Vibrotactile Guidance Cues for Target Acquisition

Tal Oron-Gilad, Joshua L. Downs, Richard D. Gilson, and Peter A. Hancock

***Abstract*—Three experiments examined the use of vibrotactile cues to guide an operator toward a target. Vibrotactile stimulation on the hand can provide spatially stabilizing cues for feedback of subtle changes in position. When such feedback is present, a deviation from the point of origin results in tactile stimulation indicating the direction and magnitude of the positional error. Likewise, spatial deviation from a desired position displayed tactually can provide robust position guidance and stabilization sufficient to improve the acquisition time and accuracy of fine cursor control. A major advantage of this mode of information representation is that it can be present at the same time as visual cues with minimal cross-modal interference. Our findings suggest that performance is actually enhanced when both tactile and visual cues are present. Although previous studies have suggested that various forms of tactile feedback can provide position guidance and stabilization, to our knowledge, this work is the first that details the effect of tactile feedback on target acquisition directly.**

***Index Terms*—Guidance cues, target acquisition, vibrotactile.**

I. Introduction

PRESENT combat operational forces must face frequent sniper opposition and often engage in small, troop-size covert operations at night where unexpected, street-to-street conflicts may develop. Under such circumstances, it is crucial to know from which direction enemy fire is coming, especially to reduce friendly-fire and civilian casualties. Within this general realm of concern for target detection and identification, the purpose of the present studies was to establish how vibrotactile guidance cues can be used to improve marksmanship. The work originated in an effort to provide covert communication, navigation, and weapon aiming cues for infantrymen. The practical implications of this study can be extended beyond marksmanship alone into the whole range of target acquisition and warning domains where the visual environment is cluttered and complex.

A. *Tactile Aiming Guidance System (TAGS)*

Vibrotactile stimulation can provide spatially stabilizing cues for feedback of subtle changes in position [1]–[4]. Once such a feedback system is engaged, any deviation from the point of origin can result in tactile stimulation indicating the direction and magnitude of any undesired change. Likewise, spatial deviations from a desired position displayed tactually can provide robust position guidance and stabilization sufficient to improve the acquisition time and accuracy of fine cursor control [5], [6]. TAGS may provide covert WY-Feel-IWYG (what you feel is what you get; an analogy to WYSIWYG, "what you see is what you get") aim-point adjustment that is as rapid and accurate as enhanced visual sights for aim-point adjustment. TAGS may also provide tactile feedback that can be used by the marksman to stabilize weapon aiming. Since TAGS apply their stimuli to the hands directly and are a tactile channel that may be capable of cooperating with the visual channel without interference [7], their stimuli may have greater affordances for aim-point guidance and stabilization than the iron and enhanced visual sights (e.g., laser and infrared optical sights). These affordances may translate into decreases in time to hit the target and decreases in the number of bullets fired relative to visual aiming cues alone.

Though the literature suggests that various forms of tactile feedback can provide position guidance and stabilization, no current published research has detailed the effect of tactile feedback on marksmanship [1], [5], [6], [8]. As such, our investigation attempted to determine if tactile feedback with or without visual cues can improve marksmanship compared to visual feedback alone.

B. *Research Questions*

Our main purpose was thus to examine whether tactile cuing with or without visual cues will improve target acquisition. Given the potential for TAGS to provide guidance cues for target selection, several fundamental design issues needed to be addressed: Where should the tactors be placed to provide directional left and right cues? Does the perception of left and right change with tactor placement? Also, what kinds of stimuli should TAGS employ to provide relative distance between aim-point and desired aim-point (on-target).

Experiment 1 was designed to address the issue of tactor placement on the hand, and examine whether change in directional right or left is related to tactor placement. Experiments 2 and 3 examined the vibrotactile cues themselves; i.e., generate stimuli that provide both direction and relative distance between the current aim-point and the desired aim-point. Both Experiments 2 and 3 explored the effect of relative distance cues and on- versus off-target tactile stimuli on reaction time and accuracy of target acquisition. Specifically, Experiment 2 examined the effect of relative distance cues and on- versus off-target tactile stimuli on reaction time and accuracy of aiming, while comparing the effect of presenting visual-only, tactile-only, or combined visual + tactile cues. Experiment 3 further investigated the interaction between the gradient of distance cues and the on- versus off-target interaction. Prior research has suggested

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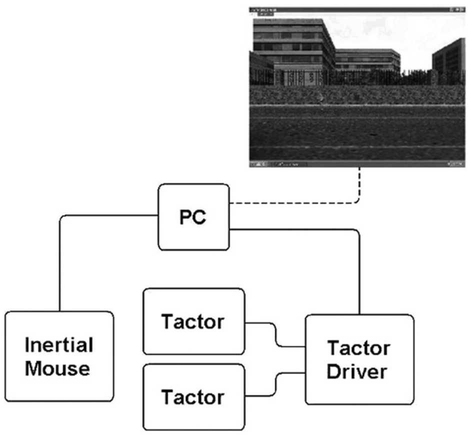


Fig. 1. Block diagram of the experimental system used in Experiments 1–3. A static background image was projected on the PC monitor; visual target cues were added when applicable.

that for a target acquisition task, the visual display is not necessary for the entire duration of the movement [9], [10]. The visual display is generally required for determining the direction of initial ballistic movement toward the target and then again for the further fine movements required for final target acquisition. Experiment 3 sought to examine whether similar characteristics are also found for tactile cuing. Both continuous and discrete vibrotactile distance cues were examined. The continuous condition was similar to that in Experiment 2, providing a continuous, relative to distance, vibrotactile cue during the entire movement. In the discrete condition, an initial vibrotactile burst was provided to trigger the ballistic movement of the hand. Then, as the cursor approached the target, the tactile display was presented continuously as in the continuous condition. The distances chosen between discrete and continuous vibrotactile cuing reflect the end of the first ballistic movement, and the tolerance for establishing unambiguous initial movement, respectively.

