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The frequency of tactile adaptation systematically biases subsequent frequency identification*

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Abstract— **Exposure to a particular sensory stimulation for a prolonged period of time often results in changes in the associated perception of subsequent stimulation. Such changes can take the form of decreases in sensitivity and/or aftereffects. Aftereffects often result in a rebound in the perception of the associated stimulus property when presented with a novel stimulus. The current study sought to determine if such perceptual aftereffects could be experienced following tactile stimulation at a particular frequency. To this end, participants' perception of a 5 Hz standard frequency stimulus was evaluated using an adaptive staircase psychophysical paradigm. Participants' perception of the standard stimulus frequency was tested a second time following the adaptation to another stimulus frequency that was either lower (i.e., 2 Hz), the same (i.e., 5 Hz), or higher (i.e., 8 Hz) than the standard stimulus (i.e., 3 groups). Following adaptation, participants who received the 5 Hz or 8 Hz stimulation reported significantly lower estimates of the standard stimulus frequency relative to the 2 Hz group. Thus, the current work provides preliminary evidence that directional after-effects can be induced when the adapting stimulus is of equal or greater frequency relative to the test stimulus, but no such influence is observed when the adapting stimulus is less than the standard stimulus.**

I. Introduction

Vibrotactile stimulation has been of great interest as a means to augment human interactions with technology. For example, the simple addition of vibrotactile feedback enhances both the speed and accuracy of typing upon a touch screen [1]. Further, vibrotactile stimulation has been used to generate relatively complex sensory substitution displays [2,3,4]. The potential utility of such oscillating stimulation in practical settings may be limited by changes in the perception of the stimulation over time (e.g., adaptation). Accordingly, the time-course of adaptation and recovery for vibrotactile stimulation has been estimated to occur in the order of minutes [5]. Nevertheless, the perceptual ramifications of the associated adaptation have not been thoroughly explored. It is likely that prolonged exposure to such vibrotactile stimulation will result in dynamic shifts in perception. As long as such changes can be anticipated and accounted for, the utility of prolonged vibrotactile feedback in applied settings can be maximized. Thus, the current study evaluated the possibility that prolonged exposure to a specific tactile stimulation frequency would bias the subsequent perception of stimulation frequencies.

II. Sensory Adaptation and its Distinct Perceptual Outcomes

The utility of vibrotactile adaptation was first demonstrated by research supporting the multiple-channels of tactile processing hypothesis. That is, adaptation to specific vibrotactile frequencies generally impairs the perceptual thresholds associated with similar frequencies. The perception of these similar frequencies are believed to be mediated by similar receptor populations [6]. By contrast, stimulation at different frequencies, associated with different sensory channels, have not been found to be comparably impaired. That is, frequencies that are associated with different receptor populations do not exhibit comparable increases in their associated threshold values in response to adaptation at a different frequency. Thus, providing a prolonged vibrotactile stimulation may alter the subsequent activity of specific receptor populations to additional stimulation. Given that changes in spatially distinct distractor stimulus targeting distinct receptor populations have been observed to bias perceptions of the frequency of a test stimulus,

The potential utility of sensory adaptation has extended beyond the identification of distinct channels of sensory processing. Indeed, vibrotactile adaptation has also been found to alter perceptual discrimination abilities. Adaptation to a specific vibrotactile stimulation frequency has been found to enhance participants' ability to discern smaller changes in both frequency and amplitude [7,8]. Yet, these studies did not inherently rule out the possibility that vibrotactile adaptation may also shift the associated perceived points of subjective equality (PSE, i.e., the value at which the perception following adaptation is judged to be equivalent to a specific un-adapted stimulus). The possibility of these two potential effects (i.e., adaptation-induced changes in both JND and PSE) are not necessarily mutually exclusive. Strong evidence for adaptation-induced shifts in PSEs have been reported in studies utilizing visual motion stimuli [9, 10]. That is, adapting to a visual motion stimulus of a particular speed-of-motion, shifted participants' perception of the speed of subsequently presented visual motion stimuli away from the adapted stimulus speed. Such 'repulsive' adaptation effects can be imagined with the anecdotal example of the experience when one has just exited a freeway and perceives their speed current speed to be much slower than what is reported on the speedometer. These types of repulsive aftereffects have been observed in a variety of contexts for visual stimuli [e.g., 11]]. The possibility of comparable aftereffects in the tactile domain is supported by common neural architecture. For example, cortical area MT+ (Middle Temporal area, known as V5), which is traditionally associated with the processing of visual motion has also been found to be associated with the processing of haptically-derived motion cues [12]. Moreover, crossmodal motion-based aftereffects motion aftereffects have been observed between visual and tactile cues [13]. Thus, it is

