An exploration on whole-body and foot-based vibrotactile sensitivity to melodic consonance

AN EXPLORATION ON WHOLE-BODY AND FOOT-BASED VIBROTACTILE SENSITIVITY TO MELODIC CONSONANCE

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ABSTRACT

Consonance is a distinctive attribute of musical sounds, for which a psychophysical explanation has been found leading to the critical band perceptual model. Recently this model has been hypothesized to play a role also during tactile perception. In this paper the sensitivity to vibrotactile consonance was subjectively tested in musicians and non-musicians. Before the test, both such groups listened to twelve melodic intervals played with a bass guitar. After being acoustically isolated, participants were exposed to the same intervals in the form of either a whole-body or foot-based vibrotactile stimulus. On each trial they had to identify whether an interval was ascending, descending or unison. Musicians were additionally asked to label every interval using standard musical nomenclature. The intervals identification as well as their labeling was above chance, but became progressively more uncertain for decreasing consonance and when the stimuli were presented underfoot. Musicians' labeling of the stimuli was incorrect when dissonant vibrotactile intervals were presented underfoot. Compared to existing literature on auditory, tactile and multisensory perception, our results reinforce the idea that vibrotactile musical consonance plays a perceptual role in both musicians and non-musicians. Might this role be the result of a process occurring at central and/or peripheral level, involving or not activation of the auditory cortex, concurrent reception from selective somatosensory channels, correlation with residual auditory information reaching the basilar membrane through bone conduction, is a question our preliminary exploration leaves open to further research work.

1. INTRODUCTION

Compared to the perception of auditory pitch, tactile frequency has a less immediate and objective interpretation. Evidence of vibrotactile pitch sensitivity was found decades ago by von Békésy, and ratio codes for pitch have been progressively refined accounting for the complex dependency on the human receptive channels, making pitch a function also of stimulus amplitude, duration, and adaptation of the receptors [1,2,3], furthermore with mechanisms operating at central level [4].

Tactile counterparts of note, consonance, and timbre have been consequently searched, also in deaf people [5], mainly using pairs of sequential stimuli. In a working memory task, Harris *et al.* [6] asked participants to compare the "frequency" of two subsequent vibrotactile square waves to investigate on the retention interval between such stimuli. Evidence of complex tactile waveform discrimination was found by presenting bi-tonal vibrations one after the other while varying the phase of the higher frequency tone [2]. With a similar methodology, varying intensity and/or frequency in the sequential pairs forming the stimulus, a psychophysical model of the Pacinian system inclusive of a critical-band hypothesis of Pacinian coding was presented [3].

In contrast to the use of sequential stimuli, in a recent research work Yoo et al. [7] actuated a graspable haptic device with two sinusoidal vibrations oscillating respectively at a base and chordal frequency, i.e. a carrier and a modulated tone using acoustics terminology, then asking participants to rate the degree of consonance of the resulting vibrotactile stimulus. Their conclusions, obtained after selecting four base and several chordal frequencies set at specific ratios above the respective base, were in favor of a strong dependence of the perceived consonance degree on the beat frequency, which is equal to the absolute difference between chordal and base. The beats, they report, may in fact cause the activation of either the Rapidly Adapting (RA) channel for lower beat frequency values or the Pacinian (PC) channel for higher beat frequency values, respectively responsible for rough as opposed to smoother perceptions and, hence, for an increasing sense of consonance with the chordal vs. base frequency ratio. Similarly to what happens in audition, hence, these results suggest the existence of a link between perceived consonance degree and absolute pitch of the vibrotactile beats, with possible additional sense of tactile roughness this time not caused by cochlear interference, but due to the involvement of separate receptive channels varying with this pitch.

