Does It Ping or Pong? Auditory and Tactile Classification of Materials by Bouncing Events

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Two experiments studied the role of impact sounds and vibrations in classification of materials. The task consisted of feeling on an actuated surface and listening through headphones to the recorded feedback of a ping-pong ball hitting three flat objects respectively made of wood, plastic, and metal, and then identifying their material. In Experiment 1, sounds and vibrations were recorded by keeping the objects in mechanical isolation. In Experiment 2, recordings were taken while the same objects stood on a table, causing their resonances to fade faster due to mechanical coupling with the support. A control experiment, where participants listened to and touched the real objects in mechanical isolation, showed high accuracy of classification from either sounds (90% correct) or vibrations (67% correct). Classification of reproduced bounces in Experiments 1 and 2 was less precise. In both experiments, the main effect of material was statistically significant; conversely, the main effect of modality (auditory or tactile) was significant only in the control. Identification of plastic and especially metal was less accurate in Experiment 2, suggesting that participants, when possible, classified materials by longer resonance tails. Audio-tactile summation of classification accuracy was found, suggesting that multisensory integration influences the perception of materials. Such results have prospective application to the nonvisual design of virtual buttons, which is the object of our current research.

CCS Concepts: • **Human-centered computing** → *Empirical studies in HCI*; *Haptic devices*; *Touch screens*; *Auditory feedback*;

Additional Key Words and Phrases: Material classification, auditory feedback, tactile feedback, multisensory integration, virtual buttons

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1 INTRODUCTION

Humans initially identify everyday materials from their visual aspect. Visual identification is often refined through touch [7] by analyzing tactile surface properties such as roughness [2] and temperature [29]. This analysis postulates a material to be fully characterized by its superficial appearance.

Inner material properties can be actively explored using touch and hearing, as when an indentation or a tap unveils the hardness of an object. Pointwise tapping particularly generates impulsive audio-tactile feedback whose role goes beyond aesthetics [41], giving rise to cross-modal cues that are difficult to disambiguate [17].

Classification of material, size, and shape from impulsive auditory feedback has been successfully performed by listeners identifying synthetic stimuli reproducing strikes on suspended plates [20, 36, 54] and clamped bars [34, 39]—see also Giordano and Avanzini [19] for a comprehensive review of related work. In fact, the simulation of objects vibrating in mechanical isolation enables fine control of their oscillatory *modes* through the amplitude, frequency, and decay parameters of each mode. Depending on their setting, these parameters link the physical properties of an object to its auditory perception by means of fundamental cues such as decay, pitch, and timbre. Experiments aiming at applying materials sound synthesis to auditory displays and interfaces [18] have suggested that everyday materials are first roughly classified into distinct groups (e.g., metals) depending on decay. Once grouped, further categorization may be based on characteristic ("material") frequencies [20]. The latter association was shown to become especially important when the stimuli are short (i.e., less than about 400 ms), as decay cues in this case become difficult to perceive [38].

Classification of materials by impulsive tactile feedback has been researched as well, albeit less systematically. Most of the works deal with direct or mediated finger tapping especially in view of applications to robotic sensing and material augmentation. Kim and Kesavadas [33] parameterized a contact model to reproduce different materials by acquiring temporal patterns of force from participants tapping on steel, aluminum, wood, and rubber surfaces during an identification task. Hachisu et al. [23] designed a stick that, when tapped, cancels its own body's response and then renders haptic sensations of aluminum, wood, and rubber by synthesizing a damped sinusoid with characteristic amplitude, decay, and frequency parameters. Both works reported successful recognition of the proposed materials, with possible support from sound in the former. The latter was later applied to touchscreen augmentation on a tablet displaying playable percussion instrument boards made of wood and metal [22]. An exception comes from the systematic research on tactile perception of hardness by Higashi et al. [28], resulting in intensity curves [25] and mechanical parameter ranges [26] of equal hardness perception, as well as in a psycho-physical map linking materials to perceived stiffness in response to a tap [27].

Our study considers both the auditory and tactile sensory channels in an effort to assess their individual contribution while forming a multisensory material category. In fact, only a minority of the literature about the influence of hearing on touch [6, 50, 51, 59] during material classification [21, 31] considers impulsive feedback. Cases in this minority include the marble-hand illusion, which affects hardness perception as subjects whose hands are gently hammered feel their own hand to become as much harder and heavier as the contact sound does [48]. Another illusion makes use of audio-tactile impact asynchrony [37], leading to softer reproductions of finger-tapped materials if delays larger than about 20 ms between the auditory and tactile stimulus are introduced.

For our study, we recorded the auditory and tactile responses to an impulsive excitation from three flat objects made of different materials, first taken in mechanical isolation and then resting on a table. Then we reproduced such recorded sounds and vibrations, either separately or together, respectively through headphones and on a hard glass plate actuated by a vibro-tactile transducer. The tactile display avoided surface texture rendering technologies [11, 60]. For its simplicity and low cost [10], this setup is ideal for testing the audio-tactile feedback of virtual buttons on touchscreens specific for operating large catering appliances, which is a goal of this research. Coherently with this goal, temperature cues that could further characterize the materials were removed from the experiments.

In this specific application context, the haptic literature provides further useful knowledge, although not referring directly to material classification. Several virtual buttons have been tested based on different actuation technologies, with a focus on their tactile properties. Park et al. [43] tuned the signal parameters of dual-mode actuators to magnify significant tactile attributes of perceived quality such as hardness, distinctiveness, and clarity. Kaaresoja et al. [32] found accurate latency thresholds, concluding that the quality of a virtual button is preserved once tactile feedback latency is kept between 5 and 50 ms, and auditory feedback latency between 20 and 70 ms. Bresciani et al. [5] highlighted the importance of multimodal integration for this research by showing that auditory sequences of beeps modulate the tactile perception of sequences of taps simultaneously delivered to the index fingertip. Our tests can be considered preliminary to an experiment using virtual buttons, as we maximized the control of the perception through the design of a passive task. In fact, active exploration through tapping is known to introduce considerable variance in impact speed and pressure of the finger, both within and among subjects [33], with consequent loss of control of the stimulus intensity.

