Exploring Frequency Modulation in Decoding Edge Perception Through Touch

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Abstract. This research explores how different vibration frequencies influence our ability to perceive and identify edges through touch. The study used a PinArray device to simulate various edge shapes, testing if participants could recognize these shapes based on pairing two frequencies (LF-HF). The findings showed that certain frequency combinations in low and medium ranges were particularly effective in conveying step edge and ridge shapes. This has important implications for enhancing tactile technology in fields like robotics and assistive devices by improving the realism of tactile virtual shapes.

Keywords: Frequency Modulation · Edge Detection · Mechanoreceptors.

1 Introduction

The quest to understand and replicate human tactile perception has been an evolving field of research, intertwining physiological, psychophysical, and engineering insights. Our work, building on the foundational concepts introduced by other researchers, seeks to address the complexities inherent in tactile perception and haptic technology, and more specifically, edge perception.

In our ongoing research, we extend this exploration by questioning some of the long-standing assumptions in the field, particularly those pertaining to mechanoreceptor specificity in tactile perception. Pioneering studies, focused on the correlation between mechanoreceptor activation and tactile sensations, often confined to threshold-level stimuli [2, 3, 9–12]. However, recent physiological evidence advocates for a more integrative approach, challenging the traditional frequency-specific models [6, 13, 22, 23]. We propose that tactile perception, especially in complex tasks like edge detection, necessitates the cooperation of multiple receptor types, aligning with emerging trends in sensory research, emphasizing pattern coding over receptor-specific responses [1, 18, 22].

2 Related Work

It has been established that changes in the shape of dermal papillae significantly influence our ability to discern edges [4, 15]. Whenever a finger touches an edge, it exerts pressure on the skin, enabling the brain to interpret these nerve signals as edge characteristics [7]. In particular, when a finger lies on a surface featuring a groove (see Fig. 1), the skin deforms, causing the dermal papillae to move due to a shift in the gradient of the papillary ridges. Since SAII and SAI receptors are situated in the dermal papillae, they too are subject to this deformation. The Merkel receptors, which are believed to be vital for perceiving stationary edges, and the Meissner corpuscles, found in the papillary ridges (fingerprints), sense the motion of the papillae caused by sideways stress, and relay this data to the brain where it is processed as information about the edge [4]. Kuroki et al. mention that the side-to-side stress corresponds directly to the gradient alteration [15]. Additionally, the papillae are thought to enhance the skin's deformation as a signal booster, transmitting detailed information about the object's shape [14].

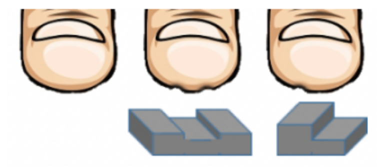

Fig. 1: Skin deformation when a finger is resting on two edges or one edge.

Various research efforts have focused on replicating edges in tactile displays through specific skin distortions [16, 20]. However, such studies, aimed at understanding the dynamics of simulated edges in haptic displays, have been limited to threshold detection levels. To truly replicate the sensation of a synthetic edge as if it were real, a comprehensive approach is needed. Recent research indicates that FAI and FAII receptors might also be involved in edge detection due to their capacity to decode frequencies across a wide range. In this context, both Ruffini receptors, reacting to constant pressure, and Pacinian receptors, sensitive to motion, play a part in recognizing objects, including edges and corners [17, 21, 25].

Lim et al. conducted a comprehensive analysis using a vibrotactile display to assess participants' ability to discern shapes by modulating vibration frequency without changing amplitude [16]. The findings revealed that vibration frequency can effectively be employed to sense shapes with different heights even under a fixed amplitude stimulus. This insight into the vibrotactile threshold and frequency modulation's impact on tactile perception has significant implications for advancing haptic technology, particularly in enhancing the realism and fidelity of tactile displays.

In this paper, our focus was on understanding the impact of frequency modulation on the perception of edges. Specifically, we altered the frequency while keeping the amplitude constant to induce a perception of varying amplitude.

The main goal of this study was to determine if a specific shape could be created using a frequency-pair with minimal amplitude changes. To explore how participants perceive differences in frequency as a tactile representation of a surface's protrusion, we conducted two experiments:

Experiment 1 - Combining Different Frequencies: This setup (illustrated in Fig. 2b) involved vibrating pins at varied frequencies (F1 and F2) to form the shapes shown in Fig. 2a. This method was based on the approach by Lim et al. 2006 [16] and expanded the frequency range tested from 3 Hz to 250 Hz to include a range of receptors.

