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Continuous Transition Impairs Discrimination of Electrotactile Frequencies

Shima Gholinezhad, Strahinja Dosen, and Jakob Dideriksen

Abstract— **Just-noticeable difference (JND), indicating the ability to accurately identify small differences in stimulation parameters, can be used to choose more sensitive stimulation methods as well as to calibrate tactile feedback in closed-loop human-machine interfacing. The JND is typically estimated using a forced-choice-discrimination task, in which two stimuli with different intensities are delivered separated by a brief pause. In the applications of tactile feedback, however, the stimulation parameters are typically modulated continuously. It is unclear if the discriminability of stimuli separated in time characterizes the ability to distinguish continuous changes in stimulation intensity. The present study compared the JND when pairs of frequency-modulated electrotactile stimuli were separated in time and presented continuously at two different baseline frequencies (20 and 60 Hz). The results showed that the JND was significantly smaller with time-separation between stimuli, but that the JND obtained with different types of transitions were in most cases linearly associated. In conclusion, the discriminability of time-separated stimuli is systematically better compared to that of the stimuli presented continuously. This can have an impact when calibrating the tactile feedback where the conventional method of the JND assessment might lead to an overly optimistic estimate of detectable changes.**

I. Introduction

The just-noticeable difference (JND) is a fundamental metric in psychophysical research, describing the minimum difference between two physical stimuli that can be perceived by a subject [1]. The JND is formally defined as a statistical quantity corresponding to the stimulus difference that can be discriminated in a certain percentage of trials. The estimation of the JND has been employed to characterize how humans perceive the intensity of tactile stimuli including temperature [2], pressure [3] and vibration [4], as well as the material properties of an object [5]. However, the JND has also been used in applied sciences, including the design of closed-loop human-machine interfaces. For example, tactile stimulation has been employed to partially restore somatosensory feedback to the user of a myoelectric prosthesis. Specifically, the amplitude or frequency of electrotactile [6], [7] or vibrotactile [8] stimulation delivered to the skin of the residual limb has been used to encode a sensory modality measured by the prosthesis sensors such as, e.g., grasping force. In this context, the JND was used to identify the most appropriate feedback design, based on the assumption that the stimulation strategy with the lowest JND will best support closed-loop prosthesis control by providing the highest resolution [9], [10]. Moreover, the JND was used to evaluate the quality of feedback originating from different sensory modalities during prosthesis control [11].

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Estimation of JND typically relies on the two-alternative forced-choice test [12], [13]. Specifically, a pair of stimuli with different intensities (test and baseline stimulus) is delivered to the subject in random order, and he/she is asked to indicate which stimulus (first/second) is perceived as being stronger (or higher in frequency). With decreasing difference in the stimulation parameters of the stimulus pair, the subject will progressively find it increasingly difficult to to correctly identify the stimulus with the higher parameter value, thereby indicating the JND. Different estimation methods vary in the way by which the test stimulus is modulated across trials [12], [13]. In adaptive/staircase procedures, the test stimulus level is determined by the subject's response (correct/incorrect) in the previous trial or trials. For example, if the subject successfully identified the stimulus with the highest intensity in the previous trial, the difference between the test and baseline stimulus in the next trial is decreased and vice versa for an incorrect guess. Normally, the test and baseline stimuli are presented sequentially separated by a brief interval without stimulation. There is no specific guideline on how to choose the pause between the stimuli and markedly different ranges have been used in the literature, i.e., 0.5-1 s [14], 1 s [6], [15] or >1 s [16].

