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The Role of Spatial Separation and Motor Control in Vibrotactile Frequency Discrimination

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***Abstract*— This study investigates how spatial separation and movement type (self-controlled vs. externally controlled) affect the ability to discriminate between vibrotactile frequencies. Forty participants were divided into four groups varying in frequency resolution. Using a PinArray device, participants completed 192 trials involving spatially separated pairs of frequencies delivered via sequential pin activation. Results revealed that self-controlled movement improved discrimination accuracy, especially at larger separations and with wider frequency gaps. These findings highlight the interplay between proprioceptive control, spatial resolution, and sensory prediction in tactile frequency perception.**

I. Introduction

Our ability to perceive and interpret tactile information is deeply intertwined with how that information is acquired—whether movement is initiated by the user or externally applied. Classic theories of sensorimotor control suggest that the brain predicts the sensory consequences of self-initiated movement using a mechanism known as the efference copy, which is used to attenuate or suppress predictable sensory feedback [1]–[3]. However, the benefits of movement control are not always straightforward. Symmons [4] showed that active exploration was found to be advantageous for more complex tasks involving three-dimensional shape perception, where voluntary control supports richer information gathering. In this study, we examine how self-controlled and externally controlled movement affect the ability to discriminate vibrotactile frequencies presented at spatially separated locations. Specifically, we ask whether proprioceptive control confers a perceptual advantage, and how spatial distance and frequency resolution interact with movement type.

II. Methods

A. Participants

Forty Bentley University participants (17 female, 23 male, $Age = 21.2 \pm 3.6$, 36 right-handed, 4 left-handed). All participants gave informed consent in accordance with Bentley University's Institutional Review Board and received compensation for their time.

B. Apparatus and Stimuli

Vibrotactile stimuli were delivered using the PinArray [5], a custom-built haptic device composed of a 3×4 array of twelve independently actuated pins (1.5 mm diameter, 2.5 mm center-to-center spacing). The device's 20 cm horizontal workspace was divided into ten equal 2 cm segments. Vibrotactile feedback was provided only when the device aligned with a predefined activation zone—pins remained silent during transitions between zones. A hand rest was positioned for comfort during interaction.

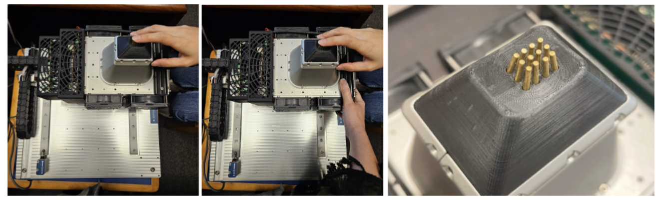

Fig. 1. The PinArray device: Self-controlled movement, Externally controlled movement, the tactile display with 12 pins

Each trial involved two vibrations: a lower frequency (LF) and a higher frequency (HF), delivered at two spatially separated activation zones along the medial-lateral axis. The separation between the stimuli was either 2, 6, 10, or 14 cm (D2, D6, D10, D14). Participants encountered the stimuli sequentially as the device was moved laterally. In self-controlled trials, participants actively moved the device; in externally controlled trials, the experimenter moved it while the participant's finger remained stationary and relaxed (see Fig. 1).

Participants were assigned to one of four frequency resolution groups, each defined by a standard stimulus (SS) and four comparison stimuli (CS):

- **Group 1:** SS = 150 Hz; CS = 50, 100, 200, 250 Hz (step: 50 Hz)
- **Group 2:** SS = 100 Hz; CS = 50, 75, 125, 150 Hz (step: 25 Hz)
- **Group 3:** SS = 75 Hz; CS = 50, 62.5, 87.5, 100 Hz (step: 12.5 Hz)
- **Group 4:** SS = 62.5 Hz; CS = 50, 56.25, 68.75, 75 Hz (step: 6.25 Hz)

Each group experienced all combinations of frequency pair, spatial distance, and movement type, yielding 32 conditions per participant. Each condition was repeated six times (192 trials total), distributed across six randomized blocks. Movement type alternated by block: blocks 1, 3, and 5 were externally controlled; blocks 2, 4, and 6 were self-controlled.

C. Procedure

The experiment began with a brief training phase to familiarize participants with the device, vibration sensations, and task. In each trial, participants explored two spatially distinct vibrotactile stimuli delivered via the PinArray device.

