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Auditory and tactile recognition of resonant material vibrations in a passive task of bouncing perception

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Besides vision and audition, everyday materials can be passively explored also using touch if they provide tactile feedback to users, for instance in consequence of an external force exciting their natural resonances. If such resonances are known to provide informative auditory cues of material, on the other hand their role when a recognition is made through touch is debatable. Even more questionable is a material recognition from their reproductions: if happening, then they could be used to enrich existing touch-screen interactions with ecological auditory and haptic feedback furthermore requiring inexpensive actuation. With this goal in mind, two experiments are proposed evaluating user's ability to classify wooden, plastic, and metallic surfaces respectively using auditory and haptic cues. Although the literature reports successful auditory classification of everyday material simulations, especially the passive recognition of such material reproductions by holding a finger on a vibrating glass surface has never been tested. By separately reproducing the sound and vibration of a ping-pong ball bouncing on wood, plastic and metal surfaces, our tests report not only auditory, but also tactile recognition of the same materials significantly above chance. Discrepancies existing between our and previously reported results are discussed.

Introduction

Everyday human interaction with objects and events is mostly multisensory [11]. In this scenario, the human classification of materials is mainly based on visual cues. Despite the importance of sight, several human-machine interactions must be performed by relying only on auditory and tactile cues (e.g., when a user is involved in multiple activities, or when an interface is visually occluded). For this reason, the simulation of surfaces of different materials in virtual environments through multisensory interaction has become an active research topic, and the identification of materials based on non-visual cues has been studied from several perspectives.

The capabilities of the auditory channel have been tested in material classification tasks using different synthetic stimuli [1, 7]. Such tests have revealed significant identification of virtual sounding materials, identified by parameters which map in the amplitude, decay and frequency of their characteristic modes. These sounding objects in par-

ticular vibrate in ideal isolation, hence preserving the characteristic vibration modes of the physical model. Further studies [2] highlighted the role played by sounds in material identification; as matter of fact, if a material is visualized then a congruent contact sound improves the identification performances in grasping actions, while an incongruent contact sound gives rise to perceptual interference. Literature also suggests dependencies between tactile perception of roughness in materials and related synthetic auditory stimuli [5].

Haptic displays have been tested as well to simulate tactile properties of materials. Experiments revealed successful material recognition with simulated vibrations and force feedback in response to a tapping action [6]. The synergy between audio and tactile stimuli has been analyzed as a temporal process too: experiments have found the time constraints for such multimodal stimuli to form a unitary perception [9].

Although this topic seems already relatively well developed, there is a lack of knowledge in the literature concerning the role that auditory and haptic feedback play to enable material classification during passive tasks, in particular when the material properties are reported on a tactile display which is almost neutral, however made of a different material as it could be, for instance, a standard touch-screen in which one would be able to reproduce the response of a metallic surface hit by a small virtual ball. Starting from this hypothesis, two experiments are reported assessing the user's ability to classify materials from auditory and haptic cues in a passive task. In both experiments a bouncing event has been reproduced over objects made of three different materials: wood, plastic, metal.

Experiment

Stimuli

A ping-pong ball was recorded when it bounced on three almost identical surfaces made of fir wood, hard plastic, and steel metal. Such surfaces were custom-made, and their U-shape was chosen so as to allow a hand or an accelerometer to find place underneath (see Fig.1). The ball was dropped onto the surfaces from a height of 40 cm. A ping-pong ball was chosen for its low weight and neat bounce, after conducting informal comparisons against metal, rubber and wooden balls; these in fact were too heavy, and their bounces gave rise to irreproducible vibrations in the low-frequency using a small, low-power tactile actuator. Sound was recorded 40 cm from the bouncing event using an Audio-Technica AT4050 condenser microphone connected to a RME Babyface audio interface. Corresponding vibrations were recorded by attaching a Wilcoxon Model 736 accelerometer to the bottom of the surfaces at the bouncing point of the ball. The RMS power of the recorded signals was

