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Centralizing bias and the vibrotactile funneling illusion on the forehead

Hamideh Kerdegari, Yeongmi Kim, Tom Stafford and Tony J. Prescott

Sheffield Center for Robotics (ScentRo), University of Sheffield, UK
{h.kerdegari, yeongmi.kim, t.stafford, t.j.prescott}@sheffield.ac.uk

Abstract. This paper provides a novel psychophysical investigation of head-mounted vibrotactile interfaces for sensory augmentation. A 1-by-7 headband vibrotactile display was used to provide stimuli on each participant's forehead. Experiment I investigated the ability to identify the location of a vibrotactile stimulus presented to a single tactor in the display; results indicated that localization error is uniform but biased towards the forehead midline. In Experiment II, two tactors were activated simultaneously, and participants were asked to indicate whether they experienced one or two stimulus locations. Participants reported the funneling illusion—experiencing one stimulus when two tactors were activated—mainly for the shortest inter-tactor difference. We discuss the significance of these results for the design of head-mounted vibrotactile displays and in relation to research on localization and funneling on different body surfaces.

Keywords: Head-mounted vibrotactile display, localization, funneling illusion

1 Introduction

Tactile displays provide an alternative way of communicating various kind of information and may be particularly useful when other communication channels, such as vision and hearing, are overloaded or compromised [1]. Consequently, tactile displays have been utilized to support a variety of applications including sensory substitution [2], sensory augmentation [3, 4], spatial orientation and navigation [5, 6] and exploration of virtual environments [7].

In several of these applications [3, 4], activation of vibrotactile stimulators at specific locations on the body provides a spatial cue to the location of an object or event in the environment or to show the navigation direction [5]. The number and configuration of the vibrotactile stimulators in the tactile display is known to play an important role in vibrotactile localization ability [8] although increasing array granularity does not necessarily improve localization ability [9, 10].

An important factor to consider in the design of tactile displays is the phenomenon known as the "funneling" illusion [11]. Funneling describes the experience of a single phantom sensation when multiple stimuli are presented simultaneously at nearby locations on the skin. If two nearby stimuli have the same intensity the phantom sensation is created in the middle of them, however, if they have different intensities, the

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sensation is “funneled” towards the actuator with higher intensity [12]. The separation distance between the tactors, their relative amplitudes, their temporal order, and their location on the body surface, have all been shown to effect the funneling illusion [11, 12, 13], moreover varying stimulation parameters at the two nearby sites can induce an experience of continuous apparent motion of the phantom stimulus [12, 14]. Hence when multiple vibrotactile actuators are activated in a tactile display the funneling effect influences the perceived pattern of stimulus in a complex manner, allowing various ways of communication direction or navigation information, whose control is still to be adequately understood.

The current paper arose from research aimed at the development of a vibrotactile headband display for fire fighter navigation. In an initial prototype ([4] and Figure 1) we connected a 1-by-4 tactor display to an external array of ultrasound sensors, converting ultrasound distance signals to nearby surfaces, such as walls, into a vibrotactile display pattern on the area of the head closest to the nearest surface. We selected a head-based display as this allows rapid reactions to unexpected obstacles (tactile response latencies are linear in distance from the brain [15]), is intuitive for navigation, protects a critical part of the body, and leaves the fire fighter’s hands free for tool use or for tactile exploration of objects and surfaces (see also [3]). In order to further optimize this design, and improve the usefulness of the low resolution tactile display, we need to better understand how simultaneous stimulation of multiple sites on the forehead is experienced and how best to configure our tactile display in order to relay effective information about object location. To this end, the current paper investigated vibrotactile localization accuracy on the forehead and the dependency of the forehead funneling illusion on inter-tactor spacing. The results of this study should help formulate guidelines for head-mounted vibrotactile displays and will also inform the wider understanding of the tactile funneling illusion.

Fig. 1. The tactile helmet: a prototype sensory augmentation device developed to assist fire-fighters navigating in smoke-filled buildings [4].

2 Experimental overview

The experimental was in accordance with University of Sheffield Ethical guidelines and conducted with approval of the local Ethics committee.

