Spatial Resolution of Vibrotactile Perception on the Human Forearm when exploiting Funneling Illusion

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Abstract—

Recent advances in man-machine interaction, telerobotics, telepresence and teleaction have shown that introducing the haptic modality to multimedia applications has the power to significantly widen their application range and to dramatically improve the user experience. Especially, the human body surface has been considered as an additional means of presenting information using vibrotactile display devices. In this context, spatial displacement of a vibrotactile stimulus can be deployed for information display. By exploiting a psychophysical illusion called "funneling illusion", we are able to increase the spatial resolution of vibrotactile displays. In this paper, we aim at investigating the spatial resolution of vibrotactile perception on the human forearm when applying multiple "funneling" stimuli. In our psychophysical experiments, we revealed the human spatial perception ability on the human forearm for stationary and moving vibrotactile stimuli.

haptics; vibrotactile display; perceptual spatial resolution; psychophysics; teleoperation; funneling illusion

I. INTRODUCTION

We, humans, rely heavily on the haptic modality to interact with our environment. However, the haptic modality is rarely used in modern multimedia systems. Novel multimodal human-computer interfaces exploit the human body surface as an additional means of presenting information using vibrotactile devices [1]. This allows for presenting extra information such as a directional cue in a car [2], interaction for touch screen mobile devices [3], tactile music [4], a grabbing force in teleoperation [5], touch sensation in a remote interpersonal communication [6], etc. A variety of tactile and other haptic interfaces and applications are also introduced in [21, 22].

Additional interest can be found in telepresence and teleaction systems, which allow a human user to immerse into a remote or inaccessible environment. To enable a realistic immersion into the distant environment, a multimodal interface device displays visual, auditory and haptic information to the human operator which is sensed within and received from the remote environment. To avoid overloading the visual modality, the vibrotactile modality can be used for displaying critical information, such as remotely measured distance-to-object information. By controlling the displacement of vibrotactile stimulus on the skin of the human operator, additional information can be displayed to the human. In that context, the human localization ability of vibrotactile feedback is fundamental. In our previous work [7], we demonstrated the use of a psychophysical phenomenon, called the funneling illusion, for overcoming limitations in spatial resolution of vibrotactile arrays. In this paper, we conduct psychophysical experiments to investigate the performance of localizing "funneled" vibrotactile stimuli.

The remainder of this paper is structured as follows. In Section 2, we present our proposed methods for creating the stationary and moving stimuli on the forearm. In addition, we present the deployed vibrotactile actuators. Section 3 discusses the experimental apparatus, design and procedure of our psychophysical experiments as well as results. Section 4 concludes the paper.

II. DISPLAYING VIBROTACTILE STIMULI

A. Funneling Illusion

The funneling illusion describes a phantom sensation midway between multiple stimuli when they are presented simultaneously at adjacent locations on the human skin [8, 9]. To create a stimulus between two vibrotactile actuators, they are activated simultaneously. If the two actuators have the same intensity, the illusionary sensation is created in the middle between them. However, if they have different intensities, the sensation is "funneled" and shifted towards the actuator with higher intensity. This illusion allows us to create an apparently continuously moving vibrotactile stimulus [7, 10]. An illustration of this approach is shown in Figure 1. By varying the intensities of two adjacent actuators, we can smoothly shift the in-between sensation from one actuator location to the other.

In [7] it has been shown that a good distance between two actuators for displaying the apparent movement sensation on the human forearm is around 40-80mm. As the average adult's forearm length is 252mm [11], four vibration motors spaced at intervals of 80mm are enough for utilizing most of the skin of the forearm.