II. General Experimental Design

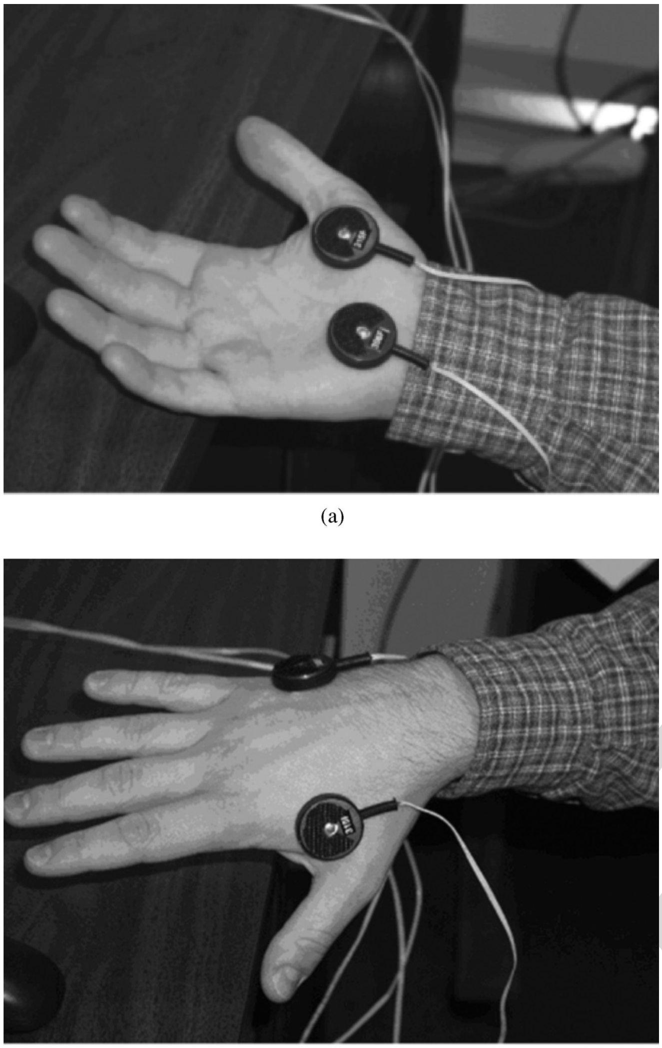
A. Apparatus

The experimental software ran on a 3.00-GHz Dell Dimension 8300 with the Windows XP Professional operating system. Screen and color resolutions were fixed at 1024 × 768 and 32-bit, respectively. A Dell M992 18-in monitor was used to project the visual display to the participants. A Gyration Ultra inertial mouse was plugged into the high-speed USB port on the computer and functioned like a conventional three-button mouse with a scrolling wheel. The vibrotactile tactor system included two EAI C2 tactors, a tactor driver, and a Velcro strap for positioning the tactors on the hand.The tactor driver was connected to the personal computer (PC) (see Fig. 1). A static background image from UbiSoft's "Ghost Recon" depicting a virtual city scene looking across a street at a brick wall was displayed for the duration of the trials (northwest wall in map "m05_embassy.env") (see Fig. 2). A small grayed rectangle at the center of the image was where the default start point of each trial began. The visual stimuli were superimposed on this background in the visual conditions (see Fig. 3).

Fig. 2. Static background image used for all three experiments. The small *grayed rectangle* at the center of the image is where the default start point of each trial began.

Fig. 3. Visual target on the background image. This particular target was a large near target.

1) Targets: To incorporate the Fitts law paradigm [11]–[14], small and large targets were generated to the left and to the right of the center of the display. Targets consisted of a soldier from the Ghost Recon game holding an AK-74 pointed at the participant (actor "m05_eli_ak74_1.atr"). The target was captured in perspective for its location and size, and included a shadow. Small targets were 14 pixels wide; large targets were 28 pixels wide. The centers of mass of the target positions were located 423 pixels from the center of the display for the far targets, and 169 pixels from the center of the display for the near targets. The order of presentation of the eight possible targets (right–left, small–large, near–far) was partially counterbalanced using a sliding Latin Square technique for each participant. The mouse cursor was depicted as a white cross ("+") 19 pixels across, and always started a trial in the center of the screen. The cursor was constrained by the software to move only in the horizontal plane passing through the center of the screen and the center of mass of all targets. Target guidance cues were provided by the visual display, by the tactile display, or by both the visual and tactile display, depending on the experimental condition. For



(a)

(b)

Fig. 4. Location of tactors on the hand in Experiment 1. (a) Ventral and (b) dorsal.

experimental conditions where visual cues were available (in Experiments 2 and 3), targets appeared visually on the screen superimposed on the background. In the tactile-only conditions, only the cursor appeared on the background image.

2) Tactor Placement: Tactors were placed either on the palm (ventral) or on the back of the hand (dorsal). Ventral placement refers to the tactors being placed between the mouse and the participant's hand [see Fig. 4(a)]. Dorsal placement refers to the participant's hand being placed between the mouse and the tactors [see Fig. 4(b)]. Both positions minimally interfere with the manipulation of the mouse. Tactor placement was adjusted for each participant separately and a Velcro strap was used to secure the tactor position.

3) Vibrotactile Stimuli: The vibrotactile stimulus was a modulated 250-Hz sinusoidal signal held at a constant gain for all participants [15], [16]. Skin is most sensitive to light vibrations around 200 Hz [17], and maximum sensitivity for vibratory touch stimuli occurs from 200 to 400 Hz at stimulus intensities ranging from -20 to $+60$ dB [15], [18], [19]. Frequency sensitivity is rather limited and should be used with great discretion as a stimulus variable in tactile communication [20]. The IEA actuators are relatively fast, and reach the set frequency within 2–3 ms, which results in clear distinctive stimulus bursts. White noise was presented via headphones to mask the sound of the mechanical relays used in the tactor driver. We used burst rate as our primary source for coding as the use of temporal patterns have been successfully demonstrated before (see, for example, [15]). The vibrotactile burst was kept constant at 100 ms for all experiments for both directional cues and on-target cues.

4) Vibrotactile Directional Cues: Burst rate varied among experiments. In Experiment 1, the burst rate was kept constant at 6.7 bursts/s (a stimulus burst of 100 ms and an interstimulus interval (ISI) of 50 ms). In Experiments 2 and 3, the burst rate changed gradually as a function of horizontal distance from the target. It was driven by a third-order polynomial function ranging from ISIs of 250 to 10 ms (where 10 ms is often considered as the lower limit for gap detection [21], [22]). Discriminability among the gradual changes of the polynomial function were not examined. Yet, discriminability between the two extremities of the function; frequent (about 9 bursts/s, 100-ms bursts, and ISI of 10 ms) and infrequent burst rate (about 3 bursts/s, 100-ms bursts, and ISI of 250 ms) was determined. Two movement profiles (gradients) of ISI changes were generated; Gradient Up in which as the cursor approaches the target, the cuing becomes more frequent or Gradient Down in which as the cursor approaches the target, the cuing becomes less frequent (see Fig. 5). The gradual change in burst rate was applied whenever the cursor was within 60° of the target; beyond 60° (which meant that the cursor was relatively far from the target), burst rate was kept constant at either frequent or infrequent burst rate depending on the gradient and the direction of the cursor (to the left or to the right of the target, respectively).