2.1 Participants

Ten participants—7 women and 3 men, average age 24—participated in each experiment; none of the participants reported any known abnormalities with haptic perception.

2.2 Apparatus

An easy-to-wear, lightweight tactile headband display was designed to provide stimuli on the user's forehead. The tactile headband consists of seven vibrating motors with 2.5 cm inter-tactor spacing that are attached to a Velcro strip that can easily be worn as a headband and that can be adjusted according to head size. The tactors used in the experiments were pancake-type vibration motors (Figure 2 left) model 310-113 by Precision Microdrives with 10mm diameter, 3.4mm thickness, 3V operating voltage and 220Hz operating frequency at 3V.

A paper ruler was attached on the outer side of the headband to aid accurate measurement of the stimulus position. The seven tactors were attached at positions 0, 2.5, 5, 7.5, 10, 12.5 and 15 cm relative to the ruler and are referred as tactors 1 (0 cm) to 7 (15 cm). Figure 2 (center) shows the headband, and (right) a participant wearing the array such that tactor 1 is on the far left of the forehead and tactor 4 is aligned with the forehead midline. In order to control the intensity of the vibrotactile actuators, a microcontroller, ATmega32u4 was used to generate pulse width modulation (PWM) signals. The microcontroller was connected to a PC through a RS232 serial port to transfer the command data to the vibration motors. A mirror was positioned so that participants were able to see the headband, and a mouse button and foot-switch were provided for participants to initiate each trial and trigger data capture, by interacting with a graphical user interface (GUI) displayed on the computer monitor.

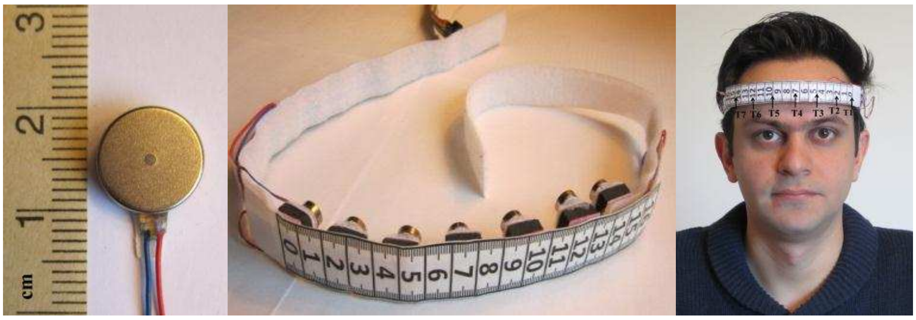

Fig. 2. Left: Pancake type vibration motor, Center: Tactile headband interface, Right: A participant wearing the tactile headband interface.

2.3 Procedure

Participants were seated comfortably in front of the computer screen, camera, mirror, mouse and foot switch while the tactile display was worn on the forehead. A short practice session was provided to allow some familiarity with the experimental set-up. Once the participant felt comfortable, the trial phase was started. During the experiment, participants wore headphone playing white noise to mask any sounds from the vibrating motors.

Each trial consists of the participant clicking the GUI start button. After experiencing a vibration stimulus (experiment I), or two simultaneous stimuli (experiment II), the participant was asked to respond by pointing to the perceived location(s) of stimulation on their forehead using one or two thin pointers and while looking into the mirror as illustrated in Figure 3. By clicking again in the GUI a snapshot was captured with the digital camera recording the indicated position. A shutter sound played after image capture to indicate to that the trial was complete, and that the next trial was ready to commence. Participants interacted with the GUI using a mouse, in experiment I, and with a foot-switch in Experiment II (since both hands were needed for pointing).