To the best of our knowledge, only one study in human factors by Smith et al. [49] indirectly links material classification to virtual buttons by proving that abstract auditory feedback can be more difficult to learn and retain than environmental sounds. In parallel, Koskinen et al. [35] confirmed that tactile feedback improves the usability of virtual buttons; however, the satisfaction of the experience is subjective and includes cases of users who prefer sharp and strong vibrations only when auditory feedback is absent, in practice making the design of audio-tactile buttons not an easy task. The decision to minimize abstraction of the audio-tactile feedback in our research hence followed from the results of Smith et al. [49] and Koskinen et al. [35], and led to the study presented here.

2 EXPERIMENTS

Two experiments used stimuli recorded from single impacts on three flat objects made of wood, plastic, and metal. The experiments differed in the main resonance decay times, as a consequence of recording sounds and vibrations either with suspended objects (Experiment 1), or more realistically with the same objects resting on a table (Experiment 2). Furthermore, a control test was set up using real impact events on the same materials when they were in mechanical isolation—that is, in the same condition as when the sound and vibrations for Experiment 1 were recorded. The purpose of the control test was to set a reference baseline on the human ability to classify materials based on our objects' audio-tactile feedback.

The general hypothesis was that participants are able to classify wood, plastic, and metal by impulsive auditory, tactile, and finally audio-tactile feedback from flat objects made of those materials.

Part of Experiment 2 was previously presented at a conference [9]. In accordance with studies by other authors [20, 33], its results suggested profitable use of the decay time as a cue for classifying materials. For this reason, about 3 months later, we performed Experiment 1 along with the control test. Together, they set a more solid basis for a general discussion about material classification based on impulsive audio-tactile feedback.

2.1 Setup

Wood, metal, and plastic materials were selected because they respond rigidly to impacts (i.e., with spectral energy concentrating in the high frequency range), thus enabling realistic tactile reproduction on a glass surface offering just vibratory feedback, rather than kinesthetic cues that are linked to soft materials [23].

Control test. Three flat objects were built out of fir wood, hard plastic, and steel. They were U-shaped by bending or carving, allowing for a hand or an accelerometer to find sufficient room in the resulting cavity underneath (Figure 1). All objects were sized 160 × 160 × 45 mm. Two circular patches with a diameter of about 4 cm and made of thin adhesive film were attached at the same location on both sides of the surfaces. Both (i.e., the patch on the reverse side for Experiment 1 and the patch on the top side for Experiment 2) offered a uniform surface spot where participants put their fingers. In this way, subjects could not use surface properties to identify materials.

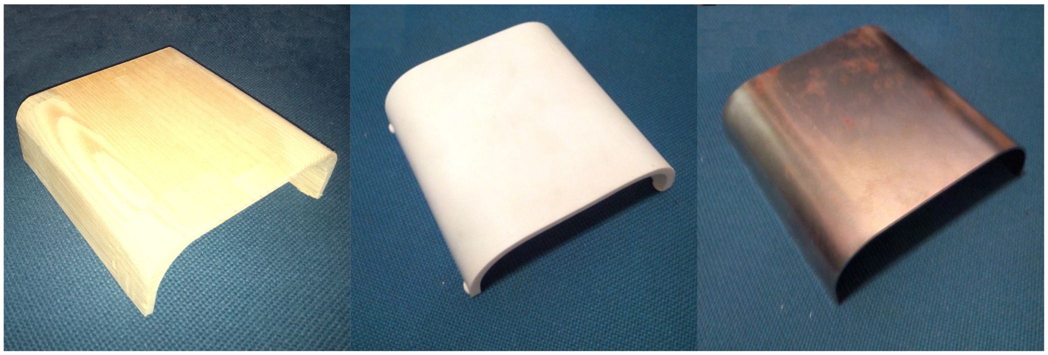

Fig. 1. Wood, plastic, and metal objects used to record stimuli and perform the control test.

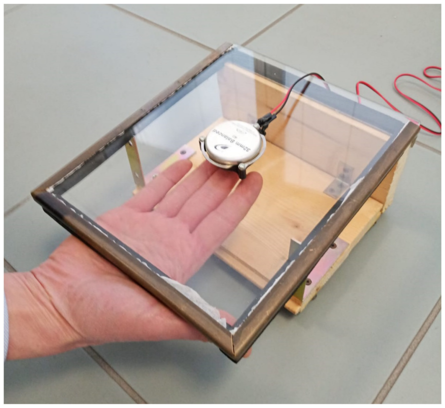

Fig. 2. Suspended glass plate with attached exciter, used in Experiments 1 and 2.

On the opposite side, these spots marked the impact point of the ball. Thanks to their low mass, thinness, and firm adhesion to the objects, they introduced almost imperceptible changes in the impact sounds and vibrations.

Experiments 1 and 2. A flat object was built by mounting a 3-mm-thick borosilicate glass plate on a metal frame suspended by means of rubber strips, then coupling the frame with a wooden structure as shown in Figure 2.

2.2 Stimuli

A ping-pong ball was used to excite the materials, as it has a light yet rigid structure, giving rise to neat impact events characterized by small energy in the low frequency range. Tests were also made with metal, rubber, and wooden balls of different size and weight; however, they produced impacts whose energy at low frequency fell outside the range of the small, low-power actuator that we required for vibration reproduction in Experiments 1 and 2.

Control test. The ball was dropped on the three objects. The intensities of the stimuli were equalized across materials by dropping the ball from varying heights: 30 cm for wood, 80 cm for plastic, and 40 cm for metal. A marked rod was placed near the cardboard support, helping the experimenter release the ball correctly during the experiment.