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plausible that PSE estimates may shift in response to adaptation to a moving tactile stimulation. Given that increases in the frequency of a vibrotactile stimulus can be intuitively considered changes in the rate of stimulation, a comparable effect in the haptic modality is plausible. This possibility was tested by McIntyre et al., [14], who applied adapting stimuli in the form of rotating drums at different speeds as well as different spatial and temporal stimulation rates. Participants were subsequently required to determine which of two stimuli were moving faster. The authors reported repulsive aftereffects only when the adapting stimulus was greater than the standard stimulus, and argued that an 'intensive' coding was likely responsible for the associated perceptions. That is, the stronger the stimulus, the greater the degree of adaptation, and the larger the repulsive aftereffect. This type of adaptation can be contrasted with the possibility of adapting neurons exhibiting a tuning curve for a preferred speed. Such tuning curves were argued to have predicted repulsive aftereffects even for adapting stimuli of lower frequency than the test stimulus, which were not observed. One potential limitation of that study was the utilization of the rotating drums as a means to deliver the stimulation. That is, a paradigm using a rotating drum has been used to demonstrate illusory reversals in perceived motion and rebound aftereffects that were increased with increasing stimulus speed [15]. Thus, the directionality of the stimulation may have invariably altered the subsequent perceptions.

The current study therefore sought to replicate the findings of McIntyre et al. [14], using linear-oscillating (i.e., left/right), rather than rotating tactile stimuli. If the unidirectional repulsive aftereffects observed by McIntyre et al. [14] were based primarily on stimulus intensity and not related to stimulus direction, then a bidirectional oscillating stimulus should yield a comparable results. In the current study, participants' fingertips were exposed to an adapting left/right oscillating stimulus at a particular frequency and the subsequent perception of a standard stimulus frequency was examined. Adapting stimuli were provided to three groups of participants with unique stimulation rates: below, equal-to, or above the standard stimulus rate.

III. Experiment

A. Participants

Data from 21 participants (16 females; age range = 18 to 38; 18 self-reported right-handed) have been collected across the three groups (i.e., 7 participants per group). These participants were recruited from the Psychology student research study pool at Northern Michigan University and were compensated with course credit for their participation. All experimental procedures were approved by the local institutional research board.

B. Apparatus and Stimuli

The current study made use of simple medial-lateral (left-right) oscillating stimulation delivered to the participant's index fingertips (the upper one third surface of the fingerpad). These stimuli were delivered using a pair of NanoCube linear positioning systems (Model: P-611.3 Positioning System, Physik Instrumente, Karlsruhe, Germany) paired with two linear servocontroller boxes (Model: E-664 LVZPT Linear Position Controller, Physik Instrumente, Karlsruhe, Germany). Both NanoCubes were fitted with a 3D-printed cap, containing a flat tactile stimulus surface. The tactile stimulus surface measured 50 mm squared. Two finger-support structures were also utilized. These finger supports were positioned in front of the NanoCubes, and extended upwards a total of 58 mm (see *Fig.* 1 for an example of the experimental setup). The top surface of each support-had a cylindrical-downward indentation extending approximately 8 mm with a curvature radius of 15 mm. This combination resulted in the tactile stimulus surface on the NanoCube sitting approximately 1 mm above the lowest position of the top surface of the finger-support.

