Sonification of virtual and real surface tapping: Evaluation of behavior changes, surface perception and emotional indices

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Sonification of Surface Tapping Changes Behavior, Surface Perception, and Emotion

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A sonic interactive surface that delivers surface tapping sounds corresponding to different applied strength during tapping changes motor behavior, emotion, and surface perception.

Our interactions with objects are characterized by the sensory feedback that accompanies them. For instance, when we touch a table surface, we may see the surface and our hand moving on top of it at the same time we receive different tactile cues that change as we move our hand, and we may also hear the interaction sound produced by our hand rubbing the surface. In fact, the perception of materials is known to be multisensory, with touch, vision, and audition all contributing to it and interacting with each other.[1] These sensory cues inform us of object properties, such as texture, shape, or hardness, but they also inform our interaction behavior, such as the speed, amplitude, and fluidity of our movements as well as the strength we put into them.

Current developments in multimodal interactive systems allow for digitally changing the sensory cues resulting from our interactions, opening new avenues in the use and design of both physical and virtual objects. For example, altering the sound an object makes when we scratch its surface with eyes closed may lead us to perceive that object as rougher and consequently to increase the strength of our scratching behavior. Our emotions may also change in response to altered audio, proprioceptive, or tactile feedback, with various studies showing a tight link between body movement and emotions—the mood expressed in the body movement influences the emotion felt by the observer or performer.[2,3]

Multimodal interactive systems with the potential to change users' perception of object properties, motor behavior, and emotional state have applicability for technology design in numerous contexts. Because interaction with objects is increasingly mediated through their digital representation, audio feedback can complement the limited amount of haptic feedback available to understand object properties and facilitate their virtual or remote handling. In the context of online shopping, for example, the perceived properties of materials and emotional responses to them are leading decisions factors.[4] Another application example is touchless surgery, which requires extreme precision in applied strength—information about a manipulated object's material properties must be fully provided, and even enhanced, to facilitate a risky surgical process.

Multimodal interactive systems might also be used in the contexts of fun- and health-promoting applications, such as videogames and physical or mental rehabilitation apps, where specific ways of performing movements are fundamental to reaching specific objectives. Providing wider sensorial experiences may impact cognitive processes, reduce the overall mental effort required to operate a system, and induce more engaging and intense emotional experiences. Evidence from various studies have shown that affective touch and movement behavior profiles do exist.[2] By using mechanisms to alter touch and motor behavior,

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game designers gain ways to modulate or enhance a player's emotional experience. In the context of physical therapy, inducing motor behavior changes in a self-controlled way may reduce the danger of over stress on limbs in the absence of physiotherapists. It may also increase perceived self-efficacy by making the user feel stronger, faster, or happier, which will eventually impact motivation and adherence to therapy.[5]

This article addresses the use of interactive sonification[6] as a compelling approach to shape tactile surface interactions. Sonification of actions—the mapping of gestures and actions into sound—is a rather new approach in the design of multimodal interactive systems, but it's a powerful one. In particular, in interactive systems, audio feedback has generally been used to notify the user of an action's success or failure instead of sonifying the action itself. Here, we present a prototype that allows for the sonification of surface tapping by delivering sounds in real time in response to a user's taps on a real or imagined "virtual" surface (tapping in air). Having real and virtual surface types allows for the exploration of audio feedback effects when tactile cues about the tapped surface and the strength applied to it are either present or absent. Multimodal interactive systems in general—and interactive sonification systems in particular—are often poorly evaluated, so we argue for adopting a multidimensional measurement approach to evaluate user experiences. This approach may combine self-reporting, physiological measurements, and objective behavioral data. Many systems might be evaluated using only one of these measures, but the combination of them brings us closer to an understanding of the system's potential effects, which will inform its design. To evaluate our system, we quantified changes in perception of surface hardness, tapping behavior, and emotional action-related responses. Our results show the power of sonification to induce changes at all these levels.

Audio Feedback during Object Interaction

When people touch or tap on a surface, they often hear the resulting interaction sounds.[7] Different physical features of the surface material will result in different auditory cues. For instance, tapping on a soft woolen surface will produce a softer sound than tapping on a hard wooden surface. Likewise, different modes of touching the surface will result in different auditory cues—for instance, tapping softly on a surface will produce weaker sounds than tapping strongly on the same surface. But to what extent do we make use of this information?

