

## RESEARCH ARTICLE

## Sensory Processing

**Tactile sensitivity to missing tones in complex vibrotactile signals**Thanh-loan Sarah Le,<sup>1</sup> Gilles Bailly,<sup>1</sup> Eric Vezzoli,<sup>2</sup> Malika Auvray,<sup>1</sup> and David Gueorguiev<sup>1</sup><sup>1</sup>Institut des systèmes intelligents et de robotique, Sorbonne Université, CNRS, Paris, France and <sup>2</sup>Interhaptics, Razer Company, Lille, France**Abstract**

Haptic interactions with objects induce complex vibrotactile signals that are central to tactile perception. Despite the broad literature on vibrotactile perception, surprisingly little is known about the sensory processing of complex tactile signals made of multiple pure tones. To fill this gap, the study reported here investigated the impact of the constitutive pure tones of a complex vibrotactile signal on its perception. Participants completed a three-alternative forced choice (3-AFC) task in which they were asked to identify an odd signal among two complex references. The odd signal was created by removing one pure tone from the reference, which varied in spectral composition, harmonicity, and interfrequency intervals. Each reference signal was made of either two, three, or four pure tones. The results revealed that the removed pure tone's value as well as the interfrequency interval play a significant role in participants' performance whereas changes in harmonicity and complexity have little impact. The smaller the ratio between the removed frequency and the lowest one of the reference signals, the better the participants' capacity to identify the signal with the missing tone. As this ratio correlates with that of pure tone's perceived intensity, participants' performance can be linked to either of them. Analysis of a subset of complex signals made of pure tones perceived with roughly equal intensity showed that the correlation still holds but slightly decreases. Overall, these results suggest that perception of complex vibrations might be mediated by tactile mechanisms related to both frequency selectivity and pure tones' perceived intensity.

**NEW & NOTEWORTHY** This research investigates the respective roles of frequency range, harmonicity, and complexity on human perception of vibrotactile signals. The results revealed that only pure tones that are close to the lower frequencies of the complex vibration are noticed when they are missing. This finding sheds new light on the mechanisms underlying the tactile perception of complex vibrations.

*complex vibration; harmonicity; interfrequency interval; psychophysics; tactile perception*

**INTRODUCTION**

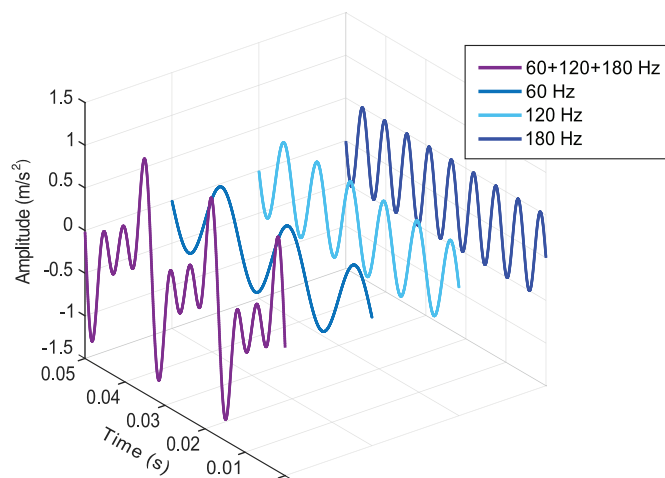
When a finger moves to explore a surface, the ensuing sliding contact elicits vibrations on the skin, which exhibit complex waveforms (1). These vibrational cues mediate the richness of tactile perception (2, 3) by endowing perceptual attributes like roughness, friction, or hardness (4, 5). Moreover, temporal codes related to the complex vibrotactile signals elicited during touch have been suggested to mediate the perception of natural textures (6, 7). Extensive research within the realm of tactile sensation has delved into the domain of vibrotactile perception, but our comprehension remains mostly limited to simple signals made of a single frequency. Research on such simple signals has shown that

humans are sensitive to both frequency and amplitude variation, commonly associated with the psychological percepts of pitch (8, 9) and intensity (10, 11), respectively. Humans can discriminate differences in frequency that range between 3% and 50% depending on the experiment's characteristics (8, 12–15). For diharmonic waves, a 9% difference in the frequency of sinusoidal vibrations was noticeable irrespective of the amplitude (16), and most studies observed that perception of differences in frequency mostly follows Weber's law (13–15, 17). Moreover, frequencies also differ by their perceived intensity at a given acceleration, which is larger for lower frequency (11, 18).

A complex signal is made up of several pure tones, each of them with its own amplitude and frequency. The sum of

these signals creates a specific waveform that is shaped by the interferences of these individual pure tones (see Fig. 1). Research has revealed that the perception of complex signals is influenced by the number of frequencies composing the signal. Notably, differentiating between two complex signals has been shown to be more difficult than between two simple signals (17, 19). The stimulated tactile channel also exerts an impact on the perception of complex signals (20). Indeed, participants are more sensitive to phase shifts in complex signals that are composed of low frequencies (10 and 30 Hz), evoking a flutter sensation, which targets the rapidly adapting type 1 receptors, compared to high frequencies (100 and 300 Hz) evoking vibratory hum sensations, which target Pacinian receptors. These results suggest that the Pacinian channel is insensitive to phase variations, whereas non-Pacinian channels encode them. The disparate sensitivity of tactile channels might also explain why simple signals characterized by sinusoidal waveforms are perceptually distinct from square and sawtooth waveforms at a given frequency because the latter are accompanied by multiple harmonics (21). Interestingly, it has been found that the capacity to discriminate between pure tones made of distinct frequencies decreases when two to-be-compared signals are complexified with the addition of a signal at 100 Hz (17). Moreover, two vibrotactile signals can elicit identical perception even if they diverge in terms of amplitude and constitutive frequencies (16, 19). For example, a pure tone is not discriminated from a diharmonic vibrotactile signal when the pure tone is higher in amplitude or when it is larger than the fundamental frequency of the diharmonic signal due to sensory masking (16). It has also been shown that the pitch of a two-tone vibration can be matched with a simple pure tone that is closer in frequency to the lower of the two tones (22). Similar research showed that the pitch of a frictional texture containing two spatial frequencies can be perceptually matched by a simple sinusoidal texture of intermediate frequency (23).

A complex signal is considered harmonic when all its frequency components are integer multiples of its fundamental frequency, and this characteristic has been investigated as a plausible cue for differentiating complex signals (24, 25).



**Figure 1.** Example of a complex signal (60 + 120 + 180 Hz) obtained by superimposing sinusoidal waveforms at 60 Hz, 120 Hz, and 180 Hz.

Picinali et al. (24) found that the addition of a nonharmonic frequency to a simple sinusoidal signal is better discriminated than the addition of a harmonic frequency. This work suggested that nonharmonic sequences inherently yield greater discriminability, probably due to the emergence of amplitude beats. Russo et al. (25) showed that humans are capable of differentiating between cello, piano, and trombone tones played on their back with matching fundamental frequencies but instrument-specific harmonics. These studies highlight the influence of the vibrotactile signal's harmonic content on its perception by humans.

The abovementioned studies have investigated the influence of frequency, amplitude, and harmonic content on tactile perception; however, they mainly focused on signals composed of at most two frequencies. In addition, most of them only featured signals above 100 Hz, hence predominantly in the range of the Pacinian channel. Although a few models have been proposed (17, 19), no general explanatory mechanism of the human perception of complex vibrations has emerged. In this context, the present study aims to investigate the detection of a missing pure tone from complex signals by implementing conditions that vary signals' harmonicity, distances between frequencies within the signal (interfrequency interval), and frequency ranges of the pure tones composing the signal. These signals consisted of two, three, or four sinusoidal signals. The first experiment tested the hypothesis that noticing missing tones from nonharmonic reference signals would be easier to detect compared to harmonic ones because of a stronger impact on the amplitude beats, which are typical of nonharmonic signals. On the basis of the literature on discrimination between two-tone and one-tone signals, we hypothesized that removal of tones with higher position within the complex signal, which correspond to higher frequencies, will be less accurately perceived. Finally, we tested the interactions with the reference signals from which pure tones were removed since their properties varied depending on the tones that composed them. Frequencies in that experiment activate both the non-Pacinian and Pacinian channels. The second experiment tested the hypothesis that when signals have larger interfrequency intervals hence spread over a wider range of frequencies, removing tones would generally be more noticeable because of a more impactful change on the balance of the complex signal. It was expected that removal of tones with higher position within the complex signal would be less accurately perceived. Thus, the position of the removed pure tone was tested as a potential factor impacting perception as well as the reference signal, which was expected to impact discrimination mainly when intervals between tones are larger. That experiment implemented signals that predominantly activate the Pacinian channel. Hence, a large number of complex signals were tested in *Experiments 1* and *2*, enabling us to investigate the potential role of the ratio between the removed pure tone and the lowest frequency of the signal. Given the results from *Experiments 1* and *2*, a third experiment was conducted to measure the perceived intensities of the pure tones from which complex signals were made to assess their potential impact on signal discrimination.