Musical instrument notes define complex stimuli gathering several pure tones with time-varying amplitude together into a harmonic series. In these cases the psychophysical approach is no longer sufficient to completely explain the consonance of a note pair, or interval. Intervals can be ascending or descending if the second note has respectively higher or lower pitch than the first; otherwise they are unisons. Furthermore they are harmonic if the two notes are played simultaneously; melodic if the notes are played sequentially. Experiments involving the vibrotactile presentation of notes investigated the importance of vibrotactile stimuli as an aid to auditory perception [8], as well as showed that Italian and Indian musicians, by touching a harmonium played to reproduce Western and Oriental music scales, were able to disambiguate either scale significantly from the corresponding cutaneous feedback [9]. Concerning musical timbre, participants with no specific musical training, including individuals with auditory impairments, correctly identified vibrotactile presentations of sounds from cello, piano and trombone playing the same note at equal loudness; accuracy in the identification was not lost after substituting these sounds with synthetic ensembles of partial components maintaining the fundamental frequency, temporal envelope and energy of the original sounds, meanwhile changing the spectral centroid [10]. Based on these results the authors suggest an expansion of the tactile critical band model to include musical stimuli, and hypothesize the integration at cortical level of independent cutaneous signals that, besides differentiating among tactile critical bands, furthermore provide somatosensory perceptions resembling acoustic timbre.

While based our methodology on a study by Killam *et al.* [11], who performed a musical interval recognition experiment in which music students were asked to label intervals, both harmonic and melodic, with their standard names in Western music. The authors did not find evidence of a greater difficulty for participants at identifying descending instead of ascending intervals. Furthermore it was observed that, apart from octaves whose simultaneous perception led to precise identifications, melodic intervals were more accurately identified than harmonic. To keep the musical vibrations simple enough as well as their energy centered in the tactile band, we selected the bass guitar for the regularity and compactness of the harmonic series it generates and for the prominence of the component oscillating at the fundamental frequency. Aware of potential bone conduction effects [12], nevertheless we chose to expose participants to vibrations similar to those experienced while attending a musical live performance: stimuli were presented using a vibrating chair along with a vibrating floor platform. Both such actuated objects are not new, used for whole-body vibrotactile stimulation of hearing or deaf individuals [13] and in experiments on foot-based tactile perception [14].

To summarize, participants were first classified as musicians or non-musicians. Both listened to the set of unison, consonant and dissonant intervals prior to the test. Then, every participant had to identify at each trial if an interval was ascending, descending or unison either by hearing, or by feeling vibrations which could be delivered at the whole body or underfoot. Once having checked that the ascending/descending order was not significant (whereas unisons were easier to identify), we categorized the answers based on the consonance degree of the intervals. In addition to the identification task, musicians were asked to label the intervals using their standard name. In the limits of control of this experiment, the results suggest that the subjective ability of both musicians and non-musicians to identify an interval increases with consonance, showing a peak for unisons, and increases if the whole body is stimulated. The musicians' ability to label the intervals varied in a similar fashion.

Yet unpublished so far, these results have been already presented at the HMP Workshop held at the Zürcher Hochschule der Künste in Switzerland[1], where they probably stimulated further research now in progress, appearing somewhere in the future[2].

2. MATERIAL AND METHODS

2.1 Participants

Ten musicians (seven male, three female, age 28.12±6.97; years of practice 12.31±3.43) and eleven non-musicians (nine male, two female, age: 34.33±17.68), all reporting normal hearing and somatosensory ability, participated in the experiment. The study protocol was approved in accordance with the Declaration of Helsinki and all participants gave their written, informed consent now logged at the Department of Neurological and Movement Sciences, University of Verona. Participants were classified as either musicians or non-musicians based on the score they totalized in a questionnaire which is standard in the Italian schools of music. The questionnaire requires knowledge of basic music theory (scales, chords and intervals), the identification of four intervals by listening and finally the ability to sing/play notes and intervals. The group of musicians comprised four classic guitar, three violin, and three cello players.

2.2 Apparatus

A chair and a floor platform were built using thick plywood, and then actuated by mounting a Tactile Sound T239-silver audio-tactile transducer by Clark Synthesis in their bottom part (Figure 1). Both transducers were driven by a Crest CA6 stereo power amplifier duplicating a monophonic sound received from a Macbook Pro laptop driving a Presonus Firebox audio interface. A pair of Sennheiser CX175 in-ear headphones was furthermore connected to the same laptop.