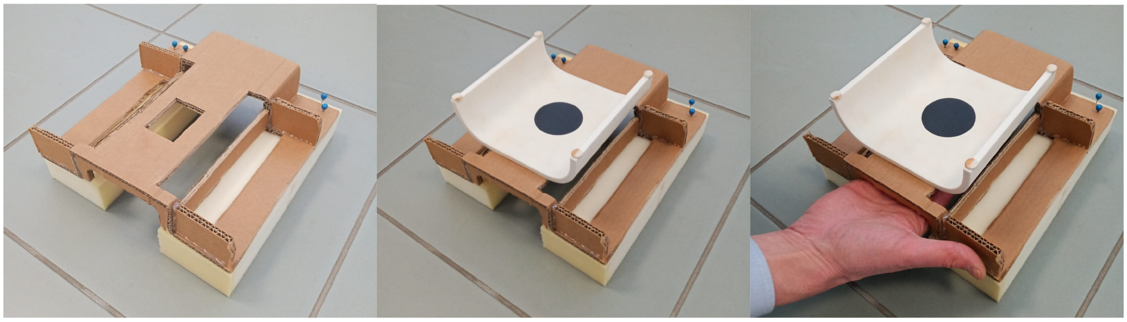

Fig. 3. Cardboard support without (left) or with (center) the plastic object turned upside down, and in use during the control test or familiarization with Experiment 1 (right).

Mechanical decoupling was realized by putting the objects upside down on a support made of foam and cardboard sized 200 × 240 × 60 mm, shown in Figure 3 (center). The support also forced participants to touch the surface only in correspondence of the adhesive film, as in Figure 3 (right).

The temperature of the objects was stabilized at approximately 30°C by keeping them under a halogen lamp starting 10 minutes before and throughout the experiment when not in use.

An inspection of the temporal signals immediately after the bounce showed the presence of a low-frequency component identical in all cases, an evident consequence of the response of the support. On top of this component, fading transients with a peak occurring within the first 100 ms were clearly visible. After removing the component in low frequency, such peaks showed a relative amplitude of approximately 0.30 mm for wood, 0.14 mm for plastic, and 0.08 mm for metal. Decreasing peak values are compatible with the implemented intensity equalization, as the corresponding materials produced different decays as explained in the following.

Experiments 1 and 2. These experiments made use of reproduced audio and tactile stimuli: sound and vibration samples were recorded from a single ball hit on each surface. The objects were either turned upside down and suspended as in Figure 3 (center), producing samples for use in Experiment 1, or resting on a table (see Figure 6) for Experiment 2.

Sounds were recorded with an Audio-Technica AT4050 condenser microphone placed 40 cm away from the bouncing point. Vibrations were recorded by attaching a Wilcoxon 736 accelerometer in correspondence of the adhesive film. Both devices were connected to an RME Babyface Pro audio interface—the accelerometer through its companion preamplifier.

Auditory stimuli were played back through a pair of Beyerdynamic DT 770 PRO closed-back headphones. Tactile stimuli were reproduced by a Dayton Audio 32-mm balanced vibro-tactile transducer, attached at the top side of the glass plate. Bimodal stimuli were provided by playing back auditory and tactile stimuli at the same time. In this case, the auditory signal was delayed by 1.14 ms, corresponding to the time needed for airborne sound to travel from the impact to the listening point.

Spectrograms of the audio recordings made for both experiments are shown in Figure 4. They show differences below 30 Hz, a consequence of the different support employed; however, they were inaudible. A closer look at the audible band reveals that the stimuli in Experiment 1 were about 0.1 second longer, with a strong resonance in metal at about 3 kHz lasting about 0.9 second.

Figure 5 shows spectrograms of the recorded vibrations in the top and middle rows, unveiling differences similar to what was found for audio. Furthermore, metal in low coupling conditions generates long-lasting vibrations at about 20 and 250 Hz, which were not efficiently radiated across the air.

Spectrograms of the vibrations after reproduction on the glass plate during Experiment 2 are also shown, in the bottom row of Figure 5. They were acquired by placing the accelerometer in correspondence of the