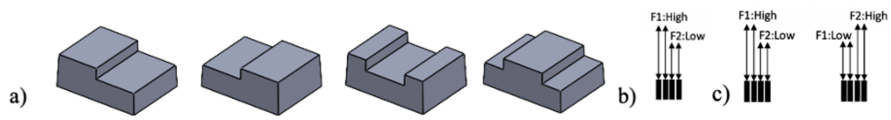

Fig. 2: a) Shapes used from left to right: S1 (ascending step edge), S2 (descending step edge), S3 (groove), S4 (ridge); b) Example of 2 × 2 frequencies for a descending edge; c) A 2 × 2 frequency shift paradigm.

Experiment 2 - Gradual Shift in Frequencies: In this case (depicted in Fig. 2c), two frequencies were quickly shifted from one side to the other. Initially, this may create a blurred sensation, but it eventually gives the impression of an edge emerging from a flat surface. In a preliminary test [8], aimed at confirming the accuracy of frequency shifts, participants successfully identified edges with shift durations of 500 ms or 1100 ms. Shorter intervals, however, led to more errors. Interestingly, even when a low frequency was used to represent a non-edge condition, participants still perceived an edge, suggesting the complexity of creating a tactile edge illusion. This indicates the need for further experimentation and validation of different conditions to accurately simulate haptic perceptions.

3 Experiment 1

3.1 Participants

Before the experiment, we conducted a power analysis to determine the optimal number of participants. Using G*Power, we aimed to detect a large effect size (f=0.25) in a repeated measures ANOVA (within factor), with a significance level α of 0.05 and a desired power of 0.90 with 7 repetitions. The recommended total sample size was determined to be 22. This study involved 23 individuals (13 female and 10 male participants), with an average age of 21.8 years (SD = 5.8). None of the participants had any reported issues with hand cutaneous or kinesthetic functions. Before starting the experiment, they completed an electronic consent and the Edinburgh Handedness Questionnaire [19], a 10-item tool used to identify their dominant hand. Results showed 20 right-handed and 3 left-handed participants. All participants received compensation for their time. The experiment's methods received approval from Bentley University Institutional Review Board (IRB).

3.2 Apparatus

Stimuli were generated using the PinArray, a custom vibrotactile device. The PinArray device consisted of twelve (3 × 4) flat-topped pins shown in Fig. 3b, each with a diameter of 1.5 mm and a center-to-center distance of 2.5 mm between them. Each pin was vertically actuated by an independent DC voice coil linear actuator (NCM02-05-005-4JBL by H2W Technologies, Inc., CA, USA) attached underneath. These voice coil actuators were controlled by a Python 2.7 script via an Ethernet connection and a custom controller box (Sigma Design, Camas, WA, USA). The primary function of the pins was to deliver vibrotactile stimulation to the fingerpad resting on top.

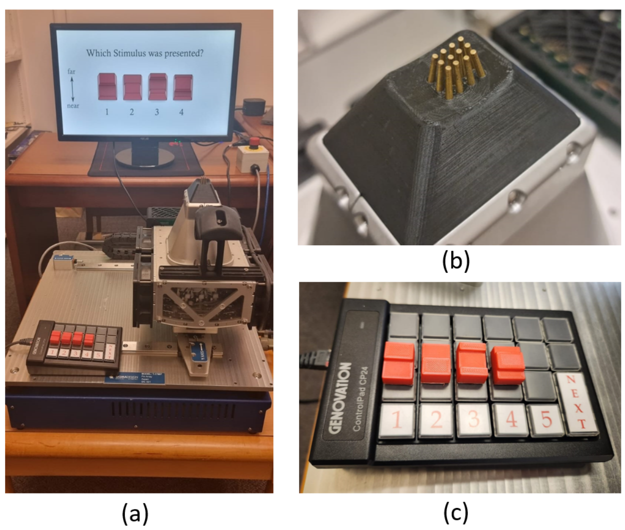

Fig. 3: a) A depiction of the experimental setup. b) Twelve vibrotactile pins. c) Response keypad.