Importantly, this way to present the two stimuli (separated in time) is fundamentally different from how tactile stimulation is modulated in most practical applications, including when providing feedback to a prosthesis user. The stimulation parameter that conveys feedback information (intensity or frequency) often changes continuously just like the relevant sensory modality. For example, when the user activates the flexor muscle, the prosthesis aperture will gradually decrease with the velocity proportional to the contraction intensity. The change in aperture will then be conveyed to the subject as a gradual modulation in the intensity and/or frequency of stimulation (artificial proprioception). Hence, it is unclear whether the magnitude of the JND, determined using the conventional approaches with a break between the stimuli, is an appropriate outcome measure for designing feedback in closed-loop human-machine interfaces. While the subject could discriminate the change in the parameters of the two stimuli when they are delivered with a pause in-between, he/she might not be able notice the same change when the parameters are modulated

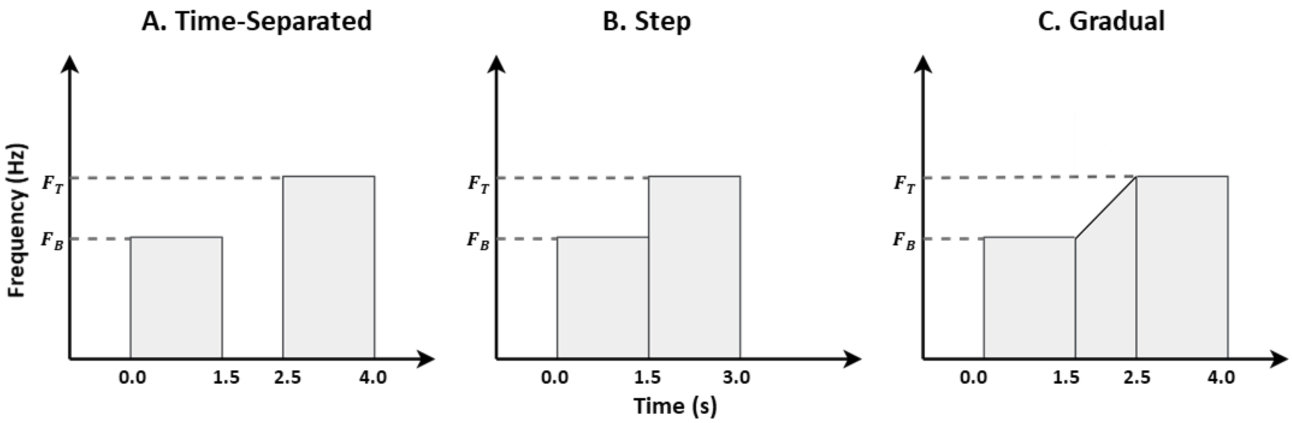

Figure 1. Illustrations of the three schemes for the transition between the two stimuli used to estimate the JND. In each trial, the subject received burst of stimulation at the baseline frequency (F_B) and test frequency (F_T). In these illustrations, the baseline is always presented first, but the order was randomized across the trials. After receiving both stimuli, the subject was asked to indicate if the first or the second pulse train had higher frequency. The frequency of the test stimuli was changed according to the subject's response. The two stimuli were separated by three different temporal transitions: *time-separated*, in which the two stimuli were separated by an inter-stimulus delay of 1 s (A); *step*, in which the pause between the stimuli was eliminated (B) and *gradual*, with a 1-s linear transition between the baseline and test stimuli (C).

gradually in a continuous fashion (or vice versa).

Therefore, in this study, we aimed to investigate whether the JND estimated classically with two time-separated stimuli predicts the ability of subjects to differentiate the same change in parameters when the transition between the stimuli is continuous**.** To this end**,** we measured the JND with separated or with continuous transitions between stimuli with different frequencies of electrotactile stimulation and compared the obtained values.

II. Method

A. Participants

Twelve healthy subjects (5 males and 7 females; age: 22.6 ± 1.9 years) were recruited. The experiment was conducted in accordance with the declaration of Helsinki and the subjects signed an informed consent form before commencing the experiment. The protocol was approved by the ethics committee of Region Nordjylland, Denmark (reference number N-20190036).