Several recent studies have shown that changing the audio feedback resulting from object surface interaction may lead to changes in an object's perceived material properties, both in the case of natural surfaces[8] and virtual haptic surfaces.[9] Other studies have shown that providing altered audio feedback may also lead to a change in how users interact with objects. For instance, hearing the expected contact sound at the onset of a reaching-to-grasp movement toward an object—that is, hearing the sound that touching that object would produce—can speed up the movement, compared with hearing an unexpected contact sound (such as the sound of an object with different material).[10]

Importantly, altering the audio feedback during object interaction may change motor behavior because the feedback informs the motor behavior itself as well as the properties of the user's own body. For example, sonification of boat motion improves how elite rowers move because it provides information about small variations and deviations in the rowers' movements.[11] Sonification of tapping actions can actually change the user's perceived length of his or her arm as it taps on a surface because the tapping sounds indicate the arm's location and dimensions.[12] Introducing a delay in footstep sounds produced when walking results in changes in gait-period and walking speed.[13] Moreover, altering footstep sounds to represent walking on different surfaces seems to have an influence when people try to walk with specific emotion-related styles.[14]

In this article, we advance these studies by focusing on altering the audio feedback related to the level of applied strength when tapping on a real or virtual surface, rather than focusing on specific materials and without requiring any specific behavior style. By means of interactive sonification of surface tapping actions, we aim to explore how sounds produced when tapping on a surface actually inform of the physical feature of hardness of the surface material; inform of the applied strength when tapping; inform of the users' ability to tap, which may impact on their own emotional state; and change the user's tapping behavior as they try to adjust their tapping actions in response to the audio