5) Vibrotactile Discrete Directional Cues: It has been suggested that visual cueing is not necessary for the entire duration of the movement of a rapid target-selection task [9], [10]. Rather, cues providing directional information must be provided during the initial movement stage and again near the target. This claim was examined for vibrotactile directional cues in Experiment 3. Based on the average movement profile derived from Experiment 1, two movement ranges were defined: 1) initial movement; from target pop-up to eight pixels of movement toward the target, and 2) the end of the first ballistic movement; movements toward the target within 105 pixels of the nearest edge of the target. Those ranges were imposed on the continuous profile to create a discrete cueing condition (see Fig. 6). Movement away from the target always resulted in a continuous tactile cue with frequent or infrequent burst rate for the Up and the Down gradients, respectively.

6) Vibrotactile On-Target Cues: On-target cues were applied from both tactors simultaneously. Burst rate on target was kept constant, but varied among experiments. In Experiment 1, the burst rate was 6.7 bursts/s. In Experiment 2, cues on target were either suppressed (silent, no cues while on target) or enhanced (frequent burst rate on target, about 9 bursts/s). In Experiment 3, cues on target were either suppressed, enhanced fast with frequent burst rate on target, or enhanced slow with

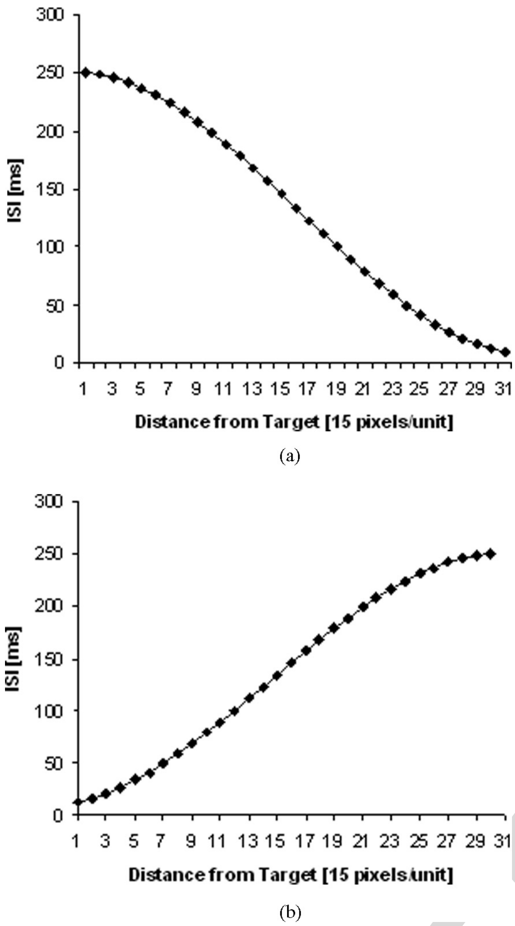


Fig. 5. Interstimulus interval by scalar distance from target used in Experiments 2 and 3. The upper gradient profile [Gradient Down (GraD)] is one in which as the cursor approaches the target, the cuing becomes less frequent. The lower gradient profile [Gradient Up (GraU)] is one in which as the cursor approaches the target, cues become more frequent. Discriminability was experimentally determined between the frequent (about 9 bursts/s, 100-ms bursts, and ISI of 10 ms) and the infrequent burst rate (about 3 bursts/s, 100-ms bursts, and ISI of 250 ms).

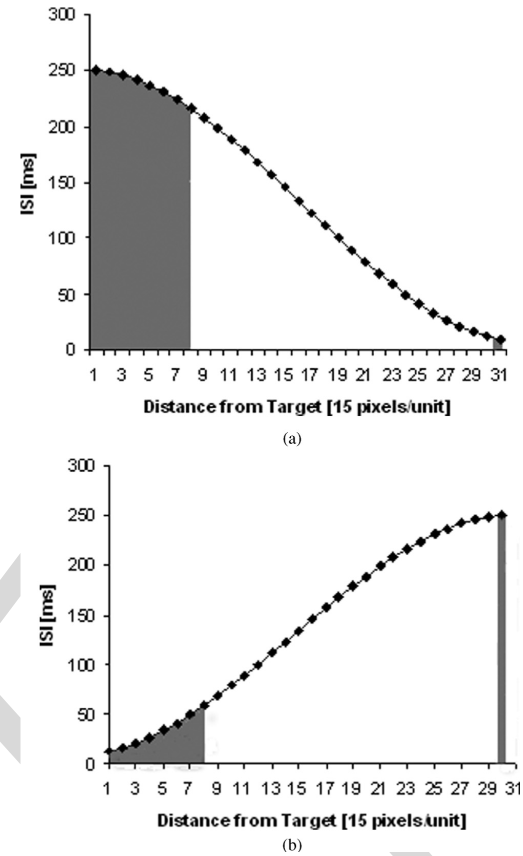


Fig. 6. Discrete and continuous profiles used in Experiment 3. The continuous profile is similar to the one used in Experiment 2. The *grayed area* represents the discrete condition. Cuing occurred only during the initial eight pixels of movement and during the last 105 pixels near the target, as the initial ballistic movement ended and fine submovements began.

infrequent burst rate on target (about 3 bursts/s) depending on the experimental trial.

7) Tactor Discrimination Test: The test was administered to establish the magnitude of bias, if any, between the two tactors. Participants were presented a randomized set of left, right, or both tactor stimuli and asked to select which tactors were activated. Each stimulus burst was of 100 ms. Each combination of tactors (left, right, and both) was presented six times, for a total of 18 trials. The "left" and "right" buttons were used for indicating the left and right tactors, respectively. The "both" button was positioned in the center of the screen. Upon completion of the 18 trials, the participants shifted a continuous scrollbar left or right to indicate the relative intensity of the left and right tactors. The gain of the tactors was kept constant throughout the test.

B. General Procedure

In all the three experiments, the participants sat comfortably in front of the computer monitor. Tactors were placed on the hand in which they normally used a computer mouse, and the tactors were adjusted properly for each participant. Tactors were placed in line with the thumb and fourth finger at the base of the palm, either on the ventral or dorsal surface of the hand, depending on the experimental condition. The tactors were held in place by a Velcro strap wrapped around the hand. Participants had the tactors in contact with their hand for the entire duration of the experiment. Prior to any trials, we made certain that participants reported 100% detection rate for the tactile stimuli for both tactors and that tactor intensity was perceived as equal from both tactors (see tactor discrimination test).

III. Experiment 1

As the locus on the skin is the primary coding mechanism for vibrotactile displays [15], it was important to establish the location of the tactors on the hand. Experiment 1 examined the initial response to directional (to the left or to the right) vibrotactile guidance cues for two tactor placements; on the palm (ventral) versus on the back of the hand (dorsal).