B. Experimental Setup

The experimental setup included a standard PC, a data acquisition board (DAQ: BNC 2090A, National Instrument, USA), and an electrical stimulator (DS8R Biphasic Constant Current Stimulator, Digitimer, USA) connected to a pair of stimulation electrodes (Dura-Stick Self-Adhesive Premium Stimulating Electrodes, 3.2 cm). The electrical stimuli were controlled by a PC using custom-made software in Matlab 2019a (MathWorks, USA) and Simulink. The analog output of a DAQ board was connected to the analog input (control channel) on the stimulator and the voltage signal generated by the DAQ was converted by the device into the current delivered through the stimulation electrodes. The generated stimulation pulses were square-wave, constant current, and biphasic compensated. Throughout the experiment, the subject was seated comfortably in front of a desk with the dominant forearm (self-reported) placed on the table surface. The stimulation electrodes were placed on the skin of the radial side of the forearm, one third of the length of the forearm measured from the wrist.

C. Experimental Procedure

The experiment consisted of two sessions performed on consecutive days to minimize the impact of cognitive fatigue. In each session, the subject's JND for stimulation frequency was estimated using three different stimulation schemes. During each trial, two stimulation pulse trains with different frequencies were delivered to the participant: one at the baseline frequency that was constant throughout the session, and the other at a test frequency that varied across trials according to the staircase procedure. The baseline and test frequency were presented in random order, and the subject was asked to indicate which of the two pulse trains had a higher frequency (two-alternative forced-choice test [13]). No auditory or visual cues that could point to the stimulus with the highest frequency were available to the subject. If the subject guessed correctly, the difference between the baseline and test frequency was decreased in the next trial and vice versa for an incorrect guess, as explained later. In one session, the baseline frequency was 20 Hz and in the other, it was 60 Hz. The order of the two sessions was randomized across subjects. We tested two baseline frequencies in order to evaluate subjects' discrimination ability across the range of frequencies typically used for sensory feedback design [7].

Prior to JND estimation in each session, the detection (DT) and pain thresholds (PT) were determined using the method of limits [17]. Specifically, a series of 1-s trains of stimulation pulses were delivered, separated by 0.5 s. The stimulation frequency was equivalent to the baseline frequency to be tested in that session (20 or 60 Hz). The stimulus pulse width was set to 500 µs in all conditions. To determine the DT and PT, the stimulation amplitude of the delivered pulse trains was increased from 0 mA in steps of 0.1 mA. The DT was defined as the lowest pulse amplitude producing detectable sensation, while the PT was the lowest current at which the subject perceived the stimulation as painful. Both thresholds were measured three times and the average values were adopted as the final thresholds. If the stimulation at any point during this procedure evoked radiating sensations or motor responses (muscle twitching), the electrodes were repositioned by 1-2 cm and the test was repeated. The pulse amplitude for the JND tests was set halfway between the DT and PT to ensure a clear and comfortable sensation.

To determine the JND, three different "transition" schemes were used to deliver the two pulse trains, as illustrated in Figure 1. In all the schemes, the two pulse trains lasted 1.5 s. In the conventional *time-separated* approach, the two pulse trains were separated by a 1-s pause. During the continuous *step* scheme, the second pulse train was presented immediately after the first (no pause). Finally, in the continuous *gradual* scheme, the two pulse trains were "separated" by a gradual linear transition between the two stimuli lasting 1 s.

To measure the JND for each transition scheme, the adaptive weighted staircase procedure was used [18]. The initial test frequency was 30 Hz (20 Hz baseline) or 90 Hz (60 Hz baseline). If the subject correctly selected the pulse train with the higher frequency, the test frequency for the next trial was decreased by 0.33 Hz (20 Hz baseline) or 1 Hz (60 Hz baseline). In case of a wrong response, the next test frequency was increased by 1 Hz (20 Hz baseline) or 3 Hz (60 Hz baseline). This procedure, in which the increment step size is 3 times higher than the decrement step size, implied that the estimated JND corresponded to the difference in frequency that the subject could recognize with a success rate of 75% [13]. The staircase procedure was terminated after 45 trials or until 15 reversals occurred, where the reversal was defined as the change from an increase to a decrease in frequency across two consecutive trials or vice versa (see Figure 2). In all but a single case, the subjects completed all 45 trials without reaching 15 reversals. The JND was then computed by averaging reversal points after trial 15 to avoid counting early mistakes. For each scheme, the staircase procedure was run twice and the order of the three schemes was randomized for each subject. The average across the two repetitions of each transition scheme was adopted as the JND and expressed as a percent of the baseline frequency.