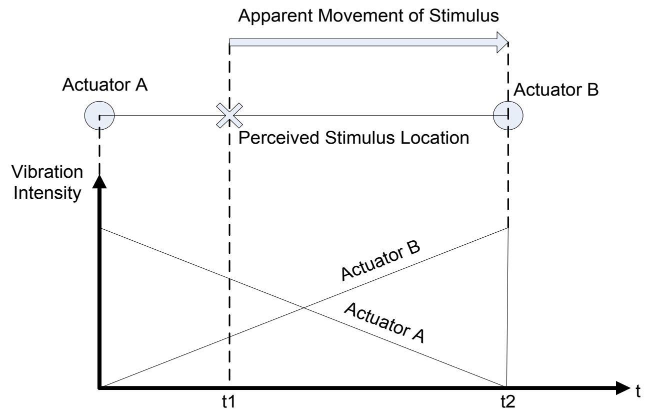

Figure 1: Illustration of exploiting the funneling illusion to create a continuously moving vibrotactile stimulus.

B. *Tactile Device*

An easy-to-wear tactile device is designed to provide the stimuli on the forearm which provides a continuous, relatively flat surface to study, permitting the required separation of the vibrators [12]. Our tactile feedback device consists of four pancake-type vibrating DC motors that are usually used in cell phones. These motors vibrate tangentially to the skin following the recommendation of [9], which says the vertical vibration can propagate on the skin and give deteriorated sensation. They are lightweight, inexpensive and easy to deploy and consume little power. Their operating voltage is 3.6 volt and their operating frequency range is up to 220Hz. They can be attached to and detached from the arm band using Velcro. To fix the vibrators, an arm band is wrapped around the forearm so that it softly presses the actuators to the skin. Figure 2 shows the placement of four actuators on the forearm.

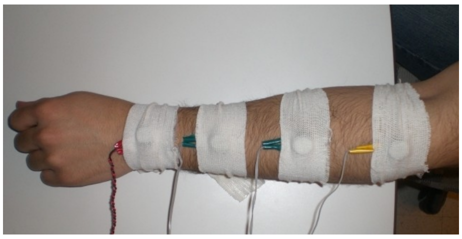

Figure 2: Vibrotactile Device

In order to control the intensity of the actuators, a microcontroller, ATMega 128 is used to generate a pulse-width modulation (PWM) signal which provides 16 levels of applied intensity. According to previous studies [7] of our actuators, we limit the range of control levels from zero to 12 to assure a linear tactile perception when driving the actuators.

III. EXPERIMENTAL EVALUATION

Psychophysical experiments are conducted to evaluate the performance of spatial vibrotactile perception when exploiting the funneling illusion. Additionally, to investigate temporal dependencies when displaying a vibrotactile stimulus, we evaluate the localization ability for stationary and for moving stimuli separately.

A. *Participants*

Twelve participants (average age of 26.5, age range from 23 to 35 years; 11 males and 1 female), who are all students at University of Ottawa, took part in this experiment. All of the participants self-reported a normal sense of touch. Eleven of the participants were right-handed, one was left-handed. The experiment took approximately 45 minutes on average.

B. *Apparatus and Experimental Design*

An overview of the experimental setup is shown in Figure 3. The experimental apparatus incorporated a PC to provide the subjects with a Graphical User Interface (GUI), a vibrotactile display array equipped with 4 actuators located at the forearm and a ruler (made of paper) placed on the arm for aiding the subject to locate the stimulus.

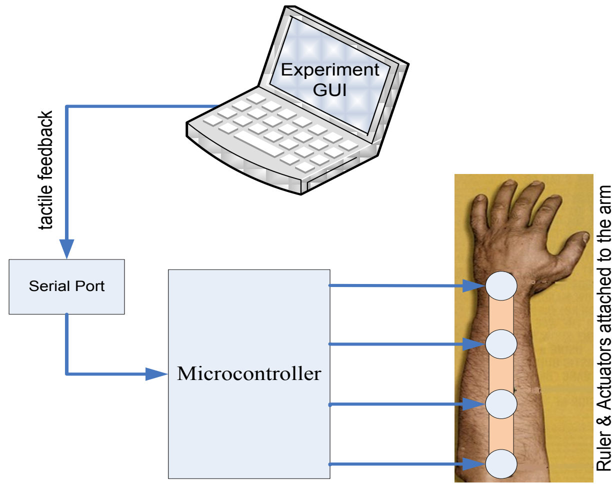

Figure 3: Overview of the experimental setup

A screenshot of the GUI is shown in Figure 4. It allows for selecting the vibrotactile display mode (stationary or moving stimulus), a start button for starting the experiment and a group of radio buttons for entering the perceived sensation position.