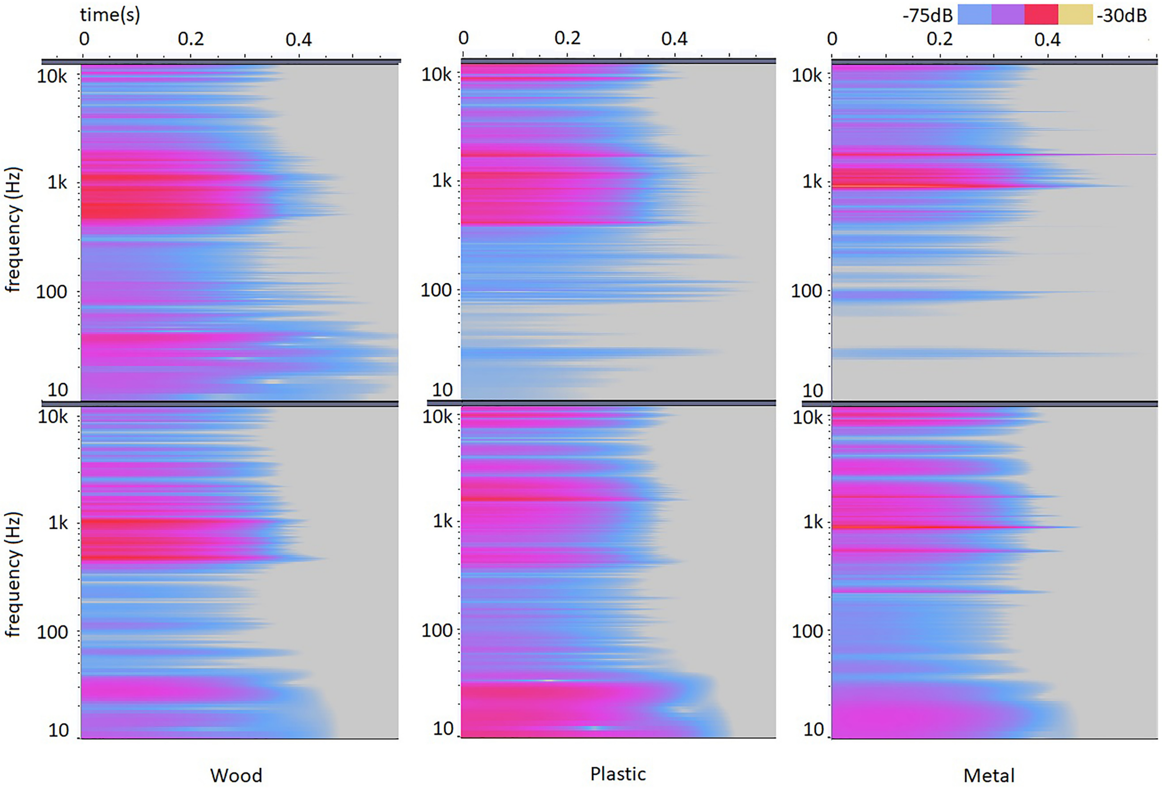

Fig. 4. Sound spectrograms in Experiment 1 (above) and 2 (below).

Table 1. Characteristics of the Stimuli Used in the Experiments

Experiment	Stimuli	Setup	Coupling	Resonance Decays
Control	Live	Cardboard support	Low	Slow
1	Recorded	Cardboard support	Low	Slow
2	Recorded	On the table	Normal	Normal

presentation point of the plate (see Figure 2). A comparison between these and the original vibrations in Experiment 2 (middle row) discloses some unavoidable differences affecting the tactile stimuli during reproduction. In fact, the limited admittance of glass at low frequencies and the frequency cutoff of the actuator progressively attenuate frequencies below 200 Hz. Moreover, the denser modal distribution of the glass causes the resonances at higher frequencies apparent double spacing between these two words into subgroups gathering two or three original vibration modes together.

Table 1 summarizes the characteristics of the stimuli used in Experiments 1 and 2, and in the control test.

2.3 Participants

Participants were recruited among students at the University of Udine and employees of Electrolux Professional SpA. They participated on a voluntary basis and were not paid. Their auditory and tactile acuity was informally tested by asking participants to close their eyes, then localize a sound source nearby, and finally identify the materials used in the experiment by touching the respective object outside the adhesive tape.

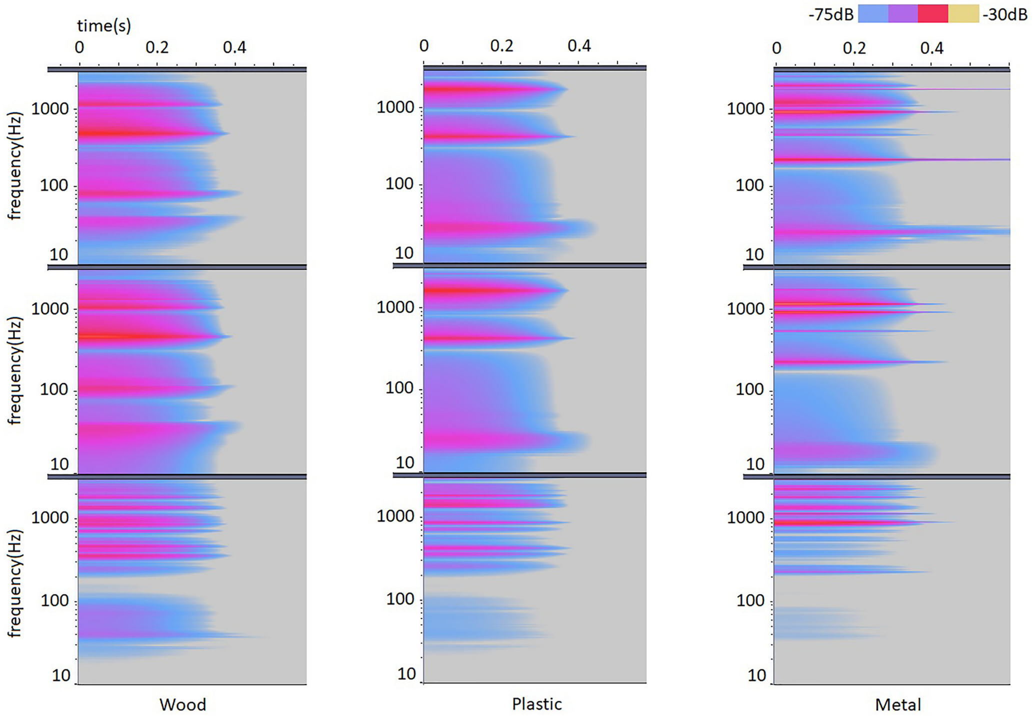

Fig. 5. Vibration spectrograms in Experiments 1 (top row) and 2 (middle row). Vibrations reproduced on the glass plate in Experiment 2 (bottom row).

Control test. Sixty participants, between 19 and 52 years old (M = 24.3, SD = 6.7), took the control experiment.

Experiments 1 and 2. Twenty-five subjects between 23 and 61 years old (M = 32.1, SD = 10.1) participated in Experiment 1, and twenty-seven (21–54 years old; M = 29.0, SD = 6.8) in Experiment 2. Eight subjects participated in both experiments. Roughly one third of the participants were female.

