The Predictive Perception of Dynamic Vibrotactile Stimuli Applied to the Fingertip*

John de Grosbois, Massimiliano Di Luca, Raymond King, and Mounia Ziat

***Abstract*— Because the world is dynamic in nature, sensory predictions are invariably important to successful interaction with it. The current experiment examined the influence of dynamic frequency information on the associated perceptions of simple geometric features. Participants were presented with short durations of vibrotactile stimulation to their fingertip across an array of oscillating pins. A pair of frequencies was used to simulate simple tactile edges across the array surface. Over a relatively short 'shift' duration, the frequencies at which these regions vibrated often switched spatial locations. Participants were required to indicate which of three possible shapes (left edge, right edge, or none) they experienced. The results were consistent with a predictive model of perceptual decision making in that responses were generally biased by the initial rather than the final configuration. Further, performance accuracy was maximized at the intermediate, 500-ms shift duration for a 10-158 Hz frequency pairing. This indicated that performance may be enhanced when larger frequency differences are used in concert with shift durations consistent with natural, exploratory movements.**

***Index Terms*—Predictive Perception, Vibrotactile Perception.**

I. Introduction

ALTHOUGH the utility of vision and visual information for the completion of simple everyday tasks is ubiquitous, valuable and informative sensory information can be attained via other sensory modalities such as touch [1]. As with vision, there are many distinct types of touch-based stimulation that can provide useful information to a perceiver [2]. One such example is the perception of vibration-based stimulation [3,4,5]. Indeed, unique mechanoreceptor populations in the skin have been observed to have preferential sensitivities to specific, and partially overlapping ranges of stimulation frequencies [6]. Given that different receptor populations have been arguably associated with different types of tactile features, modulations in frequency alone could conceivably be used to simulate different tactile stimulus features across space. Indeed, increases in frequency alone have been found to be associated with perceptions of a 'stronger stimulus' [7].

However, given the differences in sensitivity between receptor types, modulations of frequency alone are necessarily confounded with differences in relative stimulation magnitude. That is, the strict association between receptor types to changes in the frequency of vibrotactile stimulation holds for threshold values, but fails to persist for above-threshold vibrotactile amplitudes [8]. That is, if vibrotactile stimulation is provided at a consistently perceivable intensity, all main receptor populations would be active and dissociations between activity in different receptor populations could not provide sufficient information to drive perceptions of vibrotactile-based stimuli. Thus, under these circumstances, this 'labeled-line' approach to tactile perception is insufficient, and the more recent 'pattern-theory' provides a better potential explanation.

From a pattern-theory perspective, the tactile perceptions associated with supra-threshold vibrotactile stimulation create a specific pattern of activity within the central nervous system [e.g., see 1 for a review]. Distinct patterns of activity lead to specific perceptions, thus changes in the spatial distribution of frequencies of supra-threshold vibrotactile stimulation would therefore create a specific pattern of activation, despite the involvement of many, traditionally distinct receptor populations. Support for pattern-theory has been observed within neuron populations in the Cuneate Nucleus of the central nervous system (CNS) which plays a vital role in the transmission of tactile information to the CNS [e.g., 9].

Consistent with this prediction, transitions between areas of different frequencies have been utilized to generate perceptions of simple geometric shapes. That is, an area of one frequency of vibrotactile stimulation positioned adjacent to another area of a higher vibrotactile stimulation has been reported to be perceived as a rising-edge stimulus [10,11]. Thus, relatively complex patterns of stimulation have been successfully employed to yield the perception of tactile edges. Although these perceptions have been found to be more robust at larger frequency differences [10], this increase was non-linear in nature. Nevertheless, if a sufficient difference in frequency is presented, relatively predictable perceptions result, presumably through more distinct patterns of activation. Another potential means to enhance the distinctiveness of a particular pattern of activation is to provide stimulation in a dynamic, rather than the static contexts described above. Such static environments occur relatively infrequently under real-world

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John de Grosbois was with Northern Michigan University and is now with Baycrest Health Sciences, Toronto, ON, Canada. (jdegrosbois@research.baycrest.org).

Massimiliano Di Luca was with Facebook Reality Labs and is now with the University of Birmingham, Birmingham, UK. (m.diluca@bham.ac.uk).

Raymond King is with Facebook Reality Labs, Redmond, WA, (rking@fb.com).

