Multimodal Augmented Reality – Augmenting Auditory-Tactile Feedback to Change the Perception of Thickness

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Abstract. With vision being a primary sense of humans, we often first estimate the physical properties of objects by looking at them. However, when in doubt, for example, about the material they are made of or its structure, it is natural to apply other senses, such as haptics by touching them. Aiming at the ultimate goal of achieving a full-sensory augmented reality experience, we present an initial study focusing on multimodal feedback when tapping an object to estimate the thickness of its material. Our results indicate that we can change the perception of thickness of stiff objects by modulating acoustic stimuli. For flexible objects, which have a more distinctive tactile characteristic, adding vibratory responses when tapping on thick objects can make people perceive them as thin. We also identified that in the latter case, adding congruent acoustic stimuli does not further enhance the illusion but worsens it.

Keywords: Augmented reality · Multimodal AR · Multimodal perception

1 Introduction

Today's hardware for Augmented Reality (AR), such as see-through head-worn displays, allows us to project computer-generated imagery (CGI) into our surroundings at a quality of sometimes stunning realism. Hardware to stimulate other senses than vision and research on perception of these modalities is however relatively lacking, although we do experience our environment based on the integration of multiple senses; for example, auditory-tactile [1, 3, 4, 10], sound [16], smell and taste [13]. An obvious example is the exploration of objects and their material. A table might look like being made of sturdy, solid wood, but when we touch it, we realize that it is just thin synthetic material with the visual texture of wood applied on it. Likewise, picking up an object allows us to feel its weight and texture and thus make a better estimate of its volume. Haptic exploration of real objects, such scratching their surface or tapping them, results in vibrations in the object's material. These vibrations are dependent on certain

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properties of the material, some of which we can estimate when we feel or hear the vibrations. We know from elasticity theory [9] that the displacement of a rod or plate that force acts upon depends on the force, elastic modulus of the material, and its thickness. Previous work investigated stiffness perception (i.e., the inverse of elasticity) [3, 17] for virtual objects. In this research, we expand this by looking at real objects in an AR setting and investigate the influence of sound and touch feedback upon haptic exploration of thickness. Our concrete *aim* is to *verify if we can change the perception of thickness when tapping by modulating auditory-tactile feedback.*

To get a better understanding of the relative influence of acoustic and haptic feedback when tapping an object to determine its thickness, we first start by augmenting the auditory modality. In a first experiment, described in Sect. 3, we measure the correctness of discriminating between different thicknesses under varying auditory conditions. In Sect. 4, we discuss a second experiment were we first augment the tactile modality before finally studying multisensory integration, that is, the combined influence of tactile and auditory augmentations for the perception of thickness. Starting with studying sound is motivated by the fact that, compared to haptic hardware solutions, auditory hardware is easier to obtain, can create a rich, realistic sound experience, and is simple to utilize using headphones. Our results, summarized in Sect. 5, show that we can indeed manipulate how people perceive the thickness of a material by adding acoustic or tactile feedback. We also show that when both modalities are present, manipulation only one of them is not sufficient, but both should be presented congruently to achieve the desired effect.

2 Related Work

Previous work in Virtual Reality (VR) aiming to influence the perception of physical properties related to haptic sensations is seeking to mimic real sensations in such virtual environments [3, 15]. These sensations in VR can be ‘build from the ground up’ whereas real objects have inherited physical properties that are often perceived in a multimodal way. For example, Hachisu et al. [5] add or subtract vibrations to a haptic pen applying force to a material. This augmentation creates the illusion of touching a different material than the real one. This work was the inspiration for our second experiment presented in Sect. 4, where we propose an approach for augmenting vibro-tactile feedback when tapping an object with your finger to estimate its thickness.

Research in multisensory integration, that is, the way in which the human brain combines congruently or incongruently perceived stimuli of different modalities, has shown that we can, for example, get a desired effect of perception of touch by simulation of another, seemingly unrelated modality. A well-known and robust effect is the so-called ‘Size-Weight illusion’ [2]. Here, the visual indication of size has a cross-modal effect on the perception of weight of two equally heavy objects. We also know that when stroking a surface, ‘roughness’ can be changed by visual [7, 8] and auditory [4] simulation. The perception of hardness can be influenced by deforming the CGI of a texture that is projected on a surface upon pressing it [6, 14]. In our research, we are interested in similar effects using the modality of sound and tactile stimuli, and if there is a comparable integration effect for the perception of a material’s thickness.