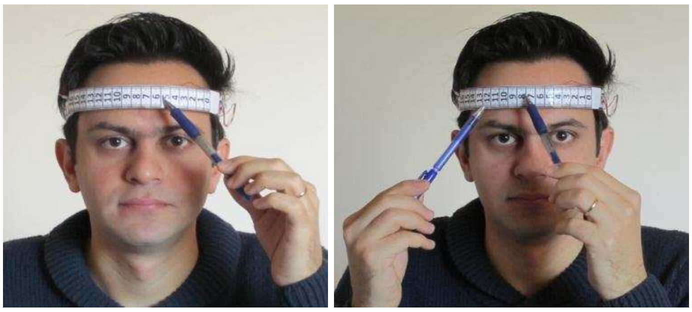

Fig. 3. Left: pointing on one location, Right: pointing on two locations

3 Experiment I: Vibrotactile localization

The objective of Experiment I was to determine localization mean error for vibrotactile stimuli on the forehead. Each trial consisted of a vibration being displayed in a pseudo-random order to each tactor for 1000ms. During the experimental session, a total of 105 trials were presented in a random order to each subject, 15 for each tactor. A practice session consisting of 5 randomly trials per tactor were provided before starting the experimental phase.

Localization mean error with standard deviation for each of the seven tactor positions is shown in Figure 4 (left). As can be seen, this varies from 0.51 cm for tactor 4 to 0.76 cm for tactor 3. ANOVA showed no significant difference in localization mean error across the seven positions ($F(6, 63) = 0.882$, $p = 0.513$), although the data indicate that the lowest error occurs above midline. Figure 4 (right) shows the mean error for left and right side pointing for each tactor. Moving from position 1 to 7 (from left to right), the error shifts from being strongly biased to the right to being strongly biased to the left. In other words, the perceived location of stimulation is biased towards the forehead midline for the outermost tactor locations.

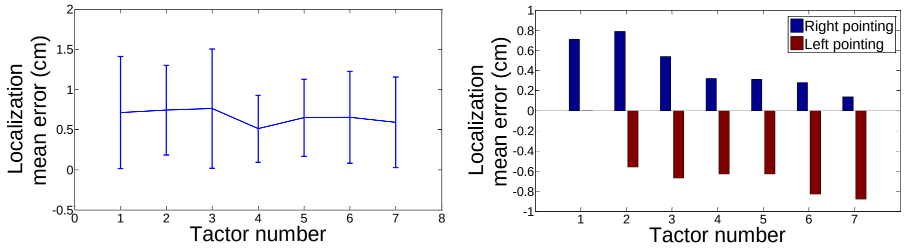

Fig. 4. Left: Localization mean error, Right: Localization mean error for left and right sides.

4 Experiment II: Dependency of funneling illusion on the distance

Experiment II was designed to evaluate the dependency of the funneling illusion on the distance between tactor. Each trial consisted of vibration stimuli being displayed at one of the following tactor combination {(1 , 4),(2 , 3),(4 , 7),(5 , 6),(2 , 6),(3 , 5)} with both tactors activated simultaneously at 3 V intensity for 1000 ms. After displaying the vibration, subjects indicated whether they perceived one or two vibration stimulation on the forehead. During the experimental session, a total of 90 trials were presented in a pseudo-random order, 15 for each tactor combination. Before the experimental session there was a practice session consisting of 5 trials per tactor combination in random order.

Figure 5 (left) shows that by increasing the distance between tactors the percentage of pointing to one location decreases while the percentage of pointing to two locations increases. Tactor combinations with inter-tactor spacing of 2.5 cm showed highest rate of pointing to one location while tactor combination with inter-tactor spacing of 10 cm revealed highest rate of pointing to two locations. Figure 5 (right) shows that subjects consistently indicated two stimuli as being closer together than their actual distance, even when not experiencing the funneling illusion.

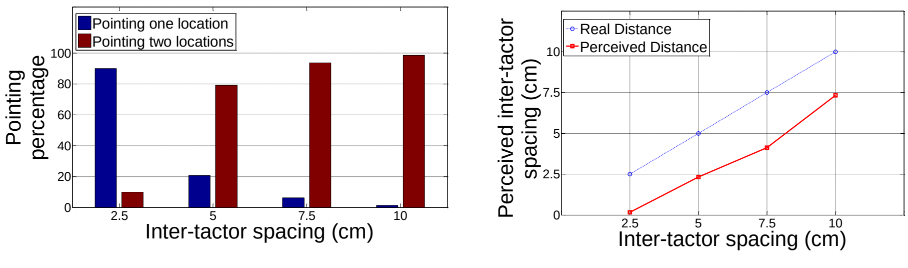

Fig. 5. Left: Percentage of correctly pointing to one and two locations for different inter-tactor spacing, Right: Perceived and actual inter-tactor spacing