Mounia Ziat was with Northern Michigan University and is now with Bentley University. Waltham, MA, USA, (mziat@bentley.edu).

circumstances. For example, patterns of activation invariably change due to changes in the environment, or movement of the individual. As such, the human central nervous system is often sensitive to such dynamic information. Further, changes in activation may even influence perception at the pre-attentive level [12]. If dynamic vibrotactile stimulation imparts its influence on perception via a pre-attentive processing, the associated perceptions may follow a predictive perceptual mechanism. That is, the ultimate perception may be more strongly influenced by the earlier, initial-state of a dynamic vibrotactile stimulus, rather than the end-state. Importantly, instances of predictive tactile perceptual decision making have been observed [13,14].

The purpose of the current study was therefore to evaluate the influence of a dynamic pattern of vibrotactile stimulation on the perception of frequency-based vibrotactile stimuli. The participant's main task on each trial was to identify which of three possible stimulus configurations they perceived on their index fingertip. On some trials the frequencies used to simulate an edge would invert on the tactile display over a duration of time ranging from zero to 1100 ms. It was hypothesized that dynamic information would lead to stronger perceptions of simulated edges, and therefore more consistent responding. Further, shorter shift durations were anticipated to yield more distinct patterns of activation, and therefore stronger associated perceptions. That is, faster changes in frequencies could generate a larger moment-to-moment contrast, leading to a more salient stimulus. Lastly, it was hypothesized that dynamic vibrotactile stimulation is processed in a predictive manner, and consequently perceptions should align with the initial-state of the pin frequencies, rather than the end-state as it has been observed in previous studies [13,14].

II. METHODS

A. Participants

Ten participants (6 females; mean age = 20.2 yrs, *SD* = 4.4) were recruited from the Northern Michigan University student population. Written informed consent was provided prior to commencement of the experiment. Participants were compensated with course credit. All experimental procedures were approved by the local institutional research ethics board.

B. Apparatus

Stimuli were generated using a custom vibrotactile stimulator device. This device housed an array of twelve (i.e., 4 wide by 3 deep) flat-topped pins with a 4.7 mm center-to-center spacing. The contact surface of each pin was circular-planar with a diameter of approximately 1.5 mm. (see *Fig*. 1). The overall stimulation surface subtended approximately 20 x 15 mm. A hand rest was positioned adjacent to the stimulator surface such that a participants' fingertip when placed, would extend along the shorter axis of the pin array. Participants also placed their elbow on a custom, cushioned arm-rest positioned I front of the hand-rest. This allowed the participant to maintain consistent-gentle pressure on the stimulator surface.

C. Stimuli

Stimuli were generated via vertical oscillatory motion in each of the pins, and when activated, the pin array delivered vibrotactile stimulation to the fingertip of participants for 2 s at a time. The individual pins were controlled moment-to-moment by a custom controller box connected to the experimental computer via an Ethernet connection. A Python 2.7 script was used to communicate with the controller box. This allowed for the presentation of dynamic patterns of vibrotactile stimulation across the surface of the fingertip.

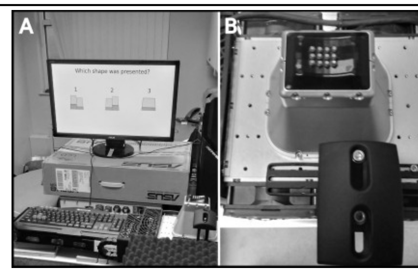

***Fig* 1. A depiction of the experimental setup. (A) The participant response screen with the three response-options. (B) A close-up view of the upper-surface of the pin-array device and the associated hand-rest.**

1) Stimulus Shape

Lim et al. [10] demonstrated a tendency to perceive regions of higher frequencies to be perceived as 'higher' surfaces. The current study made use of this phenomenon and employed three-stimulus frequency configurations (i.e., shapes) at the fingertip: 1) a left-to-right descending edge (Shape-1); 2) a right-to-left descending edge (Shape-2); and a flat no-edge surface (Shape-3) was employed as a control stimulus (see *Fig*. 2). Stimuli were delivered for a 2-s duration. Because Lim et al., [10] also reported a tendency for larger frequency differences between regions to enhance the associated perceptions, the current study employed two pairs of frequencies with which to generate the experimental stimuli (i.e., 10-158 Hz & 63-158 Hz).