2.4 Design and Procedure

In all experiments, the design consisted of two within-subjects factors: Material and Modality. Material was either Wood, Plastic, or Metal. Modality was either unimodal Auditory, unimodal Tactile, or Bimodal audio-tactile. The factors were crossed and each factor combination was repeated six times, resulting in 6 × 3 Materials × 3 Modalities = 54 trials. Trials were organized in blocks according to Modality. Both unimodal conditions were presented before the Bimodal condition, and the order of Auditory and Tactile conditions was balanced among participants. Within each block, six repetitions of each Material were presented in random order. The experiment lasted about 10 minutes.

The task was to classify and report the material by saying its name. Responses were noted by the experimenter and audio-recorded for later reference. Participants were blindfolded during the control test. In all experiments, during unimodal Tactile trials, they received pink noise through headphones to mask unwanted auditory feedback.

Prior to each experiment, participants became familiarized with the real audio-tactile events by listening to the impact sounds while keeping one or two fingers of the dominant hand on the adhesive spot (Figure 6) until they felt they could confidently recognize the respective materials through those cues.

Fig. 6. Familiarization in Experiment 2.

Table 2. Control Test: Confusion Matrix for Each Condition

Condition	Auditory				Tactile				Bimodal		
Response → / Stimulus ↓	Wood	Plastic	Metal	None	Wood	Plastic	Metal	None	Wood	Plastic	Metal
Wood	**90.0**%	9.4%	.6%	0%	**66.9**%	26.7%	6.4%	0%	**99.7**%	.3%	0%
Plastic	6.4%	**90.3**%	2.8%	.5%	21.7%	**74.7**%	3.6%	0%	0%	**96.7**%	3.3%
Metal	.3%	2.8%	**96.4**%	.5%	2.5%	6.4%	**90.8**%	.3%	0%	2%	**98.0**%

Control test. A trial consisted of the experimenter dropping a ball on one of the objects from the prescribed height. In Tactile and Audio-Tactile trials, participants placed one or two fingers below the object through the cardboard support, as during familiarization (Figure 3 (right)). The other two objects were in turn kept under the halogen lamp to avoid changes in their temperature during the session.

Experiments 1 and 2. A trial consisted of playing back a recorded impact event, presented through headphones and/or the actuated glass plate as shown in Figure 2.

3 RESULTS

3.1 Control Test

Table 2 reports the confusion matrix for the Auditory, Tactile, and Bimodal modalities. Each diagonal contains the total proportion of correct responses in bold type, whereas the other cells report false responses. Columns labeled "None" report missing responses. Figure 7 presents a boxplot of individual proportions correct for Modality (Auditory, Tactile, Bimodal) and Material (Wood, Plastic, Metal).

Concerning unimodal conditions, Wood and Plastic were classified much better in the Auditory than in the Tactile condition, whereas Metal was classified well in both conditions. In the Bimodal condition, performance was nearly perfect across materials. Hence, differences in performance were analyzed only between the two unimodal conditions as follows. We undertook a nonparametric analysis due to considerable ceiling effects in the data. A Friedman test [16] was conducted, revealing significant differences in Material ($Q = 92.25$, $p < 0.001$). Three pairwise comparisons using the Wilcoxon rank-sum test [24] highlighted that Metal differed significantly from Plastic and Wood in the Tactile condition (Wood-Metal: $Z = 5.5$, Bonferroni-corrected $p < .01$; Plastic-Metal: $Z = 3.6$, $p < .01$). Concerning Modality, the pairwise comparisons highlighted significant differences between Auditory and Tactile for all materials ($Z = 5.2$, $p < .01$). Finally, a Wilcoxon rank-sum test confirmed that presentation order (Auditory then Tactile or Tactile then Auditory) did not result in significant differences for either Auditory ($Z = .43$, $p > .05$) or Tactile ($Z = .7$, $p > .05$) identification scores.

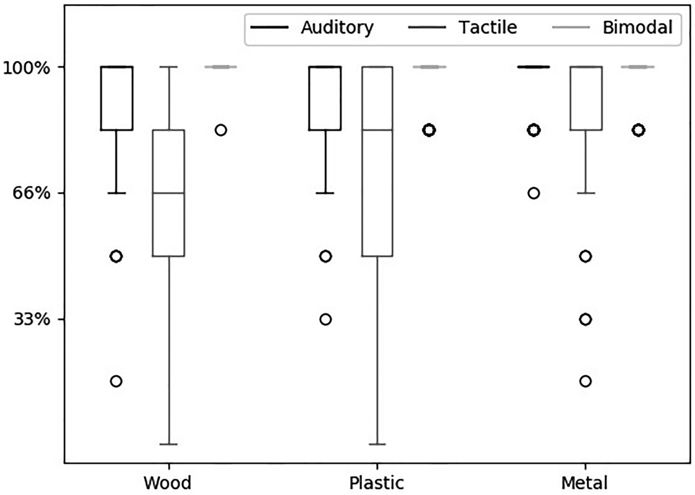

Fig. 7. Control test. Boxplot of proportions correct for all condition combinations.

Table 3. Experiment 1: Confusion Matrix for Each Condition

Condition	Auditory				Tactile				Bimodal		
Response → / Stimulus ↓	Wood	Plastic	Metal	None	Wood	Plastic	Metal	None	Wood	Plastic	Metal
Wood	**79.3**%	20.0%	0%	.7%	**62.7**%	20.0%	16.6%	.7%	**90.0**%	9.3%	.7%
Plastic	24.0%	**72.7**%	3.3%	0%	23.3%	**63.4**%	13.3%	0%	11.3%	**87.4**%	1.3%
Metal	1.3%	2.0%	**96.7**%	0%	22.7%	11.3%	**66.0**%	0%	.7%	2.7%	**96.6**%

3.2 Experiment 1

Table 3 reports the confusion matrices in the same fashion as Table 2. Figure 8 shows a boxplot of individual proportions correct. Compared to both unimodal conditions, the results suggest that performance was better in the Bimodal condition.