D. Data Analysis

The main outcome measure was the subject's JND across the three schemes and the two baseline frequencies. We applied two-way repeated measures ANOVA with factors "scheme" and "baseline" and Bonferroni corrected post hoc analysis to compare mean JNDs across different conditions. Furthermore, linear regression was used to determine correlations between pairs of estimated values of the JND across the six conditions, as well as the correlation between the average JND for each baseline frequency across all transition schemes and the pulse amplitude used.

In addition, to evaluate the effective resolution of stimulation determined by the JND obtained in each transition condition, the estimated values of JND were used to compute the number of distinct intervals (NDI), as in a previous study [10]. The NDI refers to the number of frequency levels that can be discriminated by the subject within a specific range. The NDI was calculated iteratively according to the following equation:

$$I_{k+1} \longleftarrow I_k \cdot JND/100 + I_k$$

where I_k indicates the stimulation intensity and k counts the intervals. When computing the NDI, the used JND was the average JND across two baseline frequencies of 20 and 60 Hz for each subject, expressed as the percent of the baseline. Therefore, JND/100 corresponds to the Weber fraction. Initially, k was assigned the value of 1, with I_1 set to the predefined lower limit of the frequency range, and the iteration was terminated until I_k passed the upper limit of the frequency range. Once this happened, the NDI was set to the last value of k. The frequency range was set from 10 to 70 Hz, since an underlying assumption for the estimation of NDI is that the Weber fraction is constant across the range, which may not be the case for higher frequencies [7], [19]. The NDI values were compared between the transition conditions using one-way ANOVA. Prior to the analysis, the normality of data was tested using Shapiro–Wilk test. All p-values < 0.05 were considered significant. The statistical analysis was performed using R Statistical Software (version 3.0.2; R Foundation for Statistical Computing, Vienna, Austria).

III. Results

Figure 2 illustrates the staircase procedures for one subject across the three conditions at the baseline frequency of 60 Hz. The subject responded correctly in the several first trials in each condition since the test frequency was well above the baseline. When the test frequency decreased and approached the baseline, the subject started misrecognizing the test stimulus, leading to oscillations in the staircase. In this particular subject, the lowest JND at 60 Hz baseline frequency was observed in *time-separated* scheme (JND: 10.7 %) while it was harder to discriminate frequencies in *step* (JND: 16.6%) and *gradual* schemes (JND: 18.5 %).

This observation was consistent across most subjects as shown in Figure 3. The average JND was 11.8 ± 4.3 % (20 Hz baseline) and 12.3 ± 6.3 % (60 Hz baseline) in *time-separated* scheme, 17.0 ± 4.6 % (20 Hz baseline) and 17.9 ± 7.8 % (60 Hz baseline) in *step* scheme and 17.4 ± 7.1 % (20 Hz baseline) and 20.4 ± 8.7 % (60 Hz baseline) in *gradual* scheme. Consequently, the highest values of the NDIs were observed in *time-separated* scheme (19.1 ± 6.0), compared to *step* (13.5 ± 3.5), and *gradual* scheme (13.1 ± 4.8).

Repeated measure ANOVA revealed that the JND varied across the three schemes ($p < 0.001$) but not across the baseline frequencies ($p = 0.89$). Post hoc analysis indicated better discrimination ability in *time-separated* scheme than in the two other schemes ($p < 0.005$ for *step* and the *gradual* scheme, respectively). Similarly, the NDI was significantly higher for *time-separated* scheme compared to *step* ($p = 0.005$) and *gradual* scheme ($p = 0.002$). The JND and the NDI were not statistically different between *step* and *gradual* transitions.

Across most stimulation transitions, there were significant linear correlations between the estimated values of JND.

