Vibration Enhances Geometry Perception with Tactile Shape Displays

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Abstract

Tactile displays can provide detailed spatial information to the skin, but little is known about the effects of vibrating displayed shapes. This study examines passive touch perception of flat and indented surfaces displayed on a 36 pin tactile display with 2 mm pin pitch. Subjects could not perceive a 0.1 mm deep central indentation when it was presented statically, but it was readily detected when the pattern was vibrated at 5 Hz. A central raised bar was incorrectly perceived as indented when the adjacent pins were vibrated, which is consistent with the "fishbone tactile illusion" (Nakatani et al., Proc. EuroHaptics 2006). These results suggest that tactile display devices can use vibrational stimulus to enhance perception of small differences in height.

1. Introduction

Tactile displays for conveying spatial information to the skin have been under investigation for over 40 years [1], [2]. Initial interest was motivated by sensory substitution devices for the visually impaired, while much current work addresses applications in virtual environments. The most common design approach for these displays uses arrays of pins that can be raised against the user's skin to approximate arbitrary shapes. A wide variety of actuator technologies and design configurations have been reported; see [3], [4] for recent reviews of the state-of-the-art in tactile display research.

Actuation approaches for pin-based tactile displays may be broadly divided into two categories: vibrotactile and static. Vibrotactile displays typically operate at frequencies of 200-250 Hz; at these frequencies perceptual thresholds are lowest, which permits the use of lower-cost and more compact actuators. They have most commonly been used to convey abstract forms such as letter shapes for sensory substitution applications, e.g. [1], [2]. Static displays, on the other hand, can provide continuous skin deformation with amplitudes on the order of 1 mm or more, and thus require higher actuator power levels. These displays are often intended to simulate the sensation of contact with three-dimensional objects in virtual environments, e.g. [5], [6].

Two recent psychophysical results raise new questions about the role of frequency in tactile display of spatial patterns. First, Bensmaia et al.[7] report measurements of tactile acuity as a function of stimulus vibration frequency. These measurements used the conventional grating orientation discrimination test, with the grating stimuli vibrated normal to the finger tip surface at frequencies up to 80 Hz. The results showed that highest acuity occurs at frequencies of 5-10 Hz, where it is about 30-40% better than the static case and up to 300% better than at higher frequencies.

The second result is the fishbone tactile illusion, where a raised surface feature is perceived as indented [9]. The archetypal stimulus consists of a central bar raised 0.1 mm above the surrounding surface with similar bars projecting to each side (Figure 1a). For central bar widths up to a few mm, when the central bar is stroked back-and-forth with the finger tip there is a strong illusory perception that the central bar is indented with respect to the lateral bars. In fact, for the narrower widths, the raised central bar is perceived as more indented than the true indented reference shape shown in Figure 1b, where the central area is the same height as the flat surrounding surface.

This illusion occurs for a variety of patterns where the central bar is surrounded by raised textures in place of the lateral bars projecting to each side, including textures with elements that are a small fraction of a mm in size. Motion of the finger tip over the central bar and adjacent texture is required in all cases. These results suggest that vibrotactile stimulus surrounding

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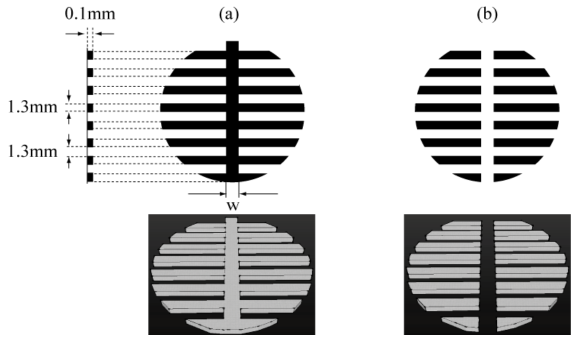

Figure 1. Fishbone illusion stimulus plates in machined aluminum. Black denotes areas raised 0.1 mm above white areas. (a) Fishbone pattern with raised central bar that is perceived as indented; (b) Reference pattern with true indented central bar.

