SONIFICATION OF SURFACE TAPPING: INFLUENCES ON BEHAVIOR, EMOTION AND SURFACE PERCEPTION

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ABSTRACT

Interaction sounds when tapping on a surface provide information about the material of the surface and about one's own motor behaviour. With the current developments in interactive sonification, it is now possible to digitally change this audio-feedback resulting from object interaction. Here we evaluated a model for a sonic interactive surface. This model uses a system capable of delivering surface tapping sounds in real-time, when triggered by the users' taps on a real surface or on an imagined, "virtual" surface (i.e., when tapping in the air). Across different conditions the audio-feedback was varied so that the heard tapping sounds corresponded to different applied strength during tapping. We evaluated the effect of the altered tapping sounds on (1) emotional action-related responses: perceived effort and aggressiveness when tapping on the surface, emotional valence, dominance, and arousal measured through self-report and biosensors, (2) participants' way of interacting with the surface: maximum acceleration and frequency of tapping movement, and (3) surface perception: perceptual quality of hardness. Results show the influence of the sonification of surface tapping at all levels: emotional, behavioral and perceptual. We conclude by addressing some implications of our results in the design of interactive sonification displays and tangible auditory interfaces aiming to change perceived and subsequent motor behaviour, as well as perceived material properties.[1]

1. INTRODUCTION

When a person touches or taps on a surface, they can often hear the resulting interaction sounds [1]. Different physical features of the material of the surface will result in different auditory cues; for instance, tapping on a soft woollen surface will produce different sounds than tapping on a hard wooden surface. Different modes of touching the surface will also result in different auditory cues; for instance, tapping soft on a surface will produce *weaker* sounds than when tapping hard on the same surface. But to what extent do we make use of this information available during surface interaction sounds? This is an important question to be addressed as interaction with objects is more and more mediated through their digital representation [2,3]. Here, by means of interactive sonification of surface tapping actions, we aim to explore how sounds produced when tapping on a surface actually (1) inform of the physical features of the surface material (e.g., hardness); (2) inform of the applied strength when tapping; (3) inform of the user's ability to tap, which may impact on one's own emotional state; and (4) change one's own tapping behaviour, as one will try to adjust the tapping actions in response to the audio-feedback, an effect referred to as auditory-action loop (e.g., [4]).

Current developments in interactive sonification and auditory augmentation allow to digitally change the audio-feedback resulting from our interaction with objects and even to fully represent objects with sound [1, 5-7]. This may lead to a change in the perceived material properties of the objects (e.g., perceived qualities of natural materials [8] or virtual haptic surfaces [9]), given that the perception of materials is known to be multisensory, with touch, vision, and audition all contributing to it and interacting with each other [10]. In addition, changing the audio-feedback resulting from our interaction with objects may also lead to a change in our way of interacting with these objects, that is, our motor behavior. For instance, hearing the expected contact sound on the onset of a reaching-to-grasp movement towards an object (i.e., hearing the sound that touching that object would produce), can speed the movement, as compared to when hearing an unexpected contact sound (i.e., the sound of an object with different material [11]).

Importantly, audio-feedback during object interaction may also change our own motor behavior because it informs of the motor behavior itself, as well as of properties of our own body. For example, sonification of boat motion improves movement execution of elite rowers, as it provides information about small variations and deviations in rowers' movements [12]. Tapping sounds inform of the location and dimensions of the body-part touching the surface, and its sonification can actually change the perceived body dimensions (e.g., length of the arm tapping [13]). The introduction of a delay in the footsteps sounds produced when walking results in changes in gait-period and walking speed [14]. Moreover, the sonification of footstep sounds to represent different ground surfaces influences the walking style when people are asked to walk in a specific emotion-related style [15]. Body movement (including touch behaviour) is in fact both a medium to express one's emotions [16, 17] but also a medium to modulate one's own emotions [18].

We advance these studies by focusing on audio-feedback related to the level of applied strength when tapping on a surface, rather than focusing on the feedback related to specific materials. We designed a prototype, based on interactive sonification of surface tapping sounds. This system is capable of delivering surface tapping sounds in real-time, when triggered by the users' taps on a real surface or on an imagined, "virtual" surface (i.e., when tapping in the air). An experiment was conducted during which blindfolded participants were asked to tap onto these two different types of surfaces, real and virtual, while receiving

[1] This work is part of the MSc project of the first author.

audio-feedback in response to their tapping actions (see Figure 1). In both cases, audio-feedback was the sound produced by tapping on a real surface. Across different conditions the feedback was varied so that the heard tapping sounds corresponded to different applied strength during tapping. Having real and virtual surface types allowed exploring the effects of audio-feedback when tactile cues informing of the tapped surface/applied strength are present or absent. Across conditions, we did not ask participants to change their tapping style, but specifically asked them to keep the same tapping style.

