the direction indicated by a vibrotactile stimulus on the torso shifts the relative egocenter towards the shoulder of the arm in question (Shimono & Higashiyama, 2011). Moreover, past tactile research suggests some areas of the body play a larger role than others in terms of egocenter placement. Beschin, Cubelli, Della Sala, and Spinazzola

(1997) compared participants' head, gaze, and torso positioning in a tactile exploration task to determine which of these potential bodily references most significantly impacted participant performance. Only torso position manipulation was found to significantly impact performance. This suggests the longitudinal midline in the torso plays a substantial role when participants determine the relative position of external objects, at least compared to the effects of head position and gaze direction. However, results from Van Erp (2005a) suggest there are, at least, two torso-based egocenters. These distinct egocenters are reportedly positioned approximately 3 cm to the left and right of participants' midline on the coronal plane, and could account for the difference in directional bias reported by Cholewiak et al.'s (2004) proximal localization study and Van Erp's (2005a) distal localization study. The existence of multiple torso-based kinesthetic egocenters would likely have a greater effect on participants' *distal* localizations (e.g., Van Erp, 2005a) because of the need for a reference point when determining the *direction* conveyed by a torso-based vibrotactile stimulus.

Conveying Vertical Torso Cues

Previous investigations have indicated no differences in tactile discrimination along the longitudinal axis of the torso that might impact the perception of elevation cues. For example, Cholewiak et al. (2004) found no significant difference in proximal localization accuracy between a horizontal tactor array placed approximately at navel level and another horizontal array placed approximately 10 cm above the navel. In terms of conveying extrapersonal elevation, TSAS (Rupert, 2000) employed the tap-on-the-shoulder metaphor to orient pilots' attention both in terms of azimuth and elevation. The effective spatial resolution for TSAS was clearly able to improve pilots' performance and decrease perceived workload; however, users' underlying perception of discrete elevation cues was not specifically evaluated. An alternative method for conveying torso-based elevation was investigated by Brill and Terrence (2007) who evaluated the use of a tactile phi "arrow" to convey one of three levels of elevation through an otherwise horizontally-aligned linear tactor array. Participants' directional responses were significantly faster and more accurate when using these vibrotactile cues versus an equivalent spatialized audio display employing frequency-dependent elevation cues. However, these findings were specific to gross levels of elevation discrimination, and may not apply to tasks requiring users to distinguish between additional elevation levels.

Display Shape. With the exception of TSAS (Rupert, 2000), the tap-on-the-shoulder metaphor has not been directly applied to vertical extrapersonal localization (Van Erp, 2005b). This lack of research could possibly be a consequence of the generally cylindrical shape of the human torso. The cylindrical torso is likely poorly suited for conveying accurate extrapersonal elevation cues because vibrotactile stimulus placement is physically limited relative to users' internal kinesthetic egocenter(s). However, a non-torso-based vibrotactile display could potentially improve users' externally-projected localization abilities, especially in terms of elevation, as a function of shape (i.e., spherical shape). Such a display could more directly supplant users' vision by accurately orienting attention towards distal targets located anywhere in extrapersonal space.

Object-Centered Egocentrism

A vibrotactile display centered on an object other than the body would require users to interpret tap-on-the-shoulder spatial cues through a non-bodily-centered frame of reference. Reference frames refer to personal coordinate systems through which one's subjective mental representation of space corresponds to real, physical space (Coluccia, Mammarella, De Beni, Ittyerah, & Cornoldi, 2007). Using these coordinate systems, users can specify explicit locations along different spatial dimensions (e.g., x, y, and z spatial axes). The most commonly cited frames of reference include the egocentric and allocentric reference frames. As discussed earlier, egocentrism refers to a coordinate system centered on the self. TSAS (Rupert, 2000) is an example of an egocentric display (i.e., bodily-centered). In contrast, the allocentric reference frame refers to a coordinate system totally independent of the self. However, egocentric and allocentric reference frames are not mutually exclusive of one another.

Object-centered egocentrism refers to an additional type of reference frame centered within an external object (Carlson-Radvansky & Irwin, 1994; Grush, 2000). Using a spatial memory recall task involving a haptically explored environment, Coluccia et al. (2007) found that participants using an object-centered egocentric reference frame demonstrated performance levels greater than those of participants using an allocentric reference frame. However, participant performance using a normative egocentric reference frame remained significantly greater than for participants using an object-center reference frame. These findings support the existence of an object-centered egocentric frame of reference, and suggest this coordinate system exists as an intermediary, in terms of performance, between the egocentric and allocentric reference frames. Object-centered egocentrism could potentially address the physical limitations of previous torso-based vibrotactile displays by facilitating the manipulation of extrapersonal display shape (e.g., a sphere-shaped configuration) so as to improve the conveyance of elevation.

Coluccia et al.'s (2007) observed performance decrement associated with object-centered egocentrism indicates participants may have experienced difficulty projecting an egocenter into a foreign object. This finding suggests perceiving directionality into extrapersonal space from a handheld vibrotactile display could come at the cost of increased subjective workload. However, this cost may be justified if handheld display shape manipulation improves participants' ability to infer external directionality, especially in terms of elevation. For example, a cylindrical handheld display would likely require more subjective workload versus an equivalently configured torso-based vibrotactile display, and not improve participants' ability to infer external directionality. In this example, both displays are limited, relative to egocenter position(s), by their cylindrical shape. Alternatively, a spherical handheld display configuration could potentially justify this additional subjective workload cost because a spherical display shape has the potential to facilitate more accurate and intuitive directional estimations relative to a projected object-centered egocenter position.

The Present Study

The present study evaluated equivalently positioned tactor positions on two handheld vibrotactile displays (spherical and cylindrical-shaped, respectively), relative to a torso-based display, in terms of participants' perceived directionality into extrapersonal space. There are literature precedents for the use of non-torso-based vibrotactile spatial displays, including handheld displays (e.g., Hirsch, 1974; Yang, Ryu, & Kang, 2009); however, it remains unknown if these displays can convey directional information about extrapersonal space via the tap-on-the-shoulder metaphor.

Hypotheses. Five *a priori* hypotheses motived by the preexisting literature were predicted for the present study. The first hypothesis predicts the spatial distribution of participants' directional estimations will be significantly more concentrated for medial versus lateral tactor positions on the torso-based display. This hypothesis is based on Van Erp's (2005a) finding that navel and spinal anchor points (Cholewiak et al., 2004) reduce extrapersonal localization variability.

The second hypothesis predicts the spatial distribution of participants' directional estimations will be significantly more concentrated for all tactor positions on the cylindrical handheld display versus the torso-based display. This prediction supposes joint proximity in the human hand will reduce participants' response variability for all handheld stimuli similar to the effects of torso-based anchor points (Van Erp, 2005a).

The third hypothesis predicts participants' directional estimations will be highest and lowest, respectively, for the top and bottom row of tactors on the spherical handheld display. This hypothesis will demonstrate a spherically shaped display (versus cylindrical) enhances participants' ability to discern elevation, something which has not been previously evaluated (Cholewiak et al., 2004; Rupert, 2000; Van Erp, 2005a).

The fourth hypothesis predicts participants' directional estimations will be closer to midline along the azimuth for lateral tactor positions on the torso-based display. This hypothesis is based on the laterally offset internal kinesthetic egocenter positions reported by Van Erp (2005a) which may skew the perception torso-based vibrotactile stimuli inward.

The fifth hypothesis predicts subjective workload scores will be higher for the spherical and cylindrical handheld displays versus the torso-based display. The use of a handheld display is predicted to require the use of an object-centered egocenter position, thereby increasing subjective workload (Coluccia et al., 2007).

CHAPTER II

METHOD

Research Design

The present study employed a 3 × 3 × 3 within groups design. Independent variables included lateral tactor position (left, center, and right), vertical tactor position (top, middle, and bottom), and display type (spherical handheld, cylindrical handheld, and torso-based). Dependent variables included the azimuth, elevation, and dispersion of participants' projected directional estimations and subjective workload scores.

Participants

Keppel and Wickens (2004, p. 428) recommend using a previously documented effect size when determining the sample size for a study involving similar factors. Brill and Terrence's (2007) reported effect of vibrotactile elevation cues on perceived directionality, $F(2,58) = 7.37$, $p = .003$, $\eta_p^2 = .35$, $n = 30$, was used to calculate an *a priori* sample size of approximately 23 participants for the present study. Forty-five participants (14 men, 31 women), aged 18-48 years ($M = 22.40$, $SD = 6.26$) volunteered for this study from a convenience sample of undergraduate psychology students enrolled at Old Dominion University. All participants reported normal somatosensation and normal, or corrected-to-normal, vision. Following participation, all volunteers were compensated with research credit. This study was approved by the Institutional Review Board at Old Dominion University.

Apparatus

Equipment. A Dell XPS L401X laptop (Intel i5 dual-core 2.53 GHz processor, 8 GB RAM) equipped with SuperLab version 4.5 (Cedrus, Inc., San Pedro, CA) controlled all stimulus presentations. Vibrotactile stimulation was presented using an array of nine EAI model C2 Tactors (Engineering Acoustics, Inc., Casselberry, FL) in all experimental conditions. Each C2 Tactor consisted of a magnetic linear actuator contained within a disk-shaped anodized aluminum and polyurethane surround (2.97 × 0.76 cm).

Stimuli. All vibrotactile stimuli were comprised of a 250 Hz sinusoidal waveform presented at 49.7 dB using an alternating 200 ms on – 400 ms off sequence. Maximum stimuli duration was 10.2 seconds. This provided participants with adequate time to detect and respond to vibrotactile stimuli. Pink noise (69 dB) presented using Sennheiser HD-280 Pro closed-back circumaural headphones prevented the perception of potentially confounding auditory cues from activated tactors.

Torso-Based Display. The torso-based vibrotactile display consisted of tactors arranged in a 3 × 3 array on an elastic hook-and-loop belt (20 × 110 cm) worn around participants' torsos (see Figure 1). The central tactor at each elevation level was aligned with the frontal edge of participants' midsagittal plane and vertically offset from one another by 9 cm. The remaining tactors were positioned 45° to the left and right of each central tactor, respectively. Lateral tactor positioning was determined relative to each participant's waist circumference. Vertical standardization was achieved by positioning participants' navel equidistant between the two lowermost tactors in the central column.

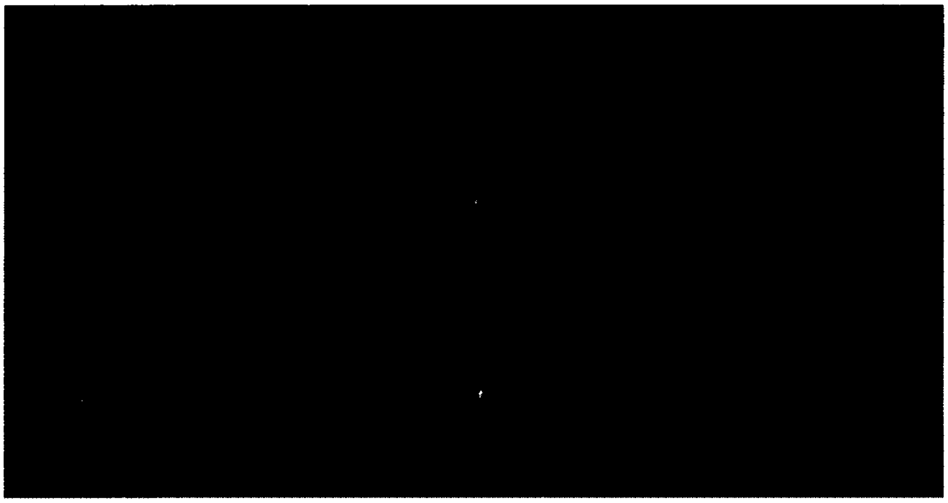

Figure 1. Torso-Based Display Tactor Configuration.