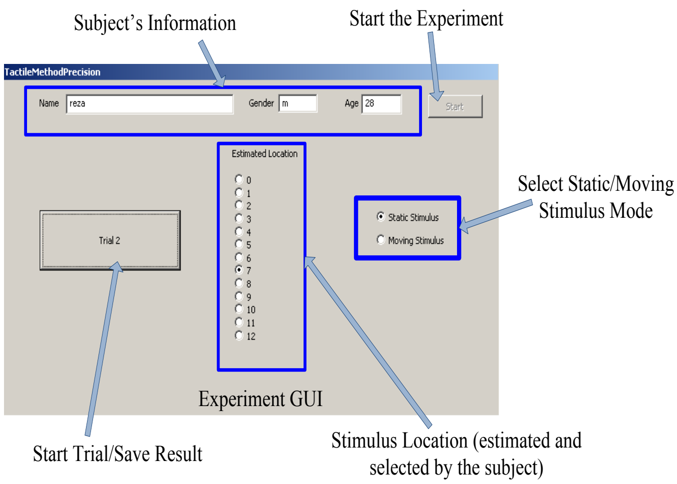

Figure 4: Screen shot of the GUI of the experiment

The four actuators of the vibrotactile display array are separated with a distance of 80mm. Hence, the actuator array covers a total distance of 240mm from the wrist towards the elbow. Along the actuator array, we define a set of 13 locations to be discriminated by the subjects. The four actuators are attached at positions 0, 4, 8 and 12 as shown in Figure 5. The attached ruler is used by the subject for pointing at the perceived stimulus location.

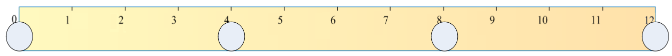

Figure 5: Ruler used to aid the subjects in identifying the stimulus location. Locations range from 0 at the elbow to 12 at the wrist.

In order to control the location of the "funneled" midway sensation between the actuators, they have to be driven with different intensities. As our actuators are limited to 12 discrete intensities [7], theoretically a maximum of 13 individual intensity combinations between two adjacent actuators are possible, {(12,0), (11,1), (10,2), (9,3), (8,4), (7,5), (6,6), (5,7), (4,8), (3,9), (2,10), (1,11), (12,0)}, where the two numbers of a couple represent intensities for each actuator. However, in our psychophysical experiments, we preselected a reduced test set of 13 equidistantly arranged funneled stimulus locations along the vibrotactile actuator array by using {(12,0,0,0), (9,3,0,0), (6,6,0,0), (3,9,0,0), (0,12,0,0), (0,9,3,0), (0,6,6,0), (0,3,9,0), (0,0,12,0), (0,0,9,3), (0,0,6,6), (0,0,3,9), (0,0,0,12)} for actuator A, actuator B, actuator C and actuator D, respectively.

Our psychophysical evaluation consists of two runs: one for evaluating the spatial location perception of a stationary stimulus and one for a moving stimulus. During each run, each of the predefined 13 test locations is evaluated 7 times. Thus, each run contains 91 trials per subject. In order to eliminate trends of task learning, the order of the two runs was counterbalanced and the investigated locations are randomized for each subject. The whole experiment took on average 35 minutes with a 10 minutes break between the two display modes.