3 Experiment 1: Augmented Sound

If we assume that there is no tactile indication of thickness, that is, no noticeable difference when touching a thick or a thin object, then perception of thickness of two visually indistinguishable objects is entirely dependent on what we hear. Therefore, we hypothesize that we can change the perception of thickness solely by modulation of the auditory feedback when tapping it. We summarize this assumption in our first research question:

RQ1: *Can we achieve a different perception of thickness (solid or hollow) of an object when tapping it by solely modifying auditory feedback and otherwise fixed physical properties?*

We approach this problem by measuring the correct identification of a cube-shaped object as ‘solid’ or ‘hollow’ in a yes/no-type psychophysical experiment. Figure 1 shows the sound spectrograms of the typical impulse responses of a thick and thin material; plastic, as used in this experiment, and wood, as used in Sect. 4. They illustrate that a long decay of low frequencies is characteristic for thin material, as opposed to a short decay of higher frequencies for bigger, more solid ones. Thus, for our experiment, we generated the needed sounds by resynthesizing the original real-time sound of a tap on a cube and transforming it according to the desired characteristic (Table 1). By resynthesizing, we take the acoustic properties of the material and object (modal models [16]) and the velocity and duration of the tap into account.

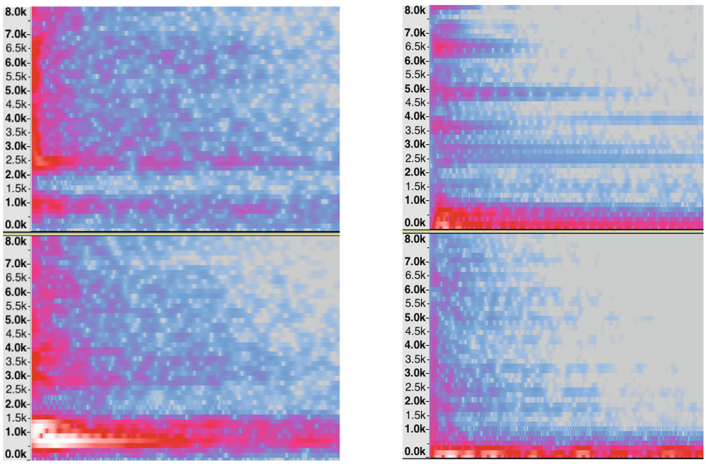

Fig. 1. Spectrograms of impulse responses of plastic cubes (left) and wooden plates (right) show characteristics of thick (top row) and thin (bottom row) material. Sounds originating from thin objects have a high amplitude, shown in white, in the lower frequency range. Furthermore, we see that these high amplitude low frequencies have a longer decay time.

Table 1. Characteristics of thickness in vibrating material

	Avg. amplitude	Frequency range of high amplitudes	Decay time
Thick	Low	1000 Hz	Short
Thin	High	0 Hz–1000 Hz	Long

3.1 Experimental Design and Setup

Used platform. Figure 2 shows the platform used in the first experiment. A Mogges piezoelectric sensor [12] is connected to the Mogees Virtual Studio Technology (VST) plugin running in Cycling'74 Max 6 on a MacBook Pro. This VST plugin transforms the vibrations measured by the piezoelectric sensor in real-time and outputs it as audio signal to the headphones worn by the participant. We used Sehnheiser CX3.00 in-ear headphones, so that earmuffs could be worn over the headphones to cancel out external sounds during the experiment. The used objects are two 3D-printed cubes of a styrenic plastic material that have a Young's Modulus of 2.0–2.6 GPa. The cubes' dimensions are 70 × 70 × 70 mm. The hollow one has walls with a thickness of 2 mm.

Fig. 2. Setup for experiment 1: (left) Participants tap the top of a solid or hollow cube. There is visually no distinction between the two thicknesses (during the experiment, the opening in the right figure was facing down). The cube is placed in a holder that is firmly attached to a table surface. A piezoelectric sensor is attached to the side of the cube (right) to capture vibrations in the material.