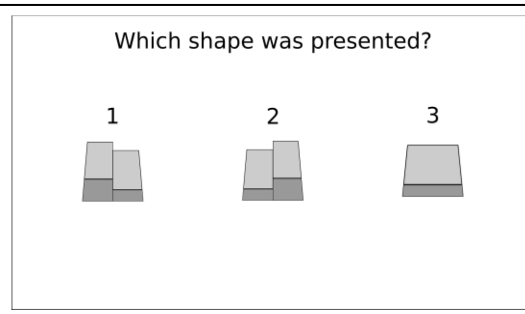

***Fig*. 2. A depiction of the three-presented stimulus shapes in the form of the 'response-screen' that was presented to participants at the end of each trial.**

2) Shift Duration

The second major manipulation utilized in the current study was a shift in the frequencies within the stimulus configurations over time. That is, the spatial arrangement of the frequencies used to simulate a shape could be gradually swapped during their presentation. For example, a left-side 10 Hz region could shift to 158 Hz over time (i.e., a shift-duration) while the right-side would see the opposite shift. A total of seven shift-duration conditions were deployed, some of which included frequency shifts over time: 1) a 0-ms shift; 2) a 100-ms shift; 3) a 500-ms shift; 4) a 1100-ms shift; 5) a no-shift; 6) a lower frequency of the pair control (i.e., one frequency across all pins); and 7) a higher frequency of the pair control (i.e., one frequency across all pins; see *Fig.* 3). The 100, 500, and 1100 ms shift-conditions included a transition period wherein intermediate frequencies were presented 100 ms at a time. These intermediate frequencies divided the difference between the initial component frequencies into equal steps. For example, with the 10-158 Hz frequency pair, a 100 ms shift condition included a single 100 ms interval where both regions delivered an 84 Hz stimulus prior to inverting to a 158-10 Hz configuration. All frequency shifts were temporally-centered within the 2-s stimulus interval. The specific shift durations were chosen such that all intermediate frequencies in the shorter duration shifts were also presented within the longer shift conditions (i.e., 1, 5 and 11 intermediate steps). Notably these shift-conditions were replicated across a manipulation of two initial-state possibilities. That is, the higher frequency could be initially presented on the left or the right.

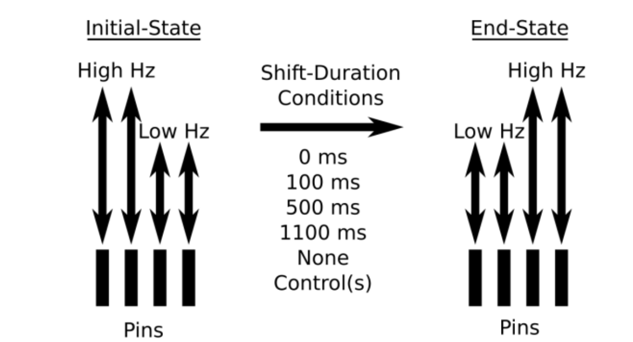

Fig 3. A depiction of the nature of the shift-conditions in the current experiment. The spatial location of the component frequencies within a pair switched over time.

These factors combined to yield 28 conditions (2 Frequency-Pairs × 2 Initial-State × 7 Shift-Duration). Note that the higher-frequency control condition provided the same stimulation for both Frequency-pairs (i.e., 158 Hz). Nevertheless, unique trials were completed for both conditions. In the interest of brevity and clarity, unique conditions will be referred to using the code in *Table* 1. For example, the 10-158 Hz Frequency-Pair with a left-to-right initial edge and a 500-ms shift-duration will be written as F1-HL-500ms. Note that aggregated mean values will use the appropriate subsets of these codes.

D. Procedures

Participants sat in front of the experimental computer that was interfaced with pin-array device. This device was located on a table immediately to the participants' right. They placed their right elbow upon a custom, padded arm-rest, their hand-upon the stimulator hand-rest, and their right-index fingertip across the central upper surface of the stimulator's pin-array. They were asked to maintain gentle contact with the pin-array surface by resting the weight of their arm upon the arm and hand-rests. In front of the participant sat a keyboard that was used to collect responses with their left hand (see *Fig.* 1).

Table 1. A depiction of the experimental factors and their associated condition codes.