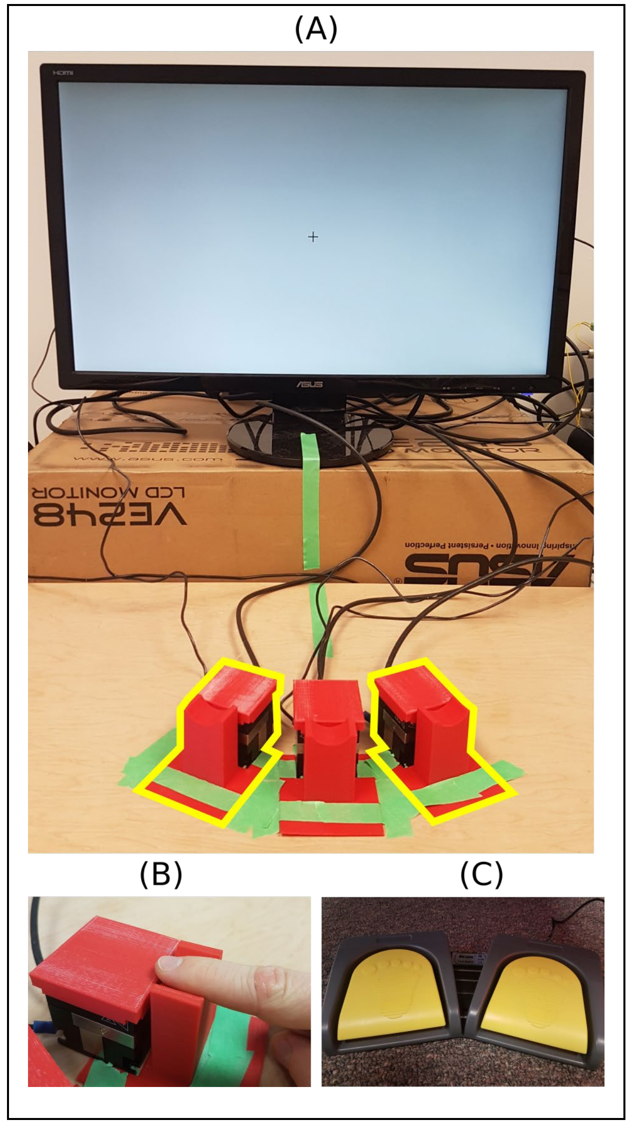

Figure 1. The organization of the experimental setup. (A) A pair of NanoCube vibrotactile stimulators were positioned approximately 20 cm apart (outer, highlighted in yellow). (B) The participant placed their index fingers on the two outer finger-supports such that the most distal 1/3 of the fingerpad gently contacted the stimulation surface. (C) Participant responses were recorded using two USB foot pedals positioned below the table.

The tactile stimulation applied to the fingertips via the NanoCubes was generated as sine waves that oscillated 50 µm in both the leftward and rightward directions (i.e., medial-lateral movement). The main manipulation in the current experiment was the frequency at which both NanoCubes oscillated during a 1-s stimulation period. The frequencies of stimulation delivered by the NanoCubes ranged from 0.5 to 15 Hz. The driving signals for these stimuli were generated though MATLAB at an output sample rate of 1000 Hz, and were routed to the NanoCubes as 0 to 10 V analog signals via a National Instruments 9264 cDAQ card (National Instruments, TX, USA).

Participant responses were recorded using a USB dual foot pedal device that simulated a USB keyboard button press (Model: FS2016_USB, IKKEGOL.com, Shenzhen, China; see Fig. 1C).

C. Procedure

All participants were tested within two blocks of trials. One block evaluated participants' perception of a standard stimulus frequency (i.e., 5 Hz) in the absence of an adapting stimulus (i.e., the baseline-condition; or 0 Hz adapting stimulus). Whereas, the other block evaluated the perception of the same standard stimulus frequency following a period of adaptation to another stimulation frequency (i.e., the adapting stimulus frequency; the post-adaptation block). Participants were randomly assigned to one of three adaptation groups associated with three levels of the adapting stimulus frequency (2, 5 and 8 Hz). The order of the two blocks (i.e., the baseline-condition block and the post-adaptation block) was randomized across participants.