Again, the score distributions deviate from normal due to a ceiling effect, and hence a Friedman test was used. A significant main effect of Modality was detected ($Q = 37.8$, $p < .01$). Three pairwise comparisons were performed between modalities using the Wilcoxon rank-sum test. Significant differences were detected between Auditory-Bimodal ($Z = -2.7$, Bonferroni-corrected $p < .01$) and Tactile-Bimodal ($Z = -5.4$, $p < .01$).

A more detailed inspection of the two unimodal conditions shows higher median scores for Auditory than Tactile. In the Auditory condition, Metal was classified especially well. A Friedman test, considering each factor combination as one of six conditions of a combination factor, revealed significant differences ($Q = 21.8$, $p < .01$). Six pairwise comparisons were performed. Three comparisons between materials in the Auditory modality revealed that Metal significantly differed from Plastic and Wood (AuditoryWood-AuditoryMetal: $Z = 4.3$, Bonferroni-corrected $p < .01$; AuditoryPlastic-AuditoryMetal: $Z = 3.4$, $p < .01$). The other three comparisons were performed for each Material between the Auditory and Tactile modalities. A significant difference was detected only for Metal (AuditoryMetal-TactileMetal: $Z = 3.5$, $p < .01$).

3.3 Experiment 2

Table 4 reports the confusion matrices in the same fashion as Table 3. Performance is now generally lower and in some cases close to chance performance. Most participants performed above chance; however, two

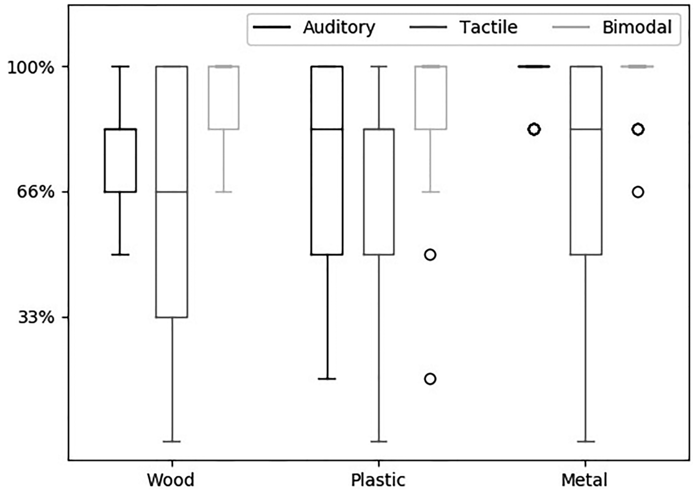

Fig. 8. Experiment 1. Boxplot of proportions correct for all condition combinations.

Table 4. Experiment 2: Confusion Matrix for Each Condition

Condition	Auditory				Tactile				Bimodal		
Response → Stimulus ↓	Wood	Plastic	Metal	None	Wood	Plastic	Metal	None	Wood	Plastic	Metal
Wood	**75.9**%	16.1%	6.8%	1.2%	**67.9**%	13.0%	17.9%	1.2%	**87.0**%	7.4%	8.3%
Plastic	11.7%	**62.4**%	24.7%	1.2%	17.9%	**53.1**%	27.8%	1.2%	7.4%	**67.6**%	29.6%
Metal	20.4%	29.0%	**50.0**%	.6%	13.0%	36.8%	**49.4**%	1.8%	5.5%	25.0%	**62.1**%

participants failed in both unimodal conditions and an additional two in one unimodal condition. Metal was frequently misclassified: 36.8% of Metal trials were classified as Plastic in the Tactile condition and 29.0% in the Auditory condition. Wood and Plastic were classified better than Metal, especially from Auditory cues.

Figure 9 reports a boxplot and means with SE of proportions correct for the same conditions as in Figure 8. Again, performance was better in the Bimodal condition than in the unimodal conditions. A nonparametric Friedman test detected a significant main effect of Modality (Q = 25.0, $p < .01$). Pairwise comparisons were performed using the Wilcoxon rank-sum test, revealing significant differences between Auditory-Bimodal (Z = −2.5, Bonferroni-corrected $p = .03$) and Tactile-Bimodal (Z = −3.7, $p < .01$).

Particularly for the unimodal conditions, scores were lower than in Experiment 1. Tests on the unimodal distributions with D'Agostino method [8] confirmed no significant deviation from normality for all factors, concluding that ceiling effects were not present. Even though some skewness was found in the combination (Auditory, Wood), a parametric analysis could be undertaken.

A two-way repeated-measures ANOVA was performed using Greenhouse-Geisser correction for insphericity. A significant main effect of Material was detected (F(1.61,41.9) = 16.3, $p \leq .001$), whereas neither the main effect of Modality ($p = .09$) nor the interaction of Modality and Material ($p = .563$) was significant.

The mean results for Materials were Wood (M = .72, SD = .033), Plastic (M = .58, SD = .033), and Metal (M = .50, SD = .04). Their respective 95% confidence intervals result in a partial overlap between Plastic (.51−.64) and Metal (.42−.57), whereas Wood is outside their combined range (.65−.78).

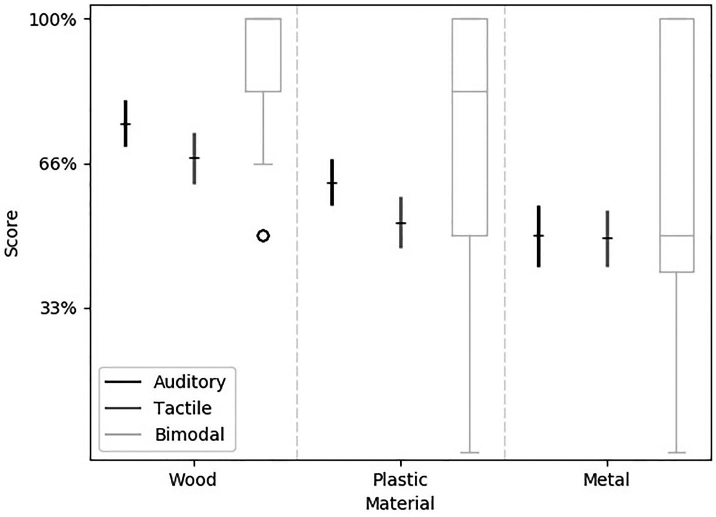

Fig. 9. Experiment 2. Mean proportions correct with SE bars (unimodal) and boxplots (Bimodal) for all condition combinations.