Factor	Levels	Level-Codes
Frequency-Pair	1) 10-158 Hz 2) 63-158 Hz	1) F1 2) F2
Initial-State	1) Higher-Frequency on Left 2) Higher Frequency on Right	1) HL 2) LH
Shift-Duration	1) 0 ms 2) 100 ms 3) 500 ms 4) 1100 ms 5) No Shift 6) Lower-Frequency Control 7) Higher-Frequency Control	1) 0ms 2) 100ms 3) 500ms 4) 1100ms 5) None 6) LControl 7) HControl

Prior to the start of the trials, participants were presented with on-screen instructions. These instructions both explained the task and provided participants with depictions of the potential stimulus-response options. The trials began when participants reported an understanding of the procedures.Each trial sequence began with a message to the participant to depress the space-bar to initiate the stimulation sequence. Once the participant followed this instruction, the phrase "Get Ready" appeared upon the screen for 1 s followed by a "+" fixation cross. A randomized fore-period of 1 to 2 s was then implemented to ensure participants waited for the stimulus prior to initiating a response [15]. Next, a two-second trial stimulus was presented to the participant's stationary right index finger. Finally, participants were presented with a response-screen wherein they were tasked with selecting one of three possible stimulus configurations by depressing a numeral ranging from 1 to 3 on the keyboard (see Fig. 2). That is, participants' main task was to report which of the three possible stimulus configurations best represented what they perceived. This was posed as the question "Which shape was presented?". The three response options were a left-to-right descending edge, a right-to-left descending edge, and a flat surface. To ensure participants did not feel rushed, they were given ten seconds to input their response. In the event that a participant did not enter a response, the trial was automatically and randomly re-run later in the session (a total of 5 trials were repeated across all participants). Overall, participants completed a total of 168 experimental trials. These trials were divided into 6 repetitions of the 28 conditions. Each trial required around 10 s to complete and the total time in testing was between 30 and 40 minutes.

E. Dependent variables and statistical design

Given that participants responded with one of three-possible response options on each trial, the number of responses (i.e., response counts) for each option for each condition served as the primary dependent variable. The primary analysis was structured as a 3 Response-Option (i.e., Shape-1, Shape-2, Shape-3) × 2 Frequency-Pair (i.e., F1, F2) × 2 Initial-State (i.e., HL, LH) × 7 Shift-Duration (i.e., 0ms, 10ms, 500ms, 1100ms, None, LControl, HControl) repeated measures *ANOVA*.

Additionally, the predictive nature of the participants' responses was evaluated via an analysis of response accuracy in a 2 Frequency-Pair x 7 Shift-Duration repeated measures *ANOVA,* with accuracy, either determined by either the initial (i.e., evidence for predictive coding), or final (i.e., evidence for postdictive coding) stimulus configurations, whichever was higher.

Post-hoc analyses were followed significant statistical effects with a simple-main-effects approach. When multiple comparisons were carried out, the associated *p*-values were corrected on a family-wise basis using the Bonferroni procedure (i.e., number of comparisons corrected for is indicated in the subscript of the *p*-values, for example p_{b2}).

III. RESULTS

A. Response Counts

The analysis of response counts resulted in a significant main effect of Response-Option, $F(2,18) = 4.08$, $p = .035$, $\eta_G^2 = .084$, as well as three significant interactions: 1) Response-Option × Shift-Duration, $F(12,108) = 10.35$, $p < .001$, $\eta_G^2 = 258$; 2) Response-Option × Frequency-Pair $F(2,18) = 5.12$, $p = .017$, $\eta_G^2 = .049$; and 3) Response-Option × Initial-State, $F(2,18) = 8.16$, $p = .003$, $\eta_G^2 = .007$. See *Fig*. 4 for a depiction of mean average cumulative response counts across all experimental conditions.

1) Main Effect of Response-Option: Post-hoc Analysis

Post-hoc analysis of the main effect of Response-Option indicated that Shape-1 was selected significantly more often (i.e., $M = 2.26$, $SD = 0.66$) as compared to Shape-2 (i.e., $M = 1.39$, $SD = 0.46$, $p_{b3} = .019$).