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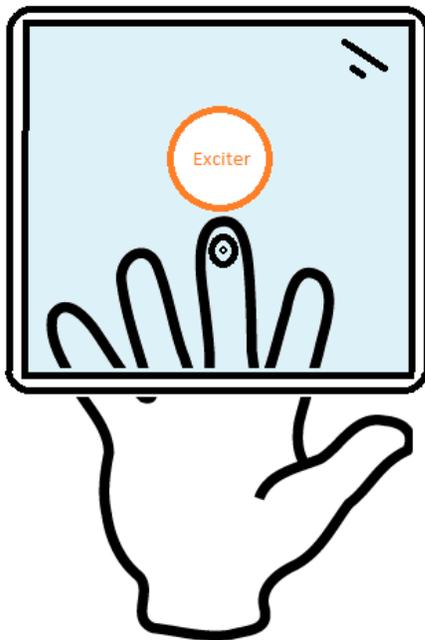[‡]hanna.jarvelainen@zhdk.ch
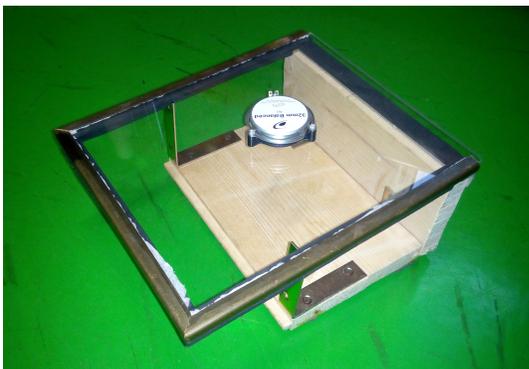[§]stefano.papetti@zhdk.ch
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Figure 1: Wood, Plastic, Metal surfaces used to record stimuli and to train participants.

(a) Sketch of the setup.

(b) Apparatus

Figure 2: Haptic display.

normalised within a 500-ms window. This intensity normalisation aimed at preventing participants from using loudness as a cue.

Such audio recordings were used as auditory stimuli, and played back through a pair of Beyerdynamic DT 770 PRO closed headphones. Concerning the haptic stimuli, the recorded vibrations were reproduced by a Dayton Audio 32-mm Balanced vibrotactile transducer [8], which was attached on a 3 mm-thick borosilicate glass plate (Fig. 2). The plate was mounted on a metal frame through rubber strips, and the frame was suspended on a wooden structure. A comparison between the recorded and reproduced vibrations was made by attaching the accelerometer on the glass plate immediately below the transducer position, and recording the latter vibrations. As can be seen from the signals and the sonograms in Fig. 3, reproduced bounces are to a good extent similar to the original ones on all surfaces. We will label them as Wood, Plastic, Metal from here on, all belonging to a category labeled as Material. In parallel, we will label the auditory and haptic modality respectively as Audio and Haptic, both belonging to a category labeled as Feedback.

PARTICIPANTS

Twenty-seven participants (20 males, 7 females), aged between 21 and 54 (M = 29.0; SD = 6.8) were invited, all reporting normal hearing and touch ability. Before the experiment such abilities were informally tested by asking each participant to close his/her eyes, then localize a sound source nearby, and finally recognize each material under test by touching the respective surface. Participants were not paid for the experiment.

PROCEDURE

Before the experiment participants were informed about the experimental protocol and procedure, first informally by the experimenter, and then by a voice recording. Then, before doing the experiment they were trained to perform audio-tactile recognitions of the physical materials on the experimental setup. Training consisted of dropping the ping-pong ball on the three surfaces, while participants could listen to the sounds and keep one or two fingers of their dominant hand underneath them. The training continued until a participant felt confident with each material.

After the training an experimental session started, split in the auditory and haptic part. The task was to recognise the material from the recorded stimuli, either auditory or haptic. In part 1, subjects heard the stimuli through headphones. In part 2 they felt the tactile stimuli through one finger as they had been trained to do. During this part masking noise was delivered through the headphones, fading in about two seconds before and fading out about two seconds after the tactile stimulus was presented. Either part contained six repetitions of each material, hence consisting of 18 trials. Presentation order was randomised. Automatic

Response Stimulus	Wood	Plastic	Metal	None
Wood	75.93%	16.05%	6.79%	1.23%
Plastic	11.73%	62.35%	24.69%	1.23%
Metal	20.37%	29.01%	50.00%	0.62%

Table 1: Audio mean responses distribution

Response Stimulus	Wood	Plastic	Metal	None
Wood	67.90%	12.96%	17.91%	1.23%
Plastic	17.90%	53.09%	27.78%	1.23%
Metal	12.96%	35.80%	49.39%	1.85%

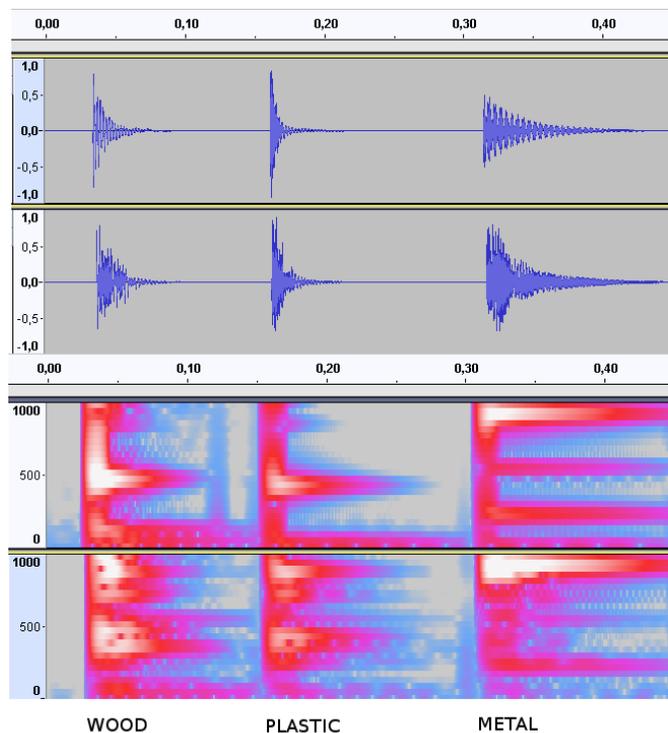*Table 2: Haptic mean responses distribution.*