Handheld Displays. The cylindrical handheld display consisted of an outward-facing 3 × 3 array of tactors on a 5 inch diameter cylinder comprised of 1 lb density expanded polystyrene (see Figure 2). Each vertical column of tactors was separated by 45° (4.90 cm), and each horizontal row of tactors was likewise separated by 4.90 cm. Tactors on the spherical handheld display were arranged in an identical pattern on a sphere (1 lb density expanded polystyrene, 5 inch diameter); however, the horizontal distance between tactors in the top and bottom rows was reduced to 3.53 cm to maintain 45° separation (see Figure 3). Tactors on both handheld displays were flush with the exterior and concealed by a cotton cloth covering to prevent participants from visually referencing individual tactor positions. In order to maintain proper orientation, each handheld display was secured to a stationary platform.

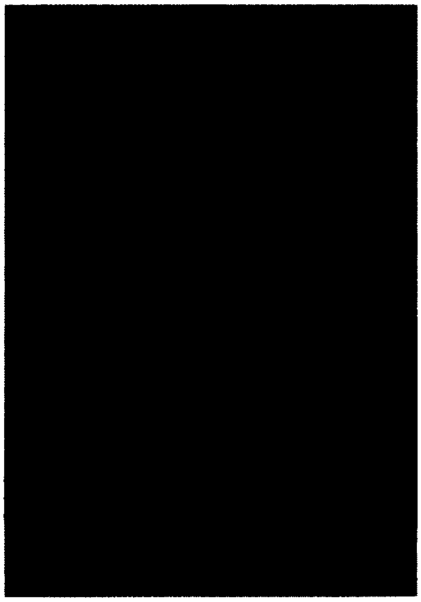

Figure 2. Cylindrical Handheld Display Tactor Configuration.

Figure 3. Spherical Handheld Display Tactor Configuration.

Tasks and Measures

Research Task. Participants responded to a single vibrotactile stimulus presented either using one of the handheld displays (i.e., sphere and cylinder-shape) or the torso-based display. Participants verbally reported the direction perceived from vibrotactile stimuli using absolute spatial coordinates (e.g., "right 53, up 30"). Similar absolute spatial judgments have previously been employed within the auditory localization domain (e.g., Wightman & Kistler, 1989). An Alternate Realities Corporation (ARC) Visiondome (4 meter diameter concave projection screen) with gridlines labeled at 10° intervals on the vertical and horizontal axes (maximum: 90°) provided a visual reference for these responses (see Figure 4). The central tactor on all three vibrotactile displays was aligned with the "0, 0" coordinate position on the Visiondome in order to ensure standardization across participants.

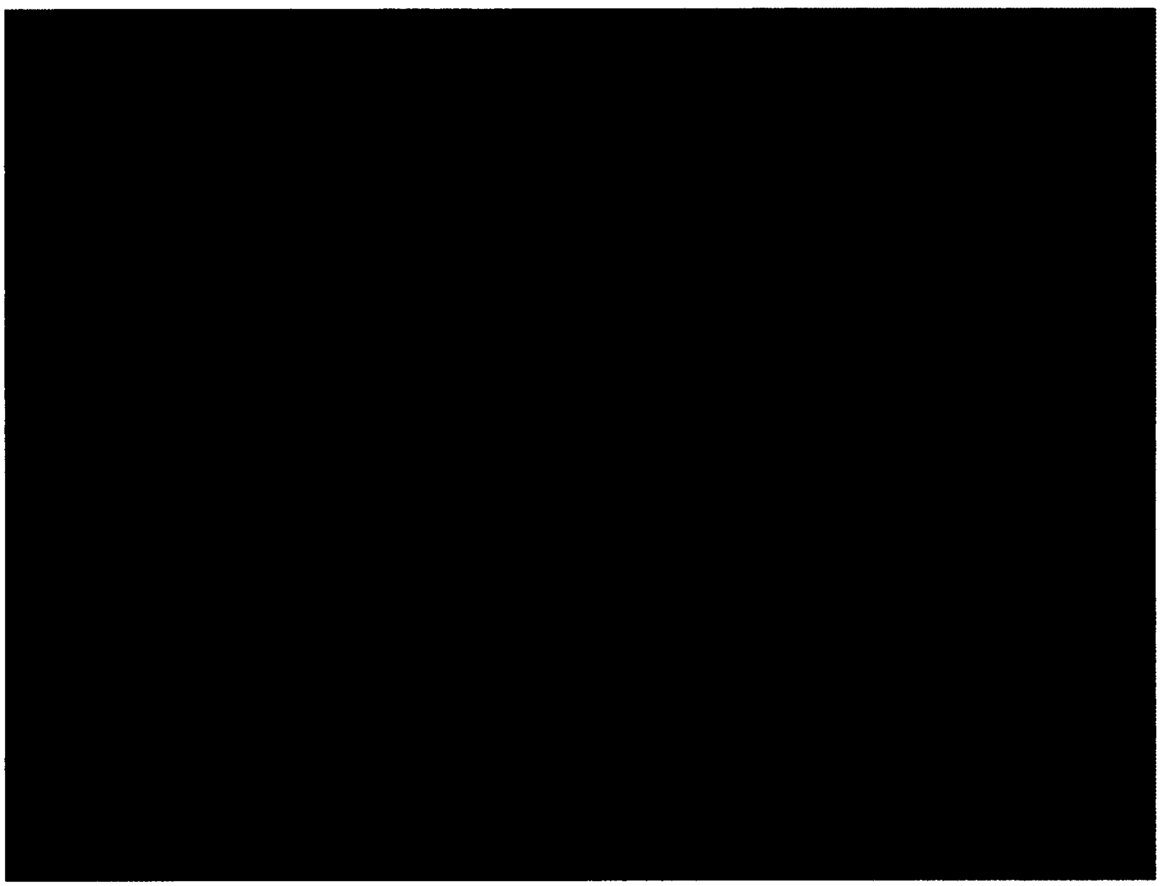

Figure 4. ARC Visiondome with Labeled Axes.

Response Dispersion. The spatial distribution of participants' directional estimations was calculated for tactor positions on each display type using the K parameter as an index of dispersion (see Appendix A). The K parameter was used in place of traditional measures of variability because participants' directional estimations were projected onto the surface of a sphere. Using the K parameter as an index of dispersion is appropriate for spherically arranged data points, and has been used in previous spatial localization studies (Fisher, Lewis, & Embleton, 1987; Wightman & Kistler, 1989).

Subjective Workload Measure. Perceived workload was evaluated using the National Aeronautics and Space Administration Task Load Index (NASA-TLX; Byers, Bittner, & Hill, 1989; Hart & Staveland, 1988). Six workload subscales (mental demand, physical demand, temporal demand, effort, performance, and frustration) were rated along verbally-anchored (low to high) visual analog scales, and subsequently summed to calculate participant's overall workload score. The NASA-TLX possesses a test-retest reliability of $r = .83$ (Hart & Staveland, 1988), and has been shown to reliably measure perceived workload when compared to other subjective measures of task difficulty (Hancock, Williams, Manning, & Miyake, 1995).

Procedure

Participants were tested in a lab space located on the campus of Old Dominion University. Written informed consent was obtained (see Appendix B), and participants were asked to complete a self-report demographics and medical questionnaire (see Appendix C) to ensure normal somatosensation and normal, or corrected-to-normal, vision.

Participants wore a cotton t-shirt to standardize the perception of vibrotactile stimuli presented using the torso-based display. A cloth measuring tape was used to measure participants' torsos at navel height in order to custom fit the torso-based display. Participants were then assigned to complete the three experimental conditions (i.e., spherical handheld, cylindrical handheld, and torso-based) with presentation order counterbalanced across participants using a Williams design order-three Latin Square (Williams, 1949). Per condition, each of the nine vibrotactile stimulus positions was randomly presented six times (9 tactor positions × 6 presentations × 3 display types = 162 trials per participant).

Torso-Based Condition. The torso-based display was outfitted on each participant's abdomen with the help of the experimenter. Participants were seated 2 meters from the center of the ARC Visiondome such that the central-most tactor was aligned with position "0, 0" on the screen. In order to familiarize participants with the vibrotactile stimuli, three randomly selected tactor positions were activated. Additionally, participants were asked to report the position of three randomly selected positions on the ARC Visiondome (identified using a laser pointer) to provide familiarization with the verbal response method. After completing these practice trials, participants began the torso-based experimental condition. Participants' verbal responses were standardized by always stating the x-coordinate (e.g., "left 15") followed by the y-coordinate (e.g., "down 47"). To prevent sensory adaptation, each participant response was followed by a fixed-interval pause of 2 seconds during which all tactors remained inactive. After completing the experimental condition, the torso-based display was removed, and participants completed the NASA-TLX (see Appendix D).

Handheld Conditions. All procedures remained the same, as described above, with the exception of adaptations specific to the use of the handheld displays. The distance between the ARC Visiondome and the handheld displays was consistent with the distance between the screen and participants' torsos during the torso-based condition. To prevent fatigue, participants' rested their arms on the platform supporting the display (see Figure 5). Before each trial, participants grasped the handheld display with both hands placed across the midline such that their fingertips were slightly interleaved (see Figure 6). Once a trial began, participants were instructed to perform a physical search with their hands until they were confident of stimulus perception. Upon finding the stimuli, participants verbally identify x and y-coordinates for the trial. Immediately following each trial, participants reassumed the initial hand position and waited for the next vibrotactile stimuli. The handheld displays presented the same type of vibrotactile stimuli employed for the torso-based condition. Upon completion, participants were verbally debriefed, thanked for their participation, and dismissed.

Figure 5. Participant grasps the Spherical Handheld Display.

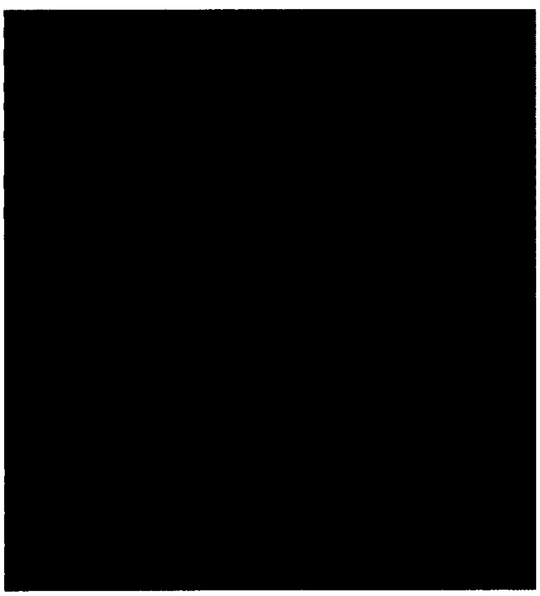

Figure 6. Starting Hand Position on the Cylindrical Handheld Display.

CHAPTER III

RESULTS

PASW Statistics version 19 with $\alpha = .05$, was used for all statistical hypothesis testing. No alpha correction was performed for *a priori* hypotheses (Keppel & Wickens, 2004, p. 115). Figures illustrating participant's mean response position by tactor position and display type can be found in Appendices E, F, and G.

Data Screening

All data were visually inspected using histograms and found to meet the ANOVA assumption of normality (Maxwell & Delaney, 2004). In the event Mauchley's test indicated sphericity violations, degrees of freedom were adjusted using a Greenhouse-Geisser correction (Geisser & Greenhouse, 1958). Outliers are discussed for individual hypotheses.

Response Dispersion

A 3 × 3 × 3 repeated measures ANOVA was conducted for the dependent variable response dispersion (measured using the K parameter). The independent variables were lateral tactor position (left, center, and right), vertical tactor position (top, middle, and bottom), and display type (spherical handheld, cylindrical handheld, and torso-based). Boxplot analyses showed no significant outliers. A significant interaction was found between lateral and vertical tactor position, $F(3.28, 144.46) = 3.20, p = .022, \eta_p^2 = .07$ (see Table 1). *A priori* contrasts were used (i.e., one for each display type) to evaluate the first hypothesis, predicting significantly more concentrated response dispersions for medial versus lateral tactor positions on the torso-based display. Response dispersion was significantly greater for lateral tactor columns versus the central tactor column on the spherical handheld display, $F(1, 44) = 6.59$, $p = .014$, $\eta_p^2 = .13$, cylindrical handheld display, $F(1, 44) = 5.83$, $p = .020$, $\eta_p^2 = .12$, and torso-based display, $F(1, 44) = 13.82$, $p = .001$, $\eta_p^2 = .24$ (see Table 2). No contrasts were needed to evaluate the second hypothesis, predicting significantly more concentrated response dispersions for all tactor positions on the cylindrical handheld display versus the torso-based display (see Table 3), because no significant main effect was found for display type ($p = .150$).