2) Response-Option × Shift-Duration Post-hoc analysis

a) Shape 1 Responses

Post-hoc analysis of the Response-Option × Shift-Duration interaction for hape-1 revealed that Shape-1 was selected significantly less often in the HControl condition (i.e., $M = 0.55$, $SD = 0.59$) relative to all other levels of Shift-Duration except for the LControl condition (i.e., p_{b21}s < .015). Further, Shape-1 was selected significantly more often than Shape-2 for the LControl condition (i.e., Shape-1: $M = 1.90$, $SD = 0.97$; Shape-2: $M = 1.33$, $SD = 0.69$, $p_{b3} = .001$) and the None condition (i.e., Shape-1: $M = 2.40$, $SD = 1.32$; Shape-2: $M = 1.03$, $SD = 0.65$, $p_{b3} = .029$). Shape-1 was also selected significantly more often than Shape-3 for the 500ms condition (i.e., Shape-1: $M = 2.98$, $SD = 0.80$; Shape-3: $M = 1.03$, $SD = 1.18$, $p_{b3} = 0.021$), the 1100ms condition (i.e., Shape-1: $M = 3.13$, $SD = 1.11$; Shape-3: $M = 1.20$, $SD = 1.10$, $p_{b3} = 0.043$). However Shape-1 was selected significantly less often than Shape-3 for the HControl condition (i.e., Shape-1: $M = 0.55$, $SD = .59$; Shape-3: $M = 4.75$, $SD = 1.19$, $p_{b3} < .001$).

b) Shape 2 Responses

Beyond the Shape-1 differences outlined above, post-hoc analysis of the Shape-2 responses revealed a single significant difference. That is Shape-2 was selected significantly less often than Shape-3 for the HControl condition (i.e., $M = 0.70$, $SD = .71$, $p_{b3} < .001$).

c) Shape 3 Responses

Beyond the differences observed for Shape-1 or Shape-2 responses, post-hoc analysis of the Shape-3 responses yielded only a complementary set of differences to those

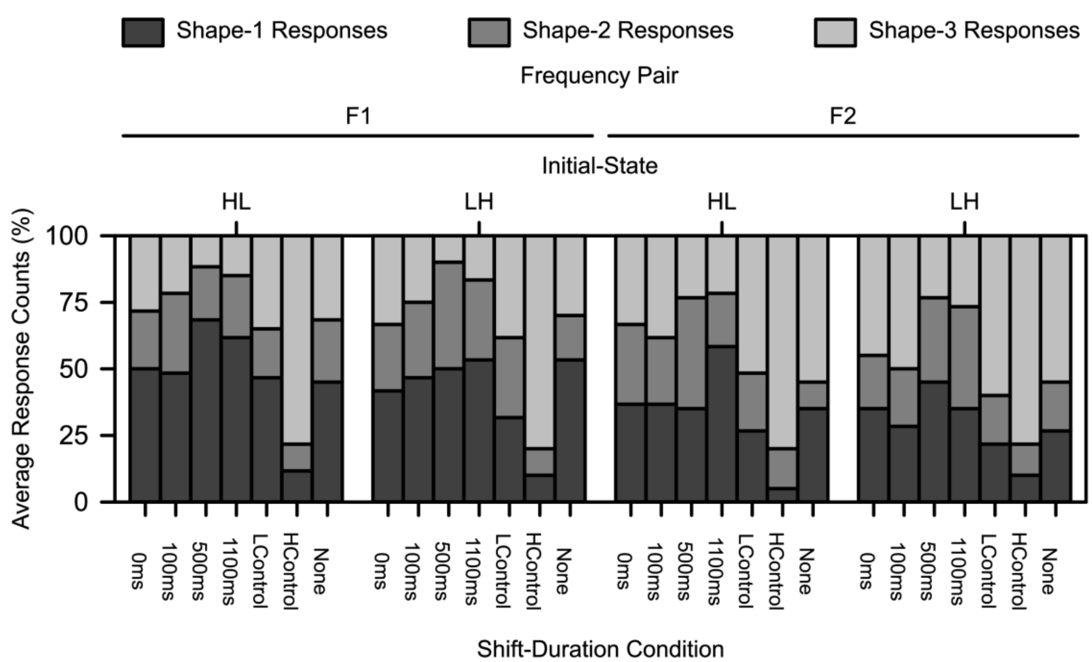

***Fig* 4. Average cumulative response-count percentage for all three response-options for all experimental conditions.**

observed for Shape-1. That is, Shape-3 was selected significantly more often when the HControl condition was presented, relative to all other Shift-Durations except for the LControl condition ($p_{b21s} < .048$).