Our hypothesis is that, by altering the audio-feedback cues that inform of the applied strength when tapping on the surface, we will observe changes at different levels. In particular, we expect to observe changes on (1) perceived applied strength when tapping, (2) perceived one's own ability to tap and emotional responses to the tapping task, (3) tapping behaviour and (4) perceived surface hardness. This research may help in the development of audio-haptic interfaces, or tangible auditory interfaces (as described in [7]), aiming to change perceived and subsequent motor behaviour, as well as perceived material properties. These interfaces might be used in the design of technology in different contexts. For instance, in the context of health-promoting and fun-related movements (e.g., videogames), for which a specific way of performing a movement is important, or in the context of online shopping, for which perceived material properties and emotional responses are important. They might be used also in applications for which extreme precision in the applied strength is required, such as in some sports or in remote object handling (e.g., dismantle bomb or clinical surgery), as further discussed in Conclusion.

The paper is structured as follows. Section 2 describes the prototype designed and the materials used, including sounds, surface and sensor to measure emotional responses. Section 3 describes the design and procedure followed in the system evaluation, providing information about the participants in the study, and the data analyses. Section 4 presents the results of the system evaluation in three subsections: (1) emotional action-related responses, (2) tapping behaviour and (3) perception of surface hardness. This section ends with a discussion of the results based on the hypotheses driving the study. Section 5 provides a conclusion, summarizing the main findings and further discussing specific applications of this research.

Figure 1. *(Top panel) A participant on the experimental setup tapping on the "real" surface and (Bottom panel) an example of the hand movement when tapping on the "virtual" surface.*

2. SYSTEM OVERVIEW

2.1. Sonification of surface tapping

Sonification of surface tapping is achieved by having the tapping action triggering, in real-time[2], the presentation of pre-recorded tapping sounds. The tapping action is detected by registering the sound signal captured by a piezoelectric transducer (see Table 1 for specific model of hardware components of the system), attached to the "real" surface, and the signal captured by an accelerometer, attached to the participants' middle finger of the participants' dominant hand using hypoallergenic tape (Figure 2). The piezo is connected to an external soundcard and the accelerometer is connected to an Arduino Uno microcontroller board. Both connect through USB ports to a computer running the real-time synthesis environment MAX/MSP[3]. The MAX/MSP patch uses the Arduino2Max library[4].

For the detection of surface taps a threshold is set as follows. For the "real" surface condition, this threshold is based on the absolute value of the peak amplitude of the piezo input signal, being specifically calibrated according to the piezo sensitivity to detect surface taps. For the "virtual" surface condition, in which the hand is kept in the air, a zero crossing of the accelerometer x-axis triggers the sound. The value of the accelerometer x-axis is linked to both the dynamic acceleration of the hand and to the angle of the hand. We use a motor-to-audio translation algorithm that triggers a feedback sound every time a "real" or "virtual" tap is detected. The pre-recorded feedback sound is the sound produced by a person tapping on a surface, and across conditions the feedback can be varied so that the heard tapping sounds correspond to different applied strength during tapping (see *Materials*). The audio-feedback is delivered through closed headphones with very high passive ambient noise attenuation, which are connected to the external soundcard.

The system allows recording the piezo and accelerometer input signals, as well as the generated audio-feedback, that can be used to analyze user's tapping behavior (i.e., maximum acceleration and frequency of participants' tapping movements). A sensor attached to the user's wrist (non-dominant hand), measures the galvanic skin response (GSR) of the user. GSR is a sensitive and valid real-time measure for emotional arousal in response to external stimuli [19].