Figure 2. Tactile display device.

the smooth central raised bar is a factor in the creation of the illusion.

In this paper, we explore the role of low-frequency vibration in perception of shapes using pin-based tactile displays. We report on two psychophysical experiments in which subjects were presented with bar patterns combining two values of height (flat vs. 0.1 mm) and frequency (static vs. 5 Hz) on a 36 pin finger tip tactile display. The first experiment investigated differences in perception of static and vibrating patterns, in both flat and indented shapes. A second experiment with vibratory patterns determined whether the fishbone illusion could be reproduced using the tactile display with the finger static but with pin motion to simulate the vibrotactile stimulus generated by stroking the actual fishbone pattern.

In the next section we describe the tactile display device and the five patterns used in the experiments, as well as the experimental setup. The following section presents the results of both experiments, which demonstrate that vibration enhances the perception of indented patterns, for both physically indented shapes and the fishbone illusion.

2. Materials and Methods

2.1. Tactile Display and Stimuli

The tactile display employed here uses RC servomotors to actuate a 6 x 6 array of pins (Figure 2) [10]. The pins are 1 mm in diameter with 2 mm center spacing in a square grid. Nominal vertical range of travel is 2 mm and height resolution is 0.1 mm. To evaluate the performance of the tactile display we used a CCD laser displacement sensor (LK-500, Keyence Corp., Osaka, Japan). Data from the sensor was digitized at 1 kHz and low-pass filtered at 50 Hz. Results showed that full commanded heights were achieved for frequencies of 5 Hz. For full details of the device design and performance, see [10].

The vibratory pin motion in these experiments consisted of a 5 Hz square wave. Adjacent vibrating pins were 180 degrees out of phase to convey an overall impression of vibration instead of a simultaneous vertical movement of all the pins. Commanded heights were either zero or 0.1 mm for both static and vibrating pins.

The experiments used the five spatial patterns shown in Figure 3, arranged in two groups corresponding to the two experiments. The first experiment uses patterns 1 to 4, which differ in spatial arrangement (flat vs. center indented) and frequency (static vs. vibrating). Pattern 1 is a flat static pattern consisting of all 36 pins 0.1 mm above the flat plate surrounding the pins. Pattern 2 presents a static indented shape, with the internal columns of pins at 0.0 mm in height. Pattern 3 is a vibratory version of pattern 1; drive electronics restrictions preclude simultaneous vibration of all 36 pins, so the two outer columns were static in the raised position. This provided 9 mm of vibrating contact area, which subtended the great majority of the contact area of subjects' finger tips. Pattern 4 represents a central indentation with the surrounding pins vibrating.

The second experiment uses patterns 4 and 5 to investigate properties of the fishbone tactile illusion.. Both of them present vibration on the outer pins and static shapes pins on the inner pins; in pattern 4 the inner pins are zeroed in height, representing an indented surface, while in pattern 5 they are raised to

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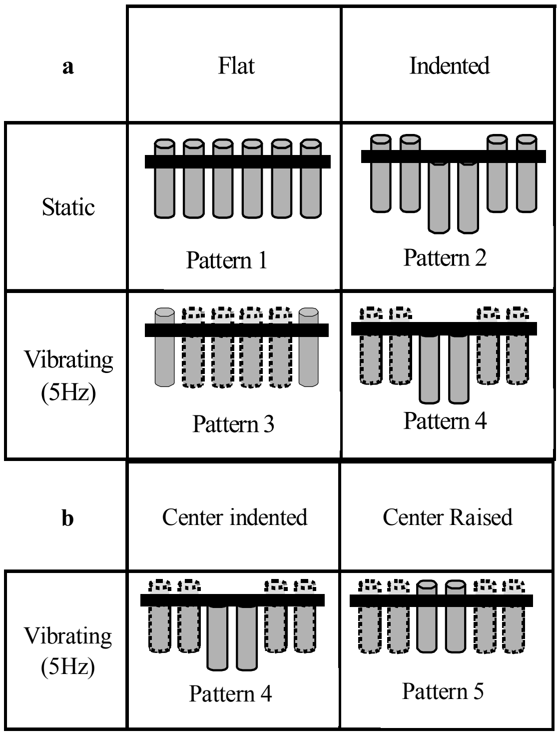

Figure 3. Side view of one row of each pattern. Dotted pins in patterns 3-5 show vibration. (a) experiment 1; (b) experiment 2.