During these two experimental blocks, participants were seated in front of a computer with their two index fingers placed upon two NanoCube actuators. These actuators were positioned about 20 cm to the left and right of the participants' midline and rotated approximately 40 degrees towards their shoulders. This positioning was chosen to maximize participant comfort during the experiment (see *Fig.* 1).

At the start of each block of trials, a 60-second adaptation interval elapsed wherein one of the two NanoCube actuators delivered the adapting stimulus frequency, while the other NanoCube remained stationary. The purpose of this initial adaptation period was to ensure that a sufficient level of baseline adaptation had been achieved prior to the initiation of the experimental trials [7,8,14]. The NanoCube that delivered the adapting stimulus was pseudo-randomly assigned and counterbalanced across participants (left or right fingertip). This assignment of the adapting NanoCube remained constant across both blocks of trials within each participant. The NanoCube that delivered the adapting stimulus also delivered the standard stimulus in the psychophysical staircase procedure that followed (i.e., standard cube; see cube 1 in *Fig.* 2), and the other cube delivered the associated comparison stimuli (i.e., comparison cube; see cube 2 in *Fig.* 2).

Each trial started with a 15-s period of top-up adaptation where the adapting stimulus was applied to the standard cube (cube 1 on *Fig.* 2). Next, following a 1-s delay, a 1-s -interval elapsed wherein the standard cube delivered the standard stimulus frequency (i.e., 5 Hz), and the other fingertip received the comparison stimulus frequency via the second, comparison cube (cube 2 on *Fig.* 2). This 1-s interval in which both NanoCubes (i.e., standard and comparison cubes) were

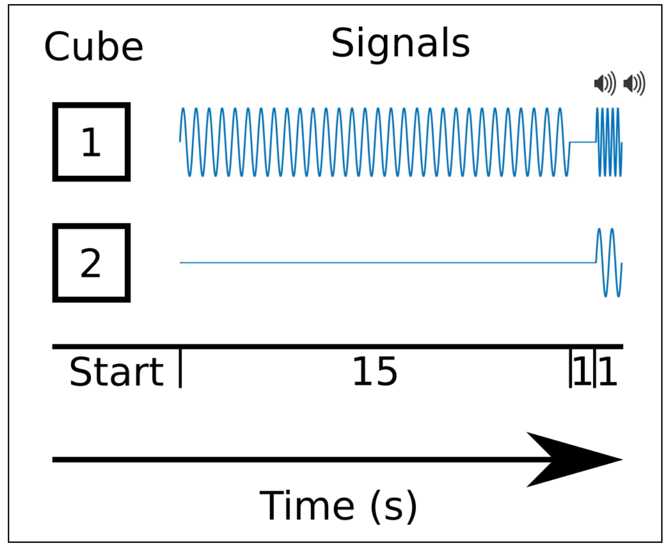

Figure 2. A depiction of the trial sequence. The standard cube (1) received the adapting stimulus for 15 s. Following a 1-s foreperiod, a 1-s interval elapsed wherein the standard stimulus (i.e., 5 Hz) was applied to the standard cube (1), and concurrently, the comparison stimulus was applied to the comparison cube (2). Next, the participants judged which cube had provided a higher frequency stimulation.

active was bounded by two beeps. Next, participants reported which of the two NanoCubes had delivered a higher frequency stimulus (i.e., which surface was moving faster; see *Fig.* 2 for a depiction of the trial sequence). On each trial, the frequency of the comparison stimulus (i.e., comparison cube) was determined via an adaptive staircase procedure with a step-size of 2 Hz. Each block of trials utilized two interleaved staircases. One of these staircases started at a comparison stimulus frequency value of 2 Hz, and the other staircase was initialized with at comparison stimulus frequency of 8 Hz. The ordering of these two staircases (i.e., 2 or 8 Hz first) was randomized across participants. The actual frequency of the comparison stimulus was restricted to a range of 0.5 to 20 Hz. The lower limit was chosen to prevent the delivery of a zero hertz stimulus, and resulted in the lowest step of the staircase being a magnitude of 1.5 Hz rather than the 2 Hz utilized otherwise [16]. The upper frequency limit of the comparison stimulus was chosen based on hardware limitations of the NanoCube system. That is, the system was not able to consistently generate comparable stimulus amplitudes beyond this frequency.