3) Response-Option × Frequency-Pair Post-hoc analysis

Post-hoc analysis of the Response-Option × Frequency-Pair interaction resulted in a significant difference wherein for Frequency-Pair F1 Shape-1 was selected significantly more often (i.e., $M = 2.65$, $SD = 0.91$) than Shape-2 (i.e., $M = 1.40$, $SD = 0.45$, $p_{b3} = .030$).

4) Response-Option × Initial-State Post-hoc analysis

a) Shape-1 Responses

Post-hoc analysis of the Response-Option × Initial-State interaction revealed that when Initial-State HL was presented, Shape-1 was selected significantly more often (i.e., M =2.42, $SD = 0.76$) than Shape-2 (i.e., $M = 1.33$, $SD = 0.48$, $p_{b3} = .015$). Additionally, when Initial-State LH was presented, Shape-1 was selected significantly more often (i.e., $M = 2.09$, $SD = 0.58$) than Shape-2 (i.e., $M = 1.46$, $SD = 0.50$, $p_{b3} = .041$). This significant interaction, however, indicated that this Shape-1 advantage was significantly larger for the Initial-State HL conditions relative to Initial-State LH conditions. Lastly, considering only Shape-1 responses, Initial-State HL had been presented significantly more often than Initial-State LH (i.e., $p_{b3} = .005$).

B. Response Accuracy

Two preliminary, measures of response accuracy were computed: 1) based on the Initial-State; and 2) based on the End-State. Initial-State accuracy was found to yield significantly higher levels of performance (i.e., M = 45 %, $SD = .04$) relative to End-State accuracy (i.e., M = 41 %, $SD = .05$; $t(9) = 2.27$, $p = .049$, Cohen's $d = .718$. Further, 8 of the 10 participants exhibited this pattern, while one participant exhibited equal accuracy, and one showed the opposite pattern. Thus, the accuracy-based analyses continued with a 2 Frequency-Pair x 7 Shift-Duration repeated measures *ANOVA*.

This analysis revealed a significant main effect of Shift-Duration, $F(6,54) = 8.07$, $p < .001$, $\eta_G^2 = .379$, and a significant Frequency-Pair × 7 Shift-Duration interaction, $F(6,54) = 3.03$, $p = .013$, $\eta_G^2 = .076$. Post-hoc analyses were completed on both the main effect and the interaction (see *Fig.* 5 for a depiction of this interaction).

1) Main effect of Shift-Duration post-hoc analysis

Post-hoc analyses of the main effect of Shift-Duration indicated that performance in the HControl condition exhibited significantly higher levels of performance accuracy (i.e., M = 79.12 %, $SD = 19.84$) relative to the 0ms (i.e., M = 32.92 %, $SD = 13.53$, $p_{b21} = .009$), the 100ms (i.e., M = 33.75 %, $SD = 14.89$, $p_{b21} = .010$), the 500ms (i.e., M = 43.75 %, $SD = 13.21$, $p_{b21} = .044$), and the None Shift-Durations (i.e., M = 28.75 %, $SD = 17.94$, $p_{b21} = .011$).

2) Frequency-Pair× Shift-Duration post-hoc analysis

Post-hoc analysis within Frequency-Pair but across Shift-Durations largely mirrored the already described main effect above. One exception was the F1-1100ms condition, which exhibited significantly lower accuracy rates (i.e., M = 45.83 %, $SD = 17.68$) relative to the F1-HControl condition (i.e., M = 79.17 %, $SD = 22.31$; $p_{b21} = .042$). All other differences persisted in a comparable way to the above-described main effect within both Frequency-Pairs (i.e., $p_{b21}s < .043$). Contrasts across Frequency-Pairs indicated that there was a relative increase in accuracy for the F1-500ms condition (i.e., M = 54.17 %, $SD = 15.84$) relative to the F2-500ms condition (i.e., M = 33.33 %, $SD = 16.20$, $p_{b7} = .038$) only.