The frequency, amplitude, and duration of each pin's activity could be set independently, enabling the creation of relatively complex patterns of vibrotactile stimulation across the fingertip. Prior to the experiments, we conducted a comprehensive evaluation of each pin in the PinArray, testing across frequency ranges of 3-350 Hz and amplitudes. Each assessment, lasting about 10 seconds, involved analyzing hall sensor data for amplitude range and frequency stability.

This rigorous calibration ensures that the device performs consistently across all experimental conditions, providing reliable data for our study. Hence, a constant ratio of 1.5 between frequency and amplitude was selected. Table 1 displays the corresponding amplitude for each frequency.

Table 1: Frequencies and corresponding amplitudes.

Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
50 Hz	0.030 mm	60 Hz	0.025 mm	75 Hz	0.020 mm
100 Hz	0.015 mm	110 Hz	0.014 mm	125 Hz	0.012 mm
150 Hz	0.010 mm	200 Hz	0.008 mm	225 Hz	0.007 mm
240 Hz	0.006 mm	250 Hz	0.006 mm		

3.3 Stimuli

Vibrotactile stimuli were generated via vertical oscillatory motion in each pin. The four edge shape configurations (S1 to S4), shown in Fig. 2, were created by pairing two frequencies: F1 and F2. This pairing is illustrated in Fig. 4, where red dots represent pins operating at the higher frequency (HF) and blue dots represent pins at the lower frequency (LF).

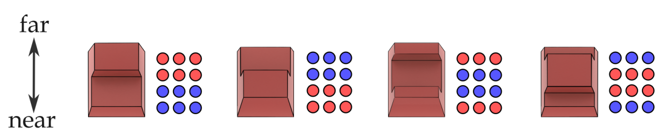

Fig. 4: Four edge shape configurations: S1 - ascending step edge (LF to HF), S2 - descending step edge (HF to LF), S3 - groove (HF-LF-HF), and S4 - ridge (LF-HF-LF).

As shown in Table 2, the tested frequency pairs (F1-F2) fell into three categories: Low Range (LF), Medium Range (MF), and High Range (HF). The differences between the frequencies in each F1-F2 pair were set at 10, 25, 50, and 100 Hz. This configuration resulted in 48 unique test conditions (4 shapes x 4 frequency pairs x 3 frequency ranges).

3.4 Procedure

Participants were seated in front of a table on which the experimental computer and the connected PinArray device were placed, as illustrated in Fig. 3. The position of the pin tactile display was adjusted to accommodate the participant's dominant hand: to the right for right-handed participants and to the left for

Table 2: Frequency pairs (FP) used in Experiment 1.

	FP1 (10 Hz $\neq$)	FP2 (25 Hz $\neq$)	FP3 (50 Hz $\neq$)	FP4 (100 Hz $\neq$)
LF	50-60 Hz	50-75 Hz	50-100 Hz	50-150 Hz
MF	100-110 Hz	100-125 Hz	100-150 Hz	100-200 Hz
HF	240-250 Hz	225-250 Hz	200-250 Hz	150-250 Hz

left-handed participants. Upon signing the consent form, each participant was instructed to gently place the index fingertip of their dominant hand on the PinArray display, where the pins were located. A handrest was positioned at the front of the stimulator surface for their comfort (see Fig. 3a).

The experiment consisted of three stages: familiarization, training, and testing. In the familiarization stage, participants were introduced to the vibrotactile stimuli through a sequence of 12 test conditions. These conditions were randomly selected to ensure exposure to each shape (S1 to S4) across all frequency ranges (LF, MF, HF). During this stage, participants were simply required to feel the stimuli without providing any response. Each stimulus was paired with a visual representation of its corresponding shape on the computer screen. No information regarding the frequency range of the stimuli was disclosed to the participants. During the training stage, participants were exposed to the four shapes randomly selected and were asked to select the corresponding key on the keypad in front of them, as shown in Fig. 3c. They then received immediate feedback indicating whether their response was correct or incorrect.

Transitioning to the testing stage, participants underwent a total of 336 trials, with the 48 test conditions repeated 7 times in random order. During this stage, they wore noise-cancelling headphones playing pink noise to block any potential auditory cues from the PinArray device. The primary task for participants was to identify the shape presented, as shown in Fig. 5. Following the delivery of each stimulus for 500 ms, they had a 5-second window to respond. If a response was not provided within this time frame, the missed trial was randomly reintroduced later in the experiment. The delivery of test trials was fully automated, eliminating the need for participants to manually proceed to the next trial. The experiment lasted approximately 45 minutes, during which two 2-minute breaks were given. At the end of the experiment, participants were invited to assess the difficulty level on a 5-point Likert scale, ranging from 1 (very easy) to 5 (very hard). Additionally, they were encouraged to share any feedback or comments regarding their overall experience.