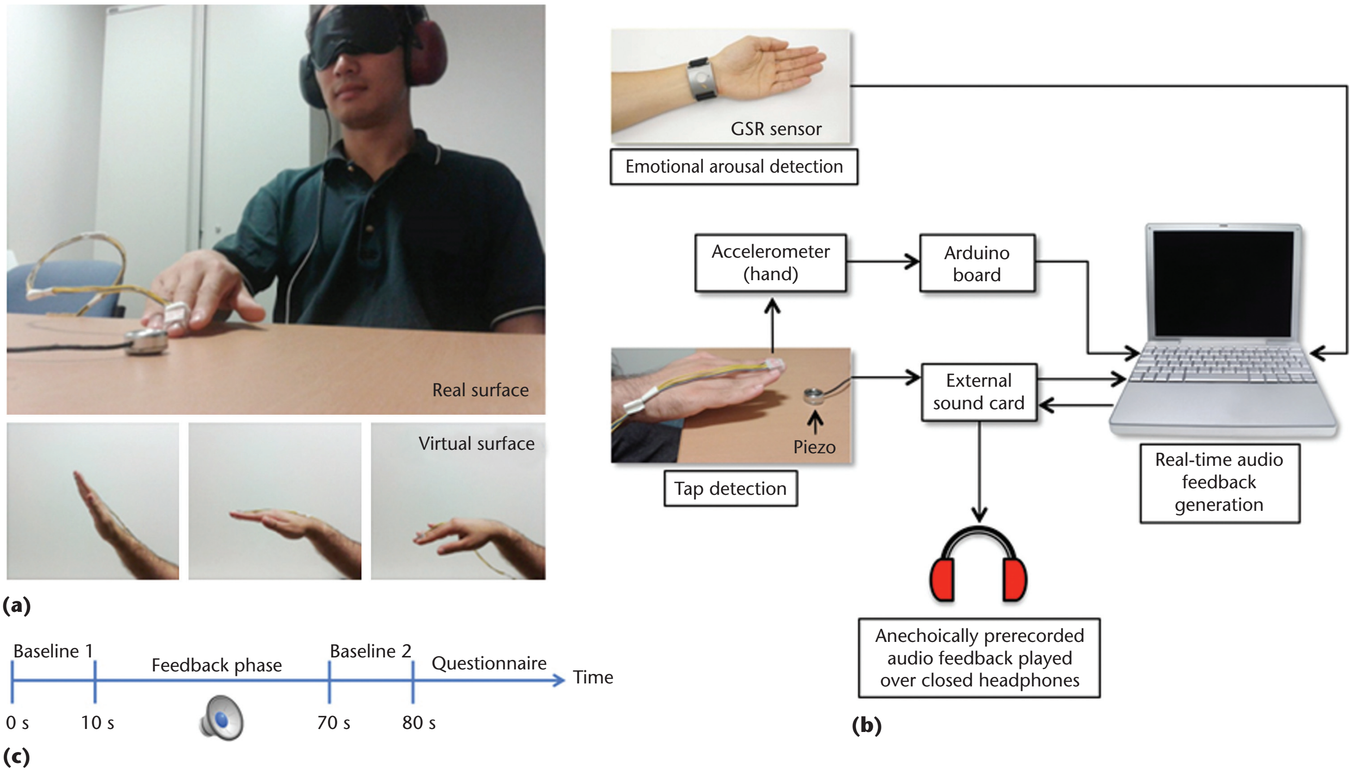

Figure 1. Surface tapping. (a) A person uses our prototype to tap on a "real" surface (top panel) and a virtual surface (bottom panel). (b) An overview of the prototype's connections shows that tapping actions are detected by using a piezoelectric transducer (attached to the real surface) and an accelerometer (attached to the user's middle finger). Every time a real or virtual tap is detected, a prerecorded feedback sound is played through headphones. (c) Each experimental block lasted for 80 seconds and contained three stages: baseline 1 for 10 seconds (participants only heard pink noise), feedback phase for 60 seconds (participants received real-time audio feedback in response to their taps and heard pink noise), and baseline 2 for 10 seconds (participants only heard pink noise). The experimental blocks differed in the type of tapped surface (real or virtual) and in the level of strength conveyed (weak, medium, or strong).

feedback, an effect often referred to as an auditory-action loop. Virtual objects are part of our everyday environment, so it's important to understand how they're handled. Figure 1a displays examples of a person tapping on these two surface types.

System Overview

Sonification of surface tapping for the system we designed is achieved by having the tapping action trigger the presentation of prerecorded tapping sounds in real time. (The mean delay introduced by the system is 10.7 +/– 1.8 ms; the maximum delay is 14 ms) The tapping action is detected by registering the signals captured by a piezoelectric transducer (Schaller Oyster 723 Piezo transducer Pickup) attached to the "real" surface and an accelerometer (Triple Axis Accelerometer Breakout MMA8452QA) attached to the middle finger of the users' dominant hand. Figure 1b gives an overview of the connections.

We use a motor-to-audio translation algorithm that triggers a feedback sound every time a real or virtual tap is detected. To detect surface taps, a threshold is set as follows. For the real surface condition, the threshold is based on the absolute value of the peak amplitude of the piezo input signal, which is specifically calibrated according to the piezo sensitivity to detect surface taps. For the virtual surface condition, the sound is triggered using the accelerometer signal because the hand is kept in the air. The prerecorded feedback sound is produced by a person tapping on a surface. Across conditions, the feedback can be varied so that the tapping sounds correspond to different applied strengths during the tapping.

The system allows recording of the piezo and accelerometer input signals as well as the generated audio feedback, which can be used to analyze a user's tapping behavior (that is, maximum acceleration and frequency of tapping movements). We calibrated the system according to the accelerometer and piezo input ranges and to remove background noise in the piezo signal. A sensor (Affectiva Q Sensor) attached to the user's wrist (nondominant hand) measures his or her galvanic skin response. GSR is a sensitive and valid real-time measure for emotional arousal in response to external stimuli.[15] The audio-feedback is played back using closed headphones with high passive ambient noise attenuation (Sennheiser HDA 200). The use of these headphones is intended to mask the sounds produced by the actual taps. To further ensure this masking, pink noise is continuously played back through the headphones as background sound.

System Evaluation

To evaluate our system, we recorded three sounds in an anechoic chamber. The duration of the sounds was 190 ms, and the sampling rate was 44.1 kHz. The sounds were of a person tapping the palm of the hand on a cardboard box with three different levels of strength: weak, medium, and strong. (We chose a cardboard box given the rather clear difference in sounds resulting from different levels of tapping strength.) The sounds were normalized using Audacity software to get an 8 dB difference between weak and medium sounds and between medium and strong sounds.

We asked 23 participants (five male and 18 female, 19 to 35 years old, with a mean age of 23.2) to take part in the evaluation. All reported having normal hearing and tactile perception. They were blindfolded, except for two people who preferred to keep their eyes closed. The participants were required to tap onto the two types of surfaces, real and virtual, while receiving audio feedback in response to their tapping actions. We followed a within-subjects design, with all participants exposed to all sound conditions, presented in randomized order. In particular, each participant completed six tapping blocks differing in the type of tapped surface (real or virtual) and the level of strength conveyed by the tapping sounds presented as feedback (weak, medium, or strong).