Table 1

ANOVA for Effects of Lateral Tactor Position, Vertical Tactor Position, and Display Type on Response Dispersion (K parameter)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Display Type	218.76	1.77	123.63	1.98	.150	.04
Lateral Tactor Position	936.66	1.70	554.06	12.78	<.001	.23
Vertical Tactor Position	1709.19	1.96	870.09	25.99	<.001	.37
Display Type × Lateral Tactor Position	116.32	3.52	33.05	1.31	.270	.03
Display Type × Vertical Tactor Position	49.66	3.78	13.13	0.56	.682	.01
Lateral × Vertical Tactor Position	372.59	3.28	113.49	3.20	.022	.07
Display Type × Lateral Tactor Position × Vertical Tactor Position	124.62	6.74	18.49	0.76	.614	.02
Error	7187.13	296.58	24.23			

Table 2

Descriptive Statistics for Response Dispersion (K parameter) by Display Type and Lateral Tactor Position

Lateral Tactor Position		*M*	*SD*	*n*	95% Confidence Interval LL	95% Confidence Interval UL
Spherical Handheld Display	Left	13.64	5.24	45	12.76	14.54
	Center	11.99	6.88	45	10.81	13.16
	Right	13.76	5.29	45	12.86	14.66
Cylindrical Handheld Display	Left	12.61	5.16	45	11.73	13.49
	Center	11.35	6.80	45	10.20	12.52
	Right	12.93	5.74	45	11.95	13.91
Torso-Based Display	Left	13.48	5.72	45	12.51	14.46
	Center	10.55	7.62	45	9.25	11.85
	Right	12.51	5.47	45	11.58	13.44

Table 3

Descriptive Statistics for Overall Response Dispersion (K parameter) by Display Type

Display Type	*M*	*SD*	*n*	95% Confidence Interval LL	95% Confidence Interval UL
Spherical Handheld	13.13	5.89	45	12.56	13.71
Cylindrical Handheld	12.30	5.96	45	11.72	12.88
Torso-Based	12.18	6.44	45	11.55	12.81

Although there were no *a priori* hypotheses predicting an effect of vertical tactor position on response dispersion due to insufficient preexisting literature, *post hoc* analyses with a Bonferroni family-wise alpha correction ($\alpha = .017$) indicated significantly less response dispersion for the middle tactor row versus the top tactor row, $F(1,44) = 44.26$, $p < .001$, $\eta_p^2 = .50$, and bottom tactor row, $F(1, 44) = 23.86$, $p < .001$, $\eta_p^2 = .35$, respectively (see Table 4). No significant difference in response dispersion was found between the top and bottom tactor rows ($p = .018$).

Table 4

Descriptive Statistics for Response Dispersion (K parameter) by Display Type and Vertical Tactor Position

Vertical Tactor Position		*M*	*SD*	*n*	95% Confidence Interval	
					LL	UL
Spherical Handheld Display	Top	14.06	5.59	45	13.11	15.01
	Middle	11.61	6.12	45	10.57	12.65
	Bottom	13.73	5.69	45	12.77	14.70
Cylindrical Handheld Display	Top	13.68	6.20	45	12.62	14.47
	Middle	10.83	5.80	45	9.84	11.81
	Bottom	12.40	5.56	45	11.45	13.34
Torso-Based Display	Top	13.69	6.37	45	12.61	14.78
	Middle	10.43	6.26	45	9.36	11.50
	Bottom	12.41	6.32	45	11.34	13.49

Response Elevation

A 3 × 3 repeated measures ANOVA was conducted for the dependent variable response elevation (i.e., measured in degrees). The independent variables were vertical tactor position (top, middle, and bottom) and display type (spherical handheld, cylindrical handheld, and torso-based). Lateral tactor position was not included as an independent variable because it is not meaningful for this analysis. Boxplot analyses identified outliers at all levels of vertical tactor position across display types with the exception of the top tactor row on the spherical handheld display and torso-based display, respectively. Outlier data were inspected by the experimenter and determined to be a part of the target distribution. Unwarranted trimming of overdispersed data can artificially reduce the error mean square creating an overall positive bias for the F-test (Keppel & Wickens, 2004, p. 146). Outlier data were retained for analysis. A significant interaction was found between vertical tactor position and display type, $F(3.15, 2548.82) = 275.46, p < .001, \eta_p^2 = .25$ (see Table 5). *A priori* contrasts were used to evaluate the third hypothesis, predicting significantly higher and lower responses, respectively, for the top tactor row and bottom tactor row on the spherical handheld display. Responses from the spherical handheld display were significantly higher for the top tactor row, $F(1, 809) = 316.69, p < .001, \eta_p^2 = .28$, and lower for the bottom tactor row, $F(1, 809) = 23.64, p < .001, \eta_p^2 = .03$, respectively, versus the torso-based display. Responses from the torso-based display were significantly higher for the top tactor row, $F(1, 809) = 21.92, p < .001, \eta_p^2 = .03$, and lower for the bottom tactor row, $F(1, 809) = 96.32, p < .001, \eta_p^2 = .11$, respectively, versus the cylindrical handheld display (see Figure 7 and Table 6).

Table 5

ANOVA for Effects of Vertical Tactor Position and Display Type on Response Elevation (degrees)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Display Type	46011.81	1.84	24968.03	97.32	<.001	.11
Vertical Tactor Position	2010421.76	1.46	1376049.72	3073.69	<.001	.79
Display Type × Vertical Tactor Position	182236.37	3.15	57842.06	275.46	<.001	.25
Error	535216.75	2548.82	209.99			

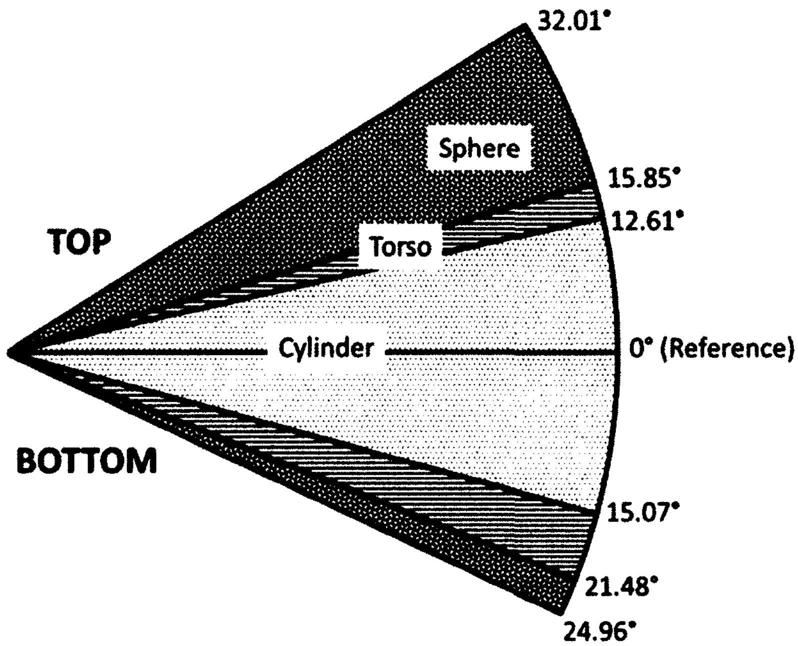

Figure 7. Mean Absolute Response Elevation for Top and Bottom Tactor Rows by Display Type.

Table 6

Descriptive Statistics for Response Elevation (degrees) by Display Type and Vertical Tactor Position

Vertical Tactor Position		*M*	*SD*	*n*	95% Confidence Interval	
					LL	UL
Spherical Handheld Display	Top	32.01	21.14	45	30.55	33.47
	Middle	1.43	13.11	45	0.52	2.33
	Bottom	-24.96	14.23	45	-25.94	-23.98
Cylindrical Handheld Display	Top	12.61	14.58	45	11.60	13.62
	Middle	-0.80	10.50	45	-1.52	-0.07
	Bottom	-15.07	12.10	45	-15.90	-14.24
Torso-Based Display	Top	15.85	21.76	45	14.35	17.35
	Middle	-4.10	15.63	45	-5.18	-3.02
	Bottom	-21.48	17.68	45	-22.70	-20.26

Response Azimuth

A 3 × 3 repeated measures ANOVA was conducted for the dependent variable response azimuth (measured in degrees). The independent variables were lateral tactor position (left, center, and right) and display type (spherical handheld, cylindrical handheld, and torso-based). Vertical tactor position was not included as an independent variable because it is not meaningful for this analysis. Boxplot analyses identified outliers at all levels of lateral tactor position across display types. Outlier data were inspected by the experimenter and determined to be a part of the target distribution.

Unwarranted trimming of overdispersed data can artificially reduce the error mean square creating an overall positive bias for the F-test (Keppel & Wickens, 2004, p. 146). Outlier data were retained for analysis. A significant interaction was found between lateral tactor position and display type, $F(2.85, 2308.88) = 418.81, p < .001, \eta_p^2 = .34$ (see Table 7). *A priori* contrasts were used to evaluate the fourth hypothesis, predicting response azimuths closer to midline for lateral tactor positions on the torso-based display. Responses from the torso-based display were significantly wider for both right and left tactor positions, respectively, versus the cylindrical handheld display (right: $F(1, 809) = 537.81, p < .001, \eta_p^2 = .40$; left: $F(1, 809) = 189.31, p < .001, \eta_p^2 = .19$). Responses from the cylindrical handheld display were significantly wider for the right and left tactor position, respectively, versus the spherical handheld display (right: $F(1, 809) = 11.55, p = .001, \eta_p^2 = .01$; left: $F(1, 809) = 30.27, p < .001, \eta_p^2 = .04$; see Figure 8 and Table 8).

Table 7

ANOVA for Effects of Lateral Tactor Position and Display Type on Response Azimuth (degrees)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Display Type	13345.15	1.82	7344.74	30.90	<.001	.04
Lateral Tactor Position	10198974.93	1.32	7756834.06	9338.43	<.001	.92
Display Type × Lateral Tactor Position	457323.08	2.85	160240.06	418.81	<.001	.34
Error	883388.92	2308.88	382.61			

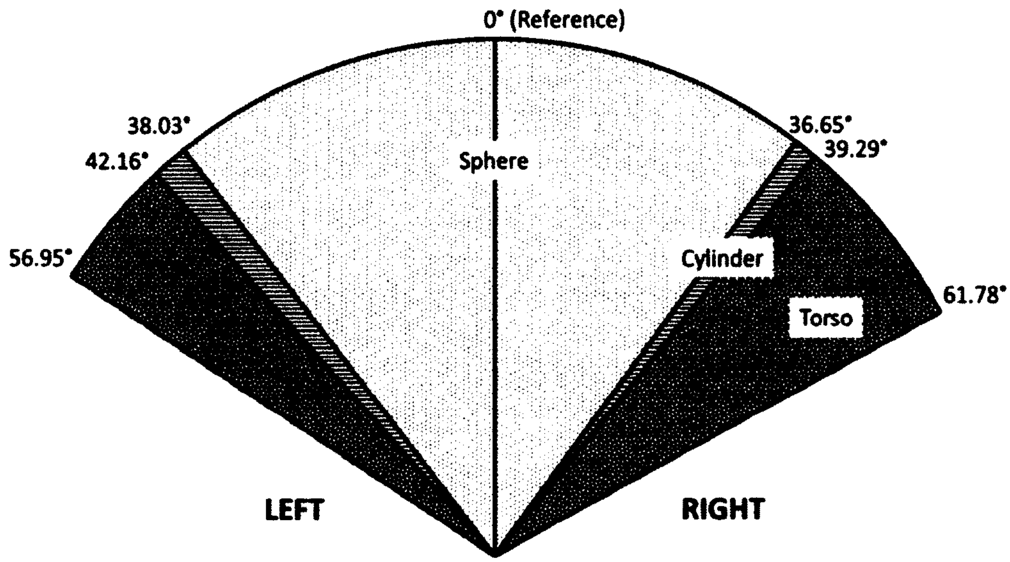

Figure 8. Mean Absolute Response Azimuth for Right and Left Tactor Columns by Display Type.