## MATERIALS AND METHODS

### Participants

Three experiments were conducted separately in time. The procedure, materials, and methods were the same for *Experiments 1* and *2*, with different vibrotactile signals. Twelve participants (3 women and 9 men; mean age 25.3 yr, SD = 3.5) completed *Experiment 1*, and 12 participants (2 women and 10 men; mean age 26.6 yr, SD = 2.8) completed *Experiment 2*. All participants from the first experiment were contacted for participation in the second experiment, and eight of them agreed to do so. Participants were compensated 20 euros to complete each experiment, which took ~2 h. Ten additional participants (4 women and 6 men; mean age 26.6 yr, SD = 1.8) completed *Experiment 3*, which lasted ~10 min. The experiments were approved by the Research Ethics Committee at Sorbonne Université under approval CER-2021-104 and were conducted in accordance with the Declaration of Helsinki.

### Apparatus

An actuator, i.e., a voice-coil vibrator specifically tuned for haptic stimulation (Tactuator MM3C-HF; TactileLabs Inc.), delivered the various vibrotactile signals used in this study. The vibrotactile signals consisted of .wav files generated by a MATLAB (MathWorks, Inc.) script, and they were verified by a fast Fourier transform (Fig. 2A). Vibrotactile pure tones were equalized to reach a peak acceleration amplitude around 7 m/s<sup>2</sup>, which is well above the human vibrotactile threshold (26), by estimating a Bode diagram expressing the acceleration amplitude at each frequency. The Bode diagram was obtained by measurements from an accelerometer (PCB Piezotronics Accelerometer 352A24) attached to the actuator and hung by nylon strings to avoid resonant coupling (Fig. 2, B and C). The signal delivered by the actuator shifted in phase depending on the frequency due to the magnetic characteristics of the actuator (Fig. 2C). No distortions of the

signal were observed after acceleration measurements on the actuator.

### Stimuli

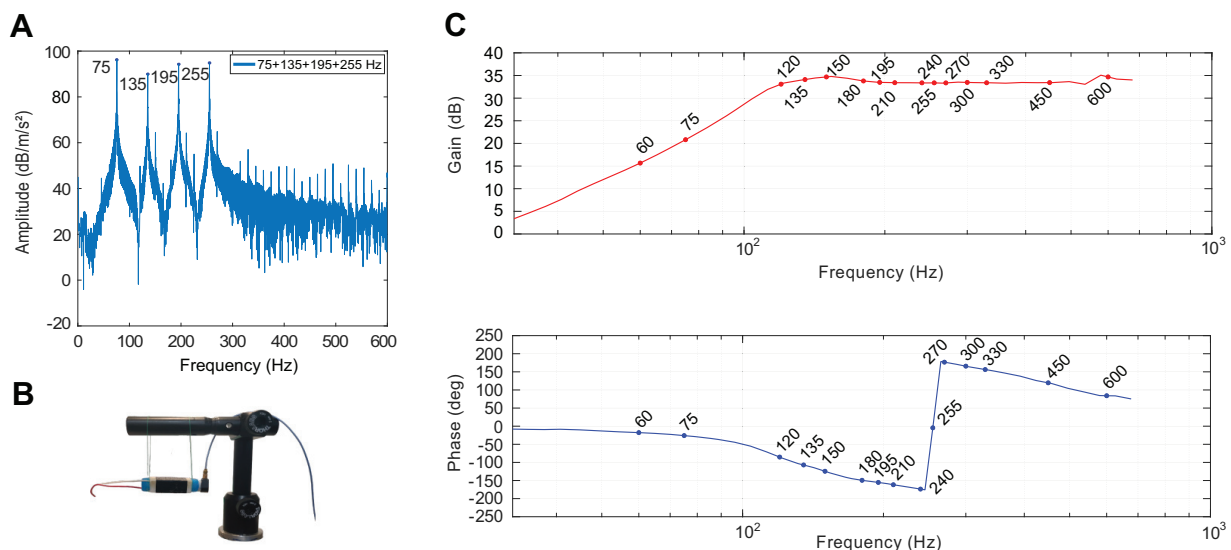
In each experiment, participants were presented with either a reference vibrotactile signal made of two, three, or four tones or a target vibrotactile signal that is identical to the reference one except for the removal of one of its pure tones (see Table 1, top). All signals followed the equation

$$y = \sum_{i=1}^n A \sin(2\pi f_i t + \varphi_i)$$

where  $A$  represents the amplitude (7 m/s<sup>2</sup>),  $f_i$  the frequency in hertz,  $\varphi_i$  the phase of each frequency (Fig. 2C) expressed in radians, and  $n$  the signal complexity (1, 2, 3, or 4). Two sets of pure tones ( $n = 4$ ) were used in each experiment (see Table 1). For each set, 11 reference signals were built based on complexity levels, with 1 reference signal having four pure tones, 4 reference signals having three pure tones, and 6 reference signals having two pure tones. Given the 44 reference signals for the two experiments, 56 different target signals can be derived, resulting in 112 different possible comparisons between a reference and a target: four tones versus three tones (16 comparisons), three tones versus two tones (48 comparisons), two tones versus one tone (48 comparisons). For more clarity, these comparisons are called “Four-tones”, “Three-tones”, and “Two-tones”, respectively, in line with the number of pure tones in the reference. As an example, the reference three-tone complex signal 75 + 195 + 255 Hz can only be compared with three two-tone targets, 75 + 195 Hz, 75 + 255 Hz, and 195 + 255 Hz (see Fig. 3A). Table 1 summarizes all the signals used in the study.

### Experimental Procedure

In the two experiments, the participants performed a three-alternative forced choice (3-AFC) task, which has the



**Figure 2.** A: fast Fourier transform of the complex signal 75 + 135 + 195 + 255 Hz. B: actuator with the accelerometer glued to one lateral side is suspended by nylon strings. C: Bode diagrams representing gain and phase of the vibrations delivered by Tactuator MM3C-HF as a function of the delivered frequency.

**Table 1.** Stimuli used for each experiment

		Comparisons			
Two-tones		Three-tones		Four-tones	
Reference	Target	Reference	Target	Reference	Target
2 tones	1 tone	3 tones	2 tones	4 tones	3 tones
Condition		Signals		Signals	
		1 tone	2 tones	3 tones	4 tones
Experiment 1: Harmonicity	Harmonic	60	60 + 120	60 + 120 + 180	60 + 120 + 180 + 240
		120	60 + 180	60 + 120 + 240	
		180	60 + 240	60 + 180 + 240	
		240	120 + 180	120 + 180 + 240	
			120 + 240		
	Nonharmonic <sup>1</sup>	75	75 + 135	75 + 135 + 195	75 + 135 + 195 + 255
		135	75 + 195	75 + 135 + 255	
		195	75 + 255	75 + 195 + 255	
		255	135 + 195	135 + 195 + 255	
			135 + 255		
Experiment 2: Interfrequency interval	Small-inter <sup>2</sup>	150	150 + 210	150 + 210 + 270	150 + 210 + 270 + 330
		210	150 + 270	150 + 210 + 330	
		270	150 + 330	150 + 270 + 330	
		330	210 + 270	210 + 270 + 330	
			210 + 330		
	Large-inter <sup>2</sup>	150	150 + 300	150 + 300 + 450	150 + 300 + 450 + 600
		300	150 + 450	150 + 300 + 600	
		450	150 + 600	150 + 450 + 600	
		600	300 + 450	300 + 450 + 600	
			300 + 600		
	450 + 600				

Top: comparisons. Bottom: references and target signals. <sup>1</sup>In the NONHARMONIC level, the set of pure tones is identical to HARMONIC except that 15 Hz was added to each of pure tones to make the stimuli nonharmonic. <sup>2</sup>The distance between 2 consecutive pure tones is either 60 Hz or 150 Hz.