Figure 1c displays the timeline for each 80-second (s) experimental block. Participants were asked to tap with their dominant hand on the real or virtual surface for the whole duration of the block and to keep their rhythm constant, producing 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 we called baseline 1 and baseline 2, participants only heard pink noise. For the remaining time in the block, which we called feedback phase, apart from pink noise, participants were presented with real-time audio feedback in response to their taps. GSR was recorded during the duration of the block, and at the end of each block, participants answered a questionnaire to help us assess their subjective experience during the block.

Before each experiment, we made sure that all input signals (piezo, accelerometer, and GSR) were detected. In particular, we tested the GSR recordings by looking at signal changes in response to participants taking a deep breath or hearing a sudden noise. During the experiment, GSR change scores were calculated by subtracting the mean response during the period of 10–65 s (feedback phase) from the mean response during the period of 7–8 s (baseline 1).[15]

User Experience

One of the aims of this article is to demonstrate the use of a multidimensional measurement approach to evaluate user experience (UX). We can broadly classify the measurement dimensions into three categories attending to whether they look at alterations in perceptual aspects (surface perception), behavior, or the emotional experience, the latter quantified by looking at subjective, behavioral, or physiological emotion-related changes. Each of these dimensions tackles a different UX aspect, which may or may not correlate with another dimension. Hence, when possible, it's strongly recommended that a UX evaluation for multimodal interactive systems combines measures taken at the three different levels. This multidimensional measurement approach does not necessarily imply increasing UX complexity, and it might bring us closer to an understanding of a given system's potential effects, which in turn will inform its design. Here, we present a practical example of a multidimensional measurement approach to demonstrate its feasibility and the richness of the UX information that it provides.

Our hypothesis was that, by altering the audio feedback cues for applied strength when tapping on a surface, our system induces changes in the perceived applied strength, tapping behavior, and perceived surface hardness. Hence, for our system's UX evaluation, we looked at alterations on all of these different levels. We looked at changes in emotional action-related responses by quantifying subjective and physiological emotion-related changes. For this purpose, we included several scales in the questionnaire. First, we used seven-point Likert scales to assess the perceived physical strength, the ability to complete the task, and the aggressiveness felt when tapping on the surface. Second, we quantified the subjective mental effort by asking participants to indicate the stress felt while tapping on a vertical analog scale.[16] Third, we quantified participants' emotional valence, dominance, and arousal by using the three nine-item graphic scales of the self-assessment manikin.[17] Arousal was further quantified by looking at the physiological changes recorded by the GSR biosensor. We also looked at alterations in the way of interacting with the surface by quantifying the changes in the movement dynamics. For this purpose, we used the logged accelerometer and piezo data. Finally, we assessed the perceived surface physical quality of hardness with a seven-point Likert scale.

Each of these dimensions tackles a different UX aspect, but these aspects may correlate with each other. For instance, induced changes in perceived applied strength when tapping or changes in the perceived ability to tap may be accompanied by corresponding changes in tapping behavior. Therefore, to understand whether the different dimensions of experience are linked, we performed correlation analyses between the different measures. All data collected were statistically analyzed with Statistical Package for the Social Sciences (SPSS) 21.0; Shaphiro-Wilk tests assessed normality of data distributions; and parametric (analysis of variance [ANOVA] and t-tests) and nonparametric (Friedman and Wilcoxon) tests were used, respectively, with normal and non-normal data.

Changing Emotion and Surface Perception

Figure 2a shows the mean self-reported perceived aggressiveness, perceived physical strength, ability to complete the tapping task, and perceived surface hardness; Figure 2b shows the self-reported valence, arousal, and dominance; Figure 2c shows the perceived effort while tapping; and Figure 2d shows the GSR change scores, all according to the level of strength of the tapping sounds presented as feedback (weak, medium, and strong) and the type of tapped surface (real or virtual). We first report the effects due to the sound strength level and then the effects due to the surface type.

Changing the strength level conveyed by the sound, contrary to our expectations, didn't alter the perceived applied strength or the aggressiveness felt when tapping (all $ps > 0.05$). However, changes in perceived applied strength and aggressiveness did correlate with changes in other dimensions, such as behavioral changes, perceived surface hardness, and several emotional dimensions. In addition, results show that, when tapping on a real surface, participants felt less able to tap and less pleasant in the case of the low intensity sound. In particular, they felt less capable of tapping for the weak than for the medium condition ($z = -2.12$, $p < 0.05$) and found that the experience of tapping was less pleasant for the weak than for the strong sound condition ($z = -2.31,\ p < 0.05$). We also found that, when tapping on a virtual surface, participants felt more physiologically aroused when the sound indicated low levels of tapping strength. In particular, participants' GSR was higher for the weak than for the strong ($z = -4.01,\ p < 0.001$) or medium sound condition ($z = -4.05,\ p < 0.001$).