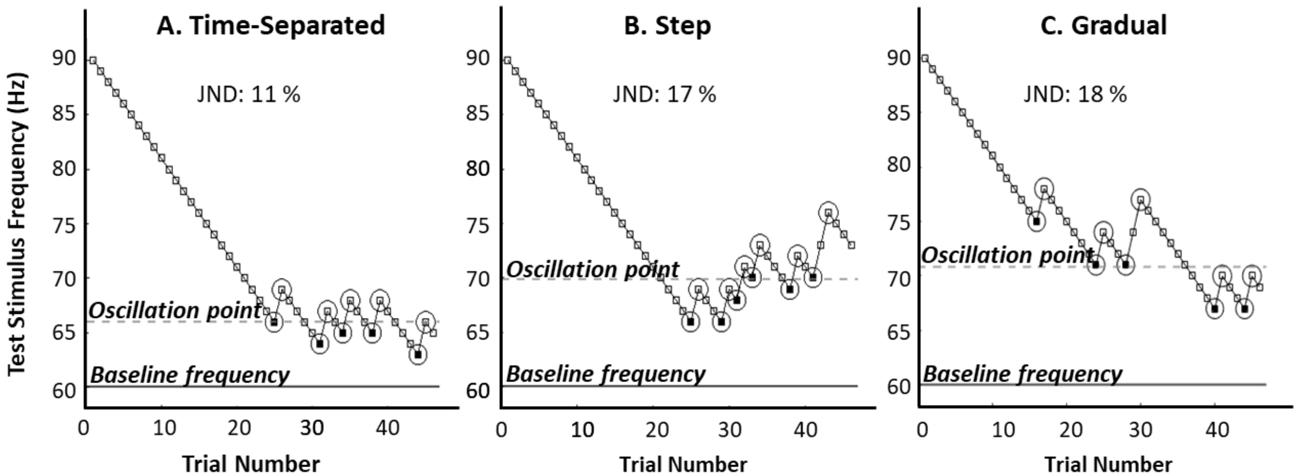

Figure 2. Illustrative examples from one repetition of the experiment with each of the three stimulation schemes (A: *time-separated*; B: *step*; C: *gradual*) for one representative subject. Each panel shows trial-to-trial variations in test frequency measured across the 45 trials. Correct and incorrect responses are indicated by the open and filled symbols, respectively. The dashed grey line indicates the oscillation level estimated by averaging stimulus intensities at reversal points.

Specifically, this was the case between *time-separated* and *gradual* schemes for both baseline frequencies (20 Hz: r^2 = 0.57, p = 0.003; 60 Hz: r^2 = 0.47, p = 0.01). Similarly, the correlation between *step* and *gradual* schemes were significant at both baseline frequencies (20 Hz: r^2 = 0.34, p = 0.02; 60 Hz: r^2 = 0.65, p = 0.002). However, between time-*separated* and *step* schemes, the correlation was significant only for the baseline frequency of 60 Hz (20 Hz: r^2=0.06, p=0.21; 60 Hz: r^2 = 0.68, p = 0.001).

The stimulation intensities used in the experiments were 3.4+0.3 mA for 20 Hz baseline and 3.2+0.4 mA for 60 Hz baseline. Across subjects, these values were not associated with the average JND computed across the three transition schemes (20 Hz: r2 = 0.10, p = 0.95; 60 Hz: r2 = 0.13, p = 0.98).

IV. Discussion

In this study, we investigated the effect of the transition between the two stimuli in a tactile discrimination task by determining the JND and the NDI in the stimulation frequency. The results showed that the temporal patterns of the stimulus pair significantly affected the obtained JNDs. Specifically, the discriminability of stimuli separated by a 1-s interval without stimulation (*time-separated* scheme) was better (i.e., lower JND and higher NDI) than when the two stimuli were delivered without the break (Fig. 3). In the latter case, whether the two stimuli were separated by a discrete step increase or a 1-s gradual linear transition had no influence on the JND. Therefore, it seems that the rate of change in the stimulation parameters does not have a significant effect on the discrimination ability, at least for the "slope" used in the present study. A longer slope might provoke adaptation and then further decrease the discriminability, but this remains to be tested.