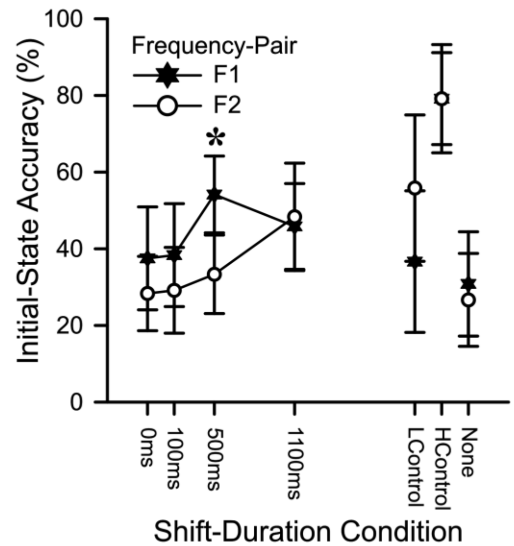

Fig 5. **Initial-State identification accuracy (%) as a function of Shift-Condition and Frequency-Pair. Error bars represent +/- 2 between-subjects SEM. "*" indicates *p* < .05.**

IV. DISCUSSION

The current experiment examined the influence of dynamic frequency information on perceptions of frequency-based simulated vibrotactile shapes applied to the fingertip. Specifically, it was hypothesized that dynamic frequency information would yield more robust patterns of neural activation that would in turn, lead to more consistent perception across participants. Further, more abrupt shifts in frequency were hypothesized to exhibit similar improvements in performance. Lastly, if perceptions of dynamic frequency information are associated with pre-attentive, predictive perceptual mechanisms, it was hypothesized that the perception of participants would bias towards the initial rather than the end stimulus states. Overall, some evidence was observed in support of these. That is, the only observed difference in accuracy within any of the dynamic stimuli was at the 500ms Shift-Condition between the 10Hz and 63Hz Frequency-Pairs. And secondly, there was, a tendency for participants to report the Initial-State of those dynamic stimuli, in support of a predictive perception mechanism.

This pattern of results is in agreement with the hypothesized influence of shifting the frequencies across time. Shifts in frequencies may have simulated the sensory consequences of a finger movement around a descending edge. As such, this additional congruent stimulus information may have simply enhanced the saliency of the simulated stimulus. However, it must be acknowledged that because the current study used a forced-choice task, the specific perceptions that participants experienced may not have explicitly matched these options. The absence of such specific appraisals, warrants alternative explanations.

Given that a majority of the participants' reports were more heavily influenced by the Initial-State stimulus configuration a predictive tactile perceptual mechanism was likely at work. Although predictive tactile perceptual mechanisms have been observed in the tactile domain, the majority of these have utilized active movements, with the sensory prediction stemming from movement-related forward models [13,14]. Indeed, postdictive perceptual mechanisms have also been reported in the tactile domain and have been observed during passive stimulation [16]. Thus, the current work showed that predictive perceptual mechanisms are also possible within passive circumstances. That said, the dynamic nature of the stimulation, i.e. rapid shift duration between frequencies from one side to another, may have created an illusory movement that could be similar to active conditions. Overall, these mechanisms may be driven by sensory expectations associated with classical conditioning [17]. However, future studies will be required to parse out this potential.

Although accuracy levels were lower than in previous studies using similar frequencies [10,11], the general trend of larger frequency differences yielding higher levels of performance accuracy was observed. Yet, the explicit analysis of performance accuracy only observed a significant difference in this direction between the two frequency-pairs at the 500 ms shift duration. Given that this difference was not maximized at the 0 ms Shift-Duration as hypothesized, indicated that the effect of the duration of changes in frequency did not monotonically enhance performance. Instead, there appeared to be an optimal duration for 'shift-speed' that enhanced performance. Notably, a 500 ms shift duration is relatively consistent within the range of durations associated with naturalistic exploratory movements [18]. Thus, simulation of dynamic vibrotactile edges stimuli may be enhanced by features delivered on timescales consistent with natural movements.

Yet, two limitations need to be acknowledged: 1) given the relatively small sample size, future work will be necessary to replicate and identify the parameters that maximize participant performance on the current task; and 2) the forced-choice nature of the current paradigm was restrictive regarding participant response options. Thus, replication of these findings using additional response paradigms would invariably strengthen the current findings. Nevertheless, the current experimental design and results have indicated that dynamic frequency information can systematically enhance the perception of vibrotactile stimulation in a predictive manner.

The current study evaluated perceptions associated with changes in the frequency of vibrotactile stimulation over time. Overall, the results offered preliminary support for a predictive model of vibrotactile edge perception. Also, these perceptions may be maximized with a combination of larger frequency differences with durations consistent with naturalistic movement-based stimulation. Thus, dynamic vibrotactile stimulation appears to be a viable route for the simulation of tactile spatial displays.

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