These results show that audio feedback related to tapping strength informs users of their performance and that emotional experience is affected by the congruence between tapping sounds and tapping actions. Audio-motor incongruences lead to unpleasant arousing experiences: when the audio feedback didn't match expectations, as with the weak sound, participants felt more aroused and less able to tap. In the case of the weak sound, the incongruence between the applied strength and the sound heard as output became more evident because the sound heard was produced by applying very little strength. Sound didn't change even if participants explored different movement strategies in this condition, which further contributed to participants realizing the incongruence. The coherence between an action and its auditory response is known as one of the principles of altering interaction sounds to successfully convey information and modulate actions in an intuitive manner (see work on "blended sonification"[18]).

Figure 2a reveals a significant correlation between the sound strength level and the mean

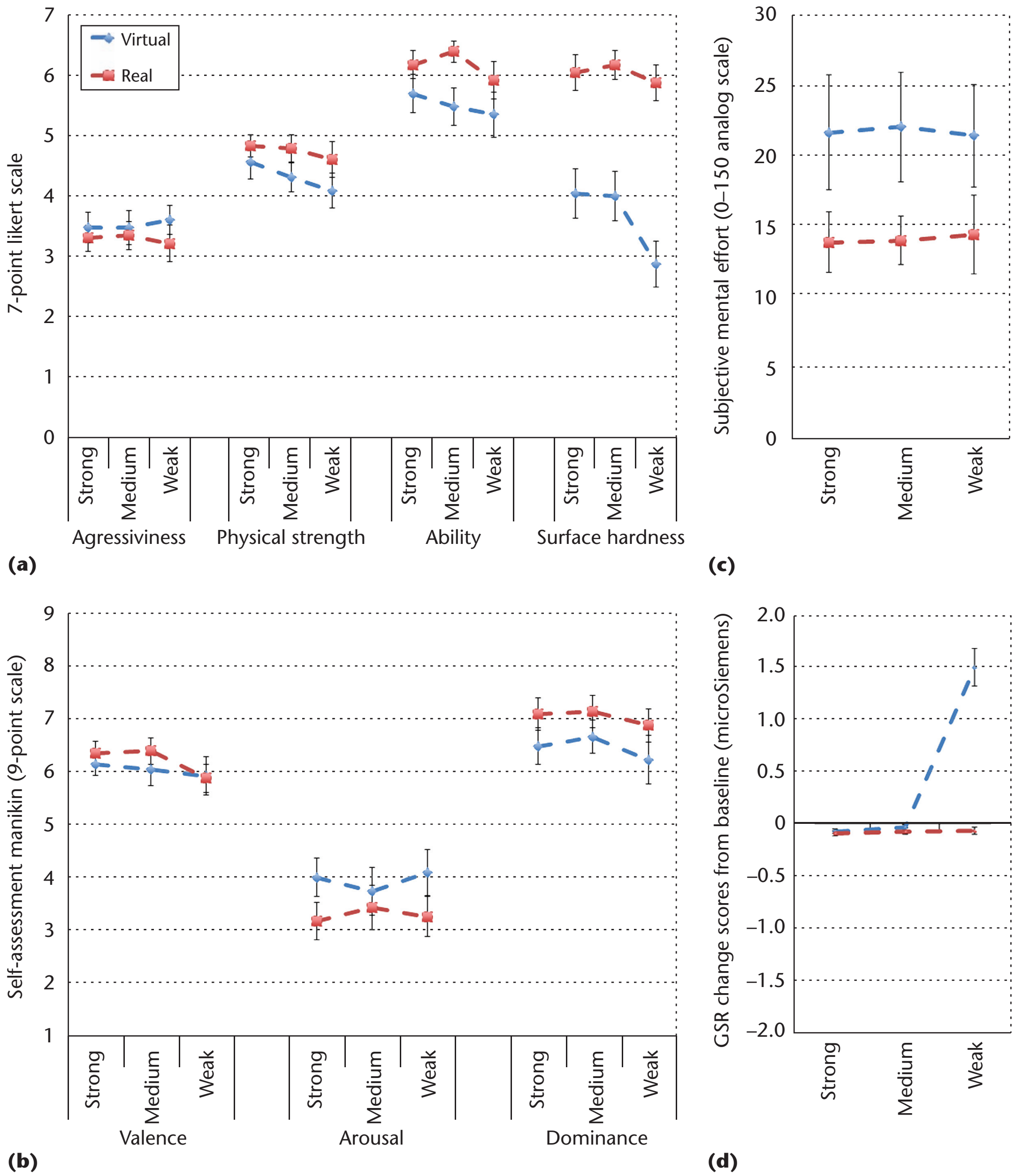

Figure 2. Participant results. (a) Mean perceived aggressiveness (from "tender" to "aggressive"), ability to perform the task (from "unable" to "able"), physical strength (from "weak" to "strong"), and surface hardness (from "soft" to "hard"). (b) Mean self-reported valence, arousal, and dominance. (c) Mean perceived effort (from "not at all hard to do" to "tremendously hard to do"). (d) GSR (μS) for the two surface types and three sound conditions. The whiskers indicate standard error of the means. Lines connecting the points for each condition are aimed to ease visualization and don't indicate a chronological order between conditions.

perceived surface hardness. We found that when no tactile cues are available (virtual surface), participants used audio feedback to decide on the hardness of the material being tapped. In particular, they seemed to match the level of strength applied when tapping, as conveyed by sound, with the level of surface hardness. Participants perceived the tapped surface as being softer for the weak than for the strong ($z = -2.34$, $p < 0.05$) and the medium ($z = -2.21$, $p < 0.05$) sound conditions. No such results were found for the real surface condition, which provided 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 seems more informative of the roughness of a surface's texture when the surface is inspected with a rigid probe than when inspected by fingers.[1]

When looking at the effects due to the surface type, we found, as expected, differences between the real and virtual surface conditions at all measured levels. The real surface was perceived as harder and caused feelings of greater strength, of larger ability to tap, and of being less stressed when tapping. First, for all sound conditions, participants perceived the tapped surface as being harder when tapping on the real than on the virtual surface (strong : $z = -3.48,\ p = 0.001$; medium : $z = -3.31, p = 0.001$; weak : $z = -3.81,\ p < 0.001$), as in Figure 2a. Second, participants felt they applied more strength