Our primary motivation for the study was related to the use of the JND as a design criterion for the provision of tactile feedback in closed-loop human-machine interfaces. Specifically, the key question was if the ability to discriminate stimuli in the *time-separated* scheme (common procedure for estimating the JND) characterizes the ability to perceive those stimuli when it is modulated in a continuous way (common implementation of tactile feedback). We found that the sensitivity in discriminating the frequencies significantly decreased when the transition between the stimuli was gradual. Therefore, the conventional method of JND estimation might lead to an overestimation of the sensitivity of perception and hence of the expected feedback resolution. For instance, to ensure that the subject can recognize the changes in the delivered feedback, the stimulation levels (frequencies) can be calibrated so that functionally significant differences in the feedback modality are separated at least by the JND. However, if the conventional method is used to determine the JND, the subject might fail to perceive changes in the feedback levels of this magnitude, once the closed-loop control is activated and the feedback starts modulating continuously. Nevertheless, we also found that the JND obtained in the *time-separated* stimulation scheme was linearly associated with the values of JND in the two other schemes in three out of four cases. This means that the higher sensitivity, as revealed by the conventional method, still leads to higher sensitivity when using continuous transitions between the stimulations and vice versa. Therefore, while the conventional method is not suitable for feedback calibration, it can be validly used to choose the optimal stimulation strategy for a closed-loop human-machine interface, i.e., the strategy that is characterized by the best sensitivity (lowest JND) [9], [10]. It should, however, be acknowledged, that this study focused on frequency-modulated electrotactile stimulation and that it is unknown if the findings apply to other stimulation approaches. JND varies with modulation scheme (intensity vs. frequency) as well as stimulation methods [10], [15], [20]. Although it may be assumed that the dependence on the temporal transition of stimuli would be similar across stimulation approaches, since they all evoke tactile sensations, this needs experimental verification.

Discrimination of stimuli delivered at two different skin locations is worse when the stimuli are delivered

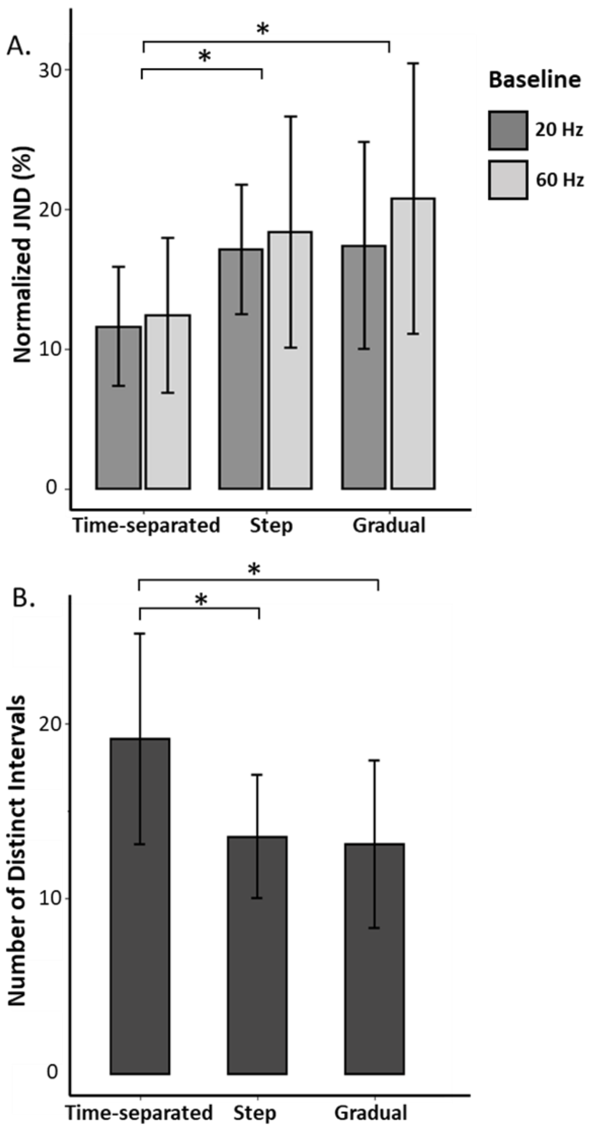

Figure 3. Average normalized JND across three stimulation schemes for the baseline frequency of 20 Hz and 60 Hz (A). NDI (B) was measured based on average JND across two baseline frequencies for each modulation condition. Error bars show average ± standard deviation and statistical significance was indicated by * ($p < 0.05$).