3.5 Results

In the three-way repeated measures ANOVA, the main effects and interactions of shape, range, and pair were examined. The main effect of shape [$F(3, 66) = 8.62$, $p = .002$, $\eta_p^2 = .28$], range [$F(2, 44) = 13.74$, $p < .001$, $\eta_p^2 = .38$], and pair [$F(3, 66) = 30.21$, $p < .001$, $\eta_p^2 = .58$] were highly significant. Significant interaction effects between shape and range [$F(6, 132) = 5.88$, $p < .001$, $\eta_p^2 = .21$], range

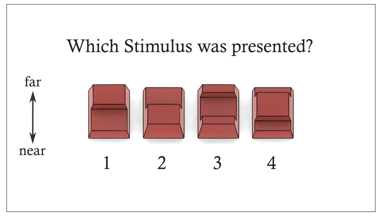

Fig. 5: The response screen displays the shapes presented to participants at the end of each trial.

and pair [F(6, 132) = 16.13, p < .001, $\eta_p^2 = .42$], and between shape, range, and pair [F(18, 396) = 3.16, p < .001, $\eta_p^2 = .13$] were also found. To analyze these interaction effects, we conducted simple pairwise comparisons. The post-hoc analysis revealed significant mean differences across various combinations of shapes (S1 to S4), frequency ranges (LF, MF, HF), and pairs (FP1 to FP4), indicating distinct patterns of interaction between these factors. Notably, in the low frequency range, S1 with FP1 and FP2 was significantly different (p < .001) from all the remaining shapes. Furthermore, performance was near chance level (.25), as confirmed by a one-sample t-test (p > .05), for S2, S3, and S4 when paired with FP3 and FP4 (Fig. 6). In the medium frequency range, performance was significantly above chance level (p > .05) for all conditions. More specifically, S1, S2, and S4 were most significantly recognized when paired with FP2 and FP4 (p < .001). In the high frequency range, except for FP3, performance was significantly different from the chance level (.25) for most conditions. However, there was a notable decrease in performance compared to the low and medium frequency (LF and MF) conditions. Additionally, no significant differences were observed between shapes for each pair condition. These findings indicate that frequency effects are especially pronounced in perceiving step edges, with these effects varying across different pairings.

4 Experiment 2

4.1 Participants

Twenty-two participants (14 female, 8 male, Mean age = 23.1, SD = 4.6) were involved in this study. Nineteen participants were right-handed, while the remaining three were left-handed. None of the participants had reported issues related to hand cutaneous or kinesthetic functions. Each participant received compensation for their time. The experimental methods were approved by the Institutional Review Board (IRB) at Bentley University.

4.2 Apparatus and Stimuli

In the second experiment, the primary modification involved dynamically shifting the vibration frequencies across the PinArray to simulate edge detection.

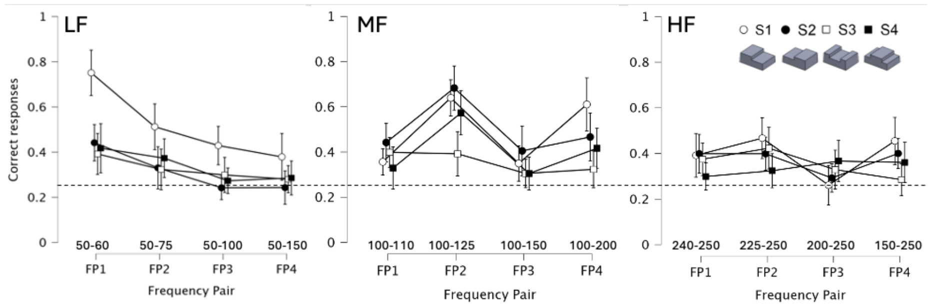

Fig. 6: Percentage of correct responses per shape (S1, S2, S3, S4) and frequency pairs (FP1, FP2, FP3, FP4) for low, medium, and high ranges (LF, MF, and HF). The error bars represent 95% confidence intervals (CIs). The dashed line represent chance level (25%).