when tapping on the real than on the virtual surface, at least for the medium sound condition ($z = -1.98,\ p < 0.05$). Third, for most sound conditions, participants felt more able to tap (medium sound : $z = -2.98$, $p < 0.005$; weak sound : $z = -2.23,\ p < 0.05$) and less aroused when tapping on a real rather than virtual surface. The arousal-related results were confirmed by looking at the self-reported arousal (strong sound : $z = -2.28,\ p < 0.05$; weak sound : $z = -2.17,\ p < 0.05$) and at the physiological GSR recordings (weak sound : $z = -4.17,\ p < 0.001$). The increase in arousal in the virtual surface may come from the unnaturalness of such an interaction, compared with the more common interaction with a real surface. In addition, 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, in addition to auditory and proprioceptive cues. 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.[1] In our experiments, participants were blindfolded, so visual cues weren't available—rather, auditory, proprioceptive, and in the case of the real surface, tactile cues contributed to surface perception.

Changing Behavior

By presenting real-time audio feedback on tapping strength, we can actually change behavior when tapping on both real and virtual surfaces. From the accelerometer values, we can estimate parameters that relate to the movement dynamics. First, accelerometer data reveal how hard the participants hit the real surface or stopped their motion in the case of the virtual surface. We can also quantify the intertapping intervals. These different measures are reported for the baseline 1, baseline 2, and feedback phases and are displayed in Figures 3a and 3b.

Separate analyses for each phase showed an effect of surface for baseline 1 ($F(1,\ 22) = 9.89$, $p = .005$), and no significant effects for baseline 2 (all $ps > 0.05$). Importantly, for the feedback phase, we found that according to the audio feedback received, participants changed their own motor behavior. In particular, the acceleration maxima were significantly affected when the sound suggested that a low strength level had been applied when tapping, compared with when it suggested a high strength level ($p < 0.05$).

Figures 3c and 3d show how the acceleration changes from baseline 1 across time. Looking at these figures allows a better interpretation of the changes in participants' behavior—for example, the medium and weak conditions are accompanied by much bigger changes in acceleration, as well as by much bigger differences between participants, than the strong sound condition. This might be interpreted as behavior being affected by the participants' expectations of the motion-sound interaction. In our system, the congruency between tapping sounds and tapping actions is highly nonlinear: while the strong and to some extent the medium sound conditions might appear as possibly congruent, the weak sound condition is highly incongruent with participants' actions. This incongruency results in participants exploring different movement strategies (trying to stop the hand or putting more strength into their taps) in an attempt to compensate for the weak audio feedback.