simultaneously than when they are separated in time (i.e., delivered sequentially with a pause in between). This has been demonstrated for estimation of the relative distance between the stimulation locations [21] as well as for the difference in stimulation intensity across the locations [22]. Similarly, the ability to discriminate stimulus location improves when the interval between the two stimuli is increased from 20 to 120 ms [23]. These observations are, on a general level, in agreement with the results of the present study, which found that the optimal discrimination of changes in frequency between two stimuli delivered sequentially to the same place requires them to be separated by an interval without stimulation. process. This may reflect that the central processing of the first stimulus (i.e. accurately perceiving its frequency) occurs over an interval of time, and that the arrival of additional similar stimuli within this interval disrupts this process. The existence of such a critical stimulus processing interval was demonstrated in a study that found that the ability to discriminate two vibration intensities (interval between the stimuli: 1.5 s) was impaired when transcranial magnetic stimulation was delivered to the contralateral somatosensory cortex to disturb the neural processing of the vibrotactile input within 0.6 s after the first stimulus [24]. However, when this disturbance was delivered after 0.9 s or more, the estimated JND was unaffected. Similarly, the accuracy of the estimated direction of finger movements across a surface decreased when it is followed by another motion [25]. This study found the estimation error to decrease gradually by >50% when the interval between the two motions increased from 0.1 to 0.8 s. Together these and our findings indicate that the neural processing required for accurate perception of a stimulus needs a "silent" period without an additional afferent input of the same type but of a different magnitude. On the other hand, the JND increases with intervals ≥ 5 s between tactile stimuli [26]. Together, this suggests that an accurate perception of the first stimulus, once formed is maintained only for a few seconds.

The values of JND found in the present study for *time-separated* electrotactile frequency-modulated stimulation (12-14%) were similar [15] or lower than the values of JNDs reported by previous studies using the same stimulation strategy, i.e., approximately 10-30% at a baseline frequency of 20 Hz, and approximately 20-30% at a baseline frequency of 60 Hz [7], [19]. Such variations may be explained by the fact that the sensitivity of tactile discrimination depends on many factors including stimulation intensity [12], location and size of the electrode [27], age [28], skin type [29], as well as the amount of training given [30]–[32]. The values of the NDI were similar to those previously reported [10]. In addition, we found that the normalized values of the JND within each stimulation scheme did not depend on baseline frequency (Fig. 3). Similarly, this has been found previously for vibratory stimulation at 20 and 40 Hz [33], while for electrotactile stimulation an increase in the normalized JND was reported for the baseline frequencies higher than those used in this study (>70 Hz) [7], [15], [19].

In conclusion, this study showed that the ability to discriminate differences in the frequency of electrotactile stimulation was better (i.e. lower JND) when the stimuli were separated in time compared to the two stimuli delivered in continuation. Similar observation would likely hold for the change in intensity of the stimuli and for the simultaneous modulation of both intensity and frequency, but this needs to be confirmed experimentally. More generally, the present study implies that for the practical applications of electrotactile stimulation it might be relevant to calibrate the feedback in the context that is closer to its use. Specifically, the JND should be determined by presenting the baseline and test stimuli according to how the stimulation will change during online closed-loop control (e.g., continuous transition). The next step in this line of research is to assess the robustness of these findings to changes in stimulation settings (e.g., different carrier intensities), stimulation modalities (e.g., amplitude modulation or vibrotactile stimulation), or stimulation locations. Moreover, it should be investigated if the JND estimated with step/gradual transition

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between stimuli predicts more accurately the performance in online control tasks by using one of the established test-bench paradigms for the assessment of closed-loop control (e.g., compensatory tracking [10], [34]) and/or an actual functional setup (e.g., prosthesis force control [35], [36]).

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