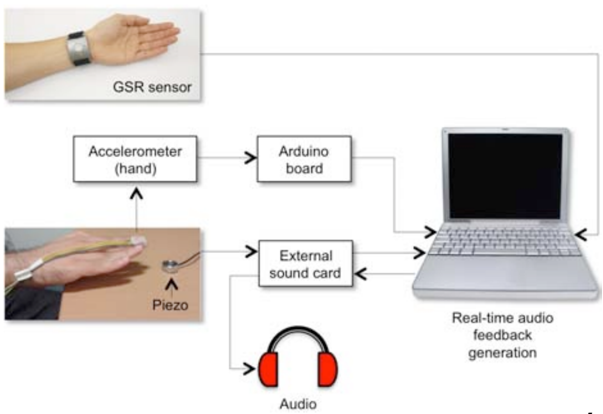

Figure 2. *Connections of the prototype physical components*[5].

[2] The mean delay introduced by the system is 10.7 +/- 1.8 ms. The maximum delay measured is 14 ms.

[3] www.cycling74.com

[4] http://playground.arduino.cc/interfacing/MaxMSP

[5] The GSR sensor shot shows the Affectiva Q Sensor (retrieved from Reuters/Affectiva/Handouts, 2012).

2.2. Materials

Three sounds[6] (44.1 kHz) were recorded in an anechoic chamber, which allowed reducing background noise. A digital recorder was used for this purpose (see Table 1). The sounds were of a person tapping with the palm of the hand on a cardboard box applying three different levels of strength. The sound of tapping on a cardboard box was chosen given the rather clear difference in sounds resulting from different levels of applied tapping strength. We refer to these three versions of the sounds as "weak", "medium" and "strong" tapping sounds. The sounds were normalized by using Audacity software so that there was a 8 dB difference between "weak" and "medium", and between "medium" and "strong" sounds. Each sound lasted 190 ms.

A wooden table was used as the "real" surface (see Figure 1). To ensure that participants could not hear the sound of their actual tap, additionally to the closed headphones, a pink noise (this is 1/f noise, in which the power spectral density of the frequency spectrum is inversely proportional to the frequency) was used as background sound for the whole tapping period[7].

When evaluating the system, the GSR sensor sampling rate was set to 8 Hz for the first 8 participants, and was changed to 32 Hz for participants 9-31, for better precision.

Table 1. Hardware components employed in the system.

Hardware components	Brand and Model
Piezoelectric transducer	Schaller Oyster 723 Piezo Transducer Pickup
Accelerometer	Triple Axis Accelerometer Breakout MMA8452QA
External soundcard	RME Fireface UC
Computer	MacBook pro
Microcontroller board	Arduino Uno
Headphones	Sennheiser HDA 200
GSR sensor	Affectiva Q Sensor
Digital recorder (for sound stimuli)	ZOOM ZH4N Handy Portable Digital Recorder

3. SYSTEM EVALUATION

3.1. Participants

Thirty-one paid participants with normal hearing and tactile perception, and naïve as to the purposes of the study, took part to the experiment. Data from 8 of these participants had to be excluded from the analyses (see section 3.3), leaving a total of 23 participants (5 male, 18 female; age range = 19-35, mean age= 23.2, standard deviation age = 3.4; 2 participants reported being left-handed, and 21 right-handed).

3.2. Design and procedure

During each block participants wore headphones, the accelerometer and the GSR sensor. Participants were blindfolded, with the exception of two participants that indicated feeling uncomfortable with the blindfold and therefore they were allowed to keep their eyes closed during the experimental blocks.

We followed a within-subjects design with six tapping blocks differing in the type of tapped surface (surface type: real or virtual) and the level of strength of the tapping sounds presented as feedback (sound strength level: weak, medium and strong). The order of the blocks was randomized across participants.

Each block lasted for 80 s, during which participants were asked to tap with their dominant hand on the table (in the real surface blocks) or on the imagined surface (in the virtual surface blocks). They were required to keep their rhythm constant and to produce one tap approximately every second. We specifically asked participants to maintain the same tapping style across the experimental blocks. During the first and last 10 s of the block (which acted as baselines), participants only heard pink noise. For the remaining time of the block, apart from pink noise, participants were presented with real-time audio-feedback in response to their taps. GSR was recorded during the whole duration of the block.