Both staircases started with a 1-up 1-down rule and continued with a 3-down 1-up rule for 25 trials after the first reversal. These parameters were chosen to ensure the efficient initial identification of the approximate location of the point of subjective equality [16] and subsequent convergence on a frequency representing the point at which the comparison stimulus would be chosen as the higher frequency 79.37 % of the time [17]. All staircase procedures were controlled from within the Palamedes toolbox in MATLAB [16].

To minimize carry-over effect of the previous adaptation from one block to the next, each participant was provided with a mandatory break of at least 5 minutes between the two blocks [5]. Following this break, participants completed their second block of trials, wherein the adapting stimulus was switched (i.e., either to the baseline-condition or the post-adaptation condition). Participants completed all the experimental procedures in approximately 60 minutes.

D. Data Analysis

The main dependent measures of the current experiment were the estimates of the point of subjective equality (PSE) and just-noticeable-difference (JND). Due to the relatively small number of trials the non-parametric Spearman-Karber method (e.g., [18], see *Fig.* 3) was utilized to generate estimates of the PSE and the JND. This method monotonizes the psychometric function and approximates the underlying cumulative distribution function, which allows for relatively simple estimates of PSE and JND [18]. That is the PSE is computed as the arithmetic mean of the monotonized psychometric function and the JND is computed by multiplyin the standard deviation of the cumulative distribution function by 0.6745 [18].

The main statistical analysis completed on both the PSE and JND values was a 3 Adaptation Group (i.e., 2, 5, & 8 Hz) x 2 Block (Baseline, Post-Adaptation) mixed ANOVA with Adaptation Group as a between-subjects factor, and Block as a within-subjects factor. Post-hoc analyses, where applicable, were completed using a simple main effects approach. That is, pairwise comparisons (i.e., *t*-tests) were completed across levels within the associated factors. The *p*-values associated with these pairwise comparisons were corrected-for using the Bonferroni correction on a family-wise basis. If Levene's test indicated that the assumption of homogeneity of variance was tenable for any between-group comparisons (i.e., across Adaptation Group levels), the pooled variance was utilized in determination of the *t*-values. Additionally, within-subjects 95% confidence intervals were computed to visualize the differences in means across conditions [e.g., 19].

It was hypothesized that if vibrotactile adaptation enhances only the just-noticeable differences, then the PSE values either should not shift, or should shift comparably irrespective of the adaption frequency (i.e., Adaptation Group). In contrast, if the adaptation frequency directionally shifts the subsequent vibrotactile frequency perception, then an adaptation-specific influence was expected. That is, lower adaptation frequencies should result in a higher subsequent perception of vibrotactile frequency, and high adaptation frequencies should show opposite pattern. Lastly, if the frequency is coded by an intensive code, then the higher, but not the lower adaptation frequencies should directionally shift the perceived frequency of the standard stimulus.

E. Results

The analysis of the PSE values resulted in a significant main effect of Block, $F(1,18) = 27.16$, $p < .001$, $\eta_G^2 = .200$, and most importantly in a significant interaction between Block and Adaptation Group, $F(2,18) = 4.16$, $p = .033$, $\eta_G^2 = .071$ (see *Fig.* 4). Post-hoc comparisons of PSE values across Adaptation Group within the Baseline Block revealed no significant differences (2 Hz: $M = 8.55$ Hz, $SD = 4.32$; 5 Hz: $M = 8.30$ Hz, $SD = 3.40$; 8 Hz: $M = 8.15$ Hz, $SD = 3.04$; $t(12)$s < 0.21, ps $> .999$). In contrast, comparisons across Adaptation Group in the Post-Adaptation Block revealed that the 2 Hz Group exhibited a significantly larger PSE value ($M = 7.92$ Hz, $SD = 3.68$) relative to both the 5 Hz and the 8 Hz groups (5 Hz: $M = 4.21$ Hz, $SD = 1.37$; $t(12) = 2.80$, $p = .047$; 8 Hz: $M = 4.11$ Hz, $SD = 2.21$; $t(12) = 2.81$, $p = .041$). PSE values for the 5 Hz and the 8 Hz groups did not differ significantly from one another (i.e., $t(12) = .07$, $p > .999$). Comparisons within Adaptation Group, but between blocks revealed no significant difference for the 2 Hz group ($t(6) = .56$, $p > .999$).

