Absolute localization of vibrotactile stimuli on the torso

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Vibrotactile mobility systems present spatial information such as the direction of a waypoint through a localized vibration on the torso. Using these systems requires the ability to determine the absolute location of the stimulus. Because data are available only on the ability to determine the relative location of stimuli on the torso, we developed a novel method for measuring absolute localization on the basis of triangulation. For 15 observers, we calculated the subjective location of visual and tactile stimuli on the frontal half of the torso. The size of the 95% confidence intervals around the subjective tactile locations is about the size of the stimuli (1.66 cm) and is slightly larger than that around the subjective visual locations (mean difference, 0.17 cm). The error in tactile judgments over and above that in the visual judgments is present only for locations near the body midline. When the subjective visual and tactile locations are not co-located, the difference can best be described by a shift along the radius from the body midaxis. The same holds for the differences between the veridical and the subjective locations. Therefore, the difference between the veridical and the subjective directions of a stimulus is small. The results make us believe that stimulus locations on the torso are coded in polar coordinates of which the angle is perceptual invariant and the distance is less important, probably because it varies with changes in, among other things, posture and breathing.

Neurophysiological and psychophysical studies have shown that the skin is a complex sensory system capable of processing large amounts of information. For example, extraordinary observers who are trained in reading patterns from a tactile display for the fingertips actually read up to 100 words per minute (Craig, 1977). Recently, a new class of information systems in which the skin is used as an information channel has emerged: orientation systems that function as sensory substitution systems (Bach-y-Rita & Kercel, 2003; Borg, Rönnerberg, & Neovius, 2001; Kadekade, Benda, Schmidt, & Wall, 2003) or that present mobility information to pedestrians or divers. These systems use a localized vibration on, for instance, the wrists, legs, or torso to indicate deviation from a planned route or the direction of a waypoint (Dobbins & Samway, 2002; Ho, Tan, & Spence, 2005; Tsukada & Yasumura, 2004; van Erp & van Veen, 2004; van Erp, van Veen, Jansen, & Dobbins, 2005). More advanced systems cover the whole upper body with a matrix of vibrators to provide three-dimensional direction information to pilots and astronauts (Bhargava et al., 2005; Bos, van Erp, Groen, & van Veen, 2005; Jones, Nakamura, & Lockyer, 2004; Rochlis & Newman, 2000; Rupert, 2000; van Erp, Groen, Bos, & van Veen, 2006; van Erp & van Veen, 2006). The strength of these information systems is that they resemble the proverbial tap on the shoulder and are able to facilitate a correct response by the user (Ho et al., 2005). The ability of observers to discriminate (adjacent) stimulus locations

(i.e., the relative location or spatial resolution) and to determine the precise location (i.e., the absolute location) of a stimulus are the key factors in the successful application of this class of displays.

Classic psychophysical studies of the spatial resolution of the sense of touch have been focused mainly on the fingers and hands (e.g., Sherrick, Cholewiak, & Collins, 1990). Despite the successful operational tests of vibratory mobility systems for the torso, only a limited number of psychophysical studies have been performed to investigate the torso, as has been indicated by Cholewiak and Collins (2003). Only recently, several laboratories have started to study the spatial resolution of the torso for vibrotactile stimuli to fill this gap (Cholewiak, Brill, & Schwab, 2004; van Erp, 2005b). Although spatial resolution (or *relative* location) is an important parameter for the design of these mobility displays, it does not tell the whole story. These displays project spatial information (usually directions, such as that of a target or waypoint) onto a specific location on the skin (van Erp, 2005a); thus, their success is based primarily on knowledge about the *absolute* location of the vibration. A high spatial discriminability or resolution does not necessarily imply high absolute localization performance, like a darter who consistently throws the darts close to each other but in the wrong number (see, e.g., Clark, Larwood, Davis, & Deffenbacher, 1995). For instance, phenomenal tactile space might be curved or distorted like haptic space (Blumenfeld, 1937; Kappers &

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Koenderink, 1999). This effect can be independent of the local spatial resolution.