The frequency responses of both the chair and the floor platform were measured under conditions reproducing the experimental test. A 0-dB reference was set in the audio interface corresponding to a loud output from the transducers, just below their distortion threshold. Measurements were made by attaching an Analog Devices model ADXL001 accelerometer to the center of the seat and then to the center of the floor platform: three sessions were made on the chair with sound levels respectively set to -3 dB, -6 dB and -15 dB; then, three sessions were made on the platform with sound levels respectively set to -3 dB, -6 dB and -10 dB. The signals from the accelerometer went through an analog low-pass filter, and

[1] https://www.zhdk.ch/index.php?id=icst_ahmi0
[2] http://www.eurohaptics2016.org/?page_id=1139

were finally acquired by an Arduino 2650 board sampling the signal at 2 kHz. During each session a person weighting 73 kg was sitting on the chair and then standing upright on the floor platform. He was asked to stand still each time the chair and then the platform were excited with a 4 seconds logarithmic sweep in the range 10-1000 Hz through the respective tactile transducer [15]. Three measurements were averaged before closing each session, to attenuate the effects of involuntary body movement on the results.

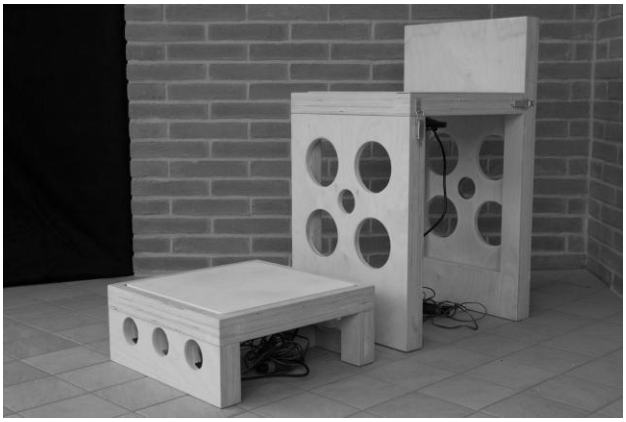

Figure 1. View of the actuated chair and floor platform.

The two averaged frequency responses showed evident spectral similarities, as both plates were made of identical wooden plates mounting the same transducer model; furthermore they were decoupled from the rest of the apparatus, by attaching rubber bands to every corner of the respective plate. Overall these responses showed a linear, though not constant transfer of energy to the body in the frequencies of interest for the experiment.

2.3 Stimuli

Twenty notes were recorded from a Fender Precision electric bass played by a professional musician, and when needed later equalized in amplitude so to have the same loudness at the subjective judgment of the bass player (Table 1). Each note was two seconds long. Such notes were combined into pairs separated by one second of silence, each pair finally representing either an ascending or a unison interval. Twelve intervals were created using these notes. There was no interval larger that the octave.

Note	*Key*	*Frequency (Hz)*	*String*
F#	2	46.25	E
G#	4	51.91	E
A	0	55.00	A
A#	1	58.27	A
B	2	61.74	A
C	3	65.41	A
C#	9	69.30	E
D	5	73.42	A
D#	6	77.78	A
E	7	82.41	A
E	12	82.41	E
F	8	87.31	A
F	13	87.31	E
F	3	87.31	D
F#	14	92.50	E
G	10	98.00	A
G#	11	103.83	A
G#	6	103.83	D
D	17	146.83	A
D#	13	155.56	D

Table 1. Electric bass notes used in the experiment.

The intervals were categorized depending on their consonance level in accordance with the standard Western music notation (Table 2): i) dissonant (4th Augmented, 5th Augmented, 7th Major and 7th Minor); ii) consonant (2nd Major, 4th Perfect, 5th Perfect, and 8th Perfect); iii) unison (the same note repeated twice). Each dissonant and consonant interval was set to be also descending. With the addition of the descending order, eight dissonant (four ascending and four descending), eight consonant (four ascending and four descending) and four unison intervals finally formed the set of stimuli for the experiment.

Category	*Interval name*	*First Note/Key*	*Second Note/Key*
Dissonant	4th Augmented	B/2	F/8
Dissonant	7th Minor	F#/2	E/7
Dissonant	5th Augmented	G/10	D#/13
Dissonant	7th Major	A/0	G#/6
Consonant	4th Perfect	A#/1	D#/6
Consonant	2nd Major	E/12	F#/14
Consonant	8th Perfect	D/5	D/17
Consonant	5th Perfect	C#/9	G#/11
Unison	1st Perfect	G#/4	G#/4
Unison	1st Perfect	C/3	C/3
Unison	1st Perfect	F/13	F/13
Unison	1st Perfect	F/3	F/3

Table 2. Musical intervals used in the experiment.