5 Conclusion and Future Work

The forehead is a promising location for vibrotactile displays for navigation since a display can easily fit inside the headband of a hat or helmet, signals reach the brain quickly allowing quick responses, and an intuitive mapping can be created between sensed objects (such as obstacles) and stimulation of the head in the direction of the object. One of the first devices to explore the use of a head-mounted interface was the "haptic radar" [3]. In this device, a one-to-one mapping was created between an infrared distance sensor and a tactor mounted directly beneath it. Users intuitively responded to objects moving close to the sensor by tilting or ducting away from the direction of the stimulus—indicating that the device could be useful for avoiding collisions. In the design for the "tactile helmet" ([4] and Figure 1), a prototype sensory augmentation device for fire-fighters, we decoupled the configuration of an array of ultrasonic distance detectors from the arrangement of the tactors—in that case having eight detectors on the outside of a safety helmet and four tactors inside a headband. However, in principle, the sensor array can have many more elements, and so be capable of building up a rich representation of the local scene. For this situation the optimal mapping of this representation onto patterns of vibrotactile stimulation has yet to be determined; signals should be intuitive and the tactile sensory channels not overloaded. Key constraints for display design will be the number and location of the tactors and appropriate use of tactile perceptual phenomena such as the funneling illusion and apparent motion.

To aid the design of head-mounted displays, such as that used in the tactile helmet, experiment I of the current study set out to explore localization accuracy on the forehead. Whereas mean error seems uniform across the forehead, somewhat to our surprise we found a strong bias towards the midline in localizing actuators that were away from the center of the forehead. Further testing is required to establish if this tactile saltation on the forehead is a robust effect, but if confirmed this would appear to be an important design constraint for head-mounted displays. For instance, if an object is displayed as being to the side of the head by stimulation in that direction, a user of the device could experience the object as being more frontally-aligned that its true location.

Our second experiment looked at the funneling illusion. Funneling can be used to increase localization accuracy [16] for a sparse array of actuators, or to communicate change of position [13] or movement [12, 14]. On the other hand, if used in an uncontrolled way, it could reduce localization accuracy or produce illusory signals that are misleading. The extent to which signals are "funneled" varies with many stimulus properties including amplitude, frequency, and onset/offset asynchrony [11, 12, 13]. The local mechanical properties of the skin, and underlying skeletal tissues are also important [17]. From the current study it would appear that funneling effects may occur primarily over fairly short distances on the forehead—we found only a small number of reports of funneling for inter-tactor distances of 5 cm or greater, whereas funneling was consistently reported (~90%) for the smallest distance of 2.5cm. In contrast, on the surface of the arm a strong experience of funneling has been reported as occurring in the range 4-8cm [16]. Further research is needed to explore the extent to which funneling on the forehead varies with stimulus parameters. For instance, an important avenue for future work is stimulus synchrony; systematic tests of asynchronous but overlapping stimuli should show to what extent timing is critical. Nevertheless our initial results do suggest that funneling could be a more localized effect on the forehead than elsewhere on the body. One possible explanation is that, compared to the arm, the skin of the forehead is stretched relatively tightly across the smooth surface of the skull with relatively little intervening fat/muscle.

In experiment II, participants reported experiencing simultaneous stimuli at two locations as consistently closer to each other than their actual distance. In experiment I we found a saltation effect whereby single stimuli are experienced as closer to the midline which could partly explain the consistent under-estimating of inter-tactor distance in the second study, however, further experimentation will be required to dissect the contribution of a centralizing bias to this result.

A critical characteristic of devices such the haptic radar and the tactile helmet is that they are under user control, allowing the wearer to use them as active sensing devices [18]. Indeed, movement of the head is one of the most natural means through which to explore the local scene. Our future experiments will compare how a given pattern of stimulation on the skin is experienced when passively presented (as in the current study) and when induced by self-movement while wearing a sensory augmentation device. It seems plausible that the user experience in the latter case will be very different due to the ‘sensorimotor contingencies’ [19] created by the interaction between self-movement, environment structure and the vibrotactile signals delivered by the device.

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