The participant's hand was oriented perpendicular with respect to the floor (see Fig. 7). This position of the hand is a common grip position and, as such, suitable for TAGS. It is also a hand position where (for a right hand) the left side of the hand (thumb up) and the right side of the hand are not in accordance

Fig. 7. Hand position and holding of the inertial mouse in Experiment 1. Note that the tactors were placed either ventral or dorsal as shown in Fig 6.

with the left side of the trunk and the right side of the trunk. It was expected, however, that for a hand facing perpendicular to the ground (as shown in Fig. 7), the vibrotactile direction cues applied to the left side of the hand (thumb) will result in movement of the hand to the left and cues applied to the right side of the hand (pinkie finger) will result in movement of the hand to the right regardless of the tactor placement (ventral or dorsal) since trunk position is the dominant factor in determining movement direction.

To solely examine the tactile affordances, no visual cues were presented in this experiment.

A. Experimental Design

A two-way repeated measures design with tactor placement (ventral versus dorsal) and target location (left versus right) as the within-participant variable.

B. Experimental Participants

Twenty-four undergraduate students at the University of Central Florida participated in this experiment. There were 12 males and 12 females. Though three males and one female stated that they wrote with their left hand, all participants stated that they use their right hand for mouse operations. There were no significant correlations between age, gender, mouse use in hours per day, and computer game play in hours per day with initial movement time and probability of correct initial movement.

C. Apparatus

Apparatus was as described in Section II. The mouse was used in its inertial mouse mode such that movement of the cursor fully left or right from the center of the screen required a wrist flexion or extension of 60°.

Initial movement time (iMT), probability of correct initial movement direction (iMove), and time-stamped movement profiles were collected for each trial. iMT for this experiment was defined as the time in milliseconds between target pop-up and the start of movement by the participant. iMove for this experiment was defined as the probability of making a correct initial movement toward the target by the participant. Movement profiles consisted of the time-stamped (in milliseconds) "x" screen coordinate of the center of the cursor recorded once every mouse tick. Mouse ticks only occur when there is movement of the mouse, with a maximum recording rate of about 100 mouse ticks per s for the described system.

D. Procedure

Participants were assigned to one of two orders of presentation of the tactor placement (ventral or dorsal). The participants were presented two blocks of 16 targets, for a total of 32 trials. Upon completion of the first 16 trials, the tactor location was switched. Before each block of trials, the tactor placement was verified by obtaining the participant's subjective perception of the discriminability and comfort of the tactors. This was accomplished by pulsing the first one, then the other tactor, and having the participant point to the tactor they felt was activated.

For all trials, the participants sat comfortably in front of the computer monitor with their hand unsupported (see Fig. 7). Participants were instructed to depress and hold the inertial mouse mode button under the mouse with their index finger whenever they wanted to move the cursor. Participants were not instructed to keep their eyes open during the experiment; however, we did not observe any of the participants closing their eyes systematically throughout the experiment.

Participants practiced using the inertial mouse to move the cursor fully left, right, up, and down by using only hand motions about the wrist. Then, the experiment began.

The primary task of the participants during a trial was to quickly move their hand in the direction of the target when they had an idea where the target was located. When a trial began, the tactile stimulus was presented. It continued to be present until the trial ended. Irrespective of the correctness of movement direction, each trial ended when the participant moved the cursor beyond the distance the target was located from the center of the screen. When the trial ended, the participant returned his or her hand position to neutral position and waited for the next trial to begin.

E. Results

The general linear model (GLM) in SPSS 11.5 was employed to analyze the two-way, repeated measures design. All tests were run at the $\alpha = 0.05$ level. Unambiguous intentional movements did not typically appear within 1° of hand movement, suggesting that the tolerance for identifying the initial movement could be widened to eight pixels (1° of hand movement) rather than the 1-pixel tolerance employed by the data collection program. This 1° tolerance was applied to the iMT and iMove data.

The data indicated that movement to the left or movement to the right based on vibrotactile guidance cues is independent of the location of the tactors on the hand when both tactors are located on the ventral or dorsal surface. There was no significant interaction between tactor placement on the ventral (V) or dorsal (D) surface and targets left (L) or right (R) on initial movement time [($M_{\mathrm{VL}} = 0.648$; $M_{\mathrm{VR}} = 0.644$;

$M_{\mathrm{DL}} = 0.709$; $M_{\mathrm{DR}} = 679$; F (1, 23) $= 0.966$, $p > 0.05$, ($\boldsymbol{\eta}_p^2 = .040$, ($\boldsymbol{\beta} = 0.156$]. There was no significant interaction between tactor placement and target left or right on iMove ($M_{\mathrm{VL}} = 0.776$; $M_{\mathrm{VR}} = 0.755$; $M_{\mathrm{DL}} = 0.734$; $M_{\mathrm{DR}} = 0.682$; F (1, 23) $= 0.195$, $p < 0.05$, ($\boldsymbol{\eta}_p^2 = 0.008$,($\boldsymbol{\beta} = 0.071$].When the user's hand orients perpendicular with respect to the floor (as shown in Fig. 7), the results suggest that there were no differences between placements in relation to the direction of movement. We, therefore, chose to use the ventral placement for the following studies as it enabled a better grip on the mouse by the participants.

IV. Experiment 2

Experiment 2 established the effect of continuous relative distance cues and on- versus off-target vibrotactile stimuli on reaction time and accuracy for target selection. Visual target cues were set against a visual background that had to be searched (as it is most likely to be in environments where targets are camouflaged intentionally). Tactile target cues were set against a relatively quiet background, and always correctly indicated the direction of the target. As such, it was expected that tactile target cues would facilitate target search and movement accuracy, and that using visual and vibrotactile direction and distance cues combined would result in faster time-to-target compared to visual cues alone.

The initial tactile burst on target pop-up provided the direction (right or left). The manipulation of tactile burst rate provided the gradient (i.e., the distance from the target). Increasing burst rate gave rapid feedback during near-target submovements. Decreasing burst rate gave initial cues on target pop-up, but less rapid feedback during near-target submovements. It was expected that faster tactile burst rates near the target would result in faster time-to-target compared to slower burst rates near the target as the faster burst rates close to the target provide feedback for the final approach to the target. Furthermore, it was also important to identify whether the vibrotactile cues on target should be enhanced (frequent burst rate on target) or suppressed [no pulsing on target (silent)]. Subject matter experts in marksmanship have indicated that a suppressed or silent target is preferred since the extra stimulation while on target may be distracting the operator from the target acquisition task. Experiment 2 was designed to empirically explore this claim.