Figure 3: Amplitude signals and corresponding sonograms of the reproduced (above in each plot) and recorded (below in each plot) vibrations for Wood, Plastic and Metal bounces (from left to right in each plot).

sequencing and recording of the responses were realized via a software procedure developed with Python 3.6. Each session lasted about 10 minutes. All participants' responses were also audio recorded in order to study their response times in a possible future extension of the analysis.

RESULTS

Fig. 4 shows that most participants performed above chance level, except for two of them who scored at chance level in both audio and haptic modalities and four of them who did the same in one modality. Normality of the distributions of results in each factor combination was tested with the D'Agostino method [3]. None of the conditions deviated significantly from normality. Only the condition (Audio, Wood) presents a relevant skewness. This might be due to the high mean of correct responses.

Table 1 and 2 report the average distributions of responses given to Audio and Haptic, respectively. Correspondingly highlighted in blue and green colors, the diagonals contain the correct response rates while the other cells contain the distribution of the mismatch responses. Columns labeled 'None' contain rates of no answer to the proposed stimuli.

Figure 5 reports mean proportions correct for Feedback and Material with Standard Error (SE). Concerning Metal, low scores for both Audio and Haptic are reported; in this case, a notable percentage of participants scored under 50%: 37% Audio, 29% Haptic. Concerning Wood and Plastic instead, mean scores for Audio are higher than Haptic.

A two-way repeated measures ANOVA was conducted on the influence of two independent variables (Feedback, Material) on the proportion of correct responses. Using Greenhouse-Geisser correction for inspheric-

ity, Material effect was found to be statistically significant at the $p<.05$ significance level ($p=2.083e-05$), whereas Feedback was not ($p=0.09$). The interaction between the two variables was not significant, either ($p=0.563$). The main effect for Material gives an F-ratio $F(1.61, 41.9) = 16.3$, $p <.001$, suggesting a significant difference between Wood (M = 0.72, SD = 0.033), Plastic (M = 0.58, SD = 0.033) and Metal (M = 0.50, SD = 0.04). Confidence Intervals 95% result in a partial overlap between Plastic (0.51 - 0.64) and Metal (0.42 - 0.57) while Wood is outside their combined range (0.65 - 0.78).

DISCUSSION

At the end of the experiment all participants felt uncertain about their result. Every participant eventually found the test more difficult than expected. During both experiments some participants occasionally used to comment on their previous response after listening/feeling the stimulus coming next in the sequence, as if they were progressively gaining awareness of the material properties along their session. With three materials the probability to perform at chance level is fairly high (33.3%), however the probability to make a correct guess in at least half of the responses (that is, nine out of eighteen trials) drops to 10.8%. During the experiment all participants revealed high concentration and will to score at their best. One subject who performed below chance level was probably unable to distinguish the stimuli, rather than being uninterested in the experiments.