In the present experiment, we investigated not the relative, but the absolute localization of tactile stimuli. It extended two recent investigations: one on identifying vibrotactile stimuli around the torso (Cholewiak et al., 2004) and one on the perceived direction for localized vibrations on the torso (van Erp, 2005a). In the experiments of Cholewiak and colleagues, observers were wearing a linear array of 6, 8, or 12 tactors encircling the torso or a 7-tactor array in a partial ellipse around the frontal part of the torso. They were instructed to indicate as quickly and accurately as possible which tactor had been active. The stimulus was a short 200-msec burst of vibration of one of the tactors. The response was a keystroke on a specifically designed three-dimensional keyboard, consisting of a cylinder with the same number of keys in a circle as the number of tactors in the array around the torso. This response system in which the observers could operate the keyboard from an "over the shoulder" perspective was intended to enable the observers to map their bodies onto the keyboard. The major results show that the information transfer in bits asymptotes close to the theoretical value for absolute judgments for one-dimensional stimuli (Miller, 1956), exactly the aspect Cholewiak and colleagues were interested in. Although this psychophysical method measures spatial discriminability and spatial processing, it does not allow one to determine the precise location at which the observer locates the stimulus, in comparison with its veridical location. A second issue is that observers need to project the stimulus array onto a keyboard of which the keys correspond neither in physical layout (the torso is usually shaped like an oval, not a circle) nor in direction (the tactors were placed at equal distances over the skin, whereas the buttons on the keyboard were placed at equal angles) to the tactor array. A third issue is that observers receive feedback after each response, making it a classification task (in line with the objective to measure information transfer). Also important is that observers can identify a tactor without needing to know its exact location. For instance, observers can

use cues such as the underlying structure (e.g., the tactor somewhere on my lower left rib) and whether a tactor is located at or close to an anchorpoint, such as the navel or spine. As Cholewiak and colleagues reported, observers are extremely good at identifying the tactors at navel and spine and are also quite confident that other stimuli are not at these anchorpoints. The results of their main experiment (Cholewiak et al., 2004, Table 1) show that of the 3,000 nonanchorpoint stimuli, only 8 were wrongly classified as an anchorpoint. This *anchorpoint bias* may also be the explanation for the results that they found for the tactors adjacent to the anchorpoints. Because observers will never respond with the navel or spine location, a bias away from the midsagittal plane is introduced. This bias is not in accordance with the results of a second study on perceived direction that showed a bias toward the midsagittal plane (van Erp, 2005b). In the latter experiment, participants did not classify the activated tactor with a limited set of keys but remotely controlled a cursor (presented around the observer) to indicate the perceived direction of a localized vibration. The results of this experiment revealed a consistent bias in the perceived directions toward the body's midsagittal plane. When the navel and the spine are considered as anchorpoints, the bias toward the midsagittal plane is in accordance with the bias found by Cholewiak and Collins (2003) for linear arrays on the arm.

A possible explanation for the directional bias is that there exists a bias in the (absolute) localization of the vibration (see Figure 1). This means that the subjective location of the vibration might be shifted with respect to its veridical location (although daily life experiences suggest that people are quite accurate in determining the absolute location of a stimulus on the body; most people are able to hit a stinging mosquito in a split second without visual guidance).

This issue cannot be investigated by the current psychophysical methods for spatial resolution or classification but requires a different psychophysical measuring method. This method should not be based on the assumption that the subjective location of the vibration is on the skin surface, should allow continuous responses instead of a limited number of categories, must prevent the *anchor-*

Figure 1. The effect of mislocalization of a stimulus on the subjective direction. In panel A, the active tactor (indicated by the circle on the torso) is, for example, expected to indicate a target at 2 o'clock (indicated by the star). However, when the observer mislocalizes the tactor, as depicted by Arrow 1 in panel B, the subjective direction of the target will be 1 o'clock, as depicted by Arrow 2 in panel C.

point bias, and must not be restricted by general limits on our capacity to process information (Miller, 1956). On the basis of these preconditions, we developed a method based on triangulation.

METHOD

Fifteen male observers participated in the experiment; 6 were recruited from the scientific staff of TNO Human Factors, and 9 were undergraduate students. All participated voluntarily; only the students received the equivalent of \$50 for their participation. Before the start of the experiment, all the individuals received written and verbal information on the experiment and read and signed an informed consent. None of the observers reported any conditions that might affect tactile perception of vibration on the torso or a distorted body schema.