Method and procedure. Before participants enter the examination room, one of the cubes (either hollow or solid) is placed in the holder on the table. Test subjects then read an information sheet before an examiner explains the procedure again verbally. Each participant tests three conditions: no sound augmentation (control), white noise sound (no auditory cues), and resynthesized sound (simulating thin or thick material). The resynthesized sounds are pitched down and up and decay time increased and decreased for the modulation of thin or thick, respectively. The values for pitch and decay are determined subjectively to create a big contrast between sounds for thick and thin.

Participants are asked to tap the cube in front of them on the top side only with the index finger of their dominant hand. They can repeat this tapping action as often as they want before writing down on an answer sheet if they think the cube is hollow or solid. Then, the cube is exchanged with the other model (out of sight of the participant, so they cannot see the thickness of either of the cubes). The order of cubes as well as audio conditions was counterbalanced among all participants.

Thus, given the two independent variables *cube thickness* (solid, hollow) and *tapping sound* (real, static noise, thin, tick), each participant repeats all permutations of these variables one time, resulting in 2 * 4 = 16 trials per participant. The duration of the whole experiment for one person is about 30 min.

Participants. Eight students with ages ranging from 20 to 31 participated in our experiment. They volunteered and were not reimbursed in any way. Their number was motivated by the number of unique permutations of the independent variables. While this sample size is not enough to gain statistical significance, it is sufficient to identify a trend confirming or rejecting our research question RQ1, that is, if sound augmentation is sufficient or if tactile augmentation is needed as well.

3.2 Results and Discussion

Figure 3 shows the results of the experiment. We see that in the control condition, where real sound is heard (*real.hollow* and *real.solid* in the diagram), on average participants estimated the thickness of the cube correctly in 81.25% of the cases (75% for hollow, 87.5% for solid cube). In the conditions where any sound cue is removed by generating static white noise (*static.hollow* and *static.solid*), the correctness for the solid cube stays high (93.75%), but for the hollow one, it drops to 18.75%. This already indicates a strong impact of the hollow tapping sound on thickness perception, whereas the relevance of the solid sound seems less apparent. Looking at the simulated hollow

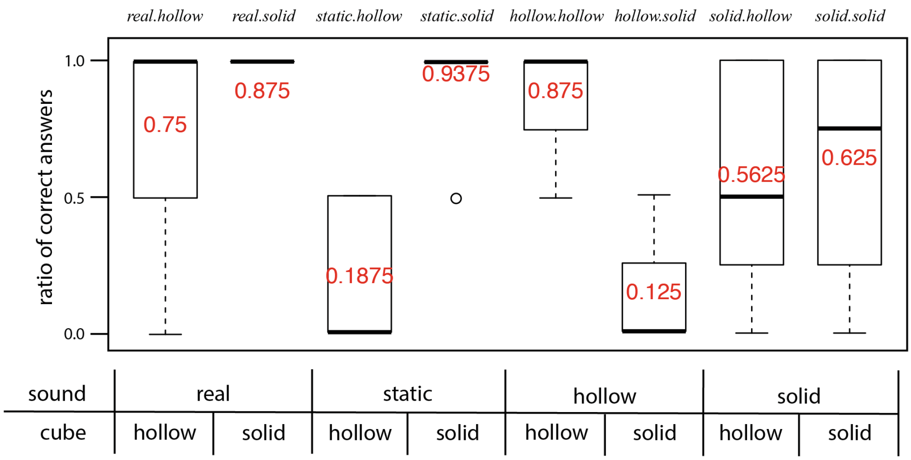

Fig. 3. Boxplot of results of the thickness discrimination task in experiment 1. Mean scores of correctly identifying the cube's real thickness are indicated in red. (Color figure online)

sound (*hollow.hollow* and *hollow.solid*), as expected, we see a high correctness when the hollow sound matches the hollow material (87.5%), but a strong drop when the hollow sound is played upon tapping a solid cube (12.5%). This proves that peoples' perception of thickness can indeed be manipulated by changing the acoustic stimuli. Yet, results for the simulated solid sound (*solid.hollow* and *solid.solid*) are close to chance level (56% for hollow cubes and 63% for solid ones) suggesting that subjects were just guessing. This shows that this sound also has an impact on the perception, because people were not able to make the right choices anymore, but that it is not enough to consistently create the target scenario.