It must be noticed that identical bass notes, and hence the intervals containing them, could have different spectral content depending on the key pressed to play the note. Table 1 shows that this was the case for the notes E, F, and G#. Composing these notes into melodic intervals led in particular to two unisons, both made with F, which vibrated differently (see Table 2). In particular, the note F had a prominent peak at twice the fundamental frequency when played at the third key. This difference is heard as a subtle change in musical timbre, of negligible importance for the auditory identification of the interval. As we will discuss later, the same change is significantly discriminated by the tactile system.

2.4 Procedure

Three conditions were defined: 1) in the Feet condition vibrations were delivered by the floor platform to participants standing upright, whereas 2) in the Hips condition participants received vibrations simultaneously under the seat and underfoot while being seated on the instrumented chair. In order to minimize transmission of sounds to the ears, in both such conditions they had to listen to white noise through the earphones meanwhile wearing insulating ear-muffs. Finally, 3) in the Ears condition participants listened to the stimuli directly through the earphones with the vibrotactile transducers switched off; in practice, Ears played the role of a control condition.

Before the test each participant listened to the stimuli, to make her or himself confident with the musical intervals they represented. Then, (s)he was asked to confirm that under conditions Feet and Hips (s)he clearly felt the vibrations resulting from the reproduction of one standard note randomly chosen from the set in Table 1. Finally, each participant was asked to stand about 20 cm far from the chair while wearing the ear-muffs and, then, to set the noise at the earphones to a level preventing him or herself from hearing the sound coming out from the transducers, actually a by-product of practically any (including our) vibrotactile system. With the transducers playing all stimuli in a predefined sequence, every participant was repeatedly asked to increase the loudness until the sound coming from the chair and the floor platform became no longer audible to her or him. This procedure was repeated ten times, and the resulting subjective average individually used for the rest of the experiment.

The test consisted of three experimental blocks respectively implementing the Feet, Hips and Ears condition. Every block was made of a randomly balanced sequence containing six repetitions of each stimulus, for a total of 120 trials. All stimuli were played by means of E-prime by Psychology Software Tools. The order of the experimental blocks was randomized within participants. Resting was allowed amidst each block.

Musicians after each trial had to 1) label the interval with its name, and 2) identify one order for the interval among three possibilities: ascending, descending, unison. Such two questions were ordered by decreasing difficulty to put musicians in condition to answer the more difficult question first. Non-musicians had to answer only question no. 2. It took about 45 to 60 minutes for non-musicians to complete the test. Musicians took more time and comparable fatigue; on the other hand they were more motivated to label each interval and its order. It consequently took 60 to 80 minutes for this group to complete the test.

2.5 Analysis

The percentages of correct answers to question no. 2 under different categories and conditions were considered in the analysis. A preliminary series of t-tests showed that in all such cases these percentages were above chance ($p<0.001$, chance level 100/3 = 33.33%). An ANOVA with repeated measures, having the two groups (musicians and non-musicians) as between factor and the three categories (dissonant, consonant, unison) and conditions (Feet, Hips, Ears) as within factors was performed; pairwise comparisons with Bonferroni corrections were used to explore significant interactions.

Concerning the labeling of intervals, the correct answers to question no. 1 provided by musicians were above chance in percentage ($p<0.05$, chance level 100/12 = 8.33%) except for the dissonant intervals in the Feet condition ($p=0.25$, same chance level). An ANOVA with repeated measures was then conducted on the correct interval labels given by musicians considering the three categories (dissonant, consonant, unison) and conditions (Feet, Hips, Ears) as within factors. Again, pairwise comparisons with Bonferroni corrections were used to explore significant interactions.

3. RESULTS

The analysis of the answers to question no. 2 showed no differences between groups ($F(1,19)=0.13$, $p=0.72$), conversely it showed main differences for category ($F(2,38)=84.36$, $p=0.001$) and condition ($F(2,38)=24.00$, $p<0.001$). Concerning the categories, identifying unisons was significantly easier ($p<0.05$) than identifying consonant and dissonant intervals; as to the conditions, recognition at Feet was significantly less accurate ($p<0.05$) compared to both Hips and Ears (Table 3, rows about identification).