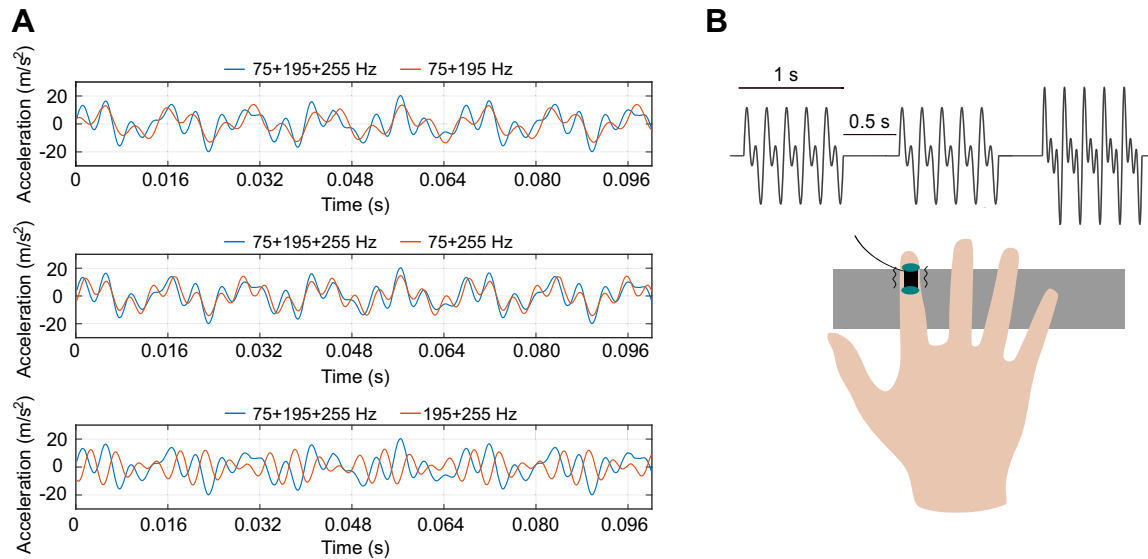
advantage of not forcing the experimenter to establish a dimensionality of interest before the experiment. The participants were comfortably seated with noise-canceling headphones that masked extraneous noise. The actuator was placed on the dorsal part of the intermediate phalange of their right hand's index finger, attached with a plaster (Fig. 3B), to avoid potential pressure being exerted on it. This configuration ensured a more practical contact surface and enabled the finger to comfortably rest on foam during the experiments. Moreover, the actuator was not touching the nail, to avoid undesired resonant frequencies. This delivered complex signal was measured on the fingertip (Fig. 2A and Fig. 3A), and the largely suprathreshold vibrations stimulated a large population of tactile afferents within several centimeters (27, 28). Once the participants read and signed the consent form, they completed six training trials to familiarize themselves with the task. To avoid influencing the main experiment, the reference signals used during the training were built on different pure tones (50, 80, 130, 200 Hz). Data collection followed immediately after the training session. Each trial consisted of a sequence of three 1-s stimuli separated by a 0.5-s interstimulus interval. The three signals comprised two identical reference signals and an odd signal that was the target signal. The participants' task was to identify which signal out of three was different from the other two (Fig. 3B). The participants were asked to indicate the position of the odd signal by pressing, with the hand that did not receive vibrations, either 1, 2, or 3 on a keyboard followed

by "Enter," with no time limit. Once the answer was validated, a new trial started after 0.5 s. The participants could replay the stimulus only if they missed it. The presentation order of the three signals was randomized within each trial.

For each experiment, the presentation order of each condition level (Experiment 1: harmonic and nonharmonic; Experiment 2: Small-inter and Large-inter) was counterbalanced across participants. Each condition included 28 unique comparisons, presented eight times each. The 224 total trials per condition (28 comparisons × 8 repetitions) were presented in pseudorandomized order. In addition to the two breaks given to the participant during a condition (every 74 trials), the participant was given a 15-min break between the two conditions.

### Dependent and Independent Variables

For Experiments 1 and 2, the dependent variable is Accuracy, corresponding to the correct answer rate (%) in the 3-AFC task. Both experiments also have in common two independent variables: Reference and Removed pure tone. Reference, from which the signal with the removed pure tone has to be discriminated, has 11 different levels whose values depend on the condition as illustrated in Table 1. Removed pure tone indicates which pure tone is removed from the reference signal to create the target signal to be compared with. The different possible levels of Removed pure tone depend on the number of constitutive frequencies of the reference signal. In addition, Experiments 1 and 2 differed by the third



**Figure 3.** *A:* example of the Three-tones vs. Two-tones comparisons with a vibrotactile reference comprising 75, 195, and 255 Hz. The blue curves represent the acceleration measure of the reference, and the red curves represent the possible target stimuli. *B:* the tactuator is placed over the top of the intermediate phalanx of the right hand's index finger, and the participant performs a 3-alternative forced choice (3-AFC) task that consists of reporting which signal out of 3 consecutive ones is different.

independent variable that was considered (i.e., *Harmonicity* and *Interfrequency interval*).

#### Experiment 1: Harmonicity.

The main independent variable is *Harmonicity*, with two levels: Harmonic and Nonharmonic. Harmonic contains a set of pure tones (60, 120, 180, and 240 Hz) in harmonic sequence. In the NONHARMONIC level, 15 Hz is added to each pure tone in the harmonic set to make the stimuli nonharmonic.

#### Experiment 2: Interequency interval.

The main independent variable is *Interequency interval*, which is the distance between the four pure tones on which the reference signals were built. Two sets of pure tones were used in this experiment: 150, 210, 270, and 330 Hz that are spaced by 60 Hz as in *Experiment 1* (Small-inter) and 150, 300, 450, and 600 Hz that are spaced by 150 Hz (Large-inter). Since the created references result from all possible combinations of the four constitutive frequencies, interfrequency intervals vary within a condition. Nonetheless, intervals in the Large-inter condition are generally larger than those in the Small-inter condition.

#### Experiment 3: Perceived intensity.

Participants were asked to report the perceived intensity of the 15 pure tones used in *Experiments 1* and 2. Each trial consisted in the presentation of a 1-s stimulus. Afterwards, the participants were required to rate the perceived intensity using a visual analog scale (VAS) displayed on a computer ranging from 0 (not intense) to 100 (very intense). To do so, they adjusted the cursor with left and right arrow keys and pressed "Enter" to validate their answers. A new stimulus was displayed 0.5 s after completion of the previous trial. Pure tones were presented three times in a pseudorandomized order for a total of 45 trials per participant.

#### Data Analysis

The data were analyzed with RStudio software (version 4.1.3). The impact of removed pure tones from reference complex signals was analyzed by implementing a generalized linear mixed model (GLMM) on individual data. Because of the differences in the number of possible pure tones combinations, the Two-tones, Three-tones, and Four-tones comparisons were analyzed separately. D'Agostino and Pearson tests showed that the data were not normally distributed. Consequently, GLMMs were fit by the maximum likelihood (Laplace approximation) with logit link and binomial error distribution. Akaike information criterion-corrected weight (AICcWt), which is the proportion of the total amount of predictive power provided by the full set of models including independent variables, was assessed, and the GLMM with the highest AICcWt value was selected (29). The regression model could include interaction terms between variables (i.e., one independent variable is influenced by another independent variable) or be simple (i.e., without interaction, each independent variable acts on the dependent variable). Independent variables were tested by analysis of deviance type II Wald chi-square tests. Post hoc analyses were conducted on significant fixed effects between estimated marginal means by using the package "emmeans" of Rstudio, and responses were back-transformed from the logit scale (probability scale). Pairwise comparisons were adjusted by Holm's method. In the additional analyses on the pure tones' frequency, the method of least squares was used to fit data. AICc, root mean square error (RMSE) and  $R^2$  as well as  $F$  test were computed to choose the best fit (high  $R^2$  and low AICc was preferred). AICc was chosen instead of AIC because of the small number of observations (30). According to Akaike's findings (31), an AIC difference  $\geq 2$  should be a reference to select the best model, which also applies to AICc.

## RESULTS

### Experiment 1: Harmonicity

Because of the inherent differences in pure tone number, each complexity level underwent separate statistical analyses. The psychophysical results for harmonic and nonharmonic conditions were almost identical, and the Wald statistical analyses conducted on the GLMM (see Table 2) yielded no significant main effect of *Harmonicity* on *Accuracy* for any of the complexity levels. The Wald analysis showed a significant main effect of *Removed pure tone* on *Accuracy* ( $P$  values  $< 0.0001$ ) for all complexity levels. Finally, the analysis showed a significant interaction between *Removed pure tone* and *Reference* ( $P$  values  $< 0.0001$ ) for Two-tones and Three-tones comparisons, since four-tone signals feature only one reference. Most post hoc pairwise comparisons showed that lower pure tones' removal was better detected (Fig. 4, A–C). However, the difference between the removal of the lowest and highest pure tone is not significant for the 120 + 180/135 + 195 Hz references (Holm's test,  $n = 192$ ,  $P = 0.28$ ), unlike for the other comparisons (Fig. 4A). For Three-tones comparisons, removing the second pure tone was significantly better detected for the 120 + 180 + 240/135 + 195 + 255 Hz references than the removal of the lowest one (Holm's test:  $n = 192$ ,  $P < 0.0001$ ) (Fig. 4B).