4 DISCUSSION

Figures 7, 8, and 9 show that in all tests, auditory cues were more effective than tactile cues for material classification. This is not surprising considering that hearing discriminates cues of frequency better than touch [55]. In the control test, however, Metal was classified almost equally well in both modalities. The most plausible explanation for this exception is that participants efficiently discriminated the longer decay of the metallic object vibrations from both sensory channels. This conclusion is consistent with previous findings, concluding that cues of damping/decay times are fundamental during material identification by hearing [20] and also by touch [28].

Further support to the preceding conclusion comes from Experiment 1, where participants, compared to the control test, were less precise in the Auditory modality when listening to Wood and Plastic but once again almost infallible when listening to Metal. In fact, the auditory confusion matrix in Table 3 disperses the data around the diagonal limited to the submatrix reporting for Wood and Plastic. Headphone listening introduces spectral (hence timbral) changes and internalizes sound sources especially if using closed-back headsets [56]. The use of such devices in our experiments therefore altered the auditory recognition process and disrupted the localization process [40]. The consequent distortion of the ecology that listeners had previously experienced during familiarization with the bouncing event may have caused larger error rates in the Auditory modality. Notably, such artifacts are less relevant for sounds made of few oscillatory components, where pitch instead of timbre cues prevail [52]. Hence, after the onset, listeners might have been able to isolate the long-lasting resonance at about 3 kHz (see Figure 4) equally well for both real and reproduced metal sounds.

A similar motivation may explain the performance drop while recognizing Metal through the Tactile modality in Experiment 1. In fact, an inspection of the bottom row in Figure 5 shows that the reproduction over glass progressively attenuates the resonances from 200 Hz down and alters those above this frequency. For this reason, participants might have lost both high- [4] and low-frequency [3] tactile pitch cues visible in the top row of Figure 5, which had been acquired during familiarization. Losing the former could have had consequences in identifying the metallic object. In parallel, the generally disappearing spectral energy below 200 Hz might have been responsible for a proportional performance decay of participants in identifying all materials through touch from reproduced vibrations during Experiment 1.

In Experiment 2, participants still performed above chance in both the Auditory and Tactile modalities; however, performance was generally lower than in Experiment 1. Wood essentially confirmed the scores of Experiment 1, whereas Plastic and especially Metal did not. This performance decay finds an explanation in the spectrograms of Figures 4 and 5 relative to this experiment (bottom rows). According to them, both channels ceased to provide the characteristic resonances acquired by subjects during familiarization. So, during the task, sounds and vibrations were perceived to have different timbre and no that distinct pitch that was still present in Experiment 1. The Auditory classification of Metal suffered particularly from this situation, scoring down until about 50%. This caused in its turn a general increase of the auditory confusion, as the expected resonant timbre of Metal and Plastic disappeared in favor of a muffled, unpitched sound inducing participants to occasionally swap the two materials or classify them indistinctly as Wood.

The preceding considerations find even more solid ground with the Tactile modality. Indeed, a comparison between the mid and bottom rows of Figure 5 respectively suggests that, during familiarization, these participants received characteristic low-frequency content and resonance modes; yet later, during the experimental tasks with reproduced stimuli, most of the energy below 200 Hz was not present, nor could the original resonances be retrieved from the spectral clusters in the tactile band [55] of the reproduced vibrations. Analogously to Experiment 1, the spectral distortion progressively got worse while moving from Wood to Plastic and finally Metal, with potentially proportional effects in the material identification.

The first general conclusion therefore is that participants identified Metal from resonances with longer decays, when available. Then, they relied on less robust timbre and pitch cues that were present in the onset of all stimuli. This conclusion echoes the results obtained by Giordano and McAdams [20] using auditory feedback; additionally, it suggests that participants made proficient use of longer resonances also in the tactile modality, as Higashi et al. [28] found while investigating tactile hardness perception. Wood and Plastic in any case had to be classified based on spectral cues, with little or no support from temporal information: in this respect, our results are aligned with existing research on tactile recognition of musical timbre [46].

In both experiments, the classification based on Bimodal stimuli was better. Especially in Experiment 1, it seems that the synergistic reproduction of audio and tactile cues was able to restore the information existing in the unimodal cues when they were experienced directly from the objects. More surprisingly, the same synergy was present also in Experiment 2, in which the sensory channels were further distorted. The logical conclusion is that participants were supported in their classification in the Bimodal condition by some form of cross-modal summation of tactile and auditory cues of material.

Sensory integration is known to optimize perceptual acuity [12]. In particular, interactions between such two channels have been reported by several authors [15], with effects depending on the spectral characteristics and temporal relationships between auditory and tactile stimuli. Even if such interactions do not necessarily lead to constructive effects [58], synchronous audio-tactile presentations of matching frequencies have been shown to improve event detection also in the presence of broadband auditory noise [57].

Constructive audio-tactile summation of particular interest to our experiment was reported by Schürmann et al. [47]. Participants performed a loudness-matching task with and without touching a bar vibrating coherently with sound. Vibrations were discovered to amplify the perception of auditory stimuli especially when their loudness was low. Further results have highlighted that the frequencies responsible for this effect range between 200 and 400 Hz [1]. In line with that and some previously cited experiments, our participants in the Bimodal condition might have detected audio-tactile cues reporting of resonance modes (be they equal in frequency or consonant [13, 42]) that conversely had disappeared or were perceptually masked in the unimodal stimuli. Their detection hence could have improved the classification performance. In this respect, literature from the musical haptics field provides intriguing, although not always robust, evidence of multisensory perception of frequency cues [14, 30, 45].