As to question no. 1, an ANOVA with repeated measures conducted limitedly to the group of musicians again showed significant main factors for the category ($F(2,20)=170.50$, $p<0.001$) and condition ($F(2,20)=12.89$, $p<0.001$), as well as a significant interaction for category x condition ($F(4,40)=4.01$, $p=0.008$). Concerning the categories, dissonant intervals were the most difficult to label followed by consonant intervals, while the easiest identification took place with unisons; furthermore, all categories were significantly different each from the other. About the condition, the intervals were identified the least when displaying the stimuli at the Feet, followed by Hips and finally Ears (Table 3, rows about labeling).

	Unison	*Consonant*	*Dissonant*
Identification	95.97±0.77%	93.02±1.06%	88.47±1.91%
Labeling	97.2±8.68%	59.6±4.40%	18.4±6.56%
	Ears	*Hips*	*Feet*
Identification	96.74±0,63%	94.53±0,84%	86.18±1,85%
Labeling	68.1±5.24%	59.3±5.77%	47.8±5.61%

Table 3. Identification and labeling under different categories (above, correct answers) and conditions (below, correct answers).

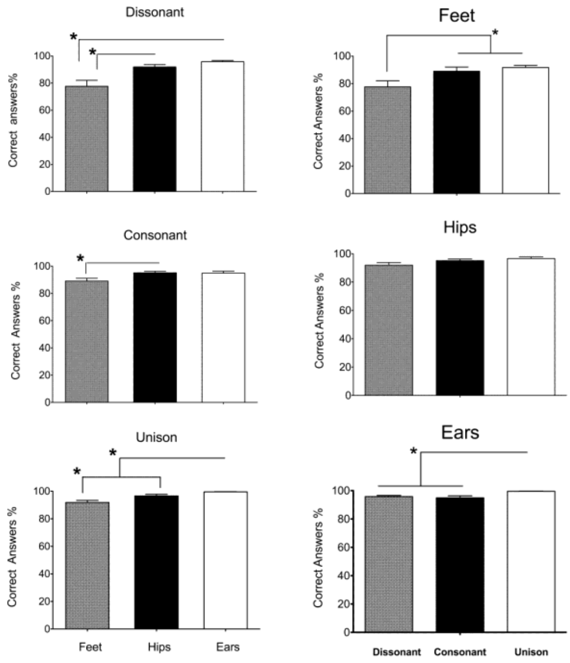

Figure 2. Interval identification: condition x category (left), category x condition (right), all participants. Arrows denote significant differences (p<0.05).

The interactions between condition and category show significant differences in the identification of the intervals (Figure 2). Differences across categories showed a more difficult identification of consonant as well as dissonant intervals by hearing compared to unisons; instead, their vibrotactile perception led only to significantly more difficult identification of dissonant intervals at foot level. Differences across conditions showed that dissonant and consonant intervals were more difficult to recognize when the stimulus was delivered at Feet compared to when the stimulus was delivered at Hips or Ears; for unisons the three conditions were all different with the highest percentage of correct answers for Ears, followed by Hips and, finally, Feet.

Concerning interval labeling, the condition x category interaction (Figure 3, left) showed that while being exposed to unisons musicians labeled the intervals successfully, with no significant differences depending on the condition; consonant as well as dissonant intervals were instead identified with an accuracy varying with the condition, with significant differences plotted in the figure. In parallel, the category x condition interaction (Figure 3, right) shows that the accuracy was proportional to the categories as well, by progressively decreasing for consonant and then dissonant intervals. In particular, under the Feet condition dissonant intervals were not identified above chance level, in this case equal to 8.3%.

Overall, the interactions in Figures 2 and 3 show that the recognition accuracy decreased along both the category and condition dimensions. The decay was more pronounced when musicians had to label the intervals relying on tactile cues.