Table 8

Descriptive Statistics for Response Azimuth (degrees) by Display Type and Lateral Tactor Position

Lateral Tactor Position		*M*	*SD*	*n*	95% Confidence Interval LL	95% Confidence Interval UL
Spherical Handheld Display	Left	-38.03	18.59	45	-39.31	-36.75
	Center	-0.32	8.73	45	-0.92	0.28
	Right	36.65	18.19	45	35.40	37.91
Cylindrical Handheld Display	Left	-42.16	18.07	45	-43.41	-40.91
	Center	0.038	8.81	45	-0.57	0.65
	Right	39.29	20.98	45	37.84	40.73
Torso-Based Display	Left	-56.95	27.98	45	-58.88	-55.02
	Center	1.45	6.97	45	0.97	1.93
	Right	61.78	21.43	45	60.30	63.26

Subjective Workload

A one-way repeated measures ANOVA was conducted for the dependent variable subjective workload (measured using NASA-TLX total workload scores). The independent variable was display type (spherical handheld, cylindrical handheld, and torso-based). Lateral and vertical tactor positions were not included as independent variables for this analysis because subjective workload was only assessed for display type. Boxplot analyses showed no significant outliers. A significant main effect was found for display type, $F(1.65, 72.59) = 7.56$, $p = .002$, $\eta_p^2 = .15$ (see Table 9). *A priori* contrasts were used to evaluate the fifth hypothesis, predicting higher subjective workload scores for the spherical and cylindrical handheld displays versus the torso-based display. Overall subjective workload scores were significantly lower for the torso-based display versus the spherical handheld display, $F(1, 44) = 6.88$, $p = .012$, $\eta_p^2 = .14$, and cylindrical handheld display, $F(1, 44) = 13.41$, $p = .001$, $\eta_p^2 = .23$, respectively (see Figure 9). There was no significant difference in subjective workload scores between the spherical and cylindrical handheld displays ($p = .584$). To further investigate the effect of display type on subjective workload, six *post hoc* analyses, using a Bonferroni family-wise alpha correction ($\alpha = .008$), were conducted to compare each of the NASA-TLX subscales as a function of display type. No significant difference was found for any NASA-TLX subscale as a function of display type (see Table 10 & Table 11).

Table 9

ANOVA for Effect of Display Type on Overall NASA-TLX Scores

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Display Type	635.81	1.65	385.38	7.56	.002	.15
Error	3700.93	72.59	50.98			

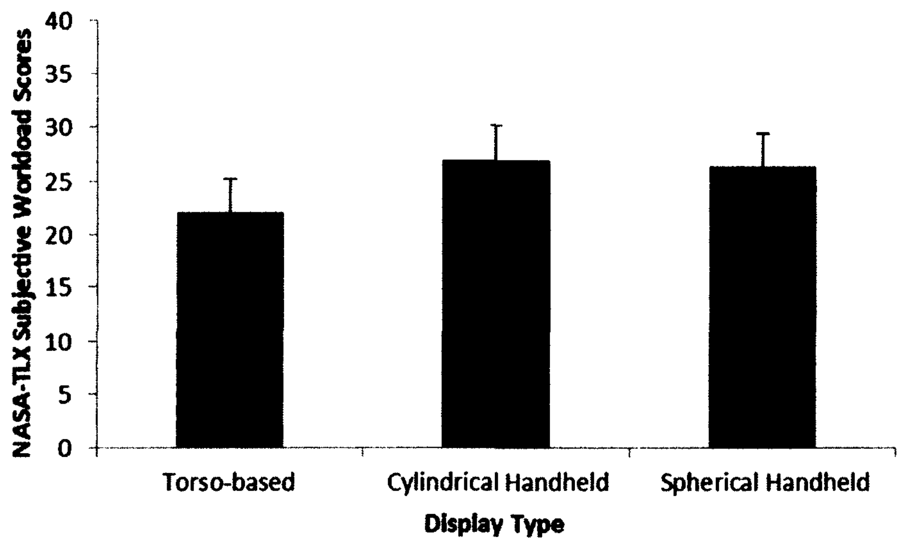

Figure 9. Mean Overall Subjective Workload Scores by Display Type. Note: Error bars represent 95% confidence intervals.

Table 10

ANOVAs for Effect of Display Type on each NASA-TLX Subscale

NASA-TLX Subscale	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Mental Demand	24.18	2	12.09	1.44	.242	.02
Error	1111.79	132	8.42			
Physical Demand	36.31	2	18.16	2.90	.059	.04
Error	827.54	132	6.27			
Temporal Demand	29.82	2	14.91	2.30	.104	.03
Error	855.36	132	6.48			
Performance	7.01	2	3.51	0.60	.552	.01
Error	775.22	132	5.87			
Effort	20.37	2	10.19	1.26	.289	.02
Error	1071.60	132	8.12			
Frustration	1.30	2	0.65	0.04	.963	.001
Error	2251.55	132	17.06			

Table 11

Descriptive Statistics for Mean Subjective Workload Scores by Subscale and Display Type

NASA-TLX Subscale		*M*	*SD*	*n*	95% Confidence Interval	
					LL	UL
Spherical Handheld Display	Mental Demand	6.15	2.53	45	5.39	6.91
	Physical Demand	2.69	2.57	45	1.92	3.46
	Temporal Demand	4.89	2.26	45	4.21	5.57
	Performance	3.76	2.34	45	3.05	4.46
	Effort	5.69	2.88	45	4.82	6.56
	Frustration	3.16	2.56	45	2.39	3.93
Cylindrical Handheld Display	Mental Demand	5.59	2.85	45	4.74	6.45
	Physical Demand	3.00	2.85	45	2.15	3.86
	Temporal Demand	4.99	2.64	45	4.20	5.79
	Performance	4.23	2.48	45	3.49	4.97
	Effort	5.83	2.66	45	5.03	6.63
	Frustration	3.29	2.82	45	2.45	4.14
Torso-Based Display	Mental Demand	5.12	3.28	45	4.13	6.10
	Physical Demand	1.78	2.01	45	1.18	2.38
	Temporal Demand	3.95	2.71	45	3.13	4.76
	Performance	3.74	2.45	45	3.00	4.48
	Effort	4.95	3.00	45	4.05	5.85
	Frustration	3.40	6.06	45	1.59	5.22

CHAPTER IV

DISCUSSION

Previous research evaluated torso-based vibrotactile displays capable of orienting attention externally, but only for lateral perception (e.g., Van Erp, 2005a) and tasks involving large angular discrimination (e.g., McGrath, 2004; Rupert, 2000). In the present study, participants' perceived directionality into extrapersonal space was evaluated using a torso-based display and two handheld vibrotactile displays (i.e., spherical and cylindrical-shaped). Three levels of lateral and vertical tactor position, respectively, were assessed, and participants' perception of these stimuli were captured in both x and y-coordinates. It was anticipated that participants would employ an object-centered egocenter to interpret vibrotactile stimuli from a handheld display similar to how one perceives a torso-based tap on the shoulder. In this context, a spherically-shaped handheld display was predicted to improve perceived directionality, specifically in terms of elevation, because of its shape. The results indicate participants' elevation discernment was improved by the spherical handheld display; however, evidence was not conclusive regarding participants use of an object-centered egocenter.

Anchor Point Effect

A robust anchor point effect (Boring, 1942) has been previously documented regarding the perception of torso-based vibrotactile stimuli (Cholewiak, 2004). Van Erp (2005a) reported a decrease in perceived directional dispersion for medial versus lateral vibrotactile stimuli positioned on the torso due to anchor point alignment. However, Van Erp's (2005a) conclusions were limited because the position of individual stimuli and participants' method of response were confined to a single horizontal plane around the navel. Accounting for these limitations, the present study confirmed a significant decrease in response dispersion for medial versus lateral tactor positions on the torso. These findings support the robustness of the torso-based anchor point effect on response dispersion, and indicate the effect is not mitigated by vertical stimuli position. However, the spherical and cylindrical handheld displays also demonstrated similar differences between medial and lateral tactor positions. Anchor points are unlikely responsible for this handheld difference in dispersion because bodily point-of-contact was not restricted for individual tactor positions on the handheld displays. Participants performed a physical search with their hands at the beginning of each experimental trial until they were confident of stimulus perception. This helped ensure participants were not responding to inadequately detected stimuli (i.e., stimuli presented at the periphery of participants' starting hand position). The present study suggests enhanced vibrotactile perception along the midsagittal plane is not restricted to torso-based displays. Handheld tactor positions aligned with the midsagittal plane exhibit a localization enhancement similar to the anchor point effect.

It was hypothesized that overall response dispersion for the cylindrical handheld display would be significantly more concentrated versus the torso-based display. Joint position proximity has previously been indicated as a factor associated with anchor points (Boring, 1942), and the proximity of joint positions in the hand was predicted to enhance participants' overall perception of stimuli presented via a handheld display. However, the present study found no significant effect of display type on participants' response dispersion. In addition to the findings reported above, the present study suggests handheld vibrotactile displays may not facilitate increased overall spatial resolution versus torso-based displays, and are subject to response dispersion biases similar to those found with torso-based displays.

Display Shape Effect

The conveyance of spatial information pertaining to extrapersonal elevation has not been previously documented for vibrotactile displays using the tap-on-the-shoulder metaphor, with the exception of TSAS (Rupert, 2000). It was speculated in the present study that vibrotactile elevation cues are physically limited, relative to participants' internal egocenter position(s), when presented on the torso due the naturally cylindrical shape of the human upper body. A spherical handheld display was hypothesized to better convey elevation versus a cylindrically-shaped display. This hypothesis was supported in the present study by participants' responses to the top and bottom tactor rows across display types. Responses were significantly higher and lower, respectively, for these tactor positions on the spherical handheld display versus each of the other display types. This suggests participants were better able to infer elevation conveyed on the spherical handheld display because activated tactors on the curved surface could be directly referenced relative to a projected object-centered egocenter position. However, participants' response elevations still fell short of the veridical position 45° above/below elevation. The mean response elevation for the top tactor row on the spherical handheld display was 32.01° (*SD* = 21.76), and the mean response for the bottom tactor row was -24.96° (*SD* = 17.68; see Figure 7). This shortfall in perceived elevation suggests a spherical display shape offers better elevation discernment versus cylindrical displays, both handheld and torso-based. However, participants may be biased to report extrapersonal direction with less elevation than conveyed by a spherical display.

Egocenter Effect

Van Erp (2005a) demonstrated the perception of directionality into extrapersonal space is determined by matching torso-based vibrotactile point stimulation with an internal egocenter position. However, instead of relying on a single egocenter position, Van Erp (2005a) reported participants use two laterally offset egocenter positions when reporting the lateral directionality conveyed by torso-based vibrotactile stimuli. In the present study, participants' responses for lateral tactor positions on the torso were predicted to be significantly closer to the midline versus lateral tactor positions on the cylindrical handheld display. The use of laterally offset internal egocenter positions suggests perceived directionality should be skewed inward when prompted with a vibrotactile stimulus on the torso. However, the opposite finding was obtained. Responses were significantly closer to the midline for the cylindrical handheld display versus the torso-based display. Van Erp's (2005a) reported finding of two laterally offset egocenter positions in the torso was not supported. Instead of underestimating spatial responses along the azimuth, participants exceeded the 45° indicated by lateral tactors on the torso (left: $M = -56.95$, $SD = 27.98$, right: $M = 61.78$, $SD = 21.43$).

