Contact Geometry and Visual Factors for Vibrotactile-Grid Location Cues

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Abstract. Visual and haptic factors can affect a user's interpretation of vibrotactile cues communicating location of objects in a real or virtual environment. Identifying and understanding relevant factors will lead to better device and interface design, for example, through procedures that adjust for systematic error or per-user differences. We considered direct effects of hand-tactor contact geometry and a possible cross-modal effect of the visual interface. Our experiment examined contact geometry on a single row of tactors and presence of a visual border on a graphical region that mapped to the tactor array. We measured the relationship between vibrotactile array stimulus coordinates and user responses. Contact geometry that emphasized a certain tactor increased tendency for subjects to mark near it. Effects of visual borders were noticeable but subtle, acting more as a modulating factor.

1 Introduction

Multi-modal approaches for communicating position and direction can include the haptic sense as a supplementary or reinforcing data channel. Our work concerns a visual scene, rendered or real-life, containing an area that maps onto a haptic device (our work is not intended as an abstract perception study, but rather a human factors evaluation of the haptic device and visual interface design choices). Consider the conceptual diagram in Figure 1. In this example, an application renders a map for the purpose of navigation. The haptic device then renders a place of interest as a vibration pattern on the user's palm depending on point of view and a map-aligned region. Vibrotactile patterns may communicate additional information, for example, identity or status messages as intensity patterns. Based on this, the user navigates the environment in search of the intriguing location or feature. We are interested in errors due to discrepancies among haptic, visual, and multimodal stimuli.

We present an experiment regarding haptic device contact geometry, stimulus coordinate, and a visual interface property for users interpreting a vibrotactile location cue at the palm. Skin-tactor contact varies with body-site shape and

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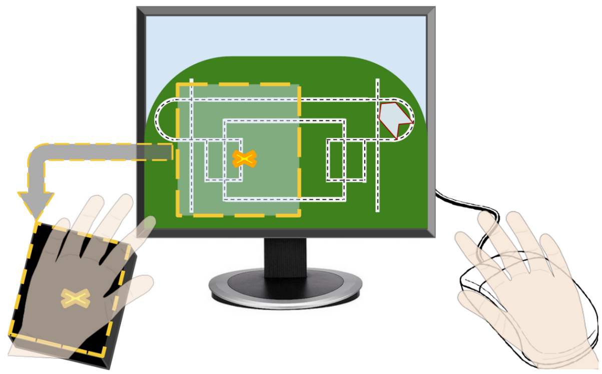

Fig. 1. Example of a location communicated haptically. The dashed border square is mapped to the tactile array and points of interest are relayed to the user as haptically rendered positions.

variations between users. When marking a haptic stimulus's location in a graphical desktop environment, subjects marked locations nearer areas of emphasized contact with the palm (where contact pressure was generally higher). In this situation, a mapping is induced between vision and taction and may be skewed by incorrect perception of tactile stimuli or variations in graphical interface parameters. We also investigated the parameter of borders in the visual scene. When borders of the response area were not present, the results suggested borders acted as a modulating factor. Such factors may influence the design of multimodal systems and calibration techniques that improve feedback by adapting to user trends.

2 Related Work

In a related experiment, Borst and Baiyya [1] investigated three parameters of a vibration pattern: position, direction, and profile. Each pattern had one of two possible shapes: point and line. The device, Figure 2 (left), activated adjacent tactors with varying intensities to provide the illusion of a point (or a point moving along a line) rendered somewhere on or between the tactors. After observing mean error approach zero at the center of the array, Borst and Baiyya postulated some systematic error could be present in the data.

We then conducted a preliminary experiment [2] to investigate systematic errors in position accuracy. The results demonstrated an effect of Visual Scale and Correct Answer Reinforcement on accuracy and suggested a metric to model systematic error. Radial error was intuitively defined as the distance between stimulus and response measured radially from the array's center. More analytically, this was the directed magnitude of the error vector projected onto the stimulus's normalized radial vector. Tendencies for positive radial error were called radial expansion and negative leanings were called contractions. We also

Fig. 2. The vibrotactile array used in previous experiments (left) and our current experiment (right). At left, six rows of five motors are mounted on a project box. Nylon washers and foam pads improve contact consistency across the palm. At right, one row of five pager motors mounted on a project box. Impostors take the place of the remaining five rows of motors. Shims are placed below foam pads to raise the height of individual motors, maintaining direct contact between tactors and skin.

proposed stimulus calibration based on this model. Assuming systematic error as radially symmetric, calibration adjusts the stimulus based on its radial distance. While the visual properties had a significant effect on radial error, we did not investigate how hand-tactor contact geometry contributed to radial error.

