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Polarity Illusion of Step Perception Induced by Amplitude Differences in Vibrotactile Stimuli

Study on Haptic Integration for Shape Perception in Dual-Finger Tracing: Part I

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I. Introduction

In multi-finger exploration, shape perception arises from integrating each finger's tactile input and their spatiotemporal relations [1]. Building on the finding that simultaneous dual-finger vibration elicits a step illusion on flat surfaces, we examine how amplitude differences control its polarity.

II. Related Work

Prior work [1] showed that, even on a flat surface, simultaneous stimulation by nail-mounted display [2] during dual-finger tracing triggers a step illusion (Fig.1(Left), Fig.2).

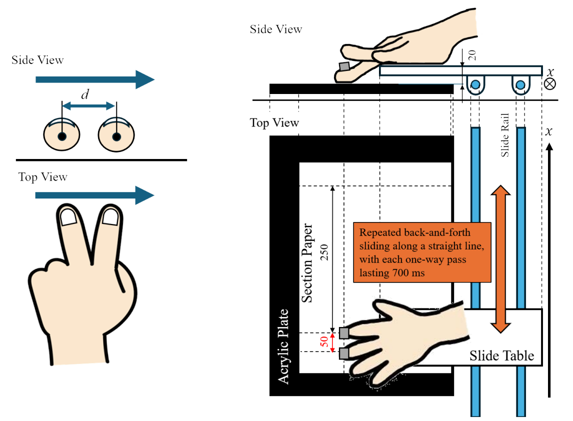

Fig. 1: (Left)Conceptual illustration of dual-finger tactile tracing using the index and middle fingers(Right)Experiment Apparatus; Participants traced 250 mm in 700 ms along the nail-surface normal.

Prior single-finger investigations have shown that modulating the amplitude of stick-slip vibrations can induce slope illusions [3], [4], attributed to vibrotactile cues substituting for proprioceptive height information.

Here, we propose a model in which the amplitude difference between two fingers under Dual-Finger Tracing determines step polarity, highlighting a distinct mechanism—simultaneous differential integration—beyond the integrative accumulation used in single-finger shape construction.

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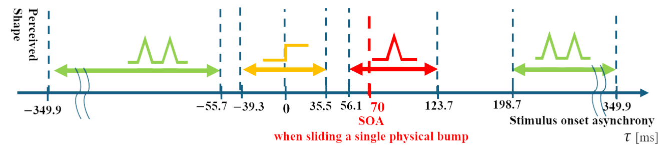

Fig. 2: Schematic of perceived shape as a function of stimulus-onset asynchrony (SOA) between a leading and a following finger (horizontal axis; positive values indicate the leading finger is stimulated earlier). In the green region large SOAs produce perception of two bumps, in the yellow region moderate SOAs yield a stepped profile, and in the red region (around 70 ms) a single bump is perceived. The shape perceptions in the blank regions are unstable. This figure was generated by data from [1].

III. Shape Perception Model by Dual-finger Tracing

We differentiate mechanical variables in physical space from perceptual variables to build our model as follows.

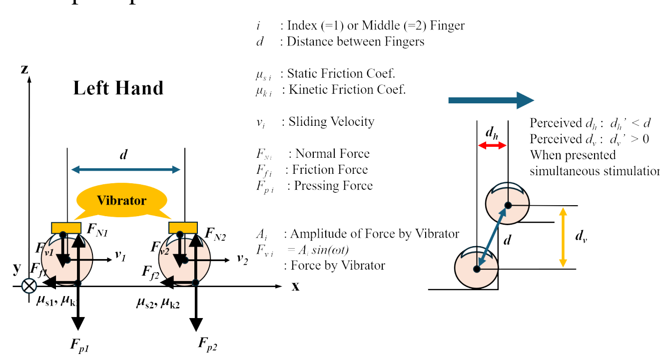

Fig. 3: Model of dual-finger tracing shape perception. The resultant force $F_{Ni} = -(F_{pi} + F_{vi})$ exhibits peak difference $(A_2 - A_1)$, producing perceived step height $d'_v \propto (A_2 - A_1)$.