Table 5. Material Classification from Incongruent Stimuli

Stimulus		Response		
Auditory	Tactile	Wood	Plastic	Metal
Wood	Plastic	63.0%	32.4%	4.6%
	Metal	58.3%	22.2%	19.5%
Plastic	Wood	30.6%	48.1%	21.3%
	Metal	6.5%	37.0%	57.5%
Metal	Wood	46.3%	25.9%	27.8%
	Plastic	13.0%	45.3%	41.7%

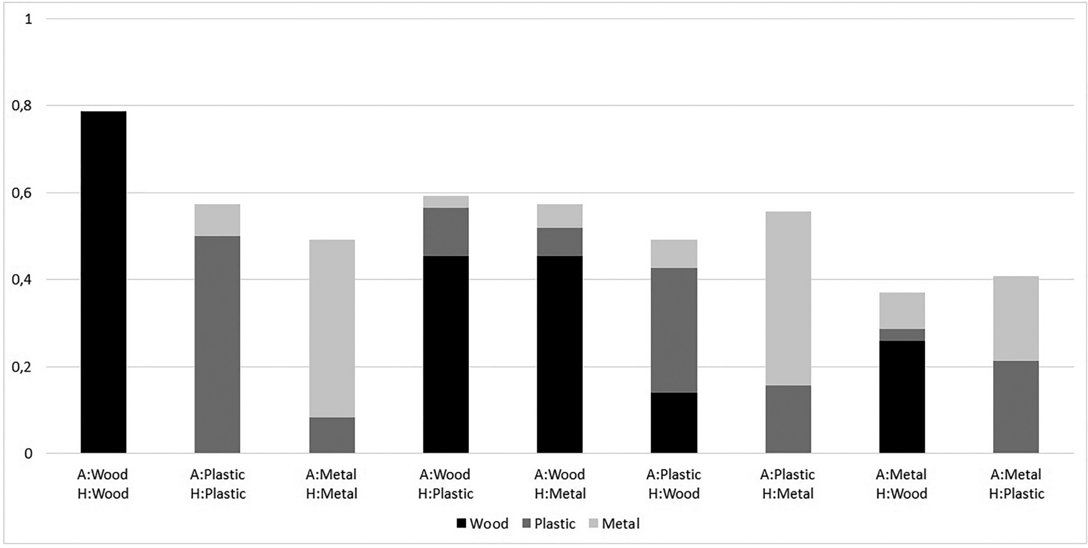

Fig. 10. Distribution of consistent classifications from congruent and incongruent Bimodal stimuli.

4.1 Incongruent Stimuli

The preceding considerations on audio-tactile synergy during material classification are even more interesting if considering responses to six *incongruent* bimodal stimuli, obtained by combining sounds and vibrations generated from different materials. Such stimuli were prepared with the recorded short-decay responses, as in Experiment 2. Immediately after the completion of a session in Experiment 2, we asked the participant to classify the same three Materials from four randomized repetitions of incongruent stimuli, for a total of $4 \times 6 = 24$ additional trials.

Table 5 reports how Materials were classified. The histogram in Figure 10 illustrates the distribution of consistent classifications across Bimodal stimuli resulting from the three congruent and six incongruent audio-tactile combinations. For each combination, classifications were considered as consistent if reiterated in more than two (i.e., half of the) repetitions irrespective of the identified material. Only the so defined consistent responses are represented in the histogram of Figure 10. Consequently, shorter bars reflect lower consistency and thus greater confusion during classification.

As the incongruent results cannot be compared to the congruent cases, the histogram can be interpreted only qualitatively. Despite this, Figure 10 suggests some interesting considerations. Congruent stimuli supported the Auditory classification of the unique Material they represented, and furthermore such classifications were mostly reliable. As reliability gradually decreases while moving to the right of the figure, consistent classifications started to occur for incongruent stimuli as well, again led by the auditory channel. However, the tactile channel prevailed in the last three (on average least reliable) consistent classifications.

We speculate that tactile feedback, in the limits of its ability to convey timbre, became progressively more important as the auditory channel, in front of incongruent materials, left its leading role while remaining supportive to cross-modal perception. This conclusion finds partial confirmation from experiments demonstrating that simultaneous presentation of sound and vibrations can lower tactile intensity thresholds [44] and enhance tactile intensity perception [53]. Concerning material classification, holding the conditions of Experiment 2 in which Metal could not be identified anymore by longer resonances, Wood established the most robust classification also when incongruent stimuli were presented: Wood was generally identified whenever it was present in at least one channel, whereas it was not identified when it was not present in either channel. The present conclusions, however, represent only a starting point and should be quantitatively confirmed by further tests.

5 CONCLUSION

The described experiments investigated the relationships and interactions existing between the auditory and tactile channels when humans are engaged in a material classification task, based on impulsive feedback from flat objects built with those materials. Our findings suggest that although both channels are able to perform this task correctly based on real feedback, the reproduction of recorded sounds and vibrations on a touchscreen-like display deteriorates the performance especially if the material's distinctive resonances are damped (e.g., because the display rests on a table). These experiments hence provide a baseline for the design of virtual buttons taking natural interaction into consideration. Our conclusions do not contradict previously accepted results, showing that few decaying resonance modes are sufficient to characterize the sounds and vibrations of a button: they indeed suggest that simple audio-tactile feedback can be contextualized to reflect material properties, through proper resonance tuning and the design of suitable broad-band onsets. In fact, the design of feedback containing subtle cues of material would be effective only if relying on technologies able to reproduce them with great accuracy. However, further research is needed to understand exactly the audio-tactile interactions that take place when humans classify impulsive feedback coming from everyday materials.

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