The current experiment investigated two possible causes of error suggested in [2]. We considered the simplified comparison between a flat row of tactors, Figure 2 (right), and a raised middle tactor. These extremes of contact geometry emphasized the array's center. To supplement this, and provide some insight where most radial error occurred, we divided stimulus points into center and edge (of the palm). The experiment also varied the visibility of the interface's border to investigate subjects' tendencies at the borders of the array.

Although not a psychophysics study, this work was informed by several studies in applied psychology, haptic interfaces, and non-visual interaction techniques. In [3], mislocalization illusions regarding tactile perception were given. In the funneling effect, a tendency exists for simultaneous, adjacent stimuli to be felt as one stimulus. This may contribute to several haptic applications, including [4], [5], [6], and the current experiment, where attempts are made to combine signals from two or more tactors into one haptic point. Ryu et al. [4] have also developed a device with similar tactors and contact site as ours, the T-hive. Consisting of thirteen tactors mounted around a spherical handle, the T-hive was designed to provide directional information using multiple simultaneous vibrations for a six degree of freedom hand controller. Oakley et al. [5] suggest that a "spatial summing" occurs for some stimuli meeting the spatial and temporal specifications of [3]. Borst and Asutay [6] also use the technique of multiple, closely spaced tactors, but with an unweighted area sampling taken from graphics concepts. It appears that such configurations satisfy the psychophysical requirements listed by Hayward [3] for the funneling illusion.

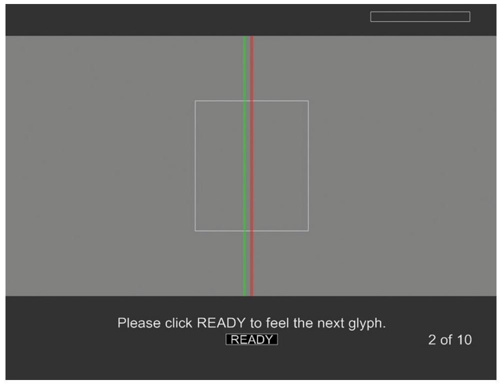

Fig. 3. A view of the data collection software for the current experiment with subject response (left) and reinforcement (right) vertical marker lines. A stimulus timer (top-right) and a session counter (bottom-right) indicated progress. Subjects were instructed to mark the horizontal position of the stimulus in the white rectangle (and in the same area for the Border Invisible case). After collecting the response, the experiment displayed the reinforcement marker.

In Lindeman et al. [7], eight tactors delivered directions at a subject's torso. Tasked with clearing a building, subjects located objects and avoided hazards in a virtual environment. Van Erp et al. demonstrated a similar apparatus in [8] for piloting a helicopter and boat. These and other similar works have contributed to research in vibrotactile feedback devices geared toward specific applications.

3 Methods

Our repeated-measures experiment presented vibrotactile stimuli via a single-row array of tactors (Figure 2, right) and an abstracted visual environment (Figure 3) to users. The experiment interface represented a virtual environment with haptic location cues. We investigated these multi-modal components by haptically rendering horizontal positions and having subjects indicate corresponding positions in a visual region matching array size.

Hand shape may cause contact to vary across the array. By presenting haptic stimuli with various contact geometries, we investigate how this influences localization. Also, visual edges of a rectangle, as in Figure 3, may mentally anchor subject responses. This is relevant when an application provides a device-oriented context for visual feedback. Users may be biased toward, or constrained by, graphical boundaries of datasets or virtual rooms, or visual subregions mapped to a haptic device. A case without visible borders could show further expansion near the edges, illuminating their influence on the mental mapping of a haptic stimulus.

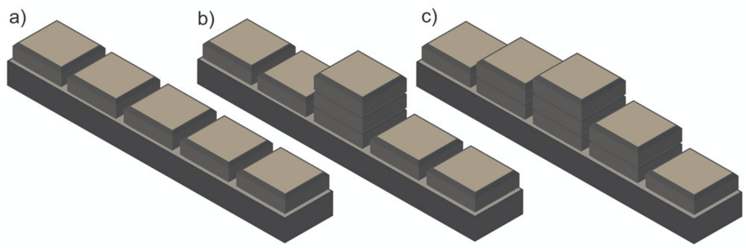

Fig. 4. Height Patterns used in the experiment and pilot study. a) Flat: all tactors have the same height. b) Exaggerated (Exag): The middle tactor is raised by two shims. c) Pilot Study: The middle tactor is raised by two shims and the adjacent tactors are raised by one. For the pilot study, (c) was also duplicated with washers above tactors.