When modeling slip-slip vibrations at the fingertip during tracing as $A_v \sin(\omega t)$ vibrotactile receptors reliably sense both the amplitude A_v and frequency $\omega/2\pi$ [5]. In contrast, mechanoreceptors for pressure have difficulty directly encoding the rapid contact–release fluctuations characteristic of dynamic stick–slip motion. Consequently, during haptic integration, the brain uses the proportionality $A_v \propto F_{Ni}$ between vibration amplitude and the normal contact force F_{Ni}, together with a monotonic relationship between vibration frequency $\omega/2\pi$ and fingertip velocity v, to infer contact pressure and relative speed indirectly and thus interpret surface geometry. Moreover, when tracing a physical ascending edge, the normal force F_{Ni} momentarily increases. We propose that this transient change in underlying mechanical parameters underlies the perception of an ascending edge. There is a proportional relationship between the maximum normal force($\max F_{Ni}$) and the maximum static friction force($\max F_{fi}$) given by $\max F_{fi} = \mu_{si} * \max F_{Ni}$. In the stick phase, the fingertip deformation equals twice the amplitude of the stick–slip vibration. At the onset of slip, equilibrium between the elastic restoring force (due to this deformation) and the maximum static friction force yields $A_v \propto \max F_{Ni}$. Because the nail-mounted vibration causes A_v to increase abruptly, this mechanism gives rise to the illusory perception of a step edge, as illustrated in Fig.3(right). In this paper, we hypothesize that these estimated pressure fluctuations, together with the two fingers' relative positions, underpin shape perception.

Our model integrates the time-varying shear-direction stick-slip vibrations with the temporal fluctuations of the normal force vector $F_{Ni} = -(F_{pi} + F_{vi})$. Hashimoto et al. [4] reported that, when the vibrator's frequency is held constant while its amplitude is continuously increased over a single stroke, participants perceive the stroke's end point as higher than its start point. In our model, we assume that as the magnitude of this force vector, $\|F_{Ni}\|$, fluctuates over time, the difference between its peak values for the two fingers, $\|F_{N2,MAX}\| - \|F_{N1,MAX}\| = A_2 - A_1$, is proportional to the perceived step height d'_v. Under the assumption that the baseline pressing forces F_{p1} and F_{p2} are equal, this peak-value difference simplifies to $A_2 - A_1$. Accordingly, we posit that, under simultaneous two-point stimulation, the perceived step height is reconstructed as $d'_v \propto (A_2 - A_1)$.

IV. Shape Perception by Simultaneous Stimulation with Amplitude Difference

A. Methods

As shown in Fig.1 (right), participants performed back-and-forth tracing using nail-mounted tactile displays. A single 140[Hz], 50[ms] simultaneous vibrotactile stimulus was delivered at the midpoint of each stroke. Trials began with equal amplitudes, manipulating only $\Delta I = I_2 - I_1$. We labeled 50-stroke consistent reports as "stable" and any change or ambiguity as "unstable". Coil currents were recorded at each transition between stable (consistent perception) and unstable states, using current as a proxy for vibration amplitude($A_i \propto I_i$). After confirming a stable state, participants chose their perceived shape from the six step patterns shown on Fig.4 right.These were the same options as in our prior work [1]. The 95% confidence interval for response reliability in stable trials (Clopper–Pearson method) was [0.9289, 1.0000], indicating at least 93% consistency in shape perception. Three adults (2 M,1 F) participated.

B. Results

In Fig. 4 (Left), perceptual responses are classified into "spatially fixed steps" (S1, S2) and "Uncommon." We define spatially fixed steps as those perceived at the same spatial location but whose polarity reverses depending on tracing direction:

- S1: ascending on left→right, descending on right→left
- S2: descending on left→right, ascending on right→left

We computed each participant's ΔI thresholds for S1⇔ Uncommon and Uncommon⇔S2 (P1: $-486/144$[mA], P2: $9/383$[mA], P3: $-152/471$[mA]); in all cases, S1→Uncommon→S2 appeared in order.

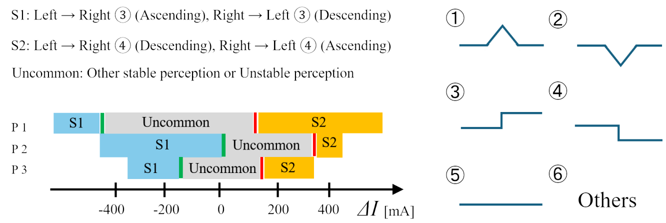

Fig. 4: (Left)Classification of stable percepts across ΔI. Light-blue segments denote S1 (ascending step on left to right strokes, descending on right to left strokes), gray denotes other stable/unstable responses ("Uncommon"), and gold denotes S2 (descending on forward, ascending on backward). Group-averaged boundaries (green: S1→Uncommon; red: Uncommon→S2) are plotted. (Right)Answer patterns from [1].

C. Discussion

In this study, we demonstrated that the polarity of the perceived step height d'_v (Fig. 3, right)—whether ascending or descending—can be arbitrarily switched solely by manipulating the amplitude difference $A_2 - A_1$ delivered to the two fingers. We attribute this illusion to participants interpreting the reduced temporal delay between stimuli as an abrupt vertical alignment of the fingers. These findings suggest a mechanism in which the sign of the perceived step is determined by the spatiotemporal integration of the vibrotactile amplitude difference across the two fingers.

V. Conclusion

We confirmed that varying vibration amplitude difference induces arbitrary step polarity. This supports that dual-finger shape perception arises from integrating amplitude differences across the two contact points.

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