Stationary stimuli were presented for a period of 1 second (well above the 0.25 s threshold set in [9]). When displaying a moving vibrotactile stimulus, we have to define a spatial range within which the temporal displacement can take place. Along the way of moving stimuli, stimulation at each location persisted for 200ms. Hence, to travel over the whole arm (240mm), it takes 2.6 seconds. To assure the user is not able to perceive the location of the stimulus from its traveling time, the moving stimulus was set to take the same time for each location by following the trajectory shown in Figure 6, starting and ending at the same location. Subjects were asked to identify the ending point that the moving stimulus reaches.

C. Procedure

The subjects are comfortably seated at a desk facing a visual display for instructions. During the experiment, the vibrotactile stimuli are displayed on the subject's left forearm. Initially, all participants are trained to be familiar with the experimental apparatus. Once they felt comfortable, the experiment is started.

After entering the subject's personal information and selecting the stimulus mode by the experimenter by counterbalanced order, the subject is instructed to press the "Start" button by using a mouse with his/her right hand and the experiment begins.

After each trial, the "Estimated Location" radio button group is enabled to allow the subject to select the location at which he/she perceived the stimulus by referring to the ruler attached to the forearm.

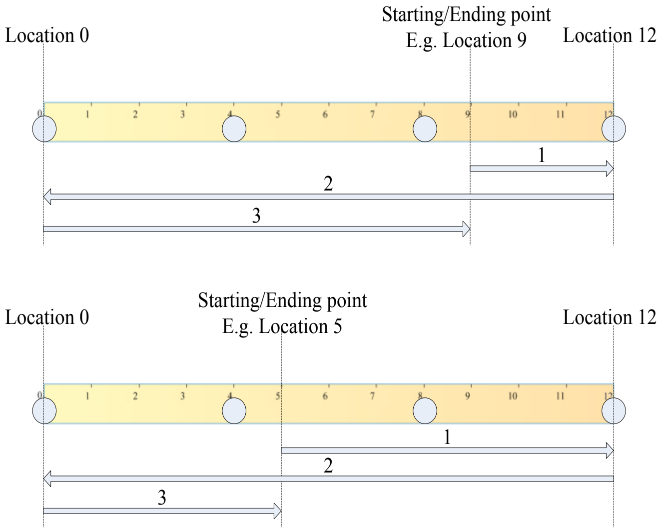

Figure 6: Two examples of the path followed by the moving stimulus for a certain location (9 and 5 in this example).

D. Results and Discussion

In Figure 7 and Figure 8, the averaged perceived stimulus locations with standard deviations are shown for the stationary and the moving vibrotactile stimuli. Our results show good localization performance for both display modes.

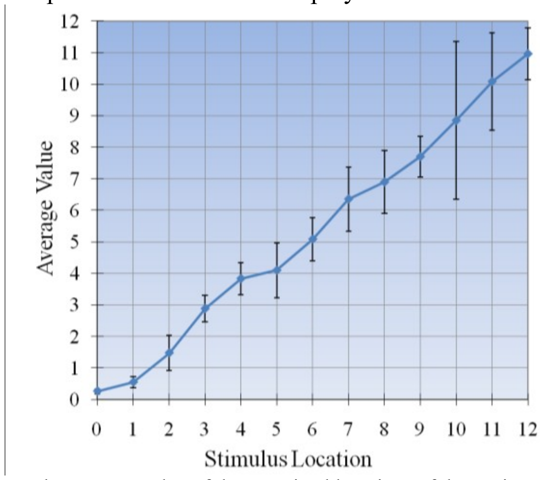

Figure 7: The average value of the perceived locations of the stationary stimulus for each location.