3.1 Design

We considered three Within-Subjects variables Height Pattern, Point Location, and Border Visibility. The two Height Patterns of tactors were Flat, with no raised tactors as in Figure 4a, and Exaggerated (Exag), having a raised center tactor as in Figure 4b. Point Location partitioned the stimulus coordinate set into Center and Edge subsets (our stimulus coordinates varied horizontally). Based on which stimulus coordinates involved the center tactor under the area sampling kernel of [6], the Center subset consisted of 41 coordinates, and the Edge had 39 coordinates. Center coordinates were those (from a random set) closer to the middle of the palm, and Edge coordinates were further. For the Border Invisible condition, the rectangle in Figure 3 was absent, and for the Border Visible case it was present. The dependent variables error magnitude and radial error were computed for each condition combination. As stimuli and responses were limited to one dimension, computation of each dependent variable was simplified to sign changes and absolute values of signed 1D error.

3.2 Apparatus

We modeled our array and haptic rendering technique after [2] and [6], but with modifications supporting our experiment. Seen in Figure 2 (left), the array used by Borst and Asutay [6] consisted of six rows of five tactors (14mm DC motors). Each tactor was placed on an 18 mm grid. Thus, 18 mm was one array unit. Borst and Baiyya [1] affixed nylon washers and foam pads to tactors to isolate vibrations and facilitate more consistent contact geometry for the palm. A controller board varied tactor levels according to an unweighted area sampling technique from [6].

The device used here, Figure 2 (right), was a one dimensional version of the device in [2]. To vary tactor heights and examine the row of tactors with the most radial expansion from [2], we arranged one row of tactors in the same grid spacing with adjustable height. In other tactor locations, we placed impostors with nearly identical heights and diameters. A Measurement Computing USB-3114 controlled the five tactors with 16-bit precision analog voltage. The USB controller was commanded by the unweighted area sampling routine [6] and only minimal changes to driver and application code from [2] were required. To ensure consistent sensation between the experiments, we matched the controller output (voltage) from the USB device to those of [2].

While the device from [2] had nylon washers atop tactors to fit the palm, we selected Flat and Exaggerated patterns, shown in Figures 4a and 4b. Two implementation options were the placement of washers above the tactors or shims below. Since this could change vibration characteristics, a pilot study determined the best option with the geometry from Figure 4c. Four subjects completed eighty trials per day for two counterbalanced sessions. Regression smoothers for the device were similar to the response curves of [2]. Since the use of shims had a similar effect to washers and allowed direct tactor-skin contact, we chose shims for implementing the Height Patterns in this experiment.

3.3 Participants

Eight male subjects took part in this study. We considered them moderately experienced. Although levels of prior experience with the device varied, each subject had at least two hours of prior exposure to 2D vibrotactile palm arrays. Our experiment presented many trials, 160 per day, to the small number of subjects instead of fewer trials with many novice users, reducing the effects of learning and better representing a regular user. Two subjects were left-handed. The median age of subjects was 26 years, with a minimum age of 24 years and a maximum age of 37 years.

Table 1. Session Order Randomization. Rows correspond to sessions, with each subject exposed to two sessions (A and C or B and D) on separate days.

Label	Height	Border Sequence
A	Flat	BV BI BI BV
B	Exag	BV BI BI BV
C	Exag	BI BV BV BI
D	Flat	BI BV BV BI

3.4 Procedure

The experiment followed an open-response paradigm in which subjects received a vibrotactile stimulus on the left palm and indicated its horizontal position by moving a vertical line. Each session consisted of Demonstration, Training, and Testing stages. Starting in the Demonstration, subjects placed the left hand on the palm-array and felt a series of point vibrations (each lasting two seconds). We