Similar to the shortfall in reported response elevation discussed in the previous section, the present study indicates participants' lateral responses fell inward of the veridical 45° indicated on the spherical and cylindrical handheld displays (see Figure 8). These findings suggest participants may have experienced difficulty projecting an object-centered egocenter into a handheld display. Unexpectedly, participants may have translated stimuli positions back to a bodily egocenter position prior to inferring directionality instead of using their hands to infer directionality *relative* to an object-centered egocenter position. In other words, participants may have retained a normative egocentric reference frame when perceiving directionality from the non-ego object reference point (i.e., the handheld displays; Grush, 2004). Using this alternative strategy, participants would have used themselves as a spatial origin point, instead of the handheld display, resulting in response azimuth (and elevation) being skewed inward. Although the present data are inconclusive, the use of an egocentric reference frame with a non-ego object reference point could explain why participants' response positions were skewed inward when prompted with handheld vibrotactile stimuli.

Subjective Workload

Unlike previous research involving torso-based vibrotactile displays (e.g., McGrath, 2004; Rupert, 2000), handheld vibrotactile displays have never before been assessed for subjective workload. However, Coluccia et al. (2007) documented a performance decrement associated with the use of an object-centered versus egocentric reference frame in the context of a haptic memory-recall task. This performance decrement suggests the use of an object-centered egocenter may be associated with high subjective workload demands. In the present study, participants were hypothesized to report significantly elevated levels of subjective workload for the spherical handheld display and cylindrical handheld display, respectively, versus the torso-based display. Findings from the present study support this hypothesis as participants indicated significantly higher levels of subjective workload associated with the handheld displays versus the torso-based display. This suggests participants may have found it difficult to project an object-centered egocenter into a handheld display, regardless of display shape. Additionally, if participants did retain a normative egocentric reference frame, as discussed in the previous section, this could have contributed to increased subjective workload levels when interpreting handheld vibrotactile stimuli. It is also possible the physical act of holding the handheld displays may have contributed to the increase in subjective workload (see Table 10). Overall, these findings suggest participants might have experienced conflict between a normative bodily egocenter position and the hypothesized use of an object-centered egocenter position when interpreting handheld vibrotactile stimuli.

Limitations

Findings from the present study were chiefly limited by the inability to directly determine participants' egocenter position. Previous research (e.g., Shimono, Higashiyama, & Tam, 2001; Shimono & Higashiyama, 2011) demonstrated the difficulty in measuring egocenter placement in the context of external localization tasks. It was hoped egocenter position could be inferred from the position and concentration of participants' responses; however, it remains unclear in the present study if participants employed an object-centered egocenter or a bodily-centered egocenter with a non-ego object reference point when responding to handheld vibrotactile stimuli.

This study was also limited by the labeling of axes on the ARC Visiondome. Due to the physical dimensions of the Visiondome, 10° markings could not be extended downward to 90°, as was the case for the other axes' directions. It is possible this limitation skewed participants' response elevation when responding to the bottommost tactor row on each of the three displays. However, response elevation for the top tactor row was analyzed independently and found to mirror findings for the bottom row across the three display types. Additionally, this limitation is ecologically rooted as most vibrotactile display applications (torso-based or handheld) involve users standing or sitting such that downward vision is occluded (e.g., a dismounted solder on the ground or a pilot sitting in a cockpit).

Future Research

Follow-up investigations involving handheld vibrotactile displays capable of externally directing users' attention should strive to more accurately evaluate participants' egocenter position. The present study suggests users experienced conflict between a normative egocenter reference frame and object-centered reference frame when using handheld displays. A more extensive understanding of this conflict could help account for perceptual biases and progress research towards the goal of a high resolution vibrotactile display capable of orienting users' attention anywhere in three-dimensional space. Additionally, findings from the present study, indicating reduced response dispersion for medially aligned tactor positions on both handheld displays, warrant additional attention. It is possible this handheld difference in response dispersion is the result of an egocenter placement conflict; however, additional research is needed to confirm this hypothesis. Finally, future research should also evaluate the effects of training on participants' ability to localize extrapersonal targets using a handheld vibrotactile display configurations. The present study's findings of perceptual biases and increased subjective workload associated with handheld vibrotactile displays could potentially be overcome with training.

CHAPTER V

CONCLUSION

The present study demonstrated a spherical handheld vibrotactile display is capable of externally orienting attention similar to vibrotactile displays positioned on the torso. As expected, the discernment of elevation from a spherical handheld display was significantly improved versus cylindrical displays, both torso-based and handheld. Unexpectedly, the use of a handheld display did not significantly reduce response dispersion or mitigate previously documented torso-based response biases (Van Erp, 2005a). The present findings suggest the adoption of a spherical handheld display may be advantageous for three-dimensional tasks; however, specific applications should be evaluated on a case-by-case basis. The ability to more directly discern elevation via a handheld vibrotactile display may come at the cost of increased workload demands due to the nonuse of a normative egocentric reference frame. The present findings were unable to conclusively demonstrate participants used an object-centered egocenter as an alternative to a normative bodily-centered egocenter. As previously discussed, participants may have retained an egocentric reference frame with the addition of a non-ego object reference point when responding to stimuli on the handheld displays. Overall, research involving handheld vibrotactile spatial displays is applicable to tasks for which supplementary, off-screen directional information could potentially improve operators' performance (i.e., TSAS; Rupert, 2000).

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APPENDIX A

K PARAMETER INDEX OF DISPERSION

K parameter values were calculated from participants' reported x and y-coordinates using the following procedure:

- Polar coordinates (Leong & Carlile, 1998):

  $\theta = 90 - y$

  $\Phi = -x$

- Direction cosines (Fisher, Lewis, & Embleton, 1987):

  $x_i = \sin\theta_i \cos\Phi_i$ $\quad y_i = \sin\theta_i \sin\Phi_i$ $\quad z_i = \cos\theta_i$

- Vector sum:

  $S_x = \sum_{i=1}^{n} x_i$ $\quad S_y = \sum_{i=1}^{n} y_i$ $\quad S_z = \sum_{i=1}^{n} z_i$

- Resultant length (Leong & Carlile, 1998):

  $$R = \sqrt{{S_x}^2 + {S_y}^2 + {S_z}^2}$$

- K Parameter formula (Wightman & Kistler, 1989):

  $$K = \frac{(N-1)^2}{N(N-R)}$$

  - Where N = number of data points

APPENDIX B

INFORMED CONSENT STATEMENT

Purpose of this Form: This form provides information that may affect your decision to participate in this research, and records the consent of those who indicate YES.

Research Project Title: Effects of Object-Centered Egocentrism on Extrapersonal Localization through Vibrotactile Stimulation

Responsible Project Investigator(s): J. Christopher Brill, Ph.D., Assistant Professor, College of Sciences, Psychology Department

Co-Investigator(s): Adam Sitz, Graduate student, College of Sciences, Psychology Department

Overview of Research Project: This experiment is intended to examine your performance in matching the location of vibrotactile signals (mild vibration against the skin – like a vibrating cell phone) to visual targets. If you choose to participate in this study, you will be asked to verbally respond to the presentation of vibrotactile signals on your torso and hands.

If I choose to participate, what will I be asked to do?
You will be asked to complete a brief medical history to ensure that you are eligible to participate in the study. This medical history primarily asks about conditions or medications that might be related to sensory deficits (e.g., loss of hearing, reduced skin sensitivity) and motor ability. You may refuse to answer any questions that make you feel uncomfortable.

If you're not already wearing a t-shirt, you will be asked to wear a laboratory provided t-shirt for a portion of this experiment. Participants are asked to wear t-shirts (either their own or laboratory provided) for two reasons: 1) Due to the construction and expense of the vibration devices (tactors), they cannot easily be cleaned or replaced. The best way to keep them clean and avoid unnecessary expense is to prevent the tactors from touching the skin. 2) Since the tactors do not touch the skin, the material between the tactors and the skin must be standardized. This standardization helps us accurately compare participant performance. Of course, you will be given privacy to change into a laboratory provided t-shirt (if you are not already wearing one) in a nearby restroom.

To ensure accurate placement of the tactors on your torso, your abdomen will need to be measured using a cloth measuring tape. The researcher will then fit you with a torso tactor display (similar to a belt). If you are uncomfortable being measured and fitted with a tactor belt by a researcher of the opposite sex, we will accommodate you by either having a researcher of the same sex perform the measurement/fitting, or by having a same-sex research assistant serve as a chaperone during that process.

The researcher will then seat you in front of the projector screen, and you will be provided with more specific instructions on how to complete the task. You will have the opportunity to ask for clarification if any aspect of the task seems confusing.

If applicable, the researcher will once again give you privacy to change back into your regular clothes upon the conclusion of the experiment session.

What steps are being taken to ensure my privacy?
All information you provide will be kept confidential, and none of the forms will list your name. This form will be separated from the rest of your data packet so no one can link your data and your identity. All written information (e.g., surveys, forms, etc.) is kept in a locked file cabinet. A numerical code will be used for all electronic information (e.g., performance data) so that your identity cannot be linked with the data file.

Are there any risks associated with participating in this experiment?
The experiment does not require you to perform actions beyond those experienced in everyday life. The tactors used for vibration stimuli are commercially available, and they are not much different from devices used in vibrating cell phones. Therefore, this protocol is deemed minimal risk.

What if I have questions about the experiment or its procedures?
You may ask questions about the experiment at any time. If you have questions after the experiment session has ended, you may contact Dr. Chris Brill at jcbrill@odu.edu or (757) 683-4242. The ODU Institutional Review Board (ODU-IRB) has reviewed my request to conduct this project. If you have any concerns about your rights in this study, you may contact the Office of Research at (757) 683-3460 or George Maihafer of the ODU-IRB at (757) 683-4520 or email gmaihafe@odu.edu.

How long does the experiment last?
It varies from person to person, but a typical time commitment is approximately 1 hour.

Will I receive any compensation for participating in this experiment?
If you decide to participate in this study, you will receive 1 Psychology Department research credit, which may be applied to course requirements or extra credit in certain Psychology courses. Equivalent credits may be obtained in other ways. You do not have to participate in this study, or any Psychology Department study, in order to obtain this credit.

Are there any benefits or costs associated with participating in this experiment?
While there are no direct benefits for participation in this study, the results will be useful for evaluating the nature of vibrotactile perception. The risks associated with participating in this experiment are similar to those of normal computer viewing and usage (e.g., eye strain). Since this study uses technology largely encountered in daily life (desktop computer, vibrating cell phones, and videogame-like systems), there are no additional risks.

Is there anything else I need to know?
You must be 18 years of age or older to participate in this experiment. Additionally, in order to be eligible for participation in this study you must not have any major sensorimotor impairment that might impact your ability to perceive or respond to visual and tactile signals. You are free to withdraw from the experiment at any time without any negative consequences; however, you will only be compensated for the amount of time you spent participating in the experiment. Approximately 50 participants will be recruited for this study.

I have read the procedure described above. I voluntarily agree to participate in the procedure and I have received a copy of this description.

________________________________ ______________________________

Participant's Signature Date Investigator's Signature

APPENDIX C

DEMOGRAPHICS AND MEDICAL QUESTIONNAIRE

This survey was designed to obtain information about our research participants prior to serving in our studies. We need this information to help us interpret your results. ALL data collected in this laboratory is to be kept confidential.

1) Age: _______

2) Sex (circle one): Male / Female

3) Handedness: Left / Right

4) Do you have any medical conditions or injuries affecting your vision? Yes / No

   4a) If yes, please explain:

   ____

   4b) If applicable, did you bring a correction with you? (i.e., glasses or contact lenses): Yes / No

5) Do you have any medical conditions or injuries affecting your hearing? Yes / No

   5a) If yes, please explain:

   ____

6) Do you have any medical conditions or injuries affecting your sensitivity to touch? Yes / No

   6a) If yes, please explain:

   ____

7) Do you have any medical conditions or injuries affecting your motor control, particularly the use of your hands? Yes / No

   7a) If yes, please explain:

   ____

8) Do you have any medical conditions affecting your ability to pay attention? Yes / No

8a) If yes, please explain:

____

9) How often do you play video/computer games? Never Monthly Weekly

Daily

9a) If you do play video/computer games, circle the number that corresponds to how **confident** you are using video/computer **games**:

1	2	3	4	5	6	7
Low			Average			High

APPENDIX D

NASA-TLX RATING SCALE DEFINITIONS

Title	Endpoints	Descriptions
MENTAL DEMAND	*Low / High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remember, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	*Low / High*	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?
TEMPORAL DEMAND	*Low / High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?
PERFORMANCE	*Good / Poor*	How successful do you think you were in accomplishing the goal of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	*Low / High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	*Low / High*	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

TLX RATING SHEET

INSTRUCTIONS: On each scale, place a mark that represents that magnitude of that factor in the task you just performed.