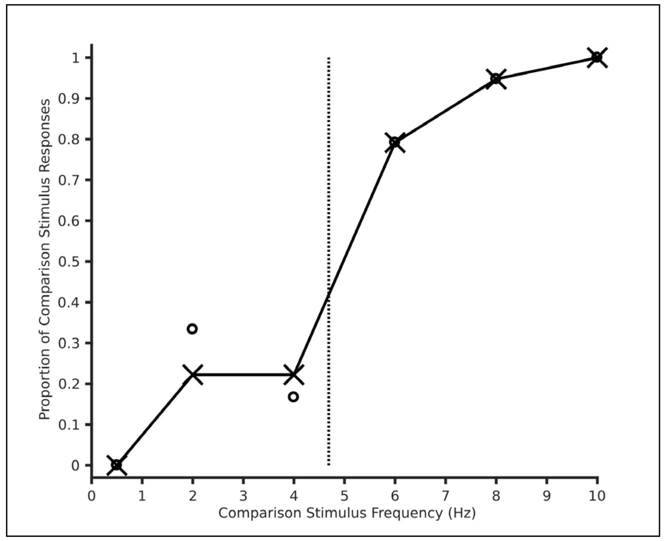

Figure 1. An example of the Spearman-Karber psychometric fitting methodology used for both staircases completed within one block for one participant. The circles represent the relative proportions of comparison stimulus responses for each associated level of comparison stimulus frequencies. The X's represent the monotonized estimates of these percentages, and the solid line represents the monotonized psychometric function. The dotted line represents the estimated PSE. The plotted data represents a single fit in the Baseline condition for a participant in the 5 Hz adaptation group.

However, both the 5 Hz ($t(6) = 4.48$, $p = .013$) and 8 Hz groups ($t(6) = 4.80$, $p = .008$) exhibited significantly smaller PSE values in the Post-Adaptation Block relative to the Baseline Block.

In contrast, the analysis of the JND values resulted only in a significant main effect of Block, $F(1,18) = 10.37$, $p = .005$, $\eta_G^2 = .119$ (see *Fig.* 5). This main effect indicated that JND values, on average, were significantly smaller in the Post-Adaptation Block (i.e., $M = 1.91$ Hz, $SD = 1.10$) relative to the Baseline Block (i.e., $M = 2.82$ Hz, $SD = 1.53$).

F. Discussion / Conclusion

The primary purpose of the current study was to evaluate the possibility of directional influences of adaptation to a oscillating tactile stimulus to subsequent perception of the frequency of oscillating tactile stimulation. Participants were separated into one of three groups and their perception of a 5 Hz standard stimulus was evaluated with and without adaptation to a pre-specified stimulus frequency (i.e., the Post-Adaptation and Baseline conditions, respectively). That is, some participants adapted to a 2 Hz stimulus (i.e., lower than the standard stimulus), some a 5 Hz stimulus (i.e., the same as the standard stimulus), and some an 8 Hz stimulus (i.e., higher than the standard stimulus). It was hypothesized that if adaptation in the current context reflected an intensive