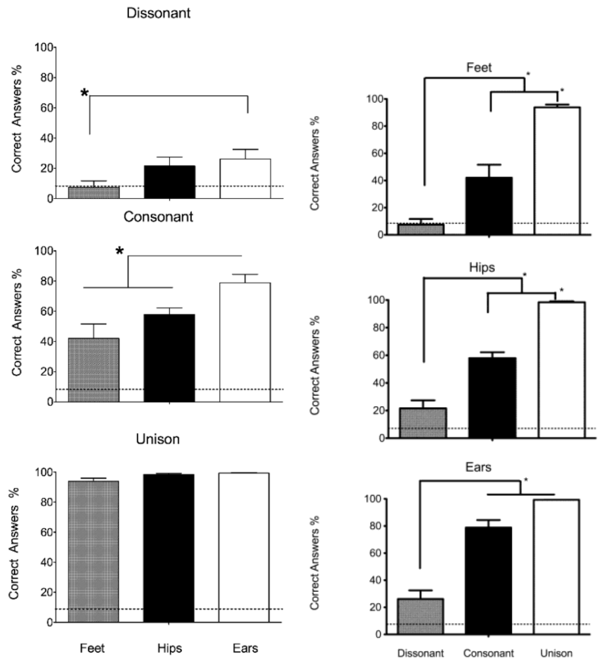

Figure 3. Interval labeling: condition x category (left), category x condition (right), musicians only. Arrows denote significant differences (p<0.05).

3.1 Contribution of different channels

The perception of cutaneous vibrations is known to depend on both the RA and PC channel. The fundamental frequency pairs which defined the intervals forming our stimuli had values falling in the pitch range [46.25 – 155.56] Hz (see Table 1). In this range both channels are stimulated, with a progressively more important contribution of PC for increasing frequency. Since this channel is known to have low sensitivity to pitch, and assuming no adaptation effects in RA under our experimental conditions [2], we might expect a decreasing sensitivity to melodic consonance in our participants for increasing pitch of the intervals.

Based on this expectation, for the unison category we performed an ANOVA considering the two groups as between factor, with the four intervals (see Table 2) and the three experimental conditions as within factors. For the consonant and dissonant categories we classified the interval pitch (see Table 2) as low or high based on the corresponding note fundamental frequency values: consonant 4th Perfect and 2nd Major as well as dissonant 4th Augmented and 7th Minor were classified as low-pitched; consonant 8th Perfect and 5th Perfect as well as dissonant 5th Augmented and 7th Major were classified as high-pitched. Holding this classification, we performed an ANOVA considering, again, the two groups as between factor with pitch (low, high) and conditions (Feet, Hips, Ears) as within factors.

The analysis on unisons showed no differences between groups (p=0.67) and a main effect of intervals (F(3,57)=6.19, p<0.0001) and conditions (F(2,38)=15.22, p<0.0001).

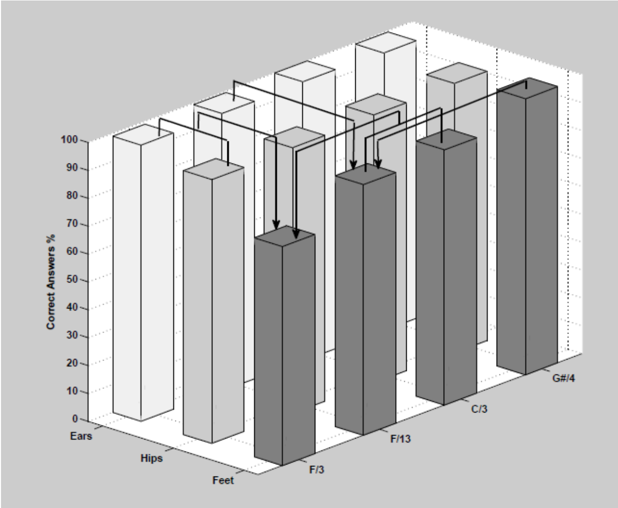

Figure 4. Unison intervals identification: condition x interval, all participants. Arrows denote significant differences (p<0.05).

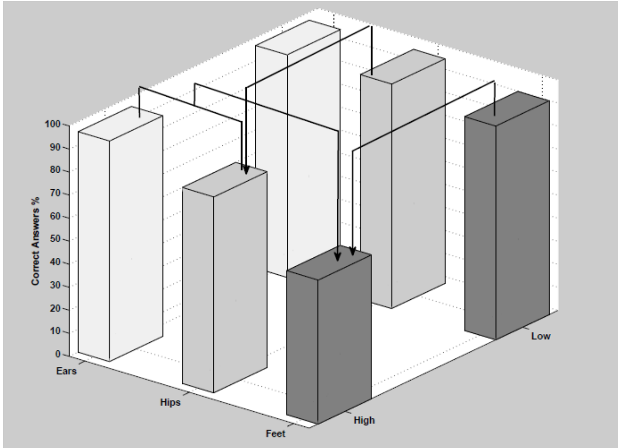

Figure 5. Dissonant intervals identification: condition x pitch, all participants. Arrows denote significant differences (p<0.05).