LOW **HIGH**

MENTAL DEMAND

LOW **HIGH**

PHYSICAL DEMAND

LOW **HIGH**

TEMPORAL DEMAND

EXCELLENT **POOR**

PERFORMANCE

LOW **HIGH**

EFFORT

LOW **HIGH**

FRUSTRATION

APPENDIX E

TORSO-BASED DISPLAY RESPONSE POSITIONS BY TACTOR POSITION

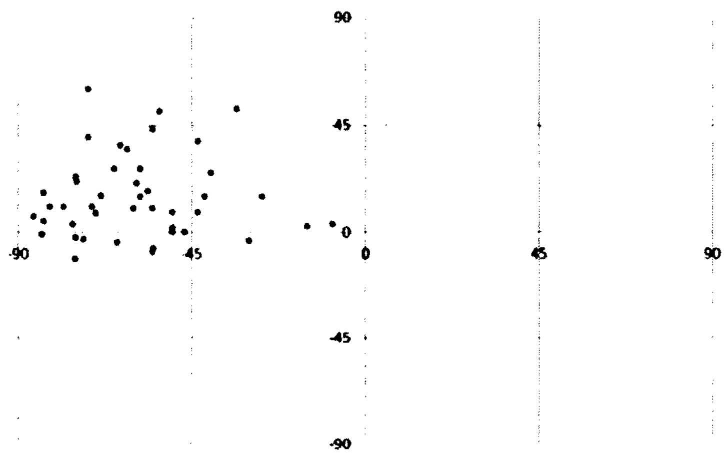

Figure E1. Mean Response Positions for Torso-Based Display Left-Top Tactor.

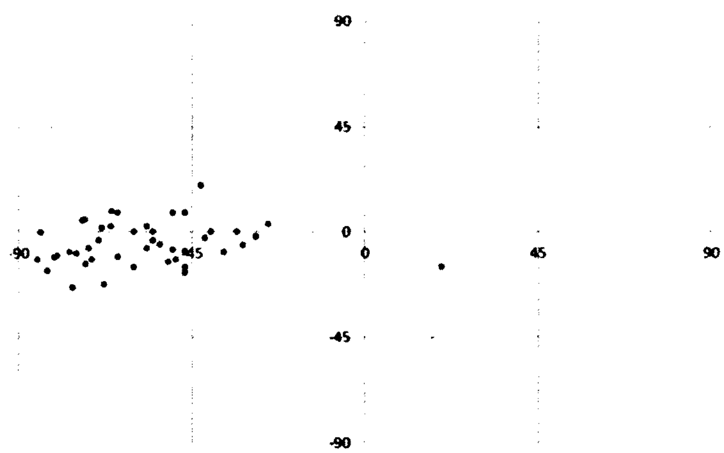

Figure E2. Mean Response Positions for Torso-Based Display Left-Middle Tactor.

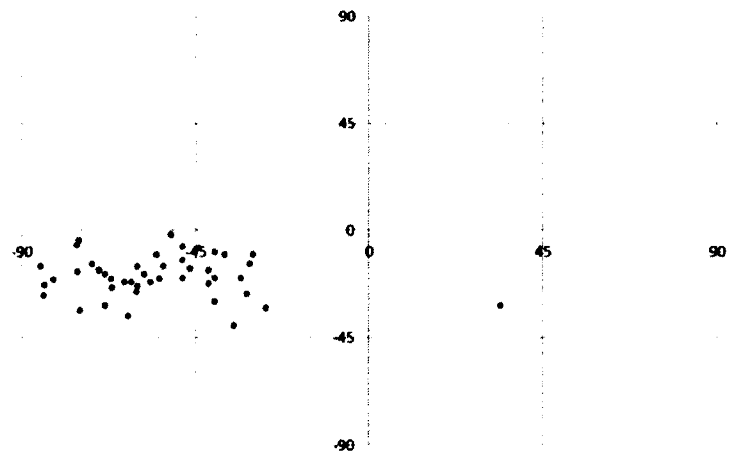

Figure E3. Mean Response Positions for Torso-Based Display Left-Bottom Tactor.

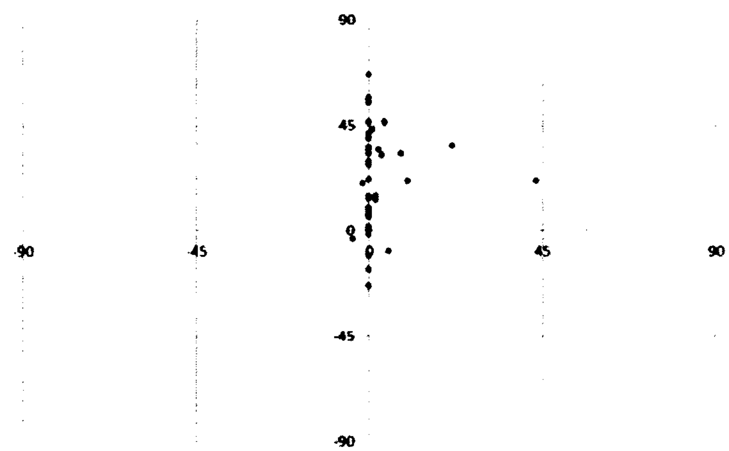

Figure E4. Mean Response Positions for Torso-Based Display Center-Top Tactor.

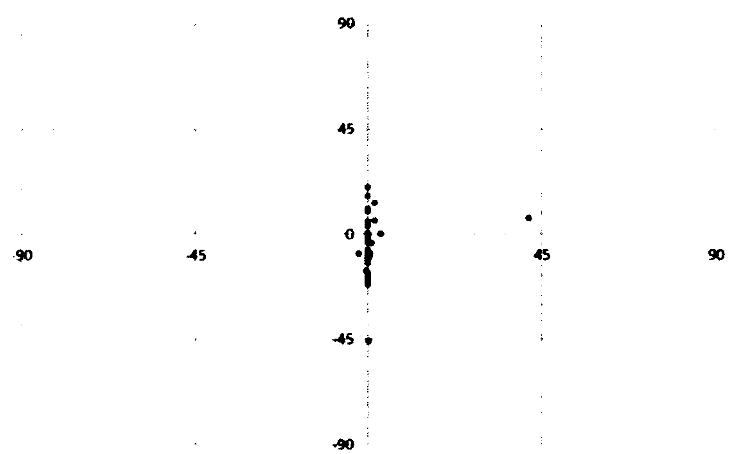

Figure E5. Mean Response Positions for Torso-Based Display Center-Middle Tactor.

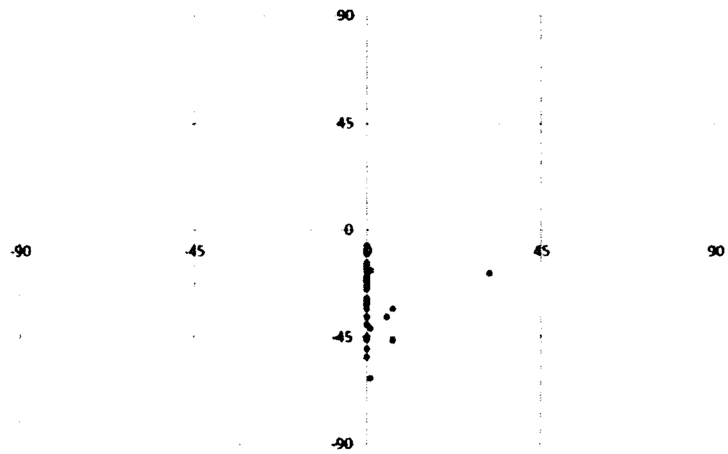

Figure E6. Mean Response Positions for Torso-Based Display Center-Bottom Tactor.

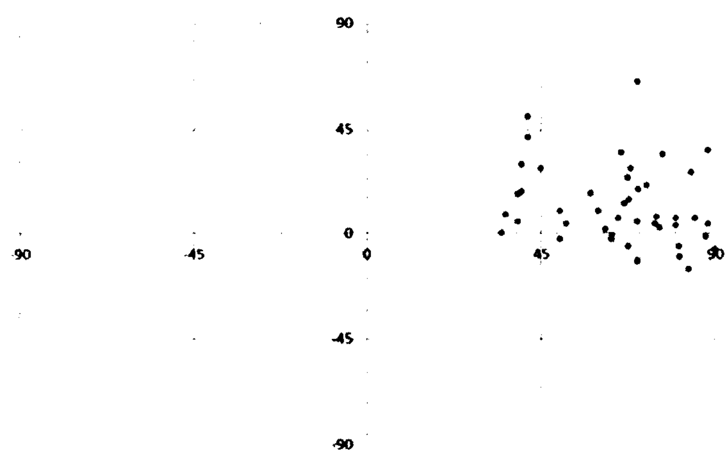

Figure E7. Mean Response Positions for Torso-Based Display Right-Top Tactor.

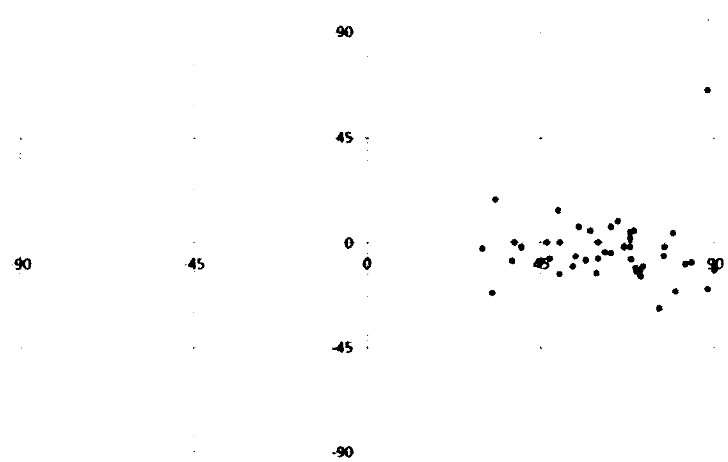

Figure E8. Mean Response Positions for Torso-Based Display Right-Middle Tactor.

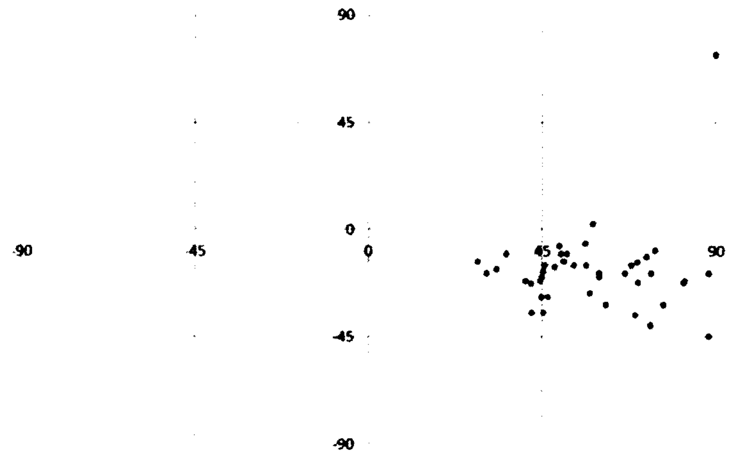

Figure E9. Mean Response Positions for Torso-Based Display Right-Bottom Tactor.