Overall, the obtained results did not show any influence of the harmonic nature of the signal on the human capacity to detect the removal of a pure tone. In most cases, participants were more accurate at discriminating modified signals from their reference when the lowest pure tone was removed rather than when other pure tones were removed. Interestingly, this phenomenon did not occur for two reference signals starting with pure tones of 120/135 Hz.

### Experiment 2: Interfrequency Interval

#### Effect of interfrequency intervals and removed pure tone.

The Wald test showed a significant main effect of *Interfrequency interval* on *Accuracy* ( $P$  values  $< 0.05$ ) for all complexity levels (Table 3, top). Post hoc Holm's tests revealed that participants better discriminate signals in the Small-inter condition than in the Large-inter condition regardless of the number of tones (Fig. 5A). The Wald test also showed a significant main effect of *Removed pure tone* on *Accuracy* ( $P$  values  $< 0.0001$ ) for all complexity levels (Fig. 5, B–G). In addition, significant interaction effects between *Interfrequency interval* and *Removed pure tone* were observed for Three-tones [ $\chi^2(2) = 69.7$ ,  $P < 0.0001$ ] and Four-tones [ $\chi^2(3) = 21.5$ ,  $P < 0.0001$ ]

comparisons. In the Large-inter condition, post hoc Holm's tests showed that the removal of the target signal with the lowest pure tone is significantly easier to discriminate than the removal of the target signal with a higher pure tone for all complexities. In the Small-inter condition, this effect occurred only for two-tone signals and signals with the highest pure tone removed were systematically less accurately discriminated than when lower pure tones were removed (Holm's test:  $n = 96$ ,  $P$  values  $< 0.05$ ). All post hoc tests are reported in the Supplemental Material.

#### Small and large intervals between tones.

When small and large intervals were considered separately for Two-tones and Three-tones comparisons (Four-tones did not feature multiple references), a GLMM analysis could be conducted on *Reference*. For Two-tones and Three-tones, the Wald tests confirmed the significant main effect of *Removed pure tone* on *Accuracy* ( $P$  values  $< 0.0001$ ) as well as an interaction effect with *Reference* ( $P$  values  $< 0.0001$ ) for both the Large-inter and Small-inter conditions (see Table 3, bottom). These additional Wald tests showed a significant main effect of *Reference* for the Small-inter condition ( $P$  values  $< 0.05$ ) but not for the Large-inter condition. The main effect of *Reference* and the interaction effect with *Removed pure tone* were further investigated by performing post hoc comparisons between all references of the Small-inter conditions for each complexity level.

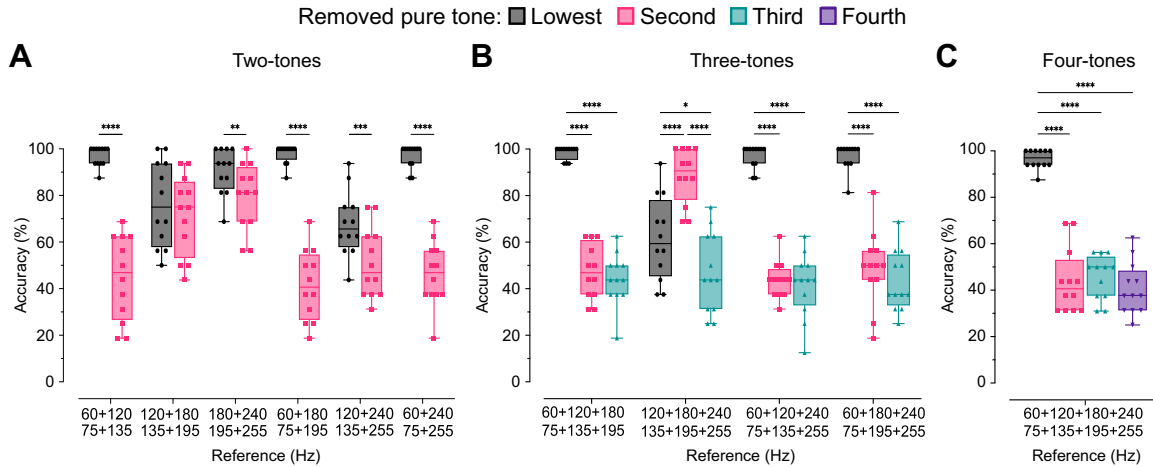
A post hoc Holm's test was conducted on the interaction effect between *Reference* and *Removed pure tone* for all complexity levels. For two-tone signals, the results revealed a significantly higher discrimination accuracy for signals with a distance between the lowest and highest pure tone  $< 60$  (global mean 84%, SD = 36.7) than with a distance  $> 60$  (global mean 47.2%, SD = 50) ( $n = 96$ ,  $P$  values  $< 0.0001$ ) (Fig. 5C). For signals with three pure tones in the Small-inter condition, a post hoc Holm's test showed that discrimination of signals with the lowest and the second pure tones removed was not significantly different regardless of the reference signal (Fig. 5, D and E). Therefore, the results suggest that the references impacted the discrimination accuracy mostly through the different distances between the pure tones that they featured.

Overall, the results from *Experiment 2* suggest an effect of the frequency interval between the tones, since participants were surprisingly more accurate at discriminating signals with small intervals. Moreover, participants were generally more accurate at discriminating target signals when the lowest pure tone was removed compared to the other pure tones, and accuracy was only slightly impacted by the reference signal.

**Table 2.** Wald chi-square tests in experiment 1

	Independent Variables	$\chi^2$	$P$ Value
Two-tones: Reference $\times$ Removed pure tone + Harmonicity	Removed pure tone	107.1	$< 0.0001$
	Removed pure tone $\times$ Reference	118.5	0.0001
Three-tones: Reference $\times$ Removed pure tone + Harmonicity	Removed pure tone	77.4	$< 0.0001$
	Removed pure tone $\times$ Reference	190.1	$< 0.0001$
Four-tones: Removed pure tone + Harmonicity	Removed pure tone	83	$< 0.0001$

The first column corresponds to the generalized linear mixed model including simple (+) or interaction ( $\times$ ) terms.  $\chi^2$  and  $P$  values are obtained by Wald chi-square tests performed on independent and dependent variables (Accuracy).



**Figure 4.** Accuracy (%) (median, interquartile range, and minimum to maximum) averaged across participants' individual data for each combination of removed pure tone and reference signal. The harmonic and nonharmonic conditions were merged since they showed no difference. *A*: references made of 2 pure tones. *B*: references made of 3 pure tones. *C*: reference made of 4 pure tones. Statistical difference: \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ , \*\*\*\* $P < 0.0001$ .

**Postanalysis of the Removed Pure Tones**

**Position of the removed pure tone.**

The results from *Experiments 1* and *2* suggest a significant influence of the removed pure tone's position within the frequency spectrum of the reference. To probe more thoroughly the role of this parameter, additional analyses taking into account the frequency of the removed pure tone were conducted. Since similar response patterns were observed in *Experiments 1* and *2* despite different frequency ranges, we tested the ratio between the removed pure tone and the lowest pure tone of the original signal:

$$\text{Ratio} = \frac{F}{F_0} \tag{1}$$

This ratio is also consistent with Weber's law in which the difference limen is typically expressed as a ratio. We expected the accuracy to be a function  $f$  of this ratio:

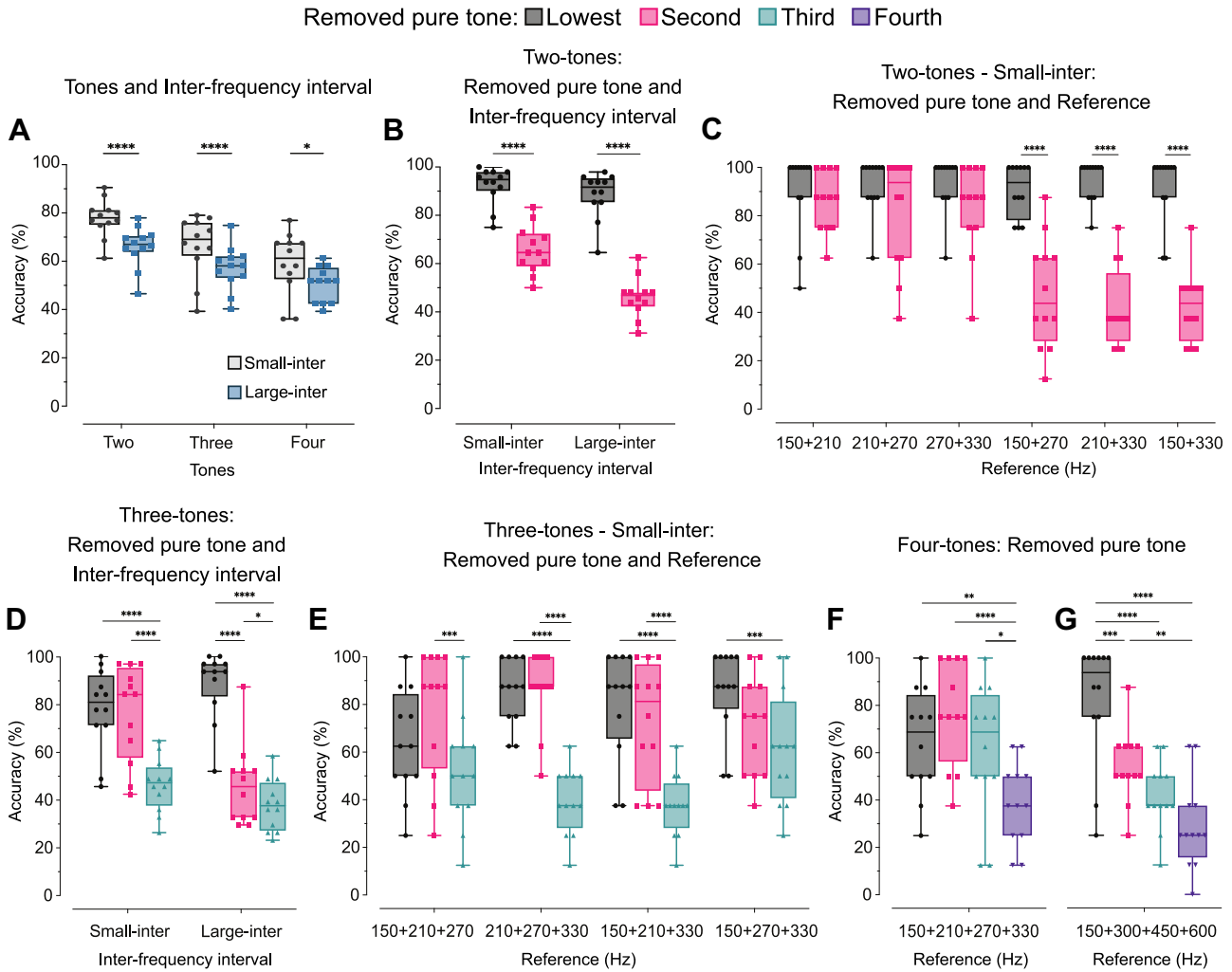
$$\text{Accuracy} = f(\text{Ratio}) \tag{2}$$

To that end, all occurring ratios within the two experiments were considered (see Fig. 6A). In addition, the three levels of complexity in our study were computed separately. These data were then fitted with four plausible functions  $f$ : linear, exponential, logarithmic, and sigmoidal (Fig. 6A). The best goodness of fit between participants' accuracy and the ratio  $F/F_0$  was achieved by a sigmoidal curve for each level of complexity (Two-tones,  $R^2 = 0.81$ ; Three-tones,  $R^2 = 0.74$ , Four-tones,  $R^2 = 0.80$ ), which

**Table 3.** Wald chi-square tests in experiment 2

Independent Variables		$\chi^2$	P Value
<i>Wald chi-square tests on generalized linear mixed models including Removed pure tone and Interfrequency interval</i>			
Two-tones: removed pure tone + interfrequency interval	Removed pure tone	308.2	<0.0001
	Interfrequency interval	48.1	<0.0001
Three-tones: Removed pure tone × Interfrequency interval	Removed pure tone	218	<0.0001
	Interfrequency interval	22.9	<0.0001
	Removed pure tone × Interfrequency interval	69.8	<0.0001
Four-tones: Removed pure tone × Interfrequency interval	Removed pure tone	60.2	<0.0001
	Interfrequency interval	6.4	0.011
	Removed pure tone × Interfrequency interval	21.5	<0.0001
<i>Wald chi-square tests on generalized linear mixed models including Removed pure tone and Reference</i>			
Two-tones Small-inter: Removed pure tone × Reference	Removed pure tone	92.1	<0.0001
	Reference	58.5	<0.0001
	Removed pure tone × Reference	27.1	<0.0001
Large-inter: Removed pure tone × Reference	Removed pure tone	188.6	<0.0001
	Removed pure tone × Reference	12.6	0.028
Three-tones Small-inter: Removed pure tone × Reference	Removed pure tone	95.3	<0.0001
	Reference	8.3	0.04
	Removed pure tone × Reference	33.4	<0.0001
Large-inter: Removed pure tone × Reference	Removed pure tone	149.4	<0.0001
	Removed pure tone × Reference	23.8	0.0005

The first column corresponds to the generalized linear mixed model including simple (+) or interaction (×) terms.  $\chi^2$  and  $P$  values are obtained by Wald chi-square tests performed on independent and dependent variables (Accuracy).



**Figure 5.** Accuracy (%) (median, interquartile range, and minimum to maximum) averaged across participants' individual data as a function of comparisons between Small-inter and Large-inter as a function of tones (A), *Removed pure tone and Interfrequency interval* for the Two-tones comparisons (B), *Removed pure tone and Reference* in Small-inter for the Two-tones comparisons (C), *Removed pure tone and Interfrequency interval* for the Three-tones comparisons (D), *Removed pure tone and Reference* in Small-inter for the Three-tones comparisons (E), *Removed pure tone in Small-inter* for the Four-tones comparisons (F), and *Removed pure tone in Large-inter* for the Four-tones comparisons (G). Statistical significance: \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ , \*\*\*\* $P < 0.0001$ .

matches the psychophysical expectation (Table 4). Moreover, a sum-of-squares statistical test showed that the curves fitting the three complexity levels were not significantly different [ $F(6,103) = 0.24, P = 0.96$ ]. Thus, a sigmoidal psychometric function was fitted to the entire dataset ( $R^2 = 0.79$ ), and the 66.7% just noticeable difference corresponded to a ratio of 1.47. Taken together, these results suggest that in the frequency range of our study, the discriminability of a removed tone is well predicted by its ratio with the lowest pure tone of the original signal. Interestingly, no significant effect of complexity was observed, suggesting that the number of frequencies in the original signal has little impact on the saliency of the removal.

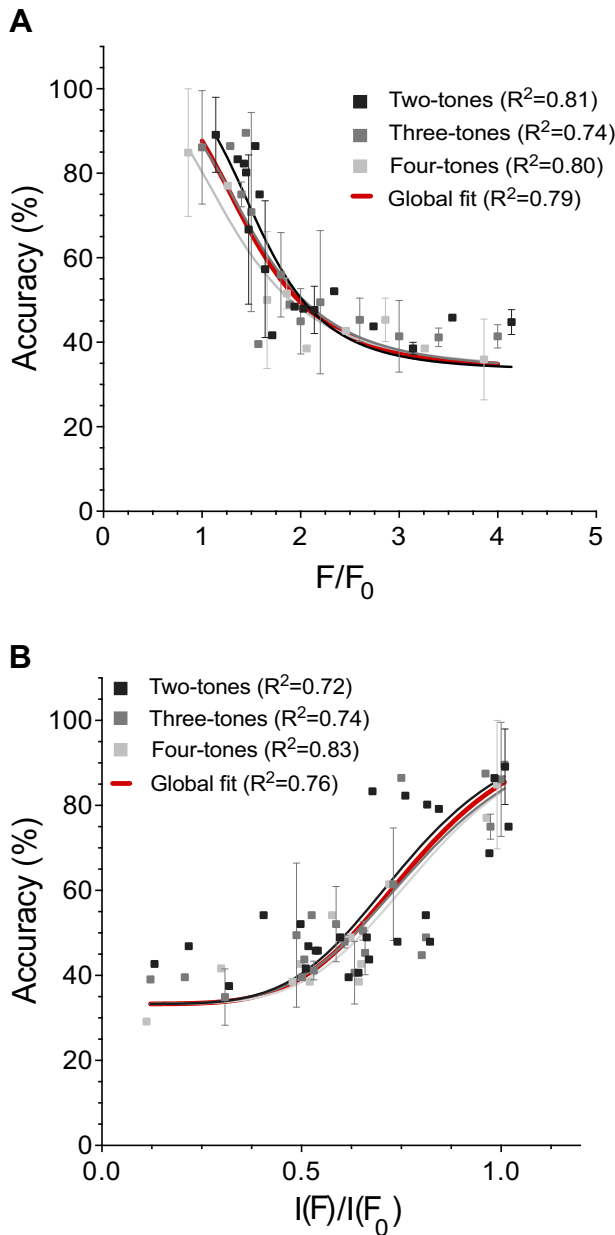
**Experiment 3: Perceived intensity of the removed pure tone.**