There are two possible explanations for why simulated solid sounds did not have a similar manipulating effect as hollow ones. First, the sound of tapping a solid object is already less significant in real life, whereas real hollow sounds are much more distinctive and meaningful. The fact that we observed a strong drop when comparing real sound feedback to white noise in case of the hollow cube, but none in case of the solid one seems to confirm this. If this assumption is correct, our results would show that we can indeed use audio to manipulate peoples' perception, but only for certain subsets of materials, characteristics, and audio signals. Another reason why results for solid cubes are around chance level could be that the sound sample used in our experiment is just not indicative or distinctive enough to cause a better effect. We can speculate that with a better sound quality we might still be able to achieve the desired effect. Also, if people would compare the solid sound to the hollow one directly, it is likely that they discriminate between the two correctly. To cope with this, we will modify the experimental design for our next experiment by using a two-alternative forced choice task. We will also use pre-recorded audio samples instead of synthesized ones. Further experiments with improved sound quality for solid sounds are left for future work.

In conclusion, we can answer our research question positively, that is, we can indeed achieve a different perception of thickness solely by auditory feedback. Yet, this does not seem to be true for all situations, and the concrete conditions and possible limitations need to be specified by further experimentation.

4 Experiment 2: Auditory-Tactile Feedback

In the introduction, we discussed that human perception is generally based on a combination of simultaneously perceived multimodal stimuli, such as visual, acoustic, and haptic feedback when tapping an object. Experiment 1 showed that acoustic stimuli might be sufficient to change perception under certain conditions. In our second experiment, we want to further focus on the integration between two modalities – sound and tactile feedback – and verify their influence on thickness perception. We summarize our goal in a second research question:

RQ2: *Can we achieve a different perception of thickness (solid or hollow) of an object when tapping it by modifying auditory and tactile feedback and otherwise fixed physical properties?*

For this second experiment, we switched the objects from cubes to larger wooden plates to make the tactile indication of thickness more pronounced. Because using the terms “hollow” and “solid” does not make sense for such an object, and the terms “thick” and “thin” might be too context dependent and be interpreted differently by subjects, we changed the experimental design. With a two-alternative forced-choice (2AFC) psychophysical experiment, subjects are now asked to correctly identify which one of two plates is “thinner” than the other one.

4.1 Experimental Design and Setup

Used platform. Two wooden frames have been constructed to each hold two wooden plates in place. The wooden plates have a dimension of 200 × 200 × <T> mm with <T> being a thickness of either T = 4 mm (thin) or T = 10 mm (thick). Each frame can hold a thin and a thick plate. Two clamps are used to hold the plates in place and preventing inter-resonance. The clamps and the wooden frames are covered with a 9 mm thick polyethylene foam to stop vibrations in the plates from resonating into the underlying surface. The setup is illustrated in Fig. 4(a) and (c). To generate tactile vibrations when users tap on the plates, we have created two tactile sensors/actuators, as shown in Fig. 4(b). They consist of a PVC cylinder with a diameter of 20 mm and a height of 8 mm with a cutout in which the vibro-actuators fit precisely. The vibro-actuators and connected AL-202H Amulech amplifier are per design of the TECHTILE toolkit [11] and can display a range of 1-20000 Hz. A Force Sensitive Resistor (Interlink FSR402) is attached on top of the vibro-actuator and PVC cylinder. Pressure on the FSR is registered by our serially connected software, which measures the tap force approximately between 0 and 50 N. Based on this tap force, the software plays a pre-recorded audio file. Measured latency between moment of impact on the FSR and audio output ranges from 20 ms to 60 ms.

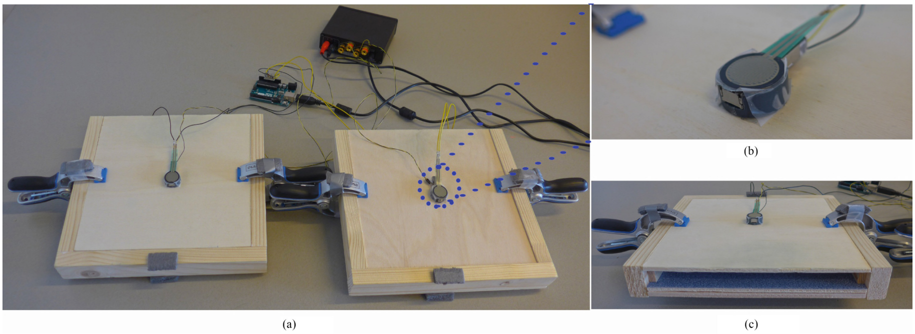

Fig. 4. Setup for experiment 2: (a) two wooden plates are clamped into two wooden frames. Vibration-damping material is attached to places where the wood or clamps touch the underlying surface. In the middle of the plates are Force Sensing Resistors (FSR) that are pasted on top of vibro-tactile actuators as shown in (b). The actuators are connected to an amplifier and together with the FSRs make a serial connection to a computer. (c) shows the back-view of the frames. Both frames can be turned-over to change the thickness of the plates.