A. Experimental Design

Experiment 2 employed a 3 × 2 × 2 mixed factorial design. The within-participant variable was Display (visual versus tactile versus visual + tactile combined). Between-participants variables included cuing on target (Suppressed or Enhanced) and gradient (Up or Down).

B. Experimental Participants

The 24 undergraduate students at the University of Central Florida who participated in Experiment 1 also participated in this experiment. Hence, there were 12 males and 12 females in the sample. Each participant performed both experiments on the same day. A short break was offered between the experiments, but all participants declined. There were no significant correlations between age, gender, and mouse use in hours per day, and computer game play in hours per day with initial movement time, probability of correct initial movement, and target selection time.

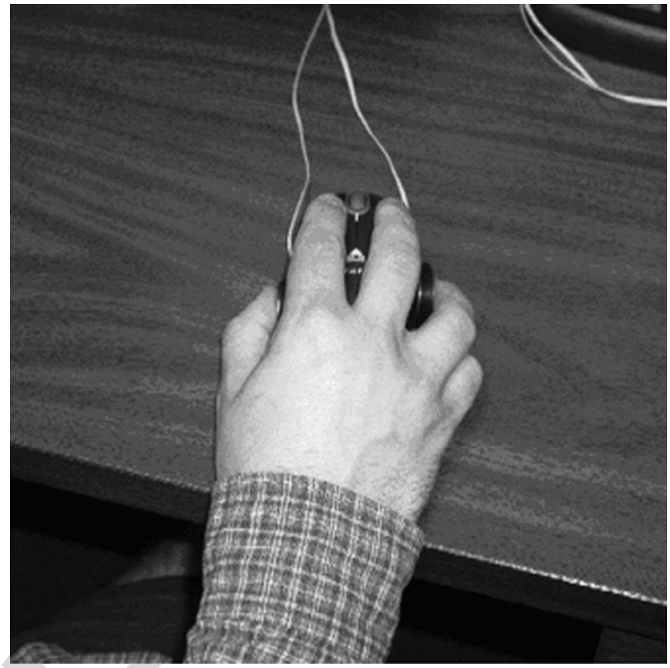


Fig. 8. Hand position using the inertial mouse for Experiments 2 and 3. Here the hand was supported by the desk and the tactors were placed on the mouse.

C. Apparatus

The setup for Experiment 2 was similar to Experiment 1, with the following changes. The mouse was used in its optical mouse mode on the desk in front of the monitor. Hence, participants no longer had to hold the mouse in their hand in the air. Practically, it was difficult for participants to hold their arm freely without support (as in Experiment 1) for the duration of a longer experiment. Tactors were positioned on either side of the mouse such that the thumb and third finger were in direct contact with the tactors' vibrating elements (see Fig. 8) similar to the ventral position in Experiment 1. Movement of the cursor onto the near targets required a 2.5-in movement of the mouse from the central point of origin. Movement of the cursor onto the far targets required a 5.0-in movement, respectively. In the visual and visual + tactile conditions, visual targets appeared as described in the general experimental method (Fig. 3).

Initial movement time (iMT), probability of correct initial movement (iMove), the number of times on-target (otCnt), time from target pop-up to target selection (ST), and time-stamped movement profiles were collected for each trial. iMT for this experiment is defined as the time in seconds between target pop-up and the start of movement by the participant. iMove is the probability of a correct initial movement toward the target by the participant. otCnt is defined as the number of times the cursor went from off-target to on-target. Movement profiles consisted of the time-stamped (in seconds) horizontal screen coordinate of the center of the cursor recorded every time the mouse position changed. A maximum recording rate of about 100 mouse movements per second was achieved for the described system.

D. Experimental Procedure

Participants were randomly assigned to one of four groups: target Suppressed (TarS), gradient Up (GraU); target Suppressed, gradient Down (GraD); target Enhanced (TarE), gradient Up; and target Enhanced, gradient Down. The participants were presented three blocks of 32 targets, for a total of 96 trials. The first block of trials was visual-only, the second block of trials was tactile-only, and the third block of trials was visual and tactile. Order of presentation of the blocks was not varied in this experiment. Before each block of trials, the instructions specific for the block were briefly reviewed. Upon completion of the experiment, the participants were asked to fill out a questionnaire about their experience with computers and video games, and their subjective experience during the experiment.

The primary task during a trial was to quickly move the cursor onto the target, and then, when on target, to click on the left mouse button. When a trial began, the white cross cursor appeared in the center of the screen for all conditions. In the visual conditions, the target appeared at random position in the horizontal plane. The target continued to be presented until the trial ended. Each trial ended when the participant clicked on the target. For the tactile condition, tactile cuing did not stop until the participant clicked on the target. If the participant missed the target and clicked elsewhere, tactile cuing continued to indicate that he did not hit the target yet. The next trial began after a random delay ranging from 2 to 9 s.

E. Results

The GLM in SPSS 11.5 was employed to analyze the $3 \times 2 \times 2$ mixed factorial design. All tests were run at the $\alpha = 0.05$ level for significance testing.

There were no significant differences for selection time between the visual condition and the visual + tactile condition ($M_{ST} = 1423$ ms (SD = 241), and $M_{ST} = 1368$ ms (SD = 175)]. However, there was a small trend (Cohen's $d = 0.261$) toward shorter selection times in the tactile + visual condition. The visual and visual + tactile conditions were significantly better than the tactile-only condition ($M_{ST} = 6647$ ms (SD = 4080)].

There was a significant interaction between the gradient of vibrotactile stimuli (GraU or GraD) and the method used to highlight the target (TarS or TarE) for selection times. The suppressed target condition ($M_{\mathrm{TarS}} = 4395$ ms) was superior to the enhanced target condition ($M_{\mathrm{TarE}} = 8899$ ms) in terms of target selection time (ST) [$\boldsymbol{F}(1,20) = 11.017, \boldsymbol{p} < 0.05$, ($mbi\eta$ $B^{2P}_{\mathrm{pPB}} = 0.355$ (see Fig. 9). This is particularly evident when the pulse rate increases as the cursor moves closer to a target (GraU).

For number of movements on target until acquisition (otCnt), there was a significant Display $\times$ Target $\times$ Gradient interaction [$\boldsymbol{F}(2,40) = 3.94, p < 0.05$,($\boldsymbol{\eta}$ $B^{2P}_{\mathrm{pPB}} = 0.165$]. Here, the

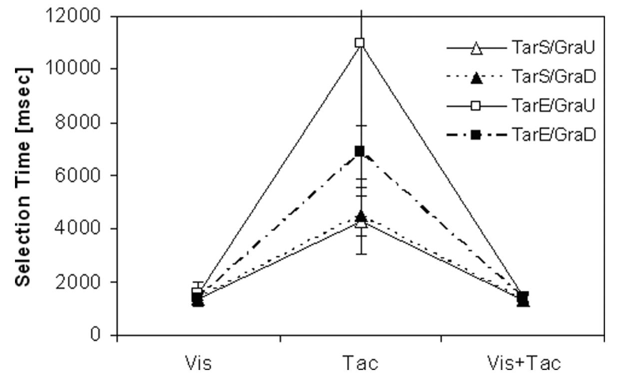


Fig. 9. Target selection time in Experiment 2 where there was a significant interaction between the cuing on target (suppressed or enhanced) and the gradient of the movement (up or down, see Fig. 7).