At the end of each block, participants were asked to fill in a questionnaire[6] that allowed assessing the subjective experience of participants during the block. The questionnaire contained:

(1) three 9-item graphic scales, assessing the emotional valence, arousal and dominance felt by participants (self-assessment manikin [20]);
(2) four 7-point Likert scales, assessing the feelings of perceived aggressiveness (from "tender" to "aggressive"), physical strength (from "weak" to "strong"), ability to complete the task (from "unable" to "able"), and the surface physical quality of hardness (from "soft" to "hard").
(3) the Subjective Mental Effort Questionnaire [21], where participants indicated the stress felt while tapping using a vertical analog scale ("Not at all hard to do" to "Tremendously hard to do");
(4) a perceived self-efficacy scale that measured the perceived ability to perform a task involving physical strength (lifting objects of different weights) [22].

3.3. Data analyses

A series of MATLAB R2012b scripts were used to extract maximum acceleration and frequency (inter-tapping interval) of tapping movement from the logged accelerometer and piezo data, as well as to extract mean values of GSR data. For 8 participants, it was observed that, due to an unexpected way of tapping, they did not received audio-feedback for more than 20 s of the trial, and therefore, their data was excluded from the subsequent analyses. For the remaining 23 participants[6], we evaluated the effect of the altered tapping sounds on (1) emotional action-related responses: perceived effort and aggressiveness when tapping on the surface, emotional valence, dominance, and arousal measured through self-report and biosensors, (2) participants' way of interacting with the surface: maximum acceleration and frequency of tapping movements, and (3) surface perception: perceptual quality of hardness.

Shaphiro-Wilk tests assessed normality of data distributions. Parametric (analysis of variance – ANOVA - and t-tests), and non-parametric (Friedman and Wilcoxon) tests were used, respectively, with normal and non-normal data [23].

[6] Sounds, MAX/MSP patches, questionnaire and data collected are available at: https://www.ucl.ac.uk/uclic/research/project-pages/hearing-body/ISON2013_supplementary

[7] Although the presentation of sounds in synchrony with own tapping and pink noise masked the actual tapping to a large extent, the masking was not 100% effective in the situations when participants applied a high level of tapping strength. Nevertheless, our results prove the expected changes in behavior, emotion and surface perception.

4. RESULTS

4.1. Emotional action-related responses

Self-reported valence: For the real surface condition, it varied between sound strength level conditions ($\chi^2(2) = 5.56$, $p = .062$; see Figure 3), with self-reported valence being significantly lower when the sound was *weak* as compared to when the sound was *strong* ($Z = -2.31$, $p < .05$). No significant effects were found due to the surface type, or due to the sound strength level for the virtual surface condition ($p > .05$ for all Wilcoxon tests).

Self-reported arousal: It varied between conditions ($\chi^2(5) = 8.13$, $p = .149$; Figure 3). Subsequent analyses revealed that, for *strong* and *weak* sound conditions, self-reported arousal was significantly lower for the real than the virtual surface (*strong* sound: $z = -2.28$, $p < .05$; *weak* sound: $z = -2.17$, $p < .05$). No significant effects resulted from the strength level (all *ps* > .05).

Self-reported dominance: Wilcoxon analyses revealed that, for *strong* and *weak* sound conditions, self-reported dominance tended to be significantly higher for the real than for the virtual surface (*strong* sound: $z = -1.82$, $p = .068$; *weak* sound: z = -1.62, $p = .11$; see Figure 3). No significant effects were observed due to the strength level (all *ps* > .05).

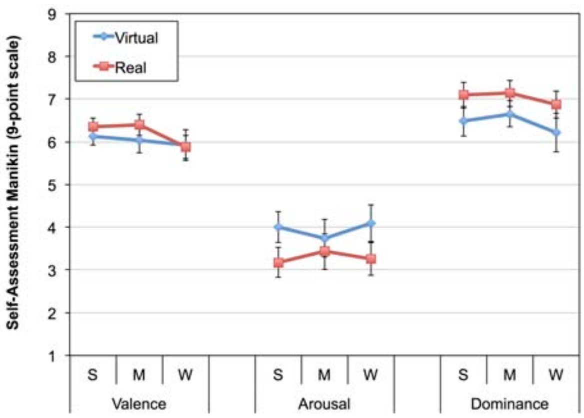

Figure 3. *Mean self-reported valence, arousal and dominance for the two surface types and three sound conditions (S = "strong", M = "medium", W = "weak"). Whiskers indicate standard error of the means (SE).*

Perceived aggressiveness: No significant differences between conditions were observed (all *ps* > .05; see Figure 4).