0.1 mm, corresponding to the fishbone illusion configuration.

2.2 Experimental Design and Procedure

Ten graduate students volunteered for the experiments, five males and five females. All of them defined themselves as right handed and did not report any hand injury or disease.

The tactile display was fixed to a table and subjects were asked to place their right index finger on the pins, so that the finger did not move once it was placed. They could, however, vary the applied finger tip force for comfort and to best feel the displayed pattern. We used a 0.15 mm thick latex rubber sheet as a spatial low pass filter to prevent subjects from feeling the effect of individual pins [11]. The stimulus was already present in the tactile display when subjects positioned their finger, so the area of the rubber in direct contact with the pins was painted black to provide a target for finger placement and to minimize visual feedback. To eliminate audio cues, subjects wore headphones playing white noise in the frequency range of sounds made by the tactile display.

During each trial, a pattern was presented to the subject's fingertip for 5 seconds. After that time, the subject would withdraw the finger from the device and state whether the pattern felt flat or indented. There was unlimited time to make the choice. After 10 practice trials, each subject proceeded to complete 50 trials, so each pattern was tested 10 times. Subjects had a 3-minute break after 25 trials, in which they were asked to rub their finger on a flat surface in order to avoid adaptation. They could also rest at any time they felt it necessary. The order in which patterns were presented to each subject was randomized, but all subjects received the same ordering. Data for the two experiments was collected during the same experimental session. A typical session lasted about 20 minutes.

3. Results

Results from the experiments are presented in Figure 4. This graph shows the probability of classifying each pattern as indented in both experiments. The mean values with corresponding standard deviations were 0.04(0.05), 0.14(0.25), 0.34(0.37) and 0.91(0.11) for the first four patterns, and 0.93(0.08) for the fifth one.

A one-factor within subject repeated measures ANOVA was performed on the probability of classifying the patterns as indented, with factor being the pattern (5 levels). Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(9)=35.72$, $p<0.001$); therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=0.342$). Results showed that the effect of pattern was statistically significant ($F(1.37,12.32)=38.14$, $p< 0.001$).

For the first experiment, we carried out several contrasts to identify the pairs of patterns that were significantly different. These contrasts showed that, while there is no significant difference between static patterns 1 and 2 ($F(1,9)=1.8$, $p=0.213$), the difference between vibrating patterns 3 and 4 is significant ($F(1,9)=25.19$, $p=0.001$). The difference between flat patterns 1 and 3 was also significant ($F(1,9)=5.55$, $p=0.043$). The effect of subject's gender was not reported as significant at $p<0.05$.

A two-factor within subject repeated measures ANOVA was then performed to data from the first four patterns, with factors being vibration (2 levels) and height of the pins (2 levels). There was a significant effect of vibration on the probability of classifying a pattern as indented ($F(1,8)=28.27$, $p=0.001$); contrasts revealed that the probability of classifying a pattern as indented was significantly higher when the pins were vibrating. The effect of height was also significant on the classification of patterns ($F(1,8)=15.53$, $p=0.004$),