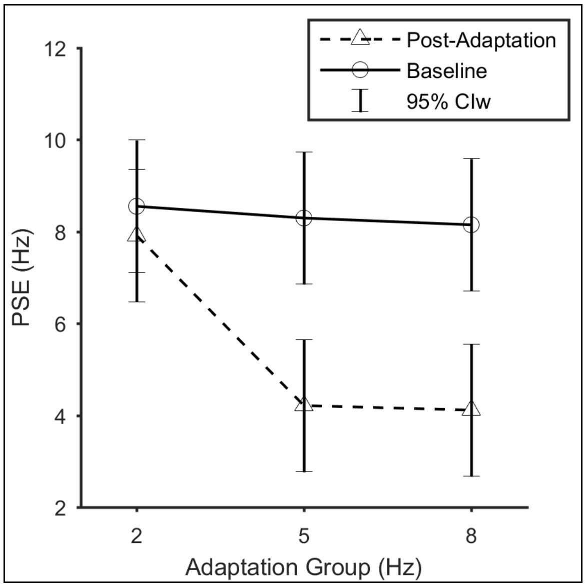

Figure 4. PSE estimates for each group as a function of experimental block. Error bars represent 95 % within-subjects confidence intervals. Significant differences were observed between blocks for the 5 and 8 Hz Adaptation Groups. Also, the 2 Hz Post-Adaptation condition exhibited significantly larger PSE values relative to the 5 and 8 Hz Post-Adaptation conditions.

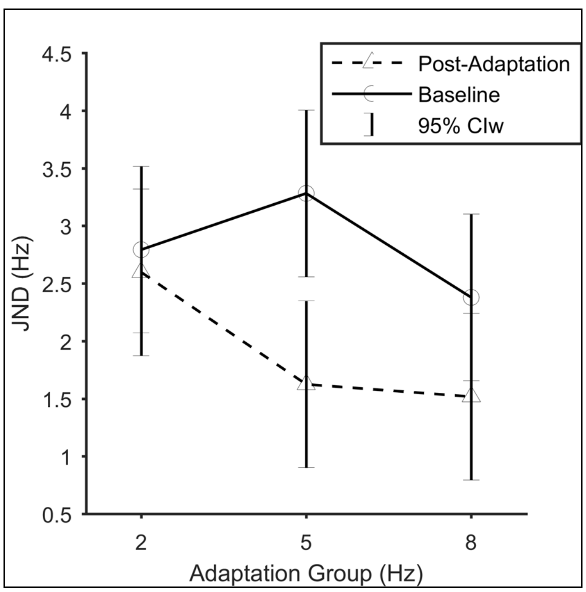

Figure 5. JND estimates for each group as a function of experimental block. Error bars represent 95 % within-subjects confidence intervals. A significant main effect of Block indicated that JND values, as a whole, were smaller in the Adaptation Blocks relative to the Baseline Blocks.

code as hypothesized by McIntyre et al., [14], then higher, but not lower adapting frequencies would bias subsequent frequency perception away from the adapted stimulus, rather than only alter sensitivity in general. Given that the amplitude of the oscillating stimuli was held constant across frequencies, higher frequency stimuli invariably provided a more intense stimulation. Overall, the results were highly consistent with the predictions of such a code. That is, following an adaptation to an 8 Hz adapting stimulus, the PSE associated with a 5 Hz standard stimulus was significantly lower relative to the PSE observed for the Baseline condition. Further, this PSE was also significantly lower than the PSE estimate achieved for the 2 Hz Post-Adaptation condition. However, the PSE associated with the 2 Hz Post-Adaptation condition was found to be not significantly different from its Baseline Condition. Lastly, the results for the 5 Hz adaptation condition mirrored those of the 8 Hz adaptation condition. Although this difference was statistically significant, the 2 Hz adapting stimulus did not exert a significant increase above and beyond performance in the Un-Adapted condition. This overall pattern of difference is highly consistent with the previous findings of McIntyre et al., [14]. That is, adapting frequencies of equal to or greater rates than the standard stimulus resulted in repulsive aftereffects in terms of the estimates of PSE. Thus, rotating continuous stimulation is not required to attain empirical support for an intensive code for tactile frequency perception. Indeed, the current results indicated that the use of a bi-directional oscillating tactile stimulus can achieve a comparable pattern of adaptation results regarding PSE estimates. Nevertheless, the currents study does not rule out the possibility of a directional influence on the observed adaptation. While a continuously rotating drum may lead to adaptation of a particular direction of tactile motion [15], it is conceivable that an oscillating tactile stimulus may lead to adaptation in both directions of motion of the stimulus pattern. To further ameliorate possible directional influence on the observed effect, future studies could employ the adapting stimulus in a rotated, orthogonal orientation to the standard stimulus, such that the directional overlap of stimulation between adaptation and test stimuli could be minimized.