APPENDIX F

CYLINDRICAL HANDHELD DISPLAY RESPONSE POSITIONS BY TACTOR POSITION

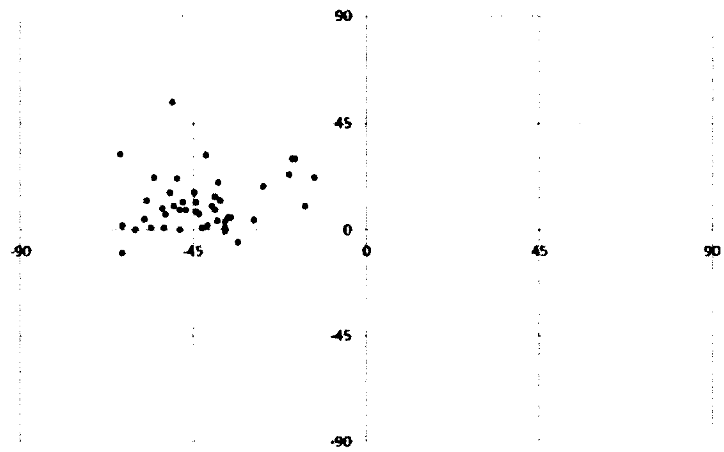

Figure F1. Mean Response Positions for Cylindrical Handheld Display Left-Top Tactor.

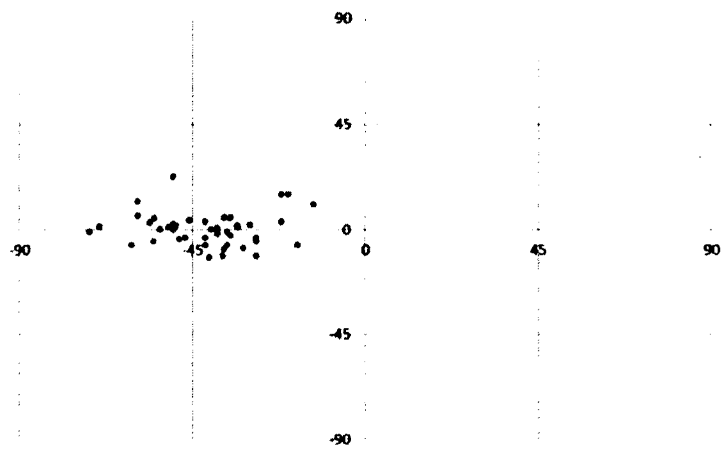

Figure F2. Mean Response Positions for Cylindrical Handheld Display Left-Middle Tactor.

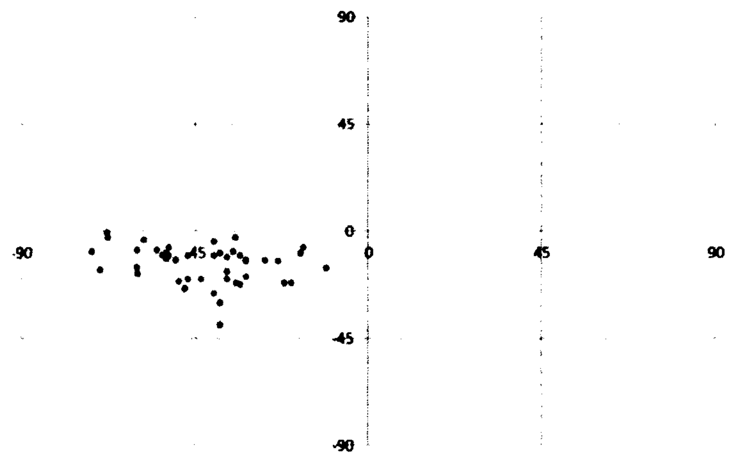

Figure F3. Mean Response Positions for Cylindrical Handheld Display Left-Bottom Tactor.

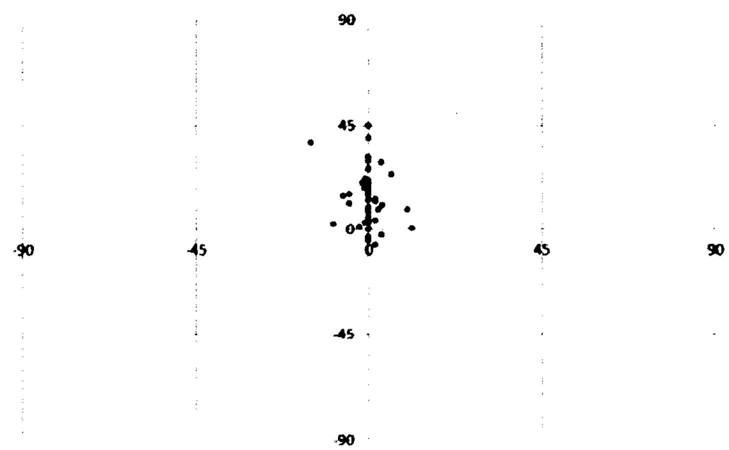

Figure F4. Mean Response Positions for Cylindrical Handheld Display Center-Top Tactor.

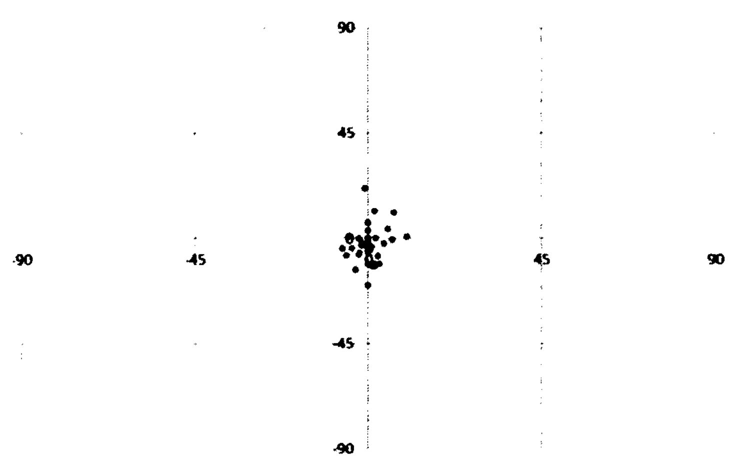

Figure F5. Mean Response Positions for Cylindrical Handheld Display Center-Middle Tactor.

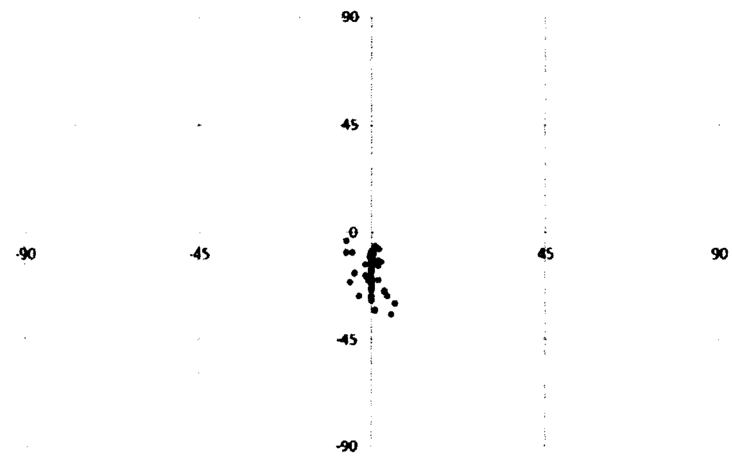

Figure F6. Mean Response Positions for Cylindrical Handheld Display Center-Bottom Tactor.

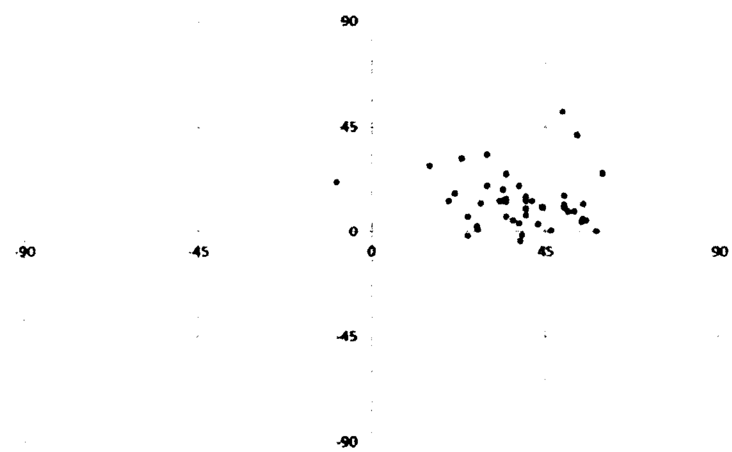

Figure F7. Mean Response Positions for Cylindrical Handheld Display Right-Top Tactor.

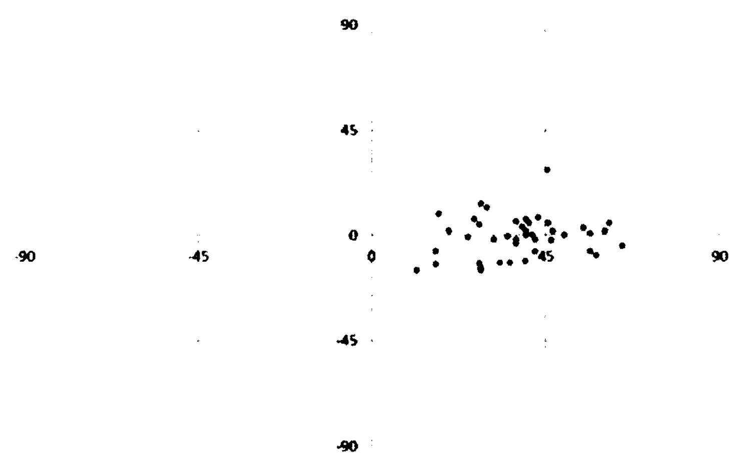

Figure F8. Mean Response Positions for Cylindrical Handheld Display Right-Middle Tactor.

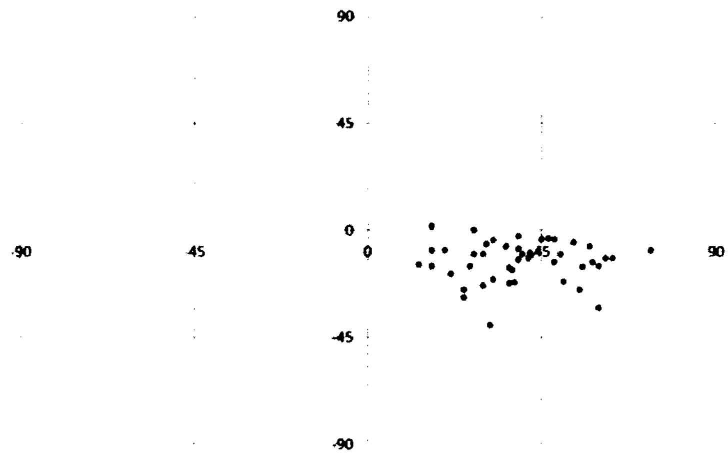

Figure F9. Mean Response Positions for Cylindrical Handheld Display Right-Bottom Tactor.

APPENDIX G

SPHERICAL HANDHELD DISPLAY RESPONSE POSITIONS BY TACTOR POSITION

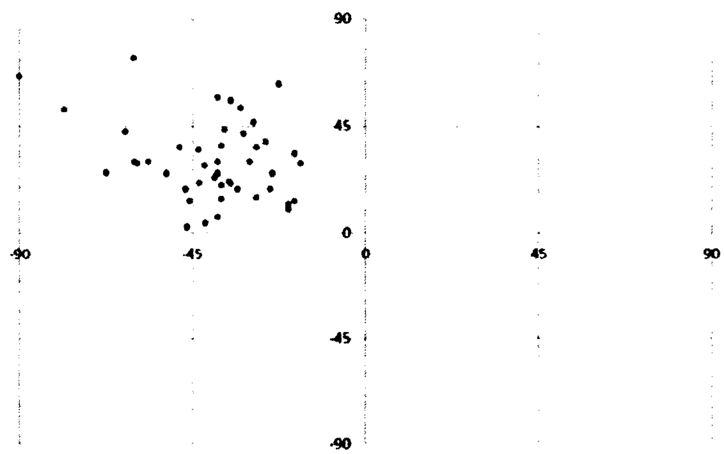

Figure G1. Mean Response Positions for Spherical Handheld Display Left-Top Tactor.