This was achieved by gradually transitioning the frequencies across the pins: half of the pins initially set to vibrate at frequency F1 switched to F2, and vice versa, over a period of 500 milliseconds. This change was symmetrically mirrored on the opposite side, creating a dynamic frequency shift. The entire sequence lasted for 2 seconds (Fig. 7). This approach, modeled after previous implementations with the device [8], allows us to examine how abrupt changes in frequency influence tactile perception and edge discernment in real-time.

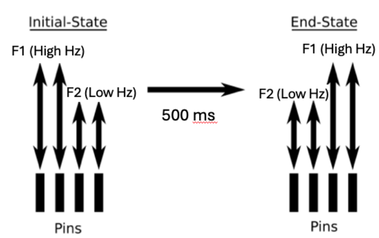

Fig. 7: The spatial location of the frequencies within a pair switched over time.

Due to the low performance observed with high-frequency (HF) pairs in Experiment 1, specifically in participants' ability to accurately identify shapes, only low-frequency (LF) and mid-frequency (MF) ranges were tested in this subsequent experiment. As in the first experiment, frequency pairs were chosen to maintain differences of 10, 25, 50, and 100 Hz between F1 and F2. Combining these frequency differences with four shape configurations, the experiment yielded 32 test conditions (8 frequency pairs × 4 shape configurations).

Table 3: Frequency pairs used in experiment 2.

	FP1 (10 Hz ≠)	FP2 (25 Hz ≠)	FP3 (50 Hz ≠)	FP4 (100 Hz ≠)
LF	50-60 Hz	50-75 Hz	50-100 Hz	50-150 Hz
MF	100-110 Hz	100-125 Hz	100-150 Hz	100-200 Hz

4.3 Procedure

Experiment 2 followed the same protocol as Experiment 1, with minor modifications. During the familiarization stage, eight stimuli were presented to the participants. In the testing stage, the experiment featured 32 test conditions, each randomly repeated seven times, totaling 224 trials. Participants were asked to respond after each stimulus. The entire duration of Experiment 2 was around 30 minutes.

4.4 Results

The three-way repeated measures ANOVA with the factors as shape, pair, and range showed significant effect of shape [$F(3, 63) = 5.79$, $p < .001$, $\eta_p^2 = .22$], range [$F(1, 21) = 6.20$, $p < .05$, $\eta_p^2 = .23$], and pair [$F(3, 63) = 2.98$, $p < .001$, $\eta_p^2 = .12$]. Significant interaction effects between the shape and range factors [$F(3, 63) = 14.09$, $p < .001$, $\eta_p^2 = .4$], and between shape and pair [$F(9, 189) = 3.54$, $p < .001$, $\eta_p^2 = .14$] were also found.

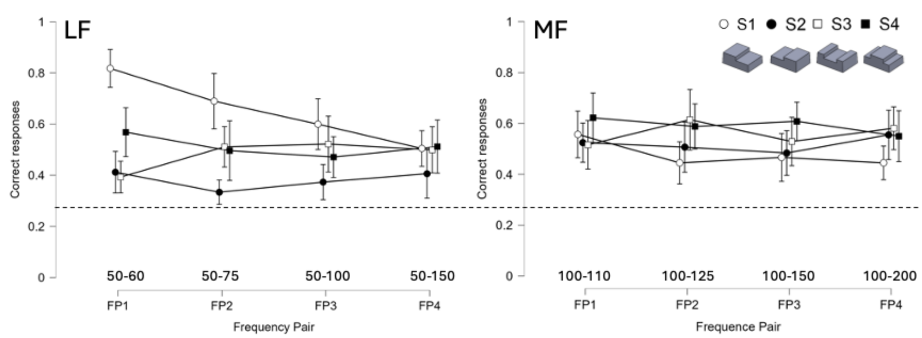

Fig. 8: Percentage of correct responses per shape (S1, S2, S3, S4) and frequency pairs (FP1, FP2, FP3, FP4) for Low and Medium ranges (LF and MF). The error bars represent 95% confidence intervals (CIs). The dashed line represent chance level (25%).