Method and procedure. Each participant is tested under the following conditions: tactile stimuli (thin, thick), auditory-tactile stimuli (congruent or discrepant with each other). Under each condition real tactile feedback of the tapped plate is present. The participants are asked to determine the thinner one of the two plates by tapping on the sensors. The two plates presented to the subjects are always of opposed thickness; a thick and a thin one. The thinner one is on the left side in 50% of the cases, but the order is randomized. There are no visual cues indicating the thickness of the plates.

In a preprocessing phase, we recorded the actual tapping sounds used later in the experiment to make them sound more realistic, thus avoiding possible negative influences on the results (cf. discussion of experiment 1 in the preceding section). When capturing the sound snippets, we have also recorded the impact force of the tap and saved it a pair to be played-back during the experiment. In total, we have recorded twelve sound-force pairs of tapping on thick wood, and nine sound-force pairs of tapping on thin wood. The forces of the taps are approximately equally distributed ranging from subjectively ‘soft’ touch to a ‘very hard’ tap.

We decided to generate vibro-tactile feedback by modulating a sine wave. Our aim is not to simulate all touch sensations, as this would arguable result in a virtual reality problem. Instead, we add vibratory cues to vibrations in the real material. Frequencies, base amplitude, and decay times for thick and thin vibrations are summarized in Table 2. The decay time represents the total time for an exponential fade-out to zero amplitude of the sine wave. These specific values have been chosen subjectively to have a large contrast in feedback between ‘thin’ and ‘thick’.

Table 2. Tactile vibratory properties

	Base amplitude	Base frequency	Decay time
Thick	0.3	500 Hz	100 ms
Thin	1.0	100 Hz	500 ms

When entering the examination room, subjects are asked to sit on a rotating chair in front of the equipment and read an information sheet. Every participant then undergoes one training round to familiarize them with the auditory and tactile experience, taking particular care on practicing tapping intensity and order. They first had to tap the left plate three times on the sensor; with a soft tap, (place finger upon the sensor; ± 1 N force), a medium tap (± 20 N force), and a hard tap (± 50 N force). During training, participants tap on the plates without any augmentation and are asked with one is thinner. They are then told if they are correct or not. Via in-ear headphones, they are presented with a sample of thick and a sample of the pre-recorded tapping sounds for wood; a ‘thin’ and a ‘thick’ one, and must indicate which one ‘sounds thinner’.

During the actual test, participants wear additional earmuffs over the in-ear headphones to eliminate external noise. For every condition, they must tap with the index finger of their dominant hand, and start with the left plate, followed by taps on the right one. After this process, they must indicate which plate they think is the thinner one by saying ‘left’ or ‘right’, which was logged by the examiner. Then their chair is rotated around, so they are facing the back wall and cannot see the examiner modifying the thickness of the plates for the next round. Every permutation of the independent variables is repeated ten times, resulting in 60 trials per participant and a total duration of about 45 min per subject.

Participants. Ten male students participated in this experiment. Participation was voluntary and subject have not been reimbursed in any way. Due to their length, one participant's nails touched the sensor when tapping it, which creates a very different haptic and auditory feedback. Thus, he was asked to tilt his finger slightly in a way that the nail would not touch the sensor. Data for this subject does not show a noteworthy difference compared to the others. Therefore, we do not expect any impact for the results.

4.2 Results and Discussion

Figure 5 illustrates the results of experiment 2 by showing the mean correctness scores for determining the thinner of the two plates. Labels on the x-axis indicate the different conditions: First, pure tactile where haptic feedback does match the real situation (*Hm*) or does not (*Hn*). They represent the tactile counterpart to the conditions *hollow.hollow, static.static* and *hollow.static, static.hollow* in experiment 1. These conditions are followed by four others where we have both haptic and acoustic feedback; first where both are congruent and either match the real situation (*HmSm*) or not (*HnSn*), then where they are not congruent, that is, either the sound (*HmSn*) or the tactile feedback (*HnSm*) diverge from the real signals.