Analyzing the tapping behavior in terms of differences between phases helped us investigate the overall effect of audio feedback in tapping behavior. This effect was significant both in terms of acceleration ($F(2,\ 44) = 10.72$, $p < 0.001$), as displayed in Figure 3a, and in terms of tapping frequency ($F(2,\ 44) = 10.24$, $p < 0.001$), as displayed in Figure 3b. Comparing the effects during the feedback phase with those during the first period of tapping (baseline 1), when participants didn't receive audio feedback, showed that introducing audio feedback, regardless of the level of strength conveyed, sped up participants' movements ($p = 0.001$) and decreased acceleration ($p < 0.001$).

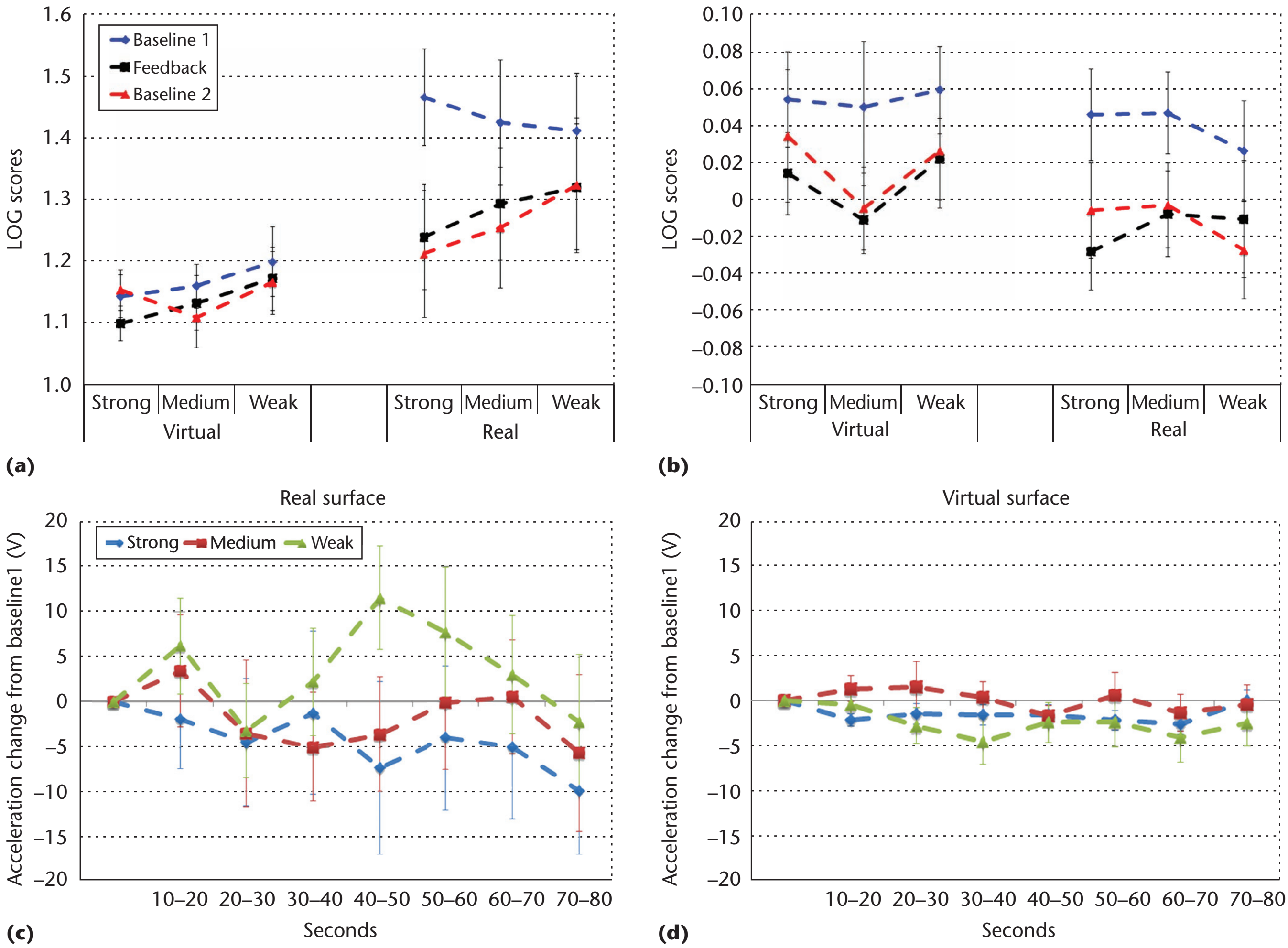

Figure 3. Surface tapping. (a) Mean (LOG scores) of maximum acceleration values of tapping movements and (b) intertapping interval across conditions for the three phases (baseline 1, baseline 2, and feedback). (c) Acceleration changes from baseline 1 across time for the real surface conditions and (d) for the virtual surface conditions. The whiskers indicate standard error of the means; lines connecting the points for each condition are aimed to ease visualization and don't indicate a chronological order between conditions.