Figure 2 depicts the experimental setup. The experiment took place in a completely darkened room. The observer was lying on a stretcher with his torso fixed but allowing head rotations. To facilitate viewing the frontal side of the torso, a cushion was placed under the observer's head. A board was placed over the observer, perpendicular to the body midaxis at a level just below the navel. Each trial consisted of the presentation of three stimuli: one on the torso, which could be either tactile (a burst of vibration) or visual (a light-emitting diode [LED]); a reference stimulus (which was an LED mounted in the board); and a visual cursor (which was projected on the board). The task of the observer was to position the cursor so that the three stimuli were on a straight line. The cursor was a round dot projected by a focused light attached to a servo-controlled platform mounted behind the observer. Cursor position resolution and readout accuracy was 0.01° . The observer steered the cursor along an imaginary circle on the board with a handheld rotary dial. When the cursor was subjectively positioned correctly, the observer pushed a button on the rotary dial and the next trial would start (for comparable equipment, see van Erp & Verschoor, 2004). The visual torso stimulus served as a control condition to investigate whether there was localization error or bias in the tactile judgments over and above those evident in the visual data.

All the stimuli were located in the same, flat plane. The radius of the circle of reference LEDs was 0.46 m; that of the cursor was 0.71 m. The exact location of the torso stimulus in the plane of the board was measured by three accurate thread potentiometers at known locations on the board. The torso stimulus and reference LED were activated in a *100-msec-on–200-msec-off* rhythm, which both is comfortable and prevents tactile adaptation. Each of the 15 torso stimuli was combined with each of the 10 reference stimuli, resulting in 150 pairs. Each pair was presented three times in one session. Each of the observers completed two sessions of 450 trials: one for the visual torso stimuli and one for the tactile torso stimuli. The 450 trials in each session were randomized, with the restriction that successive torso stimuli were at least two positions apart. Eight of the participants started with the tactile torso stimuli, and seven with the visual. The tactile stimulus was presented with a MiniVib 4 vibrator with a contact area of 22×16 mm (Special Instruments Development Corporation, Sweden) driven with a 250-Hz sine wave. The torso visual stimuli were LEDs.

After reading the instruction and signing the informed consent, the observer lay down on the stretcher. Fifteen pieces of ultra-thin double-sided sticky tape (Sellotape, Switzerland) were placed at equal distances at the frontal side of the torso and in such a way that the outer ones were located more or less at the left and right sides of the observer's torso. With a felt-tip pen, a mark was placed on each piece of sticky tape. At that time, the torso of the observer was fixated by cushions beside the legs and upper body, and the locations of the 15 felt pen marks were measured. After this measurement, the visual or tactile torso stimuli were attached at the marked locations, and the observer was given the handheld control box. After the room lights had been switched off, a total of 20 trials were presented in the

Figure 2. Layout of the experimental setup and the triangulation principle. The observer was lying on his back on a stretcher. A board was placed perpendicular to the body midaxis just below the observer's navel. Each trial consisted of three stimuli: a torso stimulus (a vibration or light-emitting diode [LED], indicated by the star), a reference LED mounted on the board, and a cursor. The observer's task was to position the cursor with a handheld dial such that the three stimuli were on a straight line. By using different reference LEDs, on different trials (e.g., A and B) for each torso stimulus, the subjective location of the torso stimulus could be calculated, using triangulation.

presence of the experimenter. When the experimenter was convinced that the instructions had clearly been followed and the observer had no more questions, he left the room, and the experiment could start. The experimenter was able to monitor the participant and setup by means of an infrared light source and a CCTV camera. The experiment was self-paced, but none of the sessions lasted longer than an hour (i.e., a mean response time below 8 sec). After the 450 trials in the first session had been completed, a short break was taken, and the torso stimuli were changed (tactile for visual or vice versa) without removing the sticky tape. The torso stimuli in the second session were placed at exactly the same locations by using the marked sites, which were checked with the thread potentiometers.

RESULTS

All the data were analyzed with a reference frame defined in the plane of the board. We defined the body midaxis as the origin, the left–right direction seen from the head of the observer as the *x*-axis, and the *y*-axis as perpendicular to the *x*-axis and the body midaxis. The subjective location of a torso stimulus was calculated as follows. For each of the 30 trials for a specific torso stimulus, a line was drawn through the reference LED and the cursor position. Next, for the set of 30 lines, the intersection of each of the possible line pairs was calculated (Figure 2 depicts one such pair). This resulted in 405 intersections per torso stimulus per observer. The intersections with an *x*- or *y*-coordinate smaller than -1 m or larger than $+1$ m were removed from further analyses. These intersections were the result of (nearly) parallel lines. The percentage of intersections removed for a torso stimulus never exceeded 10% and was 1.5% on average. The subjective location of the torso stimulus was calculated as the mean *x*- and mean *y*-coordinates of the intersections. We calculated the sub-

jective location and the uncertainty intervals around each subjective location, defined as the 95% confidence limits of the mean (separately for the x - and y -coordinates).