Perceived physical strength: It varied between all conditions ($\chi^2(5) = 10.63$, $p = .059$; see Figure 4). Subsequent analyses showed that for *medium* and *weak* sounds, perceived physical strength was higher for the real than for the virtual surface (*medium*: $z = -1.98$, $p < .05$; *weak*: $z = -1.77$, $p = .08$). No significant effects resulted from strength level (all *ps* > .05).

Perceived ability to complete the task: It varied between all conditions ($\chi^2(5) = 20.03$, $p = .001$; see Figure 4). Subsequent analyses revealed that, for the real surface condition, participants felt less able to complete the task when the sound was *weak* as compared to when the sound was *medium* ($z = -2.12$, $p < .05$). Moreover, for all sound conditions, participants felt less able to complete the task when tapping on the virtual than in the real surface (*strong* sound: $z = -1.77$, p = .08; *medium* sound: $z = -2.98$, $p < .005$; *weak* sound: $z = -2.23$, $p < .05$). All other comparisons were non-significant (all *ps* > .05).

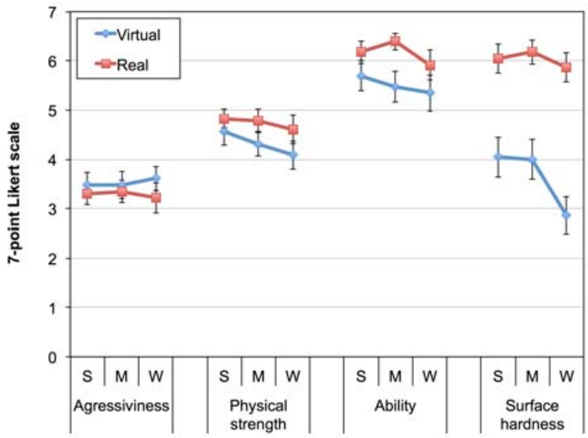

Figure 4. *Mean (±SE) perceived aggressiveness, ability to perform the task, physical strength and surface hardness (7-point Likert scale) for the two surface types and three sound conditions (S = "strong", M = "medium", W = "weak").*

Perceived effort: It varied between conditions ($\chi^2(5) = 21.12$, $p = .001$; see Table 2). Subsequent analyses revealed that, for all sound conditions, participants felt less stressed for the real than for the virtual surface (*strong*: z = -2.89, $p < .005$; *medium*: z = -2.23, $p < .05$; *weak*: z = -2.99, $p < .005$). Other comparisons were non-significant (all *ps* > .05).

Perceived self-efficacy: No significant differences between conditions were observed (all *ps* > .05; see Table 2).

GSR: Change scores were calculated for each condition, by calculating the mean response during the audio feedback period 10-65s, and by subtracting from these values the mean response during the 7-8 s baseline period [14]. Change scores were individually *z*-scored to control for variations in responsiveness [14]. Results of the 2x3 ANOVA revealed that GSR when tapping varied between surface conditions ($F(1, 22) = 9.39$, $p < .01$), with higher GSR scores registered when tapping on the virtual than in the real surface (Table 2). No significant effects were observed due to strength level or to the interaction between strength level and surface type (all *ps* > .05). These results are in agreement with those for self-reported arousal.

Table 2. *Mean (SE) perceived effort, self-efficacy and GSR z-scores for all conditions.*

Condition	Effort	Self-efficacy	GSR
Virtual strong	21.65 (4.05)	51.01 (4.20)	.14 (.22)
Virtual medium	22.04 (3.86)	51.68 (3.86)	.27 (.15)
Virtual weak	21.43 (3.61)	50.65 (3.81)	.35 (.16)
Real strong	13.91 (2.14)	51.34 (3.64)	-.31 (.17)
Real medium	14.04 (1.69)	51.51 (3.66)	-.21 (.22)
Real weak	14.43 (2.79)	50.59 (3.94)	-.23 (.18)

4.2. Tapping behavior

Tapping behavior was also analyzed in terms of differences between baselines (i.e., the first and last 10 s of the block, in which no audio-feedback was presented, referred to as baseline1 and baseline2) and the 60 s period in which participants received real-time audio-feedback in response to their taps (referred to as feedback phase). This allowed investigating the overall effect of audio-feedback in tapping behavior. Averages of maximum acceleration of tapping movements and inter-tapping intervals were calculated for baseline1, baseline2 and feedback phase. 2 (surface type) x 3 (sound strength level) x 3 (phase) ANOVAs were conducted.