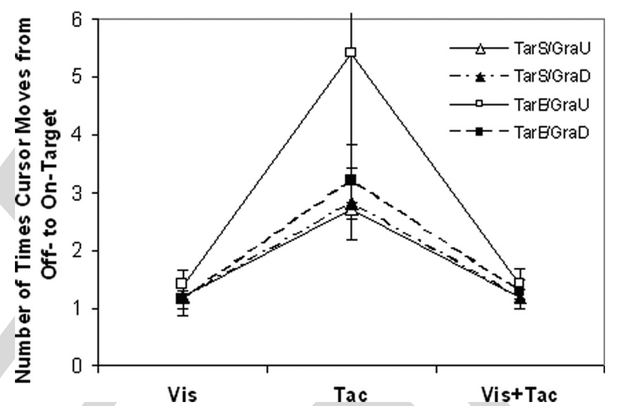


Fig. 10. Number of movements on target in Experiment 2. Here, again the same interaction between the cuing on target (suppressed or enhanced) and the gradient of the movement (up or down, see Fig. 7) was found.

tactile-only condition was inferior to the visual and the visual + tactile conditions across all combinations resulting in more times to cross over the target before acquiring it as shown in Fig. 10. The tactile + visual condition was not significantly different from the visual condition except for in the gradient Down and target Enhanced condition ($M = 1.281$ (SD = 0.201), and $M = 1.146$ (SD = 0.151), respectively].

With regard to initial movement time, there was a significant main effect of display [$\boldsymbol{F}(2,40) = 33.350, \boldsymbol{p} < 0.05$,($\boldsymbol{\eta}$ $B^{2P}_{\mathrm{pPB}} = 0.625$] indicating that the initial movements in the visual + tactile conditions were significantly faster than in either one of the other conditions ($M = 404$ (SD = 63) ms, $M = 386$ (SD = 83) ms, and $M = 288$ (SD = 59) ms, respectively, for the visual, tactile-only, and visual + tactile conditions]. There were no significant differences in initial movement between the visual and the tactile-only conditions as shown in Fig. 11.

Experiment 2 showed that there was an interaction between the gradient of vibrotactile stimuli and the method used to highlight the target. The suppressed target condition (where no tactile stimulus was present when the cursor was on target) was superior to the enhanced target condition (where perceived intensity was at its highest on the target). Experiment 2 also revealed a consistent superiority of the visual and visual-tactile conditions over tactile-only. This finding can be attributed to the fact that vision is the dominant source of information for the object selection

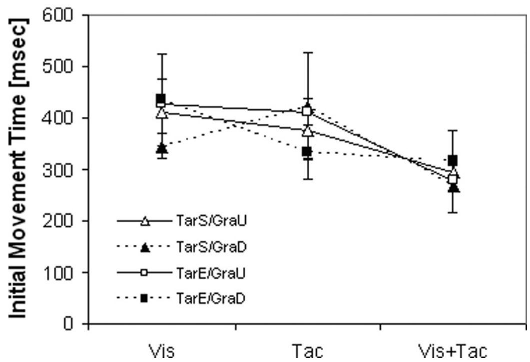


Fig 11. Initial movement times in Experiment 2 where the combined visual + tactile display provided the fastest responses.

task employed. There were advantages in initial movement time to the visual + tactile condition over the visual-only condition; however, these differences were not significantly maintained in target selection time. Possibly, the small yet significant difference in the number of times the cursor went over the target (otCnt) for the enhanced target caused the initial movement time advantage to dissipate. This may imply that for the tactile stimuli to be effective for target acquisition, a large differentiation is necessary between guidance cues and on-target cues.

V. Experiment 3

Experiment 3 was designed to establish if there are performance differences between tactile and visual + tactile displays with respect to: 1) the interaction between the near-target pulse rate and on-target cues, and 2) differences between discrete and continuous guidance cues.

Experiment 2 showed that the effectiveness of distance guidance cues may interact with the on-target cues when those cues use the same basic burst rate. Experiment 3 further investigated this interaction between the gradient of directional cues and the on-target cues. To maximize differentiation between on-target- and near-target cues [23]–[27], three different on-target cues were used. It was hypothesized that providing higher resolution feedback near the target (ISI < 100 ms) should improve target selection accuracy compared to lower resolution feedback (ISI < 100 ms) [21]. Minimum difference between the on-target- and near-target stimuli occurs when the on-target- and near-target pulse rates are the same. With this in mind, using the absence of vibrotactile stimuli on-target with infrequent burst rate near the target should result in an intermediate level of difference between the on-target- and near-target stimuli. It was, thus, expected that variation in burst rate between near-target and on-target will result in shorter time-on-target than no or smaller variations in burst rate.

Based on research in movement control [9], [10] it was hypothesized that discontinuous vibrotactile direction and distance cues (discrete cues) will result in identical target selection times to continuous vibrotactile direction and distance cues.

A. Experimental Design

Experiment 3 employed a 2 × 3 × 2 × 2 mixed factorial design (Display by On-target Cues by Gradient by Continuous versus Discrete stimuli). Within-subjects variables include Visual + Tactile or Tactile (Display), and Target Suppressed, Target Enhanced Slow, or Target Enhanced Fast (TarSEsf).

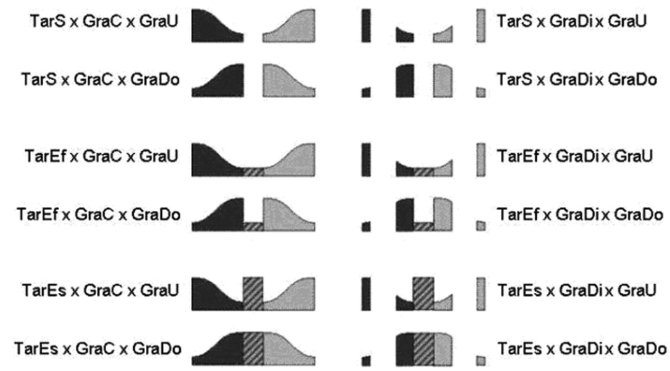


Fig. 12. Graphical depiction of the conditions in Experiment 3. The tactile display was either continuous (GraC) (as shown in the left) or discrete (GraDi). Three levels of target cuing [suppressed (S), enhanced slow (Es), and enhanced fast (Ef)] and two gradient profiles [Up(GraU) and Down (GraD)] generated 12 experimental combinations for each display type.