Uncertainty Intervals

We first analyzed the uncertainty intervals for the tactile and visual modalities separately. Subsequently, the tactile data were calibrated using the visual control data. We analyzed the uncertainty intervals with a modality (tactile or visual) $\times$ location (15) $\times$ axis (x -axis or y -axis) ANOVA. This analysis revealed main effects of all three independent variables. The effect of modality [$F(1,14) = 54.81, p < .01$] showed somewhat smaller intervals for the subjective *visual* locations (mean, 1.49 cm) than for the subjective *tactile* locations (1.66 cm). The effect of axis [$F(1,14) = 1,411.06, p < .01$] showed that the interval for the y -axis (0.79 cm) was smaller than that for the x -axis (2.36 cm). The main effect of location [$F(14,196) = 10.63, p < .01$] showed that the uncertainty intervals for the stimuli near the midline were smaller than those for the stimuli near 90° left or right. The range between the largest and smallest mean uncertainty intervals as a function of location was less than 0.5 cm. Post hoc tests on the two significant interactions with location [modality $\times$ location, $F(14,196) = 8.59, p < .01$; axis $\times$ location, $F(14,196) = 12.30, p < .01$] revealed no systematic effect other than the main effect of location. To investigate whether there was a localization error in the tactile judgments over and above that in the visual control data, we analyzed the difference (visual data minus tactile data) as a function of the 15 stimulus locations. The ANOVA showed a significant effect of location [$F(14,196) = 8.58, p < .01$], with an overall mean of -0.17 cm. As can be seen from Figure 3, the error in the tactile judgments over the visual judgments is larger near the midline but close to zero or even smaller than that in the visual judgments for the left and right locations.

Absolute Localization

The localization data for 4 typical observers are plotted in Figure 4. Each plot depicts the subjective visual loca-

tions (open squares), with arrows to the corresponding subjective tactile locations (filled circles). The uncertainty intervals are not plotted, because their size is in the same order as the size of the symbols in the plot. Observer 3 is typical for a group of 3 observers for whom the subjective tactile locations had a somewhat larger radius than did the subjective visual locations. Observer 7 is typical for a group of 3 observers for whom the subjective tactile locations had a radius smaller than that of the subjective visual locations. Three observers showed a pattern similar to that of Observer 11, in which the subjective tactile locations near the midline had a radius smaller than that of the subjective visual locations, whereas this shift was absent for locations further away from the midline. Finally, Observer 13 is typical for the remaining 6 observers, who showed no or only small differences between the subjective locations of the visual and tactile stimuli. Inspecting the data for all 15 observers, also taking into account the veridical location of the stimuli, resulted in the following observations. First, for all 15 observers, the sequence or angular order of the subjective locations corresponded to those of the veridical locations in both modalities. This indicates that the line-up task was doable and that the triangulation method resulted in meaningful data, as was already expected from the small uncertainty intervals. Second, the difference between a subjective tactile location and its corresponding visual location was best described by a shift along the radius; neither shifts purely along the x -axis nor shifts purely along the y -axis seemed to occur. This was also the case for the differences between the veridical stimulus location and the subjective tactile and subjective visual locations. Third, for most of the individual observers, the subjective tactile radii were either all smaller or all larger than the subjective visual radii. To quantify these observations, we calculated the radius and angle from the body midaxis of the veridical stimulus location, the subjective visual location, and the subjective tactile location. We analyzed the radius with a modality (tactile or visual) $\times$ location (15) ANOVA. This analysis resulted in a significant effect of stimulus location [$F(14,196) = 15.97, p < .01$], nicely following the

Figure 3. The uncertainty intervals of the subjective tactile locations calibrated with the visual control data. Negative values indicate that the error in the tactile judgment is larger than that in the visual judgment.

Figure 4. Results for 4 typical observers. The open squares represent the subjective locations of the visual torso stimuli; the filled circles those of the tactile stimuli. Corresponding stimuli are connected by arrows. The radius is in millimeters; the navel and nose are at 0°. The lines are the least squares fits. The dotted line is the fit through the veridical locations of the stimuli.

oval shape of the torso for both modalities (see Figure 5; the interaction was not significant).