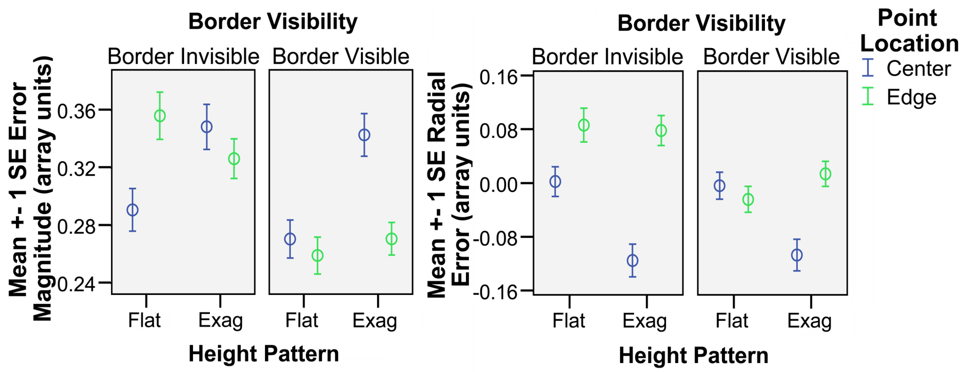

Fig. 5. Error magnitude and Radial Error against Height Pattern, Point Location, and Border Visibility.

allowed, but did not instruct, subjects to look at the hand receiving stimuli, as they would be able to during normal use. The array rendered five point vibrations and the screen displayed horizontal positions with vertical lines. Subjects did *not* indicate position. During Training, subjects felt ten haptically rendered points. After each, they adjusted the position of a vertical line to indicate the perceived horizontal position on the interface shown in Figure 3 with the current experimental condition. Correct position was shown after the response. The Testing Stage followed; subjects again marked the horizontal position of haptically rendered points. Each subject completed two sessions on two non-consecutive days. Sessions consisting of one Height Pattern and both levels of Border Visibility lasted 20-30 minutes.

The order of conditions was randomized according to the following stipulations. All sessions had both levels of Border Visibility counterbalanced in four sub-sessions with 40 trials each, as seen in Table 1. To avoid the jarring effect of the BI case on the first testing session, all subjects began with the order (BV, BI, BI, BV). Height Patterns varied similarly across different sessions. Half of the subjects completed the A and C orders, half the B and D orders. Each session presented 160 trials, with 80 distinct horizontally varying points in a random order per (BV, BV) or (BI, BI) pair. We generated points prior to data collection; the set was split randomly within each Border Visibility condition.

4 Results

Figure 5 summarizes resulting error magnitude. We applied a 3-Way Repeated Measures ANOVA over the Within-Subjects variables Height Pattern, Point Location, and Border Visibility with dependent variable error magnitude. Border Visibility ($F(7,1) = 8.203, p < 0.05$) and Point Location ($F(7,1) = 7.007, p < 0.05$) had an effect. Post-hoc tests indicated the Border Invisible and Edge cases contributed more to error magnitude than Border Visible and Center, respec-

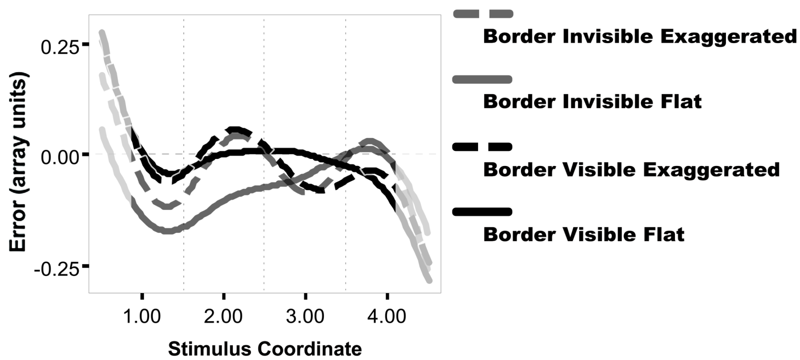

Fig. 6. Local Linear Regression Smoothers of Error (signed) over Border Visibility and Height Pattern. The horizontal axis is Stimulus Coordinate for a haptically rendered point varying horizontally. The horizontal dashed line is at zero radial error. The outer two vertical dashed lines are at the extents of the Center-Edge Point Locations. The middle vertical dashed line is the array's center tactor. Outer portions of the curves are faded to deemphasize points for which confidence diverges.

tively. Height Pattern showed a *near* significant ($F(7,1) = 4.155, p < 0.085$) effect for error magnitude (due to a small number of subjects, p-values between 0.05 and 0.10 are noted as interesting and referred to as "near significant").