Maximum acceleration of tapping movement: A 2x3x3 ANOVA on the log-transformed maximum acceleration values of the tapping movements showed significant effect of surface type ($F(1, 22) = 4.77$, $p < .05$) and phase ($F(2, 44) = 10.72$, $p < .001$; see Figure 5). Movement acceleration was larger when tapping on a real than on a virtual surface. This might simply be due to the shock received from the table not being present in the virtual surface. It would be in fact interesting to perform a more detailed analysis on the acceleration before the shock occurred. Movement acceleration was also larger during baseline1 than during the feedback phase ($p < .001$) and baseline2 ($p < .005$). There was also a significant interaction between surface type and phase ($F(2, 44) = 9.02$, $p = .001$), showing that while for the real surface condition there were differences between baseline1 and feedback phase ($p < .01$) and baseline 2 ($p < .05$), these differences were not observed for the virtual surface condition (all *ps* > .05).

Finally, there was a close to significant triple interaction effect ($F(4, 88) = 2.17$, $p = .079$). Separate ANOVAs for each phase, showed that close to significant effects were found for surface type ($F(1, 22) = 3.41$, $p = .078$) and sound strength level ($F(2, 44) = 2.72$, $p = .077$) for the feedback phase. Participants' movement acceleration was larger when tapping on a real than on a virtual surface. In addition, movement acceleration was larger when hearing a *weak* versus a *strong* sound feedback ($p < .005$). For baseline1 only an effect of surface was found ($F(1, 22) = 9.89$, $p = .005$), and for baseline2 no significant effects were found (all *ps* > .05).

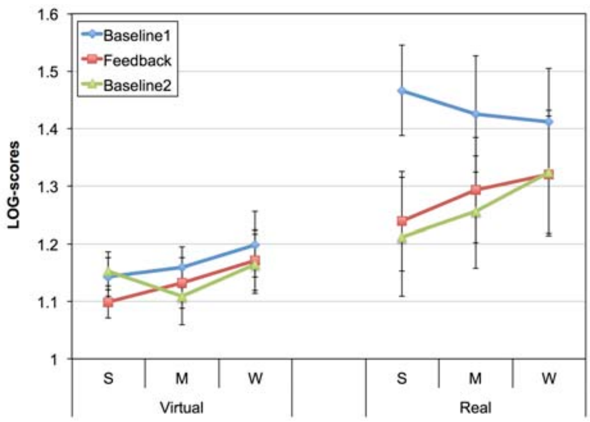

Figure 5. *Mean (±SE) of maximum acceleration values of tapping movements (LOG-scores) across conditions for the three phases (baseline1-2 and feedback phase).*

Frequency of tapping movement (inter-tapping interval): A 2x3x3 ANOVA on the log-transformed inter-tapping interval showed significant effect of phase ($F(2, 44) = 10.24$, $p < .001$), while the other main effects or interactions were non-significant (all *ps* > .05; Figure 6). In particular, people tapped slower during baseline1 than during the feedback phase ($p = .001$) and baseline2 ($p < .01$).

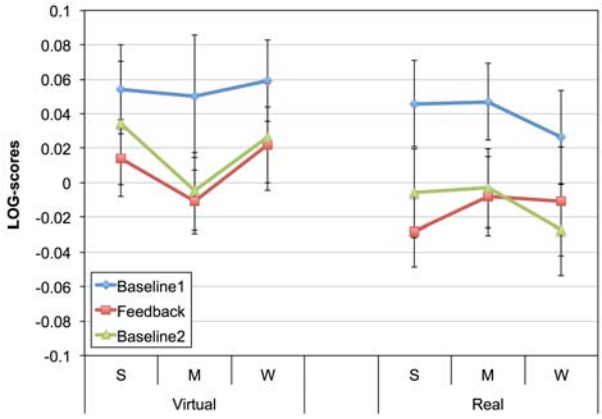

Figure 6. *Mean (±SE) inter-tapping interval (LOG-scores) across conditions for the three phases (baseline1-2 and feedback phase).*

4.3. Perception of surface hardness

Regarding perceived surface physical qualities, we found that the perceived surface hardness varied significantly between conditions ($\chi^2(5) = 63.07$, $p < .001$; see Figure 4). Subsequent analyses revealed that, for the virtual surface condition, there were differences in perceived hardness due to the sound strength level ($\chi^2(2) = 5.01$, $p = .08$). Participants perceived the tapped surface as being softer when the sound was *weak* as compared to when it was *strong* ($z = -2.34$, $p < .05$) or *medium* ($z = -2.21$, $p < .05$). Moreover, for all sound conditions, participants perceived the tapped surface as being harder when tapping on the real than in the virtual surface (*strong*: $z = -3.48$, $p = .001$; *medium*: $z = -3.31$, $p = .001$; *weak*: $z = -3.81$, $p < .001$). All other comparisons were non-significant (all *ps* > .05).