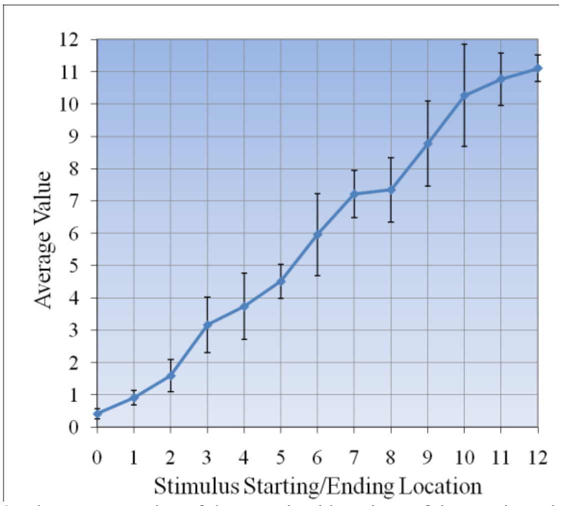

Figure 8: The average value of the perceived locations of the moving stimulus for each location.

Figure 9 and Figure 10 illustrate the percentage of correctly identified test items. Surprisingly, the perceived location for the stationary display mode seems to be shifted towards the elbow. Independently from the display mode, the results show best performance at the beginning and the end of the actuator array (closest to the elbow and wrist). Here, the localization of the stationary stimulus at location 0 (elbow) reached an accuracy of 75% whereas at location 12 (wrist) it reached 60%. For the moving stimulus, we obtained 65% and 55%, respectively. However, this observation does not necessarily show improved performance. As towards the ends of the vibrotactile actuator array the number of possible candidates decreases, we obtain a reduced set of alternatives, which facilitates the trial.

Nevertheless, a careful look at the literature [12] shows that this result at the array limits is not related to the number of alternatives as explained above. A similar result was obtained with a 7-tactors array that showed better performance at the human joints. When the authors in [12] moved the array of tactors to have the middle tactor (number 4) at the elbow (having the array to start from the upper arm), they still got the best localization results at the elbow. Figure 11 illustrates their results. The solid line shows localization results when the 7 tactors are at the forearm and the 7th tactor is at the elbow. The dashed line shows localization results when the 7-tactors array is shifted upwards so that tactor 4 is at the elbow. Comparing the two lines emphasizes the higher localization ability at the elbow. On an anatomical and physiological level, this foundation is supported by many resources. Acuity, as defined in [16], "refers to the ability to locate the site of the initiation of a stimulus. High acuity allows for fine distinction and requires a greater density of neurons". In addition, receptors in muscles and joints may contribute to the tactile sensations besides the receptors in the skin [17]. Although different receptors seem to respond best to particular types of stimuli, they also respond to some degree to all types of tactual stimuli [18]. This is the case here as the body joints, tendons, and muscles hold a large amount of tactile receptors [18, 19]. More specifically, Pacinian corpuscles, tactile receptors mostly sensitive to vibrations [16, 20], normally found under the skin, are scattered within the body, particularly around muscles and joints [20]. This physiological distribution of tactile receptors is behind the superior localization performance at the edges of the actuators array.

When analyzing the performance in localization of midway sensations, our results show a significant difference between the stationary and moving stimuli. Here, the performance of correctly identified test items ranges from 11-48% for the stationary stimulus mode and 18-42% for the moving stimulus mode. Please note, that the results for all test items are clearly above the 100/13 = 7.7% chance performance level for 13 test items.

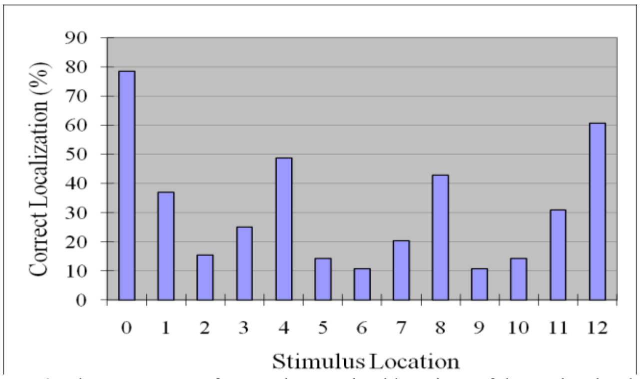

Figure 9: The percentage of correctly perceived locations of the static stimulus for each location.