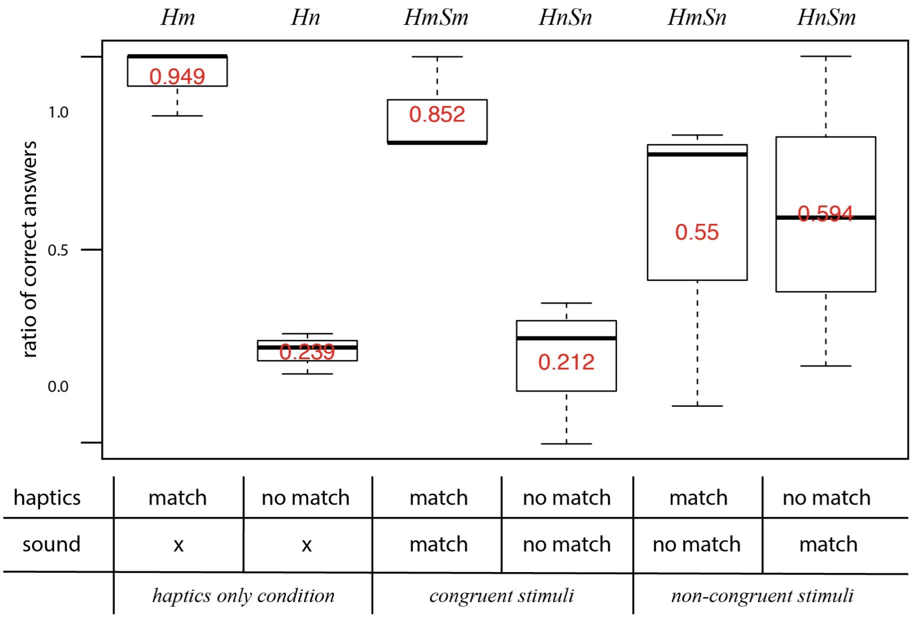

Fig. 5. Boxplot of results of experiment 2 with means shown in red. Labels below the x-axis specify the related conditions. (Color figure online)

Like in experiment 1, we want to verify if a non-matching signal can be used to manipulate the perception of users. We see that this is clearly the case for the pure haptic situation. Like with pure audio feedback in experiment 1, there is a huge drop in correctness from 94.9% to 23.0% when the haptic feedback does not match the real one (*Hn* and *Hm*). A similar decrease appears when we have matching modalities for haptics and sound; correct answers drop from 85.2% when both signals match the real situation (*HmSm*) to 23.9% when they both do not (*HnSn*). Thus, as expected, by representing an opposed signal for both modalities, we can manipulate people's perception in a way to experience the 'wrong', that is opposite characteristic of the material. Yet, if only one of the two modalities do not match (*HnSm*, *HmSn*), results are at chance level (55% and 59.4%). Running a two-way ANOVA with repeated measures and an error term on differences between participants over the data showed a significant effect ($p < 0.1$) of sound on correct discrimination of thickness ($p = 0.0959$) as well as of tactile feedback ($p = 0.0441$). However, an interaction effect between the two was not significant ($p = 0.492$). Normality of the mean data was confirmed using a Shapiro-Wilk test and QQ-normals plot.

Thus, we can positively answer our research question by concluding that perception of thickness can indeed be manipulated by providing opposed haptic and auditory feedback. Yet, this is only the case if both signals are congruent, as our results show that one of the two is not enough to achieve this effect.

5 Conclusion and Future Work

We presented two experiments verifying that we can influence how people perceive certain characteristics of material when tapping on them by manipulating auditory and haptic feedback. In a first initial test, we showed that we could 'trick' people into perceiving the volume of a solid cube as hollow by just changing the auditory feedback. Despite the small sample size, the trend clearly suggests the potential of such an approach. Yet, the results also show that there are limitations to this, since a similar effect could not be achieved for a solid, non-hollow cube. A second experiment confirmed these observations in a similar scenario (estimating the thickness of a wooden plate) and haptic feedback. Again, using different stimuli than the real situation changed the users' perception and experience of it. Yet, it also showed that in a more realistic scenario involving both senses, manipulating one of the stimuli is not sufficient. When manipulating one of them, results were on chance level; neither was the matching one strong enough to let people experience the situation as it