4.4. Discussion

In summary, our results show an effect of auditory cues informing of the applied strength when tapping at all emotional, behavioural and perceptual levels. In particular, regarding our hypotheses, our results show that in our study these cues:
(1) did not alter perceived applied strength when tapping; but
(2) did alter perceived ability to tap for the "real" surface condition, as participants felt less capable to tap in the *weak* sound condition. In addition, and also for the "real" surface, these cues altered tapping-related emotional responses. The experience of tapping was less pleasant for the *weak* sound condition;
(3) did alter tapping behaviour, as acceleration of tapping movements was larger when hearing a *weak* versus a *strong* sound feedback, as if one would attempt to intensify movements perceived as being *weak*, given that acceleration relates to the strength applied when tapping. Overall, receiving sound feedback speeded the movements and decreased their acceleration, with respect to the first period of tapping (baseline1) where participants did not receive sound feedback. Interestingly, the fact that behaviour for the second period of silent tapping (baseline2, after 60s of tapping with sound feedback) remained

similar to the feedback phase might indicate some adaptation or persistence of the audio-feedback effect;
(4) did alter perceived surface hardness for the "virtual" surface condition, as participants perceived the tapped surface as being softer when the sound was *weak*.

Our results also show that there were main differences at all emotional, behavioural and perceptual levels between the conditions involving tapping on a real surface and the conditions involving tapping on an imagined, "virtual" surface. Our participants felt they applied more strength when tapping on the real than on the virtual surface. They also felt more able to tap, more in control of the task and less stressed when tapping on a real rather than virtual surface. The stress-related results were confirmed both by self-report and by physiological (GSR) recordings. Finally, participants perceived the tapped surface as being harder when tapping on the real than in the virtual surface. The observed differences between the effects of tapping on real and virtual surfaces might relate to the fact that during the real surface conditions there were also tactile cues present, apart from auditory and proprioceptive cues. Nevertheless, one cannot exclude the fact that the tapping posture was probably more comfortable when resting one's tapping hand on a real, rather than on virtual, surface.

5. CONCLUSION

In this paper we present a study based on interactive sonification of surface tapping sounds. We designed a prototype that triggers real-time presentation of pre-recorded tapping sounds when the user taps on a surface. In our system, it is possible to choose the level of tapping strength that was applied when recording the sounds used for audio-feedback. This system can be used when tapping both on real surfaces (e.g., a table) and on imagined, "virtual" surfaces (i.e., when tapping in the air). We found that, although participants did not explicitly report perceiving their applied strength altered across different audio-feedback conditions in which the level of tapping strength was varied, they did experience other behavioral, emotional and perceptual changes due to the audio-feedback.

We show that by presenting real-time audio-feedback regarding tapping strength, we can actually change the tapping behavior when tapping in both real and virtual surfaces. According to the audio-feedback received, participants changed their own motor behavior. In particular, they accelerated their movements when the sound suggested that a low strength level had been applied when tapping, as compared to when it suggested a high strength level. This may indicate that they were trying to apply higher level of strength to their own taps to compensate the feedback sound, as acceleration relates to the tapping strength. Other studies have shown a similar auditory-action loop that can result in changes in movement execution (e.g., when rowing [12] and walking [14,15]), but here we show that, by presenting real-time audio-feedback regarding tapping strength, we can actually change the tapping behavior, even in a virtual environment, where the surface in which tapping is performed is simulated. It should be noted that, simply by introducing audio-feedback, regardless of the level of strength conveyed, speeded participants' movements and decreased their acceleration with respect to baseline (no audio-feedback), showing that audio-feedback seems to facilitate tapping actions. Interestingly, these effects seem to persist after a period of audio-feedback (here 60 seconds), even when audio-feedback is not present anymore (see results for baseline2).

Moreover, we show that, when tapping on a real surface, participants feel less able to tap and less comfortable (i.e., lower valence value) when the sound informed of low level of tapping strength. This highlights that audio-feedback related to tapping strength informs users of their performance. Participants' emotional experience is affected by the congruence between tapping sounds and tapping actions. This relates to findings showing that altering footsteps sounds cues relating to surface texture alters the emotion-related walking behavior [15].

In addition, we show that when no tactile cues are available (i.e., virtual surface), participants make use of the audio-feedback to decide on the hardness of the material being tapped. In particular, participants seem to match the level of strength applied when tapping, as conveyed by sound, with the level of hardness of the surface (i.e., *weak* sounds inform of the surface being soft). No such results were found for the real surface condition, which provides additional tactile cues about the surface. Differences between conditions in which a surface is explored by sound and finger touch, as opposed to when no finger touch is available, have been previously reported. For instance, sound feedback is informative of the roughness of the texture of a surface when the surface is inspected with a rigid probe, but not when inspected by the fingers [10].

It should be noted that having a real surface provides additional tactile cues that cause main differences, with respect to the virtual surface condition, at all measured levels, resulting in (1) the surface being perceived as harder; (2) larger perceived strength when tapping; (3) larger perceived ability to tap, and (4) feelings of being in control and being less stressed when tapping. This contribution of tactile cues was expected, given that the perception of materials, and our perception in general, is known to be multisensory, with all sensory modalities contributing to it and interacting with each other [10,24].

These results have important implications for the design of technology in different contexts. As interaction with objects is increasingly mediated through their digital representation [2], audio-feedback can be used to complement the limited amount of haptic feedback available to understand the object properties and facilitate its virtual manipulation. A first important group of areas that may benefit from the results presented here are those where performance-related movements (e.g., fine grain finger movement, extreme precision in applied strength) are critical. Audio feedback has already been shown to facilitate navigation in clinical surgery [25]. As technology for touch less surgery is emerging [26], it is important that information about the material properties of the objects manipulated is fully provided, and even enhanced, to facilitate such a risky process.

A second area where these findings could be applied is physical rehabilitation (e.g., [27,28]). As virtual reality (VR) and augmented reality (where real objects are used in the VR world [7]) are increasingly used in this area, audio-feedback can be used to alter the perception of objects manipulated. This would provide a way to induce motor behaviour changes during the therapy (e.g., inducing an increase in applied strength or in movement speed) in a more self-controlled way [29], rather than being imposed by haptic devices, thus reducing danger of over stress on the limb in the absence of physiotherapists. This is important, for example, in chronic pain rehabilitation, where physical constraints in movement are due to emotional barriers rather than biomechanical ones [30]. The resulting emotional experience may also produce an increase in perceived self-efficacy by making the patient feel stronger or faster. Perceived self-efficacy is very important for motivation and adherence to therapy [30].

Shopping on-line is an area that would also benefit by the addition of audio-feedback, as a form of tactile-sensory substitution [31]. Studies have shown that consumers base their initial judgement about a product on the basis of its tactile properties [32] and marketing communication often exploits when possible these tactile elements in order to increase emotional response in consumers [33]. Finally, games used either in serious contexts (mental rehabilitation, education) or for entertainment, can make use of audio-feedback of the environment players are interacting with to provide a wider sensorial experience that will impact on cognitive processes, and may help to reduce the overall mental effort required to operate the system [7,24]. Games may also use audio-feedback to induce a more engaging and more intense emotional experience by providing opportunities for a larger variety of touch behaviour as it has been shown for full-body technology [34]. Evidences from various studies have shown that affective touch behaviour profiles (e.g., higher applied pressure which relates to higher arousal) do exist (for a review see [17]). By using audio-feedback mechanisms in response to touch, game designers are provided with a way to alter the player's touch behaviour and hence modulate or enhance the player's emotional experience through proprioceptive feedback [18,34,35].

More research is of course necessary to apply such findings in these domains. The present results are however very promising, as they open new avenues for research aiming to change movement behaviour, emotional state and material perception, in both real and virtual environments. Future research should further explore these effects and their applications, by combining both quantitative and qualitative methods to better understand the effects and possibilities these mechanisms provide. Among the qualitative methods, the ones based on grounded theory may allow finding unexpected effects, as they are explicitly emergent (i.e., they do not test specific hypotheses, but rather use convergent interviewing techniques [36]).

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