No further main effects or interactions were found. The correct answers were respectively equal to 98.3±0.9% for G#/4, 95.9±1.4% for C/3, 94.9±1.37% for F/13 and 90.7±1.9% for F/3, with significant differences between G#/4 and F/3 as well as C/3 and F/3. Furthermore it showed significant differences in interval x condition (F(6,114)=6.07, p<0.0001), shown in Fig. 4. This result speaks in favor of a progressively more intense involvement of the PC channel with increasing frequency, with consequent loss of temporal discrimination as suggested by the literature. The same result suggests that the pitch of F/3, although being the same as that of F/13 in auditory sense for what we said in the section on stimuli, was conversely perceived higher in tactile sense, with consequent loss of precision in categorizing the corresponding unison. Finally, the perception was best at the ear and worst underfoot, with significant differences among all the three experimental conditions.

The analysis on the consonant intervals showed no differences between groups (p=0.66) and a main effect of conditions (F(2,38)=9.67, p=0.005), revealing that when the stimuli were delivered underfoot (correct answers equal to 85.8±3.13%) the performance was worse than when they were delivered at the hips (92.6±2.2%) and ears (95.1±1.4%). No further effects or interactions were found. The analysis on the dissonant intervals showed no differences between groups (p=0.91) and a main effect of pitch (F(1,19)=16.481, p=0.001) and conditions (F(2,38)=38.35, p<0.0001). No further main effects or interactions were found. Participants guessed low-pitched intervals (95.7±1.4%) more correctly than high-pitched intervals (81.1±3.7%). As before, the best perceptual condition was Ears (correct answers equal to 96.2±1.1%) followed by Hips (91.2±2.8%) and Feet (77.7±4.6%). Furthermore it showed significant differences in pitch x condition (F(2,38)=9.23, p=0.001), shown in Fig. 5.

Taken together, these results indicate that lower-pitched notes were perceived more accurately than higher-pitched notes, with an obvious exception for the Ears condition.

4. DISCUSSION

The performance trend under the tactile categories suggests the existence of an identification process that for some reason worked better when the stimuli were presented to the whole body. The narrower stimulation region associated to the Feet condition might be responsible for the corresponding performance decay.

The two interactions we found once the intervals were classified based on their pitch suggest an extension to the discussion on summation. In fact, the participants' accuracy in classifying unisons across the tactile conditions decayed more rapidly when the pitch of the stimulus was high (Fig. 4); a similar dependence on frequency emerged also when they had to classify dissonant intervals (Fig. 5). Conversely, for low-pitched intervals of any category no significant differences were found across conditions. The logical conclusion is that the RA channel did not need to rely on spatial summation when decoding the intervals falling in its sensitivity range; the PC channel instead benefited from stimulation of larger body areas. This conclusion agrees with results found by Gescheider *et al.* [16] about the summation effects existing for these channels.

An alternative explanation of these results is that some form of auditory perception trough bone conduction took place during the experiment. There are several physiological pathways vibrations can follow to reach the basilar membrane, including those that put the whole cochlea into vibration at audible tactile frequencies [12]: although the auditory masking through white noise of audible byproducts coming from vibrotactile devices is standard in these kinds of experiments [1,2,3,7,9,10], in the authors' opinion there is still lack of systematic studies analyzing in detail the potential auditory effects of bone conduction during tactile perception tests, especially when powerful transducers are employed to put the body into vibration in part or as a whole. Since our participants received the stimuli from both transducers only while being seated, we can hypothesize that this condition provided more energetic vibrations to their heads. Furthermore, if we assume that under our experimental conditions bone conduction at low frequencies was more efficient, indeed an hypothesis demonstrated by several researchers [17], then in favor of the same conclusion may also play the pitch-dependent interactions summarized by Fig. 4 and Fig. 5.