One rather obvious caveat must be acknowledged regarding the PSE findings from the current study. That is, the reported PSE values for all three groups in the Un-Adapted block were significantly higher than the anticipated 5 Hz value. These estimates are less surprising given the combination of a 3-down one-up rule, which would have biased trials to generally higher comparison frequencies, and the relatively high task difficulty as evidenced by the relatively large JND values compared to the step sizes. Further, the longer staircase runs may have allowed for better convergence of estimates on the expected baseline values. The task difficulty was likely also enhanced by the presentation of both the standard and comparison stimuli at the same time within each trial. Beyond the intuitive increases in difficulty such a dual task invariably entails, the difficulty may have been further increased due to interference between the fingers themselves. That is, when judging the frequency of a vibrotactile stimulation to one finger in the presence of a distractor stimulation on another finger, estimates of the frequency tend to be biased towards the distractor frequency [20]. Despite the fact that both stimuli were task relevant in the current study, such a cross-finger influence may have increased the JNDs in general. Nevertheless, this influence was consistent across all adaptation groups, and therefore the conclusions that can be drawn from the differences between blocks remain valid.

In addition to the primary finding regarding the shifts in the PSE, a main effect of experimental Block was also observed for the analysis of the JNDs. That is, performance in the Adaptation block exhibited significantly greater level of discrimination (i.e., lower JNDs), which partially replicated the previous findings of Goble and Hollins [8] who reported that frequency discrimination improved when the adapting stimulus had a similar amplitude and frequency to the standard stimulus. However, Goble and Hollins [8] only utilized a single adaptation frequency to come to this conclusion. The current study indicated that such frequency discrimination enhancement may extend to adapting stimuli of higher frequencies as well. Although a main effect of Adaptation Block was observed in the current study, a visual examination of *Figure* 5 makes a rather compelling case that this enhancement may not extend to frequencies lower than the standard stimulus. Further research is required to strengthen this position. Yet, in the current study the adaptation to oscillating stimulation resulted in both shifts in the PSE and enhancement of the JND when the adapting stimulus was of an equal or higher frequency than the standard stimulus. Notably, the patterns of the PSE and the JND are quite similar and may indicate a rescaling of the JND in concert with decreases in PSE values (i.e., a relatively consistent Weber fraction). This apparent correspondence could be tested in future studies with a more comprehensive experimental design that includes a greater variety of adapting stimulus frequencies and significant increase in the number of trials. Although a similar enhancement of frequency discrimination was reported by Goble and Hollins [8], a comparable shift in the JND values for frequency discrimination was not reported by McIntyre et al. [14]. Thus, although the PSE results were mirrored in the current study, differences in the stimuli between these two studies may have inferred subtle differences in the nature of the associated adaptation.

Ultimately, the current study replicated repulsive shifts in PSE estimates consistent with intensive coding of frequency previously suggested by McIntyre et al., [14]. That is, despite a shift from continuous rotating-drum stimuli, to laterally oscillating stimulation, when the adapting stimulus oscillated at frequencies equal or greater than the subsequent standard stimulus, repulsive shifts in the PSE away from the adapting stimulus were observed. If the adapting stimulus frequency was lower then the subsequent standard stimulus frequency, no repulsive shifts in the PSE were observed. Further, enhancement of the associated JND for frequency discrimination followed a similar pattern. Thus, the current study showed that both the PSE and JND are influenced by frequency-dependent adaptation when interacting with a simple laterally oscillating stimulus. Overall, when prolonged exposure to oscillating tactile stimuli is unavoidable, perception can be best maintained at Baseline levels as long as the subsequent relevant stimulation oscillates at a greater frequency.

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