Post-hoc analysis of simple main effects revealed that for the low-frequency range, S1 and S4 were significantly different from S2 and S3 when using FP1. S1 was also significantly different from S2 using FP2 and FP3. Across all frequency pairs in the medium range, there were non-significant differences between the shapes. However, with the understanding that recognition is still above chance in all these conditions ($p < .001$), it indicates that participants were effectively identifying shapes, albeit without significant variation in performance between different shapes. Comparing the results of both experiments, independent t-tests showed that performance increased significantly in Experiment 2 for S3 and S4, suggesting that shifts in frequency improve the perception of two-edge shapes such as grooves and ridges.

5 Discussion and Conclusion

The results from Experiments 1 and 2 contribute to a growing body of research related to edge detection [4, 7, 20]. Our study aims to clarify how edge recognition via vibrotactile feedback is influenced by variations in frequency ranges and specific frequency pairings, while maintaining constant amplitude changes. A key finding from Experiment 1 was the differentiation in shape recognition across frequency ranges. Specifically, S1 was distinctly recognized when paired with FP1 (50-60 Hz) and FP2 (50-75 Hz) in the LF range. This unique recognition of S1 in the LF range may be linked to increased spatial acuity in the proximal third of the distal phalanx of the fingerpad [5]. Research by Ziat and colleagues [26] has demonstrated that tactile perception is enhanced when stimuli move distally, transitioning from areas of higher receptor density to lower density. Conversely, perception tends to diminish when stimuli remain in the same proximal region, which is inherently less sensitive. The perceptual distinction for S1, an ascending step edge, could be attributed to this phenomenon, as the higher frequency in the pair consistently engages the receptor-dense area on the fingertip. The medium frequency range expanded the perceptible spectrum, with S1, S2, and S4 being distinctly recognized with FP2 (100-125 Hz) and FP4 (100-200 Hz), suggesting optimal edge perception within this range. However, high frequencies were associated with a general decline in perceptual accuracy. Notably, S3 was consistently the most challenging for participants to recognize across all frequency ranges. Its difficulty in recognition suggests complexities or ambiguities in how frequency modulation simulates grooves and other tactile features. This challenge may be due to various factors, including the inherent difficulty in conveying certain shapes or textures through frequency changes alone.

Experiment 2 expanded these findings by introducing dynamic frequency shifts. In the low-frequency range, there was significant differentiation in recognizing S1 from S2 and S3 across multiple frequency pairs (FP1, FP2, and FP3). Additionally, S4 was distinguishable from S2 and S3 with FP1. In contrast, the medium frequency range showed consistent performance across different shapes, suggesting perceptual stability and adaptability. This was evidenced by uniformly and significantly above-chance performance across these shapes, where no single shape was notably more perceived than another. The performance for S3 and S4, representing a groove and a ridge, respectively, improved significantly from Experiment 1 in terms of accuracy and perceptual clarity. In tactile edge detection, discerning both grooves and ridges is crucial. A groove is a linear indentation, felt as a drop in the surface followed by a rise, allowing for the detection of its edges, depth, and width. Conversely, a ridge is a raised band on a surface, perceived through an elevation in the surface followed by a descent back to the original level. Detecting these opposing features—the inward dip of a groove and the outward rise of a ridge—is essential in applications such as robotics telemanipulation and assistive tactile displays, providing crucial spatial information. The consistent recognition of various shapes in the medium frequency range (100-200 Hz) aligns with pattern coding, suggesting that the human tactile system might be proficient at processing complex patterns of stimulation, rather than relying solely on specific receptor activation. This could indicate a more holistic approach to tactile perception, where integrating multiple sensory inputs is key. The distinct performances in different frequency ranges and with specific frequency pairings in Experiment 1, along with the dynamic frequency temporal shift in Experiment 2, demonstrate the complexity of edge perception.

The next stage of this research is to explore the role of action (passive, marginally active, and active) on tactile edge perception. The goal is to determine whether the direction of movement influences performance. This will enable us to investigate the significant role that proprioception plays in everyday tasks, such as typing on a keyboard without looking at our hands. When the proprioceptive sense is diminished or lost, perceptual thresholds for angle discrimination increase [15, 24, 25], suggesting that angle discrimination is an integrative process involving both the cutaneous and proprioceptive senses. Moreover, further exploration into how multiple sensory inputs such as visual-tactile or auditory-tactile are integrated and processed by the central nervous system could offer deeper insights into the nature of perceiving an edge in a multimodal setting.

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