There is, however, the concrete possibility that no form of auditory perception took place during the experiment. In this sense the most careful experimental design we were able to find in the literature implemented, besides noisy masking and ear insulation from sounds on air, additional vibrotactile masking through the use of bone headphones delivering white noise to the participant's left and right mastoid [10]. This particular work, for which a concise summary has already been given in the introduction, opens an interesting perspective on experiments that, similarly to our one, aimed at investigating the vibrotactile recognition of musical cues and for this reason disconnected the auditory channel limitedly to sounds on air: Russo and colleagues in fact showed that the use of additional vibrotactile masking did not affect their results.

Since timbre perception implies sensitivity to consonance, the critical band model proposed by Russo *et al.* [10] could explain the sensitivity of our participants once the cortical integration they hypothesize were able to work also across time, by retaining the former note belonging to a melodic interval in the working memory until the latter note was received. As mentioned in the introduction, Harris *et al.* [6] found evidence of this retention using sequential pairs of square waves; since a square wave essentially contains musical cues of dissonance due to its characteristic spectrum, the percentage of correctness (i.e. around 80%) they report for the identification of different retention intervals looks suggestive when compared to the data in our histogram in Fig. 2 about consonance and dissonance perception underfoot, displaying similar percentages.

One further look at Table 1 shows that the fundamentals forming our stimuli ranged quite in the same frequency as the sinusoids used by Yoo *et al.* [7]. While identifying whether an interval was ascending, descending, or unison, our participants were certainly able to decode qualitative tactile cues of relative (that is, either positive or negative) frequency difference between the note fundamentals in the interval. The extent to which this decoding process was also quantitative, hence useful for assessing the consonance degree of a melodic instead of harmonic (e.g. Yoo's) interval, is a question that our experiment cannot answer.

The sensitivity to consonance may have also been influenced by the auditory session our participants attended before the tactile identification tasks. If during these tasks they perceived also with the ears through a pre-attentive or subliminal, however unconscious process caused by bone conduction, the consequent auditory cues may have positively cross-correlated with the vibrotactile stimuli. In fact, a number of research studies have uncovered the existence of cross-modal amplifications which are consequence of the integration, at peripheral and/or central level, of auditory and tactile cues [18,19]. Besides interesting the nervous system from its periphery to the central level, these amplification mechanisms seem to result in greater effects as far as the multimodal stimuli contain components each in relation with the other through consonant frequency ratios [20,21].

We already mentioned that musicians did not perform significantly better than non-musicians while categorizing the vibrotactile stimuli. This evidence reinforces the idea that musicians did not rely on previous musical knowledge while deciding for the increasing or decreasing order of the intervals. Now, once this decision was made, they conversely had to access this knowledge in an aim to label the respective intervals: at this point they labeled consonant intervals well above chance; on the contrary, they were in trouble when associating dissonant intervals to their respective names. Besides an overall offset that affects also the Ears condition, arguing in favor of a moderate difficulty for our musicians to recall the names of the dissonant intervals during the test, once again we speculate that the performance increase obtained with consonant intervals may be the effect of an auditory process occurring when vibrations were produced both under the seat and underfoot, perhaps starting in the basilar membrane due to bone conduction and in possible synergy with a cross-modal amplification process occurring at central level, due to the consonance of the intervals.

5. CONCLUSIONS

Our participants identified the tactile melodic relation between two bass guitar notes with an accuracy that depended on the consonance degree; furthermore, their performance improved by stimulating the whole body. Especially the former dependence reflects a tendency humans experience also when they listen: although dissonance is easy to recognize, consonant cues are inherently preferred. Evidence of this preference has been found in newborns also from deaf parents [22] and in animals [23], bringing researchers to search for universal explanations involving, for instance, geometrical symmetries existing in chords [24] or the existence of forms of entrainment between consonant stimuli and oscillatory neural networks involved in auditory processing [25]. While adding no deeper insight on such explanations, our results at least suggest that humans may process vibrotactile consonance in similar ways they do when they listen to auditory consonance. Since these results were obtained by simulating conditions resembling those that occur when a music performance is attended, we lost much of the control that is instead needed to quantify and explain a perceptual phenomenon. For this reason we remained non-committal about the possible origins of melodic consonance sensitivity, rather highlighting several affinities existing between our results and a context of previous experimental research from which a robust study of the phenomena underpinning tactile consonance perception could start.

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