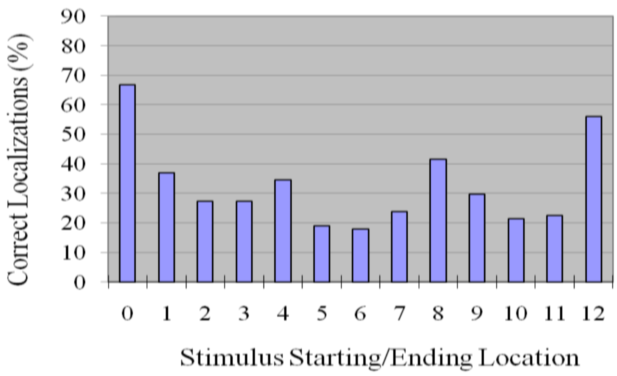

Figure 10: The percentage of correctly perceived locations of the moving stimulus for each starting/ending location.

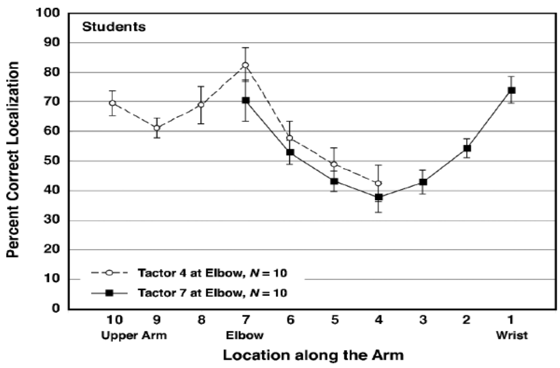

Figure 11: The percentage of correctly perceived locations of the static stimulus for each location in Cholewiak's work [7].

Furthermore, our results reveal that the performance is better in the vicinity of the actuators than in-between them where the virtual locations are generated. By looking at Figure 9 and Figure 10, we can see that the minimum accuracy is obtained in the middle of two adjacent actuators (locations 2, 6 and 9). However, the results for the moving stimulus mode show slightly better performance in presenting a "funneled" midway stimulation between adjacent actuators.

After all, this result is consistent with the findings of Weinstein [15] which states that the two-point discrimination threshold ranges from 38mm to 40mm. It was difficult for the subjects to discriminate adjacent locations separated by a distance of 20mm which is less than the mentioned threshold.

Comparing the performance of the two display modes reveals, that the moving stimulus is characterized by improved spatial localization of "funneled" midway sensations (2, 3, 5, 6, 7, 9, 10) at the expense of impaired localizing ability at the actuator locations (0, 4, 8, 12) when stimulated. The average accuracy for localizing stationary stimulus is 31.5% within which midway stimuli have a detection rate of 19.84%. Respectively, the average accuracy for the moving stimulus is 32.69% within which the accuracy for virtual locations is 25.13%.

IV. Conclusion

With the growing trend of deploying haptically enabled multimodal human-computer interfaces, the human body surface has been considered as an additional means for information display. By mapping a numeric quantity to a moving vibrotactile stimulus on the forearm we are able to establish an additional information channel, which can be used to avoid overloading existing modalities. In this context, the spatial perception of a vibrotactile stimulus on the human skin is critical for the performance of such a display method. In this work, we conduct a psychophysical experiment in order to investigate the spatial resolution of vibrotactile stimuli on the human forearm. 13 test items of stationary and moving vibrotactile stimuli are evaluated. Both display methods show best localization accuracy in the vicinity of the joints (elbow and wrist), followed by the locations of the actuators themselves. When displaying a moving vibrotactile stimulus, improved performance of "funneled" midway sensations is achieved.

Our future work addresses an extension of the spanning area of the device to cover the whole arm. This is to allow more separation between adjacent locations and possibly higher correct localization rates.

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