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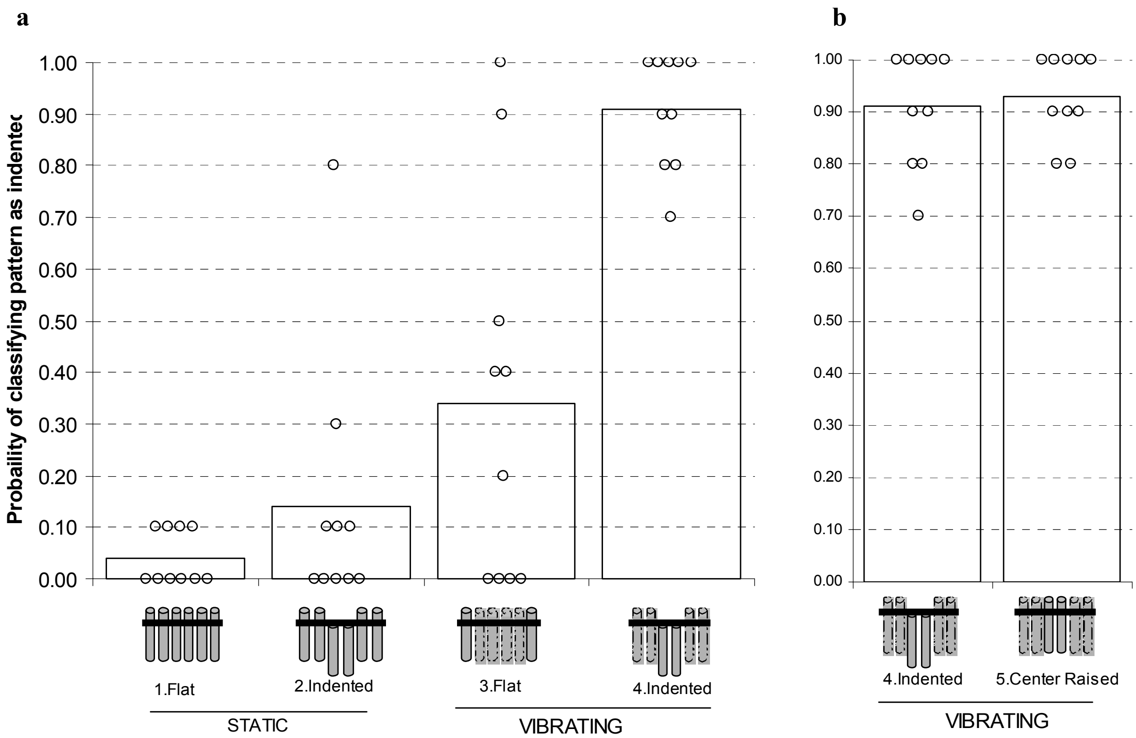

Figure 4. Results from (a) experiment 1 and (b) experiment 2. For each pattern, dots represent data from one subject and bars represent the mean of the ten subjects.

with indented patterns having a significantly higher probability of being classified as indented.

Most interesting results come from the significant interaction effect between height and frequency (F(1,8)=22.31, p=0.001). This indicates that frequency had different effect on subjects' perception depending on the indentation of the pattern. The interaction graph (Figure 5), shows that vibration raised the probability of feeling a pattern as indented more in indented patterns than in flat patterns. For flat patterns, the effect that adding vibration had on the probability of identifying the patterns as indented was very small, whereas for indented patterns this effect raised the probability of classifying the pattern as indented from 0.14(0.08) to 0.91(0.03).

For the second experiment, we analyzed data from the one-factor within subjects repeated measures ANOVA. Contrasts revealed that there was no significant difference between patterns four and five (F(1,9)=1.00, p =0.34).

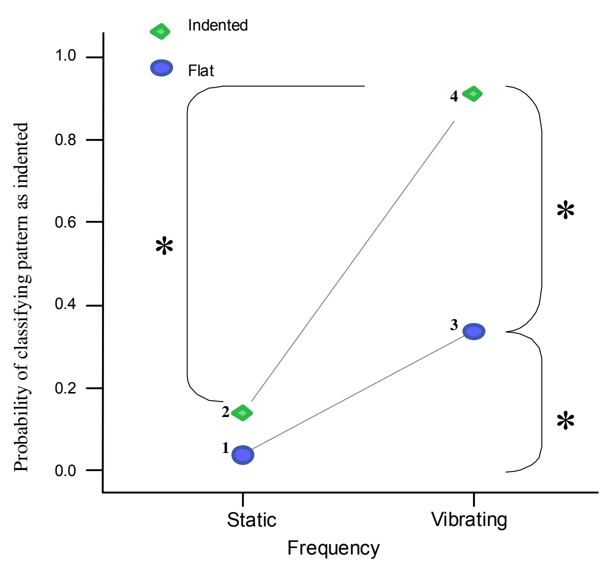

Figure 5. Height and Frequency interaction graph for the first study. Number refer to patterns. * denotes statistically significant difference (p<0.05).