Since the perceived intensity of the individual pure tones could also provide a meaningful cue for discrimination, we measured the perceived intensity  $I(F)$  of all pure tones with a

frequency  $F$  across participants in *Experiment 3*. We found that it generally decreases with frequency (see Fig. 7A). To test the potential sensory contribution of pure tones' perceived intensity, the intensity ratio was defined as follows:

$$\text{Intensity Ratio} = \frac{I(F)}{I(F_0)} \quad (3)$$

The ratio was fitted by a sigmoidal curve for each level of complexity (Two-tones,  $R^2 = 0.72$ ; Three-tones,  $R^2 = 0.74$ , Four-tones,  $R^2 = 0.83$ ) (Fig. 6B). The relatively good fitting ( $R^2 > 0.70$ ) shows that the perceived intensity is also a plausible factor to explain the observed impact of the ratio  $F/F_0$ . This is not surprising given the relationship between frequency and perceived intensity. To disentangle these two plausible mechanisms, we performed an analysis within the range between 120 Hz and 270 Hz. In that range, the perceived intensity mostly plateaued and a Friedman analysis [ $n = 10, \chi^2(8) = 15.42, P = 0.052$ ] showed that the perceived intensity differed only marginally for these frequencies. We



**Figure 6.** A: accuracy (%) (mean and SE) for all the comparisons as a function of the ratio between the removed pure tone and the lowest pure tone of the complex signal. The data points represent the averaged ratio between the removed pure tone and the lowest pure tone of the original signal ( $F/F_0$ ) values encountered in the study. A horizontal jitter was performed ( $x = 0.14$ ). Lines correspond to a sigmoid fit for each possible complexity level of the reference signals. The red line corresponds to the global fit for all datasets. B: same as A for the intensity ratio [ $I(F)/I(F_0)$ ]. A horizontal jitter was performed ( $x = 0.01$ ).

evaluated the goodness of fit of a sigmoid function for  $F/F_0$  and  $I(F)/I(F_0)$  on reference signals that included only frequencies within that range, resulting in a subset of 27 data points. The goodness of fit was  $R^2 = 0.60$  for  $F/F_0$  and  $R^2 = 0.26$  for  $I(F)/I(F_0)$ , showing that the frequency ratio retains a high level of correlation with participants' answers whereas the correlation with the perceived intensity is largely reduced (Fig. 7, B and C). These results suggest that  $F/F_0$  is more informative than  $I(F)/I(F_0)$ .

## DISCUSSION

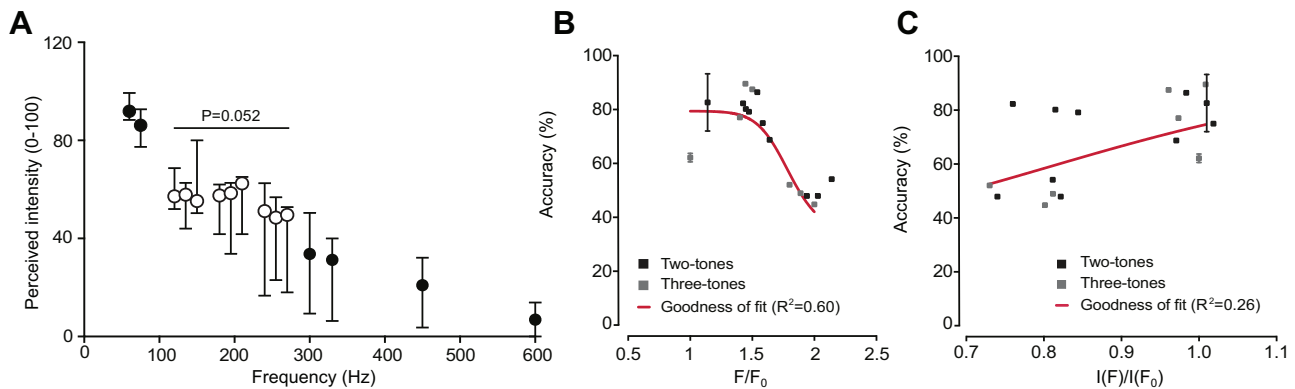
Our study investigated the potential effect of harmonicity, interval between the frequencies of the reference signal, and complexity on whether a removed tone from a complex signal would be noticeable. The obtained results showed a great variability in performance as a function of these factors. Predominantly, the results showed a significant impact of the removed pure tone's position on discrimination abilities. In most conditions, the lower the frequency of the removed pure tone, the more noticeable its absence. However, when a comparatively smaller relative distance between the signal's frequencies was tested in the second experiment, the prominence of the lowest pure tone decreased compared to the other constitutive tones of the signal. Taken together, the results of the two experiments suggest that noticing the removal of a pure tone from a complex signal relies on the pure tone's proximity to the lowest tone of the complex signal. However, the pure tones were equalized in amplitude, preventing the impact of that cue, and it is likely that other sensory mechanisms exist, since for the 120 + 180 + 240/135 + 195 + 255 Hz signals in *Experiment 1*, the removal of the second pure tone was noticed with significantly higher accuracy.

Interestingly, no specific effect of harmonicity was observed when participants completed the task with harmonic reference signals compared to nonharmonic ones. In addition, the psychometric analyses did not show any significant effect of the complexity of the reference signal. Although the dominant role of the fundamental has been pointed out in touch (22) and hearing (32), our study suggests that this specific saliency extends to tones that are similar enough following a psychometric function. This finding is consistent with masking predominantly impacting higher frequencies in both modalities (33, 34). Thus, the perceptual dynamics seem similar between touch and hearing, but the underlying mechanisms are likely different since, unlike hearing (35), the sense of touch only provides low-resolution frequency selectivity and masking does not seem to occur across tactile channels (36).

**Table 4.** Fit selection based on AICc on the accuracy as a function of ratio

Fit	AICc	RMSE	$R^2$
<i>Two-tones</i>			
Linear	245.2	13.53	0.60
Exponential	229.4	11.4	0.72
Logarithmic	215.4	9.53	0.80
<b>Sigmoid</b>	<b>213.8</b>	<b>9.3</b>	<b>0.81</b>
<i>Three-tones</i>			
Linear	252.3	14.6	0.56
Exponential	241.1	12.94	0.66
Logarithmic	233.6	11.61	0.72
<b>Sigmoid</b>	<b>230.3</b>	<b>11.2</b>	<b>0.74</b>
<i>Four-tones</i>			
Linear	103.4	12.8	0.64
Exponential	99.1	11.41	0.73
Logarithmic	100.8	10.95	0.75
<b>Sigmoid</b>	<b>96.6</b>	<b>9.8</b>	<b>0.80</b>

AICc, Akaike information criterion cumulative; RMSE, root mean square error. Linear:  $y = a + bX$ . Exponential:  $y = y_0 \times \exp(kX)$ . Logarithmic:  $y = a \times \ln(X - c) + b$ . Sigmoid:  $y = \min + (X \cdot \text{steepness}) \cdot (\max - \min) / (X^{\text{steepness}} + \frac{1}{2} \text{steepness})$ . As constraints, the min is equal to 33.3 and the max is  $< 100$ . Values in bold correspond to the fit that better explains the data.



**Figure 7.** A: subjective perceived intensity of pure tones [median and interquartile range (IQR)] across all participants. Each data point represents the averaged perceived intensity for each pure tone across participants. Empty circles represent a range of frequencies that are quite similar in intensity and form a plateau. B: accuracy with respect to the ratio between the removed pure tone and the lowest pure tone of the original signal ( $F/F_0$ ) (mean and SE) for comparisons including pure tones made of the frequencies within the plateau ( $n = 27$ ). Data points represent the averaged ratio values encountered in the study. A horizontal jitter was performed ( $\chi = 0.14$ ). The red line corresponds to the best-fitting sigmoidal curve for all data sets. C: same as B for the intensity ratio [ $I(F)/I(F_0)$ ]. A horizontal jitter was performed ( $\chi = 0.01$ ).