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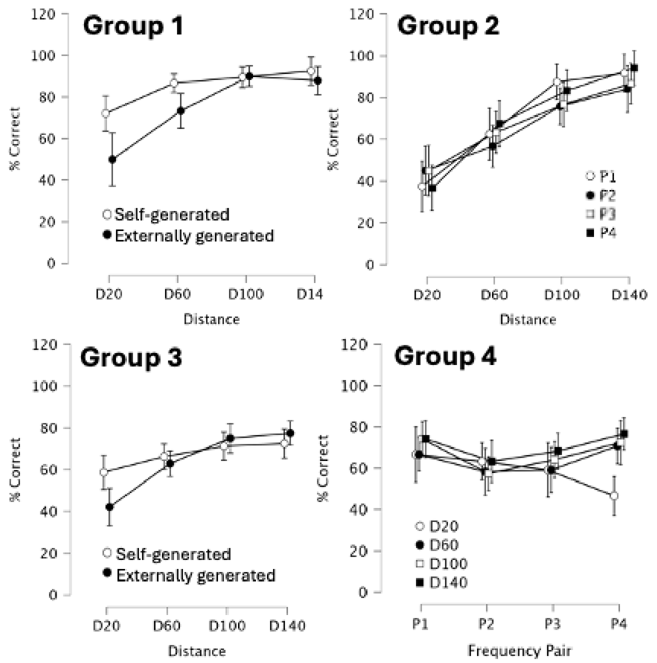

Fig. 2. Discrimination accuracy for the four groups: Group 1) Distance per Movement type, Group 2) Distance per Frequency pair, Group 3) Distance per Movement type, and Group 4) Frequency pair per Distance. Error bars represent 95% confidence intervals.

During training, feedback was provided after each trial. In the experimental phase, participants were presented with pairs of vibrotactile stimuli separated horizontally and were asked to indicate which side (left or right) had the higher frequency. No feedback was provided during testing. Participants responded using a keypad and wore noise-canceling headphones playing pink noise to eliminate auditory cues.

III. Results

A three-way repeated measures ANOVA was conducted for each experimental group with movement type (self-controlled vs. externally controlled), frequency pair (P1 to P4), and spatial distance (D2, D60, D100, D140) as within-subject factors. Fig. 2 summarizes the results.

A. Group 1: 50 Hz Step Size

There were significant main effects of distance, $F(3,27) = 6.694, p < .05$, and movement type, $F(1,9) = 5.450, p < .05$. Discrimination accuracy was higher for self-controlled movement, and performance improved as spatial separation increased, with accuracy for D20 significantly lower than the three other distances.

B. Group 2: 25 Hz Step Size

The effect of spatial distance was significant, $F(3,27) = 17.043$, $p < .05$. Additionally, a significant interaction between frequency pair and distance was found, $F(9,81) = 3.142$, $p < .05$. Simple main effects analysis indicated that the shortest distance (D2) significantly differed from D10 and D14 for all frequency pairs ($p < .05$).

C. Group 3: 12.5 Hz Step Size

A significant main effect of distance was found, $F(3,27) = 9.575$, $p < .05$, along with a significant interaction between distance and movement type, $F(9,81) = 3.142$, $p < .05$. Simple main effects analysis revealed that at the shortest distance (2 cm), performance was significantly worse than at 6 cm, 10 cm, and 14 cm in both movement conditions. However, the drop in performance was more pronounced in the self-controlled condition.

D. Group 4: 6.25 Hz Step Size

There were significant main effects of frequency pair, $F(3,27) = 3.637$, $p < .05$, distance, $F(3,27) = 4.467$, $p < .05$, and movement type, $F(1,9) = 6.180$, $p < .05$. A significant interaction was found between frequency pair and distance, $F(9,81) = 2.408$, $p < .05$. Simple main effects revealed that in the externally controlled condition, the 2 cm separation produced significantly lower accuracy than the 6, 10, and 14 cm distances across all frequency pairs.

IV. Discussion and Conclusion

Across all frequency resolution groups, participants' performance was strongly modulated by spatial distance. Discrimination accuracy improved as the separation between stimuli increased, suggesting that closely spaced vibrations may interfere with spatial or temporal integration processes, potentially due to spatial masking or the inability to individuate activation zones at shorter distances. Notably, self-controlled movement led to significantly better performance in Groups 1 and 4. Group 3 revealed a more complex pattern, where self-controlled movement was not always advantageous and Group 2 showed no significant effect of movement. Taken together, these findings emphasize that self-controlled control is not universally beneficial in haptic tasks—it depends on spatial and frequency resolution. While proprioceptive engagement can enhance perception in certain contexts, it may introduce interference when discrimination demands exceed the integrative capacity of the haptic system. We are currently analyzing the movement trajectories and timing characteristics to determine whether the observed differences in performance correlate with exploratory dynamics.

V. Acknowledgments

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