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4. Discussion

4.1 Experiment 1

The first experiment investigated the role of vibration in distinguishing indented patterns of 0.1 mm height by passive touch. Results showed that subjects were not able to perceive the indentation with a static tactile display (pattern 2). As expected, adding vibration (pattern 4) increased the probability of perceiving the indentation to near unity.

This is likely due to the small height of the indentation and the lack of stimuli from active touch. Bensmaia et al. [7] showed that tactile acuity thresholds are better if patterns are vibrated at 5-10 Hz than for static presentation. Hollins and Risner [8] found that under passive touch the discrimination of sandpaper surfaces was difficult for fine grits (under 0.015 mm particle size) but readily accomplished for coarser grades (over 0.141 mm). When the sandpaper surfaces were drawn over subjects' fingers, the finer grits were also easily distinguished. Together with the results of the present study, this suggests that adding vibration to tactile rendering algorithms can enhance the perception of fine surface features with tactile displays.

It is interesting to note that the vibrating flat pattern (pattern 3) was classified as indented in about a third of the trials. Contrasts showed that there was a significant difference between the flat static pattern (pattern 1) and this pattern. One possible explanation is that vibratory stimulus was not the type of information subjects expected, and some confused vibration with indentation. We also note that the edge pins in pattern 3 were fixed due to hardware limitations, which may be a confounding factor.

Nevertheless, the fact that the probability of identifying pattern 3 as indented is still well below chance, suggests that vibration on its own, with no specific pattern, is not enough for strong identification of an indented shape. Even with vibratory stimulus, a strong perception of indentation requires a contrasting central element such as patterns 4 or 5.

Surprisingly, while some subjects identified the flat vibrating pattern as indented, others informally reported feeling it as rounded. Both the indented and rounded responses to the flat vibrating surface demonstrate that high-performance tactile displays have the capability to deliver stimuli with no counterpart in the physical stimuli experienced in everyday manual tasks. This has the potential for delivering confusing sensations if deficient rendering algorithms are employed. Conversely, it may be possible to create new sensations that cannot be experienced in the physical world, opening new possibilities for communications and aesthetics.

4.2 Experiment 2

The purpose of our second experiment was to find the effect of raising the static center in a vibrating pattern (Pattern 5), in analogy with the fishbone tactile illusion. Contrasts showed there was no significant difference between Pattern 4 and Pattern 5. Both patterns were perceived as indented, no matter if the pins in the center were 0 or 0.1 mm high. This means that as long as adjacent region of contact area was vibrated, the central area of the pattern would be perceived as indented.

It is clear from this result that it is the difference in stimulus between the central and lateral regions that creates the sensation of indentation and not a difference of height. This matches the conclusion from previous studies of the fishbone illusion [9]. One hypothesis to explain this illusion begins with the observation that the copious tactile stimulus in the lateral region greatly exceeds the stimulus in the smooth, static central region. This relative absence of stimulus is then equated with the absence of a surface, which is a description of an indented surface. Thus the stimulus contrast is equated with a geometric contrast.

The present study shows that this illusion can be readily created through vibration of the adjacent region while the finger is static. Thus active motion of the finger is not needed to invoke the illusion, which removes proprioception as contributing factor. This implies that vibration serves the same role in the tactile display version of the illusion as motion plays in the active version.

4.3 Conclusions and Future Work

Results from both experiments are limited to the simple indented shape, and data concerning Pattern 3 suggests that the effects of vibration could be different when analyzing other shapes. From these experiments we know the effect of vibration at 5 Hz on a 0.1 mm indentation that is 4 mm wide, and considerable work will be required to develop a more thorough understanding of height, frequency and width in the use of tactile displays.

Our experiments have shown that, for small height variances, a difference in height is not essential to produce the indented sensation. This result suggests that developers of tactile displays and tactile rendering algorithms can take advantage of using vibrational

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stimulus intensity difference in place of differences in height.

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