### Comparison with Previous Findings

The lack of influence of the harmonicity of the signal is somewhat surprising, given that the harmonicity and consonance of vibrotactile signals have been shown to impact perception (24, 25, 37). However, previous studies compared signals of identical complexity whereas the signals in our experiments differ by a missing frequency, which probably introduces stronger sensory phenomena than harmonicity. Additionally, differences in diharmonic signals have been shown to be slightly more difficult to distinguish than in pure tones (17, 19), whereas the results of our study did not show an impact of complexity. Based on the frequency selectivity of psychophysical channels (26, 38, 39) and their independence when it comes to masking (40–42), one could have expected the effect of removing pure tones to differ depending on whether or not they belong to the same tactile channel. However, the experimental results, which encompass a large frequency range from 60 Hz to 600 Hz, suggest that the main tactile channel activated by the removed pure tone has little impact on how its removal is perceived. The results are also in line with recent research showing that changes in the balance between high and low frequencies of a complex signal mostly mediate perceived dissimilarity (43). The observed human sensitivity to removed pure tones is also intriguing since it does not follow the classical relationship of tactile sensitivity in which the detection threshold is lowest for high frequencies around 300 Hz (26, 44). However, our stimuli were chosen to be largely over the human threshold for detecting vibrations and would rather be affected by the higher perceived intensity for lower frequencies at equal acceleration (18), which was also observed in our study and might have made the most salient tones' absence more noticeable.

### Physical and Cognitive Mechanisms Underlying Vibrotactile Perception

The possible existence of mechanisms for complex signal discrimination that rely on frequency is supported by the spectral model of vibrotactile perception (19). This model suggests that the percept of a complex signal comes from the sum of the relative activations of the frequency-tuned

minichannels in the Pacinian sensitivity range. However, this model stems from the Pacinian activity, whereas the supra-threshold nature of the stimuli in this study suggests that the delivered vibrations were encoded by most of the tactile receptors. It is also known that several fundamental tactile cues are processed in the somatosensory cortex (45), including sensory integration of vibrotactile frequencies mediated by distinct tactile channels (46). Similarly, Russo et al. (25) supported the idea that frequency-tuned populations of mechanoreceptors filter complex tones into their component frequencies. Moreover, frequency-mediated sensory mechanisms are supported by evidence that vibrotactile frequency perception relies on the duration of individual intertap intervals rather than the average firing rate (47, 48), and this even for complex frequency compositions or signals without fixed periodicity. Although the perceptual cues used by participants remain to be elucidated, this could explain the dominant role of the lower frequencies, which are responsible for the larger and possibly most salient intervals between vibrotactile bursts. However, another explanation for our results could be masking phenomena due to the higher perceived intensity for low frequencies, which could have made the removal of high-frequency pure tones less salient. Indeed, previous research suggests that masking affects more frequencies that are higher than the masking signal. For example, narrowband noise in the Pacinian channel has a slightly weaker masking effect on the detection of a 20-Hz sinusoidal signal than non-Pacinian noise on a 200-Hz signal (40). These results do not fully follow the predictions based on the separation of tactile channels and might also relate to the perceptual mechanisms for discrimination observed in our study. However, little is known about how complex signals in which such interplay occurs are encoded by the sense of touch. Overall, our results suggest a combination of physical, sensory, and cognitive mechanisms involved in the discrimination of complex vibrotactile signals.

### Perspectives and Significance

Our study shows different perceptual saliency for pure tones that are equalized in acceleration within complex signals of up to four tones. The dominance of the fundamental

pure tone of a diharmonic signal has already been suggested (22), but our results additionally suggest that it is either the frequency or the perceived intensity of the removed tone compared to the lowest one that matters. The number of frequencies within the signal does not seem to influence the perceptual value of a given pure tone. To investigate further the generality of these findings, it would be interesting to extend the experiments to frequencies under 60 Hz, more variable interfrequency intervals, and stimuli that are closer to the human sensory threshold. Although non-Pacinian channels were also targeted in *Experiment 1* with 60 and 75 Hz, these frequencies also activated the Pacinian channel. Testing frequencies around 10–30 Hz that dissociate the activation of the psychophysical tactile channels (26, 38, 39) would enable us to thoroughly investigate their potential role in the perception of complex vibrotactile signals. Extending the comparisons to complex signals with a larger number of frequencies and a different organization of the frequency spectrum would also be insightful. Measuring the detection threshold of complex signals could also be useful for predicting discrimination (21) as well as determining the masking effects elicited by the interplay between frequencies (40–42). Finally, we chose to equalize the amplitude of the constitutive pure tones in peak acceleration, but it would also be essential to evaluate the same task with pure tones of various amplitudes or equalized in perceived intensity to disambiguate sensory mechanisms. The present study paves the way for a better understanding of the main factors affecting perception of complex vibrotactile signals and the development of a more general psychophysical model. It also opens new perspectives regarding the design of vibrotactile signals in industry applications since it shows that complex vibrotactile signals can be largely simplified without any perceptual change for the user.

## DATA AVAILABILITY

The data associated with this study are available to the scientific community to ensure transparency, reproducibility, and further exploration of the findings presented in this article. Researchers interested in accessing the data can find it at <https://doi.org/10.5281/zenodo.10578044>. For any inquiries or requests related to the data, please feel free to contact the corresponding author at [thanh-loan.le@sorbonne-universite.fr](mailto:thanh-loan.le@sorbonne-universite.fr) or D. Gueorguiev at [david.gueorguiev@uclouvain.be](mailto:david.gueorguiev@uclouvain.be).

## SUPPLEMENTAL MATERIAL

Supplemental Computer Code S1: <https://doi.org/10.5281/zenodo.10578044>.

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## DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

## AUTHOR CONTRIBUTIONS

T.-I.S.L., G.B., E.V., M.A., and D.G. conceived and designed research; T.-I.S.L. performed experiments; T.-I.S.L., G.B., M.A., and D.G. analyzed data; T.-I.S.L., G.B., M.A., and D.G. interpreted results of experiments; T.-I.S.L., G.B., and D.G. prepared figures; T.-I.S.L., G.B., and D.G. drafted manuscript; T.-I.S.L., G.B., M.A., and D.G. edited and revised manuscript; T.-I.S.L., G.B., M.A., and D.G. approved final version of manuscript.

## REFERENCES

- Culbertson H, Schorr SB, Okamura AM. Haptics: the present and future of artificial touch sensation. *Annu Rev Control Robot Auton Syst* 1: 385–409, 2018. doi:10.1146/annurev-control-060117-105043.
- Bensmaïa SJ, Hollins M. Pacinian representations of fine surface texture. *Percept Psychophys* 67: 842–854, 2005. doi:10.3758/BF03193537.
- Hollins M, Risner SR. Evidence for the duplex theory of tactile texture perception. *Percept Psychophys* 62: 695–705, 2000. doi:10.3758/BF03206916.
- Bergmann Tiest WM. Tactile perception of material properties. *Vision Res* 50: 2775–2782, 2010. doi:10.1016/j.visres.2010.10.005.
- Okamoto S, Nagano H, Yamada Y. Psychophysical dimensions of tactile perception of textures. *IEEE Trans Haptics* 6: 81–93, 2013. doi:10.1109/TOH.2012.32.
- Manfredi LR, Saal HP, Brown KJ, Zielinski MC, Dammann JF 3rd, Polashock VS, Bensmaïa SJ. Natural scenes in tactile texture. *J Neurophysiol* 111: 1792–1802, 2014. doi:10.1152/jn.00680.2013.
- Weber AI, Saal HP, Lieber JD, Cheng JW, Manfredi LR, Dammann JF 3rd, Bensmaïa SJ. Spatial and temporal codes mediate the tactile perception of natural textures. *Proc Natl Acad Sci USA* 110: 17107–17112, 2013. doi:10.1073/pnas.1305509110.
- Franzén O, Nordmark J. Vibrotactile frequency discrimination. *Percept Psychophys* 17: 480–484, 1975. doi:10.3758/BF03203298.
- Morley JW, Rowe MJ. Perceived pitch of vibrotactile stimuli: effects of vibration amplitude, and implications for vibration frequency coding. *J Physiol* 431: 403–416, 1990. doi:10.1113/jphysiol.1990.sp018336.
- Hollins M, Roy EA. Perceived intensity of vibrotactile stimuli: the role of mechanoreceptive channels. *Somatosens Mot Res* 13: 273–286, 1996. doi:10.3109/08990229609052583.
- Verrillo RT, Fraioli AJ, Smith RL. Sensation magnitude of vibrotactile stimuli. *Percept Psychophys* 6: 366–372, 1969. doi:10.3758/BF03212793.
- Birznies I, McIntyre S, Nilsson HM, Nagi SS, Macefield VG, Mahns DA, Vickers RM. Tactile sensory channels over-ruled by frequency decoding system that utilizes spike pattern regardless of receptor type. *eLife* 8: e46510, 2019. doi:10.7554/eLife.46510.
- Goff GD. Differential discrimination of frequency of cutaneous mechanical vibration. *J Exp Psychol* 74: 294–299, 1967. doi:10.1037/h0024561.
- Mahns DA, Perkins NM, Sahai V, Robinson L, Rowe MJ. Vibrotactile frequency discrimination in human hairy skin. *J Neurophysiol* 95: 1442–1450, 2006. doi:10.1152/jn.00483.2005.
- Pongrac H. Vibrotactile perception: examining the coding of vibrations and the just noticeable difference under various conditions. *Multimed Syst* 13: 297–307, 2007. doi:10.1007/s00530-007-0105-x.
- Horch K. Coding of vibrotactile stimulus frequency by Pacinian corpuscle afferents. *J Acoust Soc Am* 89: 2827–2836, 1991. doi:10.1121/1.400688.
- Senkow TL, Theis ND, Quindlen-Hotek JC, Barocas VH. Computational and psychophysical experiments on the Pacinian corpuscle's ability to discriminate complex stimuli. *IEEE Trans Haptics* 12: 635–644, 2019. doi:10.1109/TOH.2019.2903500.
- Hwang I, Seo J, Kim M, Choi S. Vibrotactile perceived intensity for mobile devices as a function of direction, amplitude, and frequency. *IEEE Trans Haptics* 6: 352–362, 2013. doi:10.1109/TOH.2013.2.