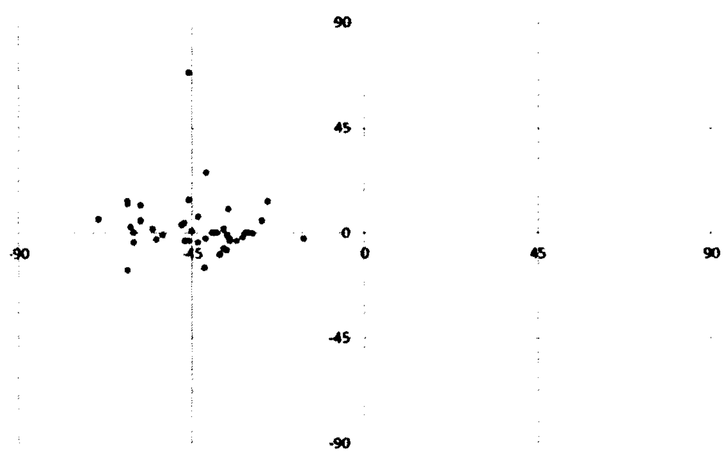

Figure G2. Mean Response Positions for Spherical Handheld Display Left-Middle Tactor.

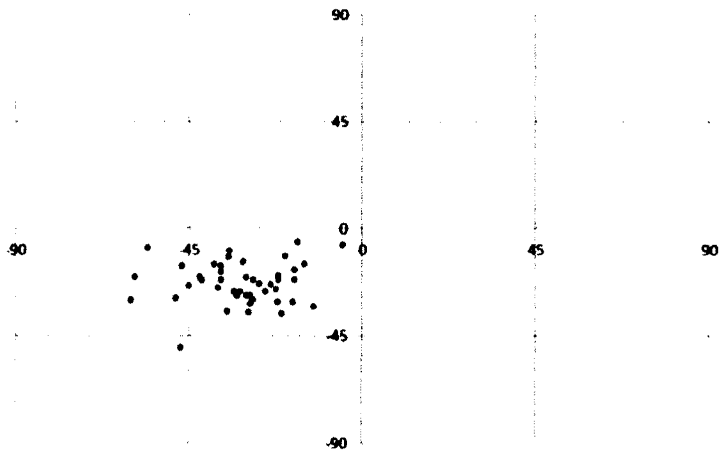

Figure G3. Mean Response Positions for Spherical Handheld Display Left-Bottom Tactor.

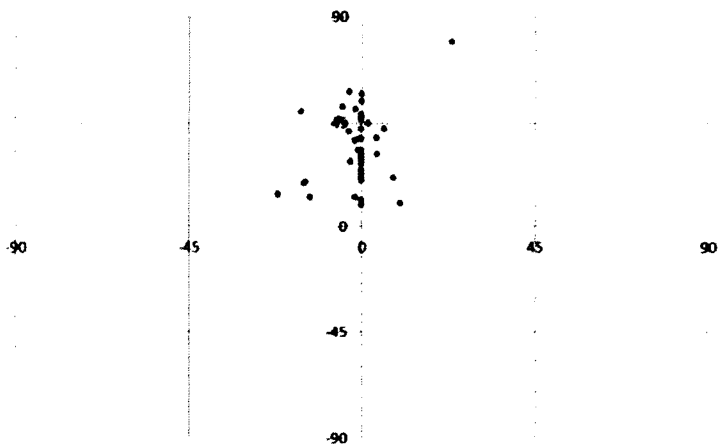

Figure G4. Mean Response Positions for Spherical Handheld Display Center-Top Tactor.

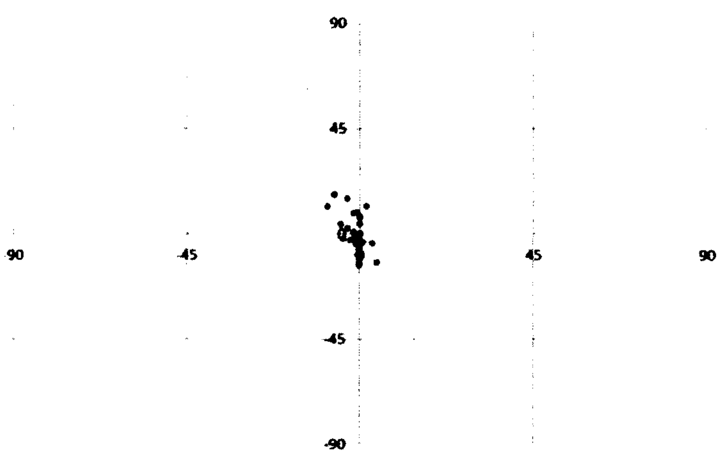

Figure G5. Mean Response Positions for Spherical Handheld Display Center-Middle Tactor.

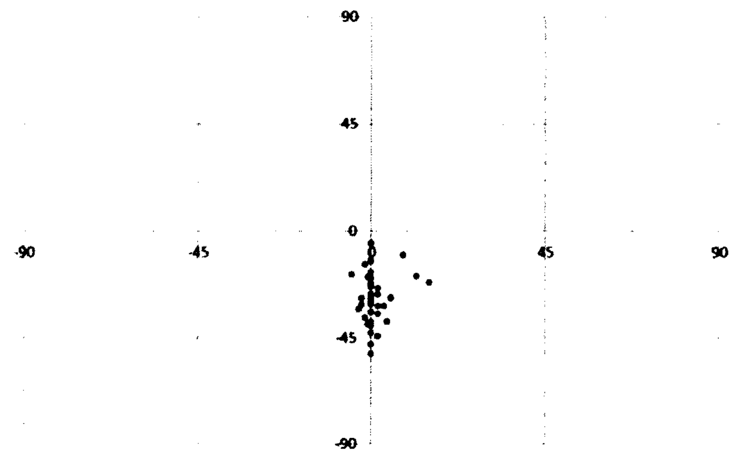

Figure G6. Mean Response Positions for Spherical Handheld Display Center-Bottom Tactor.

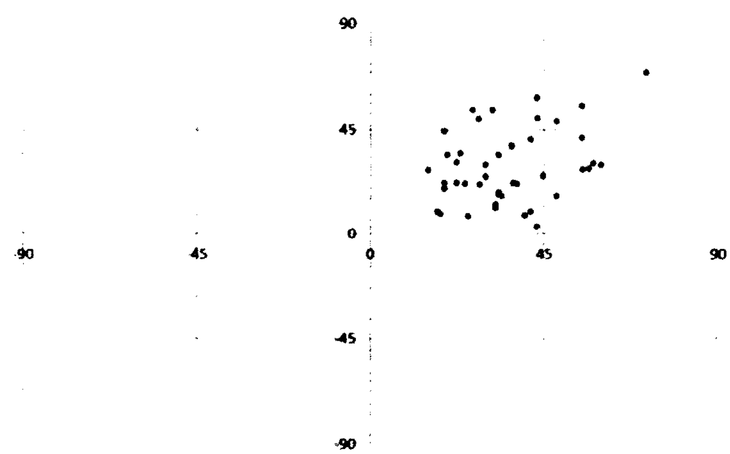

Figure G7. Mean Response Positions for Spherical Handheld Display Right-Top Tactor.

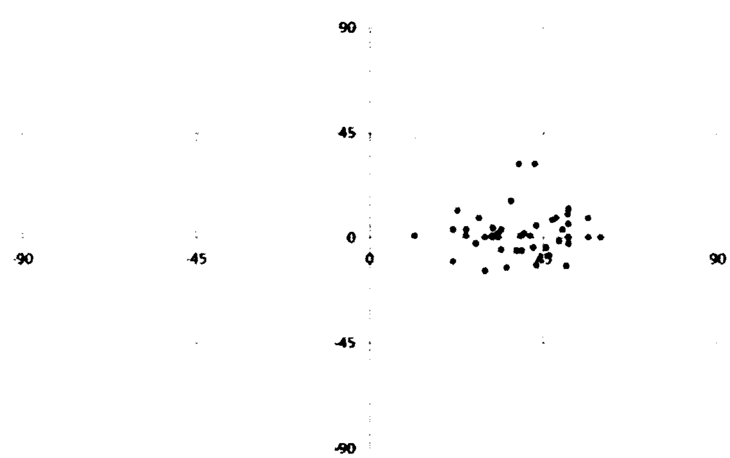

Figure G8. Mean Response Positions for Spherical Handheld Display Right-Middle Tactor.

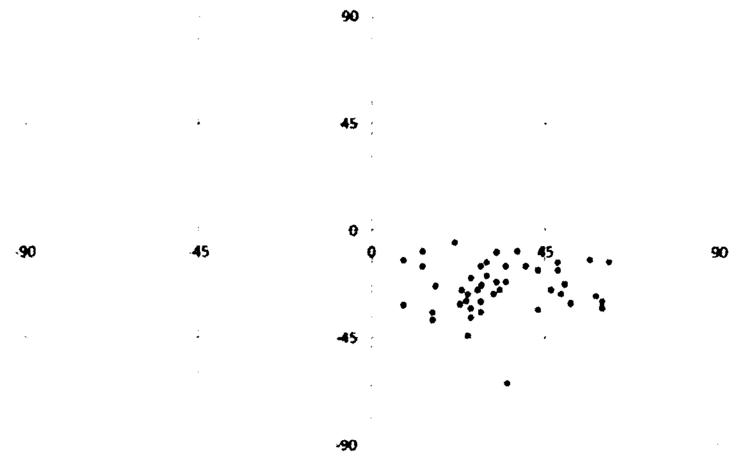

Figure G9. Mean Response Positions for Spherical Handheld Display Right-Bottom Tactor.

VITA

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PROFESSIONAL PRESENTATIONS

Sitz, A. & Brill, J. C. (2014, April). *An object-centered vibrotactile display for spatial localization in aerospace systems*. Paper presented at the Virginia Space Grant Consortium Research Conference, Hampton, VA.

Sitz, A. & Brill, J. C. (2013, October). *Limits of asynchrony and spatial incongruence for unified audiotactile cues*. Paper presented at the Human Factors and Ergonomics Society 57th Annual Meeting, San Diego, CA.

Finomore, V., Sitz, A., Blair, E., Rahill, K., Champion, M., Funke, G., Mancuso, V., & Knott, B. (2013, October). *Effects of cyber disruption in a distributed team decision making task*. Paper presented at the Human Factors and Ergonomics Society 57th Annual Meeting, San Diego, CA.

Finomore, V., Satterfield, K., Sitz, A., Castle, C., Funke, G., Shaw, T., & Funke, M. (2012, October). *Effects of the multi-modal communication tool on communication and change detection for command & control operators*. Paper presented at the Human Factors and Ergonomics Society 56th Annual Meeting, Boston, MA.

Sitz, A., Davis, S., & Finomore, V. (2012, April). *Multimodal Evaluation of Resource Allocation in a Communication Monitoring Task*. Poster presented at the 23rd Annual Stander Symposium, Dayton, OH.

Sitz, A., Barnas, A., & Kunz, B. (2012, April). *The Role of Visual and Proprioceptive Limb Information in Object Size and Affordance Judgments*. Poster presented at the 23rd Annual Stander Symposium, Dayton, OH.

ADDITIONAL PROCEEDINGS

Chancey, E. T., Sitz, A., Brill, J. C., Schmuntzsch, U., & Bliss, J. P. (Accepted). Vibrotactile Stimuli Parameters on Detection Reaction Times. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 58.*

Finomore, V., Sitz, A., Satterfield, K., Castle, C., & Blair, E. (2013). Evaluation of advanced multi-modal command and control communication management suite. In D. Harris (Ed.), *Lecture Notes in Artificial Intelligence: Vol. 8019. Engineering Psychology and Cognitive Ergonomics. Understanding Human Cognition* (pp. 215-221).

The word processor for this thesis was Microsoft Word 2010.