Finally, Figure 6 depicts the subjective visual angle (upper left) and subjective tactile angle (upper right) as a function of the veridical angle and the subjective tactile angle as a function of the subjective visual angle (bottom). For both modalities, the subjective angle corresponded well to the veridical angle, an important observation in relation to the use in mobility systems. For the subjective

visual angles, there seemed to be an undershoot over the whole range. For 90° left and right, the undershoots were 15° and 8°, respectively. This left–right asymmetry might be related to eye and/or hand dominance, since the hardware setup is symmetrical. The subjective tactile angles equaled the veridical ones up to about 45° left and right and showed an undershoot for larger veridical angles. The undershoots for the left and right sides (i.e., at –90° and 90°) were 17° and 10°, respectively, showing the same left–

Figure 5. The radius of the subjective locations as a function of the location on the torso and the modality of the stimulus.

Figure 6. The subjective angle as a function of the veridical angle for the visual stimuli (upper left) and the tactile stimuli (upper right), and the subjective tactile angle as a function of the subjective visual angle (bottom). Each plot contains the combined data for the 15 observers and the 15 locations on the torso. The curved lines are the least squares fits to the data.

right asymmetry as the visual stimuli. These effects are also revealed when the subjective tactile angle is plotted as a function of the subjective visual angle. In the forward cone (between -60° and $+60^\circ$), the subjective tactile angles were larger than the subjective visual angles, whereas this pattern was reversed outside this forward cone.

DISCUSSION AND CONCLUSIONS

The triangulation method employed in this experiment resulted in accurate determination of the subjective location of visual and tactile stimuli on the torso. The uncertainty intervals were smaller than 2.5 cm for the x -axis and smaller than 1 cm for the y -axis. The fact that the uncertainty interval in the x -axis is about three times that of the y -axis may be due to the layout of the reference LEDs. The method employed is sensitive to near parallel lines, because the coordinates of their intersections approach $\pm\infty$. The present layout with reference LEDs near -90° and $+90^\circ$ enlarged the uncertainty in the x -axis, but not in the y -axis, for torso stimuli close to -90° and $+90^\circ$. The comparable situation for the reference LEDs near 0° that would have affected the uncertainty of the torso stimuli close to 0° did not occur, since there were no reference LEDs near 180° .

Calibrating the tactile data with the visual control data reveals that there was additional noise in the tactile judgments above that present in the visual judgments with a mean size of 0.17 cm. This noise was larger for veridical locations near the midline but was small or absent for stimulus locations left and right. The size of the uncertainty intervals, and the fact that the spatial ordering of the observed location corresponded to that of the physical locations, justifies the conclusion that the triangulation resulted in accurate and meaningful results.

The data for the subjective locations show that the differences in the subjective locations of the visual and tactile stimuli were along the radii originating from the body midaxis, and not along the x - or y -axis. The difference between the veridical stimulus direction from the midaxis and the direction of the subjective location was small, especially in the forward 90° cone. Outside this cone, the subjective angle was closer to the body midline. To compensate for the potential effect that such factors as eye or hand dominance might result in a larger angle undershoot for locations left of the body midline, we can calibrate the subjective tactile directions with the subjective visual directions. Doing so leaves a small tactile undershoot of 2° left and right.

Interestingly, although there are differences between the observers, they were all quite consistent in localizing either all tactile stimuli with a radius that was smaller or all tactile stimuli with a radius that was larger than that of the visual stimuli. Even when there were shifts between the veridical and the subjective locations, the shift was always along the radius both for visual and tactile stimuli. This may indicate that (stimuli on) the skin of the torso are coded in polar coordinates (i.e., an angle and distance). The present results indicate that angles are probably *perceptual invariant* for torso stimuli. Apparently, either

distance is less relevant in localizing torso stimuli, or the sensory system required to adjust the distance for posture, breathing, pregnancy, or a copious meal is not worth the trouble. As long as we move our hand along the radius, we will hit that stinging mosquito sooner or later.

All in all, the data show that observers are able to localize a vibratory stimulus close to its veridical location, a prerequisite for the successful development of tactile mobility displays on the torso. When the veridical and subjective locations do not coalesce, the shifts are mainly along the radius, which has no effect on the subjective direction of the stimulus.

AUTHOR NOTE

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(Manuscript received February 9, 2006;
revision accepted for publication March 4, 2008.)