19. **Bensmaïa SJ, Hollins M, Yau J.** Vibrotactile intensity and frequency information in the Pacinian system: a psychophysical model. *Percept Psychophys* 67: 828–841, 2005. doi:10.3758/BF03193536.
20. **Bensmaïa SJ, Hollins M.** Complex tactile waveform discrimination. *J Acoust Soc Am* 108: 1236–1245, 2000. doi:10.1121/1.1288937.
21. **Young G, Murphy D, Jeffrey W.** Vibrotactile discrimination of pure and complex waveforms. *12th Sound and Music Computing Conference (SMC)*, 2015, p. 59–362. doi:10.13140/RG.2.1.3205.3608.
22. **Hwang I, Seo J, Choi S.** Perceptual space of superimposed dual-frequency vibrations in the hands. *PLoS One* 12: e0169570, 2017. doi:10.1371/journal.pone.0169570.
23. **Friesen RF, Klatzky RL, Peshkin MA, Colgate JE.** Single pitch perception of multi-frequency textures. *2018 IEEE Haptics Symposium (HAPTICS)*, 2018, p. 290–295. doi:10.1109/HAPTICS.2018.8357190.
24. **Picinali L, Feakes C, Mauro DA, Katz BF.** Tone-2 tones discrimination task comparing audio and haptics. *2012 IEEE International Symposium on Haptic Audio Visual Environments and Games (HAVE)*. 2012, p. 19–24. doi:10.1109/HAVE.2012.6374432.
25. **Russo FA, Ammirante P, Fels DI.** Vibrotactile discrimination of musical timbre. *J Exp Psychol Hum Percept Perform* 38: 822–826, 2012. doi:10.1037/a0029046.
26. **Bolanowski SJ Jr, Gescheider GA, Verrillo RT, Checkosky CM.** Four channels mediate the mechanical aspects of touch. *J Acoust Soc Am* 84: 1680–1694, 1988. doi:10.1121/1.397184.
27. **Manfredi LR, Baker AT, Elias DO, Dammann JF 3rd, Zielinski MC, Polashock VS, Bensmaïa SJ.** The effect of surface wave propagation on neural responses to vibration in primate glabrous skin. *PLoS One* 7: e31203, 2012. doi:10.1371/journal.pone.0031203.
28. **Shao Y, Hayward V, Visell Y.** Spatial patterns of cutaneous vibration during whole-hand haptic interactions. *Proc Natl Acad Sci USA* 113: 4188–4193, 2016. doi:10.1073/pnas.1520866113.
29. **Wagenmakers EJ, Farrell S.** AIC model selection using Akaike weights. *Psychon Bull Rev* 11: 192–196, 2004. doi:10.3758/BF03206482.
30. **Burnham KP, Anderson DR.** *Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach* (2nd ed.). New York: Springer, 2002.
31. **Akaike H.** A new look at the statistical model identification. *IEEE Trans Automat Contr* 19: 716–723, 1974. doi:10.1109/TAC.1974.1100705.
32. **Moore BC, Glasberg BR, Peters RW.** Relative dominance of individual partials in determining the pitch of complex tones. *J Acoust Soc Am* 77: 1853–1860, 1985. doi:10.1121/1.391936.
33. **Tobias JV.** Low-frequency masking patterns. *J Acoust Soc Am* 61: 571–575, 1977. doi:10.1121/1.381299.
34. **Merchel S, Altinsoy ME.** Psychophysical comparison of the auditory and tactile perception: a survey. *J Multimodal User Interfaces* 14: 271–283, 2020. doi:10.1007/s12193-020-00333-z.
35. **Moore BC.** *An Introduction to the Psychology of Hearing* (5th ed.). New York: Academic Press, 2003.
36. **Gescheider GA, Verrillo RT, Van Doren CL.** Prediction of vibrotactile masking functions. *J Acoust Soc Am* 72: 1421–1426, 1982. doi:10.1121/1.388449.
37. **Yoo Y, Hwang I, Choi S.** Consonance of vibrotactile chords. *IEEE Trans Haptics* 7: 3–13, 2014. doi:10.1109/TOH.2013.57.
38. **Gescheider GA, Bolanowski SJ, Pope JV, Verrillo RT.** A four-channel analysis of the tactile sensitivity of the fingertip: frequency selectivity, spatial summation, and temporal summation. *Somatosens Mot Res* 19: 114–124, 2002. doi:10.1080/08990220220131505.
39. **Gescheider GA, Bolanowski SJ, Verrillo RT.** Some characteristics of tactile channels. *Behav Brain Res* 148: 35–40, 2004. doi:10.1016/S0166-4328(03)00177-3.
40. **Hamer RD, Verrillo RT, Zwislocki JJ.** Vibrotactile masking of Pacinian and non-Pacinian channels. *J Acoust Soc Am* 73: 1293–1303, 1983. doi:10.1121/1.389278.
41. **Israr A, Tan HZ, Reed CM.** Frequency and amplitude discrimination along the kinesthetic- cutaneous continuum in the presence of masking stimuli. *J Acoust Soc Am* 120: 2789–2800, 2006. doi:10.1121/1.2354022.
42. **Gescheider GA, O'Malley MJ, Verrillo RT.** Vibrotactile forward masking: evidence for channel independence. *J Acoust Soc Am* 74: 474–485, 1983. doi:10.1121/1.389813.
43. **Bernard C, Thoret E, Huloux N, Ystad S.** The high/low frequency balance drives the perception of noisy vibrations. *IEEE Trans Haptics* 2024: 1–11, 2024. doi:10.1109/TOH.2024.3371264.
44. **Verrillo RT.** Vibrotactile thresholds measured at the finger. *Percept Psychophys* 9: 329–330, 1971. doi:10.3758/BF03208688.
45. **Saal HP, Bensmaïa SJ.** Touch is a team effort: interplay of submodalities in cutaneous sensibility. *Trends Neurosci* 37: 689–697, 2014. doi:10.1016/j.tins.2014.08.012.
46. **Kuroki S, Watanabe J, Nishida S.** Integration of vibrotactile frequency information beyond the mechanoreceptor channel and somatotopy. *Sci Rep* 7: 2758, 2017. doi:10.1038/s41598-017-02922-7.
47. **Birznieks I, Vickery RM.** Spike timing matters in novel neuronal code involved in vibrotactile frequency perception. *Curr Biol* 27: 1485–1490.e2, 2017. doi:10.1016/j.cub.2017.04.011.
48. **Mackevicius EL, Best MD, Saal HP, Bensmaïa SJ.** Millisecond precision spike timing shapes tactile perception. *J Neurosci* 32: 15309–15317, 2012. doi:10.1523/JNEUROSCI.2161-12.2012.