Between-subjects variables include Gradient Continuous or Gradient Discrete (GraCDi), and ISI Gradient sweeps Up or Down (GraUDo).

Fig. 12 graphically depicts the 12 possible combinations for TarSEsf ×GraCDi × GraUDo. The height of the curves represents the duration of ISI, where higher points on the curves represent longer ISI. The width of the curves represents the scalar distance from the target, where the target is in the center of convergence of each set of curves. TarSEsf is represented by the blank space or mixed-color bar between the converging curves. GraCDi is represented by the continuity of the curves; the left set of curves is Continuous, while the right set is Discrete. Finally, GraUDo is represented by the height of the curves at the center of convergence of the set of curves.

B. Participants

Thirty-two undergraduate students at the University of Central Florida participated in this experiment. There were nine male participants and 23 females in this sample. Participant's handedness was measured using the Edinburgh Handedness Inventory [28]. Participant questionnaire collected data about their experience with computers and video games. None of the male participants indicated left-hand bias. Three female participants, however, indicated a left-hand bias. All participants chose to use the mouse with their right hand. Participants were assigned to an order of presentation of the within-subjects conditions by Latin Square. Each participant was assigned to the next order of presentation of the Display conditions in the Display Latin Square. Each participant was then assigned the next order of presentation of the TarSEsf conditions in the TarSEsf Latin Square.

C. Apparatus

The same software deployed for Experiment 2 was used in this experiment. Initial movement time (iMT), probability of correct initial movement (iMove), the number of times on-target (otCnt), time from target pop-up to target selection (ST), and time-stamped movement profiles were collected for each trial.

D. Experimental Procedure

The procedure was similar to Experiment 2, with a few exceptions. A computer-based version of the Edinburgh Handedness Inventory (EHI) [28] was administered. The tactors were then applied to the participant's preferred hand. The tactor discrimination test was then administered and the tactors repositioned as necessary to achieve zero perceived bias between the tactors.

Training before each block included a review of the stimuli that will be presented for the block, eight training targets, and a posttraining opportunity to ask questions about the stimuli.

The primary task of the participants during a trial was to quickly move the cursor onto the target and then click on the left mouse button. Each testing block included 32 trials. When a trial began, the target stimuli were presented as appropriate for the block, and the cursor appeared at the center of the screen. The stimuli continued to be presented until the trial ended. Each trial ended when the participant clicked on the target. The following trial began after a randomly generated delay ranging from 2 to 9 s.

E. Results

The GLM in SPSS 11.5 was employed to analyze the $2 \times 3 \times 2 \times 2$ mixed factorial design. All tests were run at the $\alpha = 0.05$ level.

For Selection time, the tactile-only display resulted in significantly slower target selection times than the visual + tactile display $[\boldsymbol{F}(1,28) = 274.33, \boldsymbol{p} < 0.000, (\boldsymbol{\eta}\ B^{2P}_{\rm pPB} = 0.907]$ $M_{ST} = 5363$ and $M_{ST} = 1395$ ms, respectively. No other main effects were significant. There was a significant Display × TarSEsf × GarUDo interaction $[\boldsymbol{F}(2,56) = 3.375, \boldsymbol{p} < 0.005$, $(\boldsymbol{\eta}\ B^{2P}_{\rm pPB} = 0.118]$ (see Table I for means). There was also a significant TarSEsf × GarUDo interaction $[(F(2, 56) = 3.399$, $p <\ 0.005$, $(\eta\ B^{2P}_{\rm pPB} = 0.125)$ indicating that there was an interaction between the gradient of vibrotactile stimuli (GraU or GraD) and the method used to highlight the target (TarS, TarEf, or TarEs) for selection time as shown in Fig. 13. The larger the difference between off- and on-target cues (e.g., TarS/GraU, TarEs/GraU, TarEf/GraDo), the less time the participant spends on the target before selecting the target, and the less time it takes from target pop-up for the participant to select the target. This appears to be particularly true when the approach to the target is with an increasing pulse rate (GraU). These results support the hypothesis that variation in pulse rate when moving On/Off the target will result in shorter time-on-target than no variation in pulse rate.

For the number of movements on target until acquisition (otCnt), there was a significant main effect for display $[\boldsymbol{F}(1,28) = 125.84, \boldsymbol{p} < 0.000, (\boldsymbol{\eta}\ B^{2P}_{\rm pPB} = 0.818]$ $(M_{\rm otCnt} = 1.37$ for the visual + tactile display and $M_{\rm otCnt} = 2.69$ for the tactile-only display). There was also a main effect for target cuing $\$[F(2,28) = 4.351,\ \boldsymbol{p} < 0.018, \boldsymbol{\eta}\}\ B^{2P}_{\rm pPB} = 0.134]$ where the suppressed target (no cues on target) caused more repetitions on target than either one of the enhanced conditions ($M_{\rm otCnt} = 2.16$ (SD = 0.33, $M_{\rm otCnt} = 1.96$ (SD = 0.25), and $M_{\rm otCnt} = 1.96$ (SD = 0.28) for the suppressed, enhanced fast, and enhanced slow, respectively). The interaction Display × Target was also significant $[\boldsymbol{F}(2,56) = 3.29,\ \boldsymbol{p} < 0.05$, $(\boldsymbol{\eta} B^{2P}_{\rm pPB} = 0.105]$.

TABLE I
TARGET SELECTION TIMES (IN SECONDS)

Gradient		Target Suppressed	Target Enhanced Fast	Target Enhanced Slow
Visual+Tactile				
Continuous	Up	1.37	1.40	1.41
		(0.13)	(0.15)	(0.22)
	Down	1.32	1.30	1.31
		(0.22)	(0.20)	(0.19)
Discrete	Up	1.47	1.46	1.48
		(0.22)	(0.12)	(0.23)
	Down	1.41	1.43	1.39
		(0.19)	(0.21)	(0.17)
Tactile Only				
Continuous	Up	4.30	5.41	4.06
		(2.08)	(1.58)	(0.94)
	Down	5.89	5.43	5.83
		(2.39)	(2.56)	(1.41)
Discrete	Up	5.20	5.44	5.48
		(1.40)	(0.75)	(1.37)
	Down	6.91	4.57	5.83
		(3.24)	(1.44)	(1.92)

Note: Values in parenthesis are standard deviations. There were no significant differences among the discrete and continuous conditions. However there were significant differences between the Visual+Tactile and the Tactile only conditions.