Concerning Experiment 1, previous literature [1, 7] reports successful auditory discriminations that can be mainly explained by the perception of decay and frequency cues. Although the materials selected for our tests didn't exactly match the synthetic materials used in those experiments, our results on average revealed worse auditory discrimination. This performance decay may depend on a proportionally less accurate sound our materials produced as they had to be in contact with the user's finger and furthermore with the desk, inevitably altering their characteristic vibrations in spite of the presence of a foam panel isolating the vibrating body. Conversely, virtual sounding objects that previously simulated resonant materials are kept in isolation, hence preserving their characteristic vibrations unaltered. As reported by Giordano *et al.* [4],
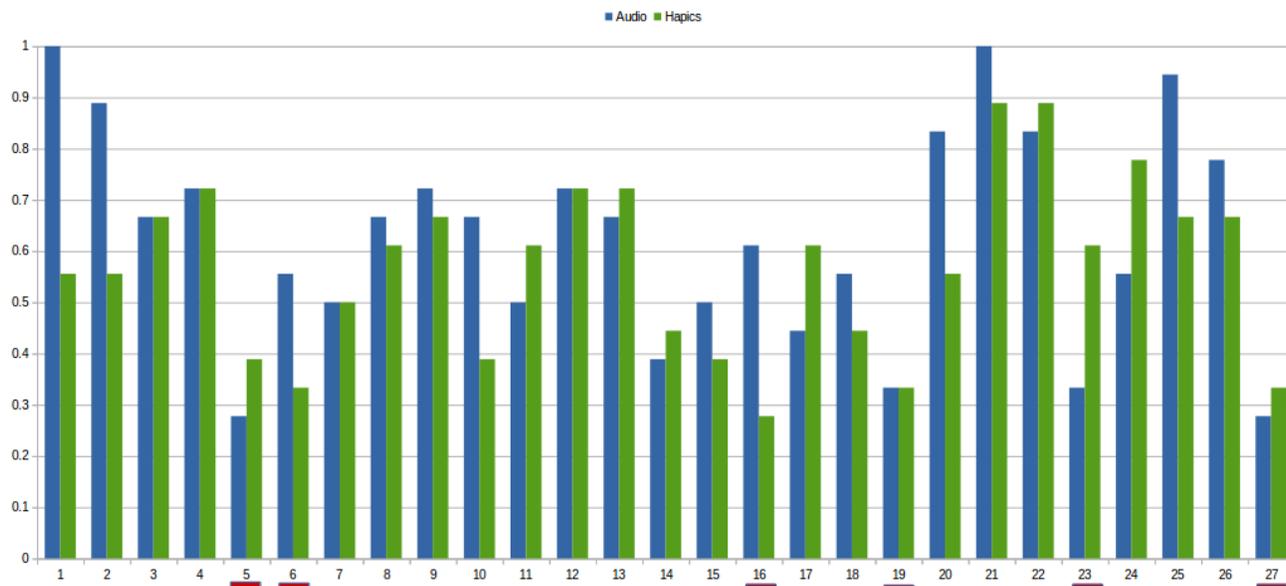
Figure 4: Individual correct response rates for Audio (blue bars) and Haptic (green bars) Feedback. Subjects highlighted with red underlining did not perform above chance level.
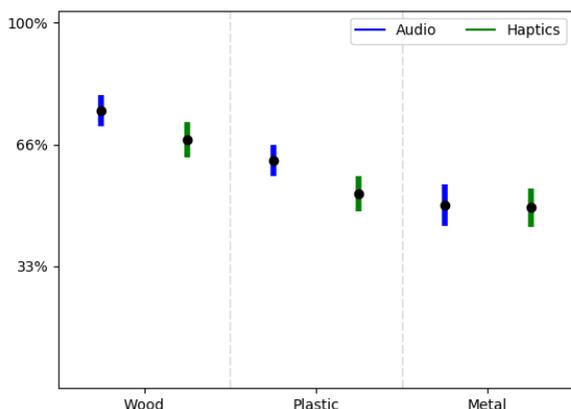

Figure 5: Mean proportions correct with SE bars for all factor combinations

while gross categorization is generally easy to obtain from sounds of vibrating plates, an impaired categorization of materials within the same gross category (e.g. glass-steel) has been observed. As a matter of fact, in that experiment categorization was based on the dimension of the plate rather than the material itself. We conjecture also that participants, during the test, recalled the characteristic vibrations of familiar objects made of the same materials. This bias might be more significant for materials having longer decay time after the bouncing event (e.g. Metal).

Although part 2 (Haptic feedback) reveals on average lower correct response rates than part 1 (Audio feedback) of the experiment, some subjects scored even better in the second part (Fig. 4). This makes the differences computed with ANOVA concerning the variable Feedback to be statistically insignificant. The average correct response rate for Material

identification was lower than previous studies based on haptic stimuli [10, 6], reporting higher discrimination rate (up to 85%). Some reasons explaining these differences could be: the materials chosen (Steel, Rubber, Wood in the previous experiments), the type of user task (active tapping), and the existence of force feedback cues that are conversely absent in our experiment.

Finally, the ANOVA analysis suggests that scores depend on Material. Moreover, the 95% confidence intervals are partly overlapping for Plastic and Metal, while Wood is outside their combined range. This fact is expressed informally also in Table 1 and 2, where Plastic and Metal on average are confounded more than other material pairs.

CONCLUSION

The main outcome of the experiment is the role played by the factors which were the object of this investigation: Material influences the recognition more than Feedback.

It may be interesting to put the materials in cross-modal comparison, to test possible prevalence of the sensory modality of one material vs. others. Hence, future studies will make use of the current experimental setup to investigate additive effects of congruent Audio and Haptic feedback, and recognition inaccuracies when conversely incongruent multimodal stimuli are presented.

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