We also analyzed radial error from the same data. Height Pattern ($F(7,1) = 10.446, p < 0.05$) and Point Location ($F(7,1) = 19.504, p < 0.05$) both had a significant effect on radial error. Post-hoc tests with Bonferonni corrections indicated the Flat and Center cases contributed more to radial error than Exaggerated and Edge, respectively. A *near* significant interaction existed between Border Visibility and Point Location ($F(7,1) = 5.223, p < 0.06$).

5 Discussion

The above results demonstrate an effect of each independent variable for at least one metric. Height Pattern's significance in radial error, and near significance in error magnitude, signified an effect more apparent when investigating signed error, Figure 6. In Exaggerated (dashed) plots, responses had more oscillations, shifting left and right (negative and positive) of left and right Edge points, respectively. Then, subjects marked closer to the Exaggerated tactor for Center stimuli. In both of these cases, and for Border Visible Flat, mean error tended toward zero at the array's center (middle vertical dashed line). The relation to radial error can be seen by considering error relative to array center.

In the smoothed error plots of Flat Height Patterns (solid), less dramatic oscillations appear. Additionally, with the Border Visible Flat case (solid back), subjects performed better than both Exaggerated Height cases, suggesting the emphasized contact geometry increased perceived loudness of the middle tactor. Similarly, the slight negative tendencies for Border Visible Flat, and more drastically for Border Invisible Flat, occurred near the fleshy portion of the left palm where contact pressure with flat surfaces was likely highest. Note an interplay between contact pressure and vibration frequency may impact perceived location for the eccentric-mass motors. As these motors have a low cost and are available in many sizes, they are easily applicable to many situations. However, motor behavior regarding contact pressure, frequency, and vibration amplitude make it unclear which of these contributes most to the preference for areas of overly-conformant contact geometry.

Border Invisibility likely made subjects less confident, but its effects also vary depending on stimulus location. This was suggested by the near significant interaction of Border Visibility and Point Location. Both Border Invisible (grey) cases, Flat and Exaggerated, show how border invisibility served to amplify the error relative to the Border Visible cases. In both pairs of Height cases similar curves appeared, but with marked shifts away from the Border Visible (black) cases (erring away from the center) at the respective outer inflection points. A possible cause lies in the thought process for mapping a body part to a visual area. Since error at array center was near zero in both Exaggerated cases, subjects may have used the interface's center or response button for a reference point. If the point locations away from the center were judged relative to the center and nearest border, then the Border Invisible cases may have caused an over-estimated distance from the center reference point.

Considering contact geometry a factor in radial expansion, future devices should account for hand (or another stimulus site's) shape. This experiment indicated expected errors with inconsistent contact geometry. While our model of radial expansion provided insight into user performance, this effect was partly based on the structure of the hand, the composition of which varies from a fleshy perimeter to a denser, bony interior. This structure may contribute to the longitudinal asymmetry of the response curves, since a solid contact site in the center would make vibrations here more pronounced.

6 Conclusion

Contact geometry and visual references influence the mapping of haptic cues in a virtual environment. Results exhibited the least error near the array's center tactor. Error rose near the Center-Edge boundaries, at nearly identical coordinates in all cases. We have previously demonstrated [2] stimulus calibration using radial error. The highest points in radial error smoothers from [2] occurred at equivalent radial measures to here (1.2-1.25 array units from center). The peaks in [2] also occurred across three levels of Visual Scale, suggesting both effects originated with the devices but was modulated by visual stimuli. Involvement and understanding of haptic and visual conditions increases the power of stimulus calibration by allowing for their inclusion in calibration models.

Visual Borders also contribute to error as modulating factors, and the effects are relevant as design considerations for visualization applications. In our experiment, the background items were constant, yet the lack of Visual Borders increased subjects' error. In the case of a visualization system with an active scene and user interaction, the missing reference may also be detrimental.

A different body location could improve the contact between skin and tactors. With a more planar body-site, better conformance to a grid of tactors would be possible without height adjustments. While few applicable sites are as non-intrusive as the palm, the forearm and wrist do offer promising alternatives. These, however, have less area of glabrous (hairless) skin and lower tactile sensitivity than the palm, a change that would need to be investigated. Also, tactor response was dependent on contact pressure. Nonetheless, the questions raised remain relevant for any tactor type since variations in perceived loudness may cause irregular response shapes, as suggested here. A more definitive understanding of radial error gives insight into device design and modeling for stimulus calibration. Given the current trend of consumer grade virtual reality devices, haptic-enabled touch screens, and vibrational game controllers, we may see devices similar to ours in navigation, communication, or entertainment applications.

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