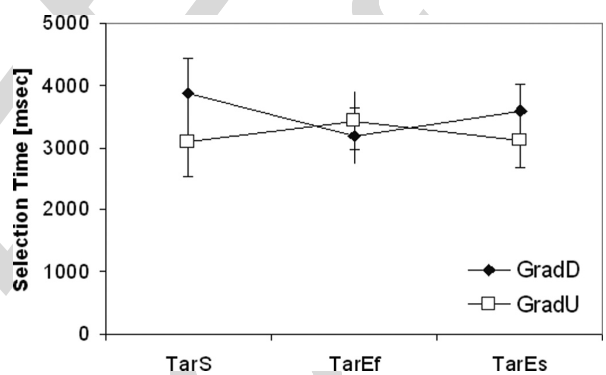


Fig. 13. Target selection time in Experiment 3 as a function of gradient and target cuing. There was a significant interaction between the cuing on target (suppressed, enhanced fast, or enhanced slow) and the gradient of the movement (up or down, see Fig. 12).

With regard to initial movement time (in milliseconds), there was a significant main effect of display $[\boldsymbol{F}(1,28) = 47.663, \boldsymbol{p} <$ $0.000, (\boldsymbol{\eta} B^{2P}_{\rm pPB} = 0.630]$ indicating that the initial movement in the visual + tactile conditions was significantly faster than in the tactile-only condition ($M = 0.349$ (SD = 0.88), $M = 0.484$ (SD = 148)]. These results are similar to the ones found in Experiment 2.

Given that there was no difference in target selection time, or numbers of time on target across the continuous and discrete conditions, the data suggest that gradient continuity is not necessary in this measure of marksmanship. The results support the hypothesis that discontinuous vibrotactile direction and distance cues will result in identical target selection times to continuous vibrotactile direction and distance cues. It should be noted, however, that in *all* cases the visual + tactile display conditions were superior to the tactile-only conditions.

VI. Discussion and Conclusion

The purpose of this study was twofold: 1) to establish whether vibrotactile guidance cues can improve target acquisition over visual cues alone and 2) to examine whether vibrotacitle cues can effectively convey not only the direction but also the magnitude of movement.

Experiment 1 established the effect on initial response to vibrotactile guidance cues of tactor placements on the palm (ventral) versus on the back of the hand (dorsal), and targets appearing left versus right of center. Results suggest that tactile cues provided on the left side of the medial line of the hand afford moving the hand to the left, while tactile cues on the right side of the medial line afford moving the hand to the right.

Experiment 2 established the effect of continuous relative distance cues and on- versus off-target vibrotactile stimuli on reaction time and accuracy for target selection. Results suggest that there may be an interaction between the pulse rate of vibrotactile stimuli and the method used to highlight an "on-target" condition. Generally, the suppressed target condition was superior to the enhanced target condition. This was particularly true when the pulse rate increased as the cursor moved closer to a target.

Experiment 2 also demonstrated the dominance of visual perception over tactile perception. When visual displays are available, the tactile cues significantly improved initial movement time. Hence, the direction of movement can be determined much faster and with more reliability when tactile cues are provided than with visual cues alone. This may be attributed to the fact that the addition of tactile stimuli reduces the need to visually search for the appearance of a new target. Particularly, in the conditions simulated in our experiments, there was a high degree of uncertainty regarding target onset and it most likely may be encouraging participants to adopt a strategy of attending to the tactile event cue. However, the fact that we did not find similar initial movements in the tactile-only condition reinforces the notion that the tactile cues facilitate the faster movement only when the visual cues are also present. There was no significant difference in target selection time between the visual and visual + tactile condition, possibly due to the interaction between the tactile cueing gradient and the way the target was highlighted.

Experiment 3 examined the performance differences between discrete and continuous distance information for target selection, and investigated the interaction between the near-target pulse rate and on-target cues. Results suggest that maximizing the difference between near-target guidance cues and on-target cues reduces the target selection time, particularly when the near-target burst rates are frequent (about 9 bursts/s). The results also confirm that, as with vision, the vibrotactile off-target guidance cues are not necessary during the entire target selection task. Rather, the guidance cues can be provided only during the initial pop-up condition and during the submovements closing on the target with little or no change in performance. Futhermore, Experiment 3 showed again, as in Experiment 2, that for tactile cues there was an interaction between the tactile gradient and the way the target is highlighted.

TABLE II
Rank Order of the Best Selection Time Profiles

Profile	Selection Time (sec)	Final Time on Target before selection (sec)
TarEs x GraU	2.73	.63
TarS x GraU	2.83	.49
TarEf x GraU	2.85	.50
TarEf x GraDo	3.36	.54

A. Practical Implications

The results obtained in this study offer some practical implications for the design of vibrotactile guidance cues for target acquisition.

1) It is possible to reduce the visual search time, i.e., promote the initial movement toward a target by almost half when adding tactile cues.
2) When varying the pulse rate as a function of distance off-target, and when providing for on-target cues, the larger the difference between near- and on-target cues, the better. The worst combination of cues is to have the same on-target burst rate as the near-target burst rate. Here, we found the best combination of cues is to have a frequent burst rate (about 9 bursts/s, e.g., ISI = 10 ms) near the target, with vibrotactile cues absent on-target. The next best combination of cues is to have a frequent burst rate near the target, with infrequent burst rate (about 3 bursts/s, e.g., ISI = 250 ms) from both tactors on-target (see Table II).
3) A concern with vibrotactile sensors is that they remain fixed in place when operators move about, as in combat situation. The ventral tactor position enables positioning the tactors on the aiming tool rather than on the hand.

B. Recommendations for Future Research

Since the tactors would most likely be applied to only one surface of the hand in TAGS (i.e., ventral or dorsal), our purpose for these studies was to establish, among other things, which surface of the hand should be employed for our given application rather than exploring the more fundamental affordance issues requiring an exhaustive analysis of the possible combinations of tactor placement and hand orientation. Such a study would permit a more complete analysis of the possible shift between negative- and positive-feedback that may occur with multisurface tactor placement spanning a wide range of hand orientations with respect to the acceleration reference frame.

Our design focused on establishing the effect of subtle versus extreme variations in on- versus off-target guidance cues, and whether or not a continuously presented gradient is necessary for providing guidance cues to the target. This was done using a single gradient (see Fig. 7) based on the analysis of movement in one study. Future research needs to explore a variety of gradients.

Experience with the tactors seems to affect participants' ability to perform the target selection task irrespective of the type of tactile guidance cues provided. From our experience, we have noted that participants take the time to explore the full range of the tactile display during training rather than simply acquire the target. The effect of familiarity, experience, and training in tactile displays needs to be further examined.

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