Interestingly, these effects seem to persist after 60 seconds of audio feedback, even when audio feedback isn't present anymore. This is confirmed by the insignificant differences between the feedback and baseline 2 phases (all $ps > 0.05$), which might indicate some adaptation or persistence of the audio feedback effect.

Finally, there was also a significant interaction in terms of movement acceleration between surface type and phase ($F(2, 44) = 9.02$, $p = 0.001$), showing that while for the real surface condition there were differences between baseline 1 and the feedback phase ($p < 0.01$) and baseline 2 ($p < 0.05$), these differences weren't observed for the virtual surface condition (all $ps > 0.05$).

Other studies have shown similar auditory-action loops that can result in changes in movement execution, for instance, when rowing[11] or walking.[13,14] However, we found that by presenting real-time audio feedback related to the tapping strength, we could indeed change tapping behavior. Changes occurred even in a virtual environment, where the surface on which the tapping is performed is simulated.

Correlation between Measures

To further understand how the different dimensions of experience are linked, we performed correlation analyses in which we looked at the changes across measures as a result of the sound strength level, from strong to weak. Table 1 presents these correlations. Changes in

Table 1. Correlations between measures for virtual (V) and real (R) surfaces.†

	Valence	Dominance	Arousal	Aggressiveness	Strength	Ability to tap	Hardness	Effort	Acceleration	Frequency	GSR
Valence		V (+)* R (+)**			V (+)* R (+)*	V (+)* R (+)**					
Dominance	V (+)* R (+)**				R (+)*	R (+)**	V (+)**	R (+)			V (–)*
Arousal				V (+)** R (+)**							
Aggressiveness			V (+)** R (+)**				V (–)*				
Strength	V (+)* R (+)*	R (+)*				R (+)**	R (+)**		V (–)* R (+)**		
Ability to tap	V (+)* R (+)**	R (+)*			R (+)**						
Hardness		V (+)**		V (–)*	R (+)**				R (+)**		
Effort		R (–)*									
Acceleration					V (–)* R(+)**		R (+)**			V (–)**	
Frequency									V (–)**		
GSR		V (–)*									

†The plus and minus signs indicate if the correlation is positive or negative; * and ** indicate that correlation is significant at the 0.05 level or the 0.01 level (two-tailed), respectively.

behavior (acceleration patterns) were accompanied by changes in perceived applied strength, in both real ($r = 0.55$, $p < 0.01$) and virtual surfaces ($r = -0.42$, $p < 0.05$), although the direction of change varied with surface type. Behavioral changes were also accompanied by changes in perceived surface hardness for the real surface ($r = 0.62$, $p < 0.005$). In addition, perceived surface hardness correlated with other emotional measures, such as dominance ($r = 0.58$, $p < 0.005$) and aggressiveness ($r = -0.44$, $p < 0.05$) for the virtual surface condition, and perceived physical strength for the real surface condition ($r = 0.69$, $p < 0.001$). Self-reported feelings of control (emotional dominance) correlated with physiological arousal for the virtual surface (GSR; $r = -0.43$, $p < 0.05$).

Conclusion

This article addresses the use of interactive sonification as a powerful tool to shape tactile surface interactions as well as the use of a multidimensional measurement approach to evaluate user experiences of multimodal interactive systems. The obtained results may be applied to the design of interactive sonification displays and tangible auditory interfaces aiming to change perceived and subsequent motor behavior, emotional state, and perceived material properties.

More research is necessary to apply our findings to technology design. To further explain the differences between the real and virtual surfaces, it would be interesting to perform a more detailed analysis of behavior changes, for instance, looking at the acceleration before the shock on the table occurred or looking at the envelope of the movement signals to understand behavior changes both when moving the hand upward and downward. It would also be interesting to test the system when using sounds that can induce larger emotional responses or result in a more aggressive behavior. The present results are promising because they open new avenues for research aiming to change movement behavior, 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 multidimensional measurement methods to better understand the effects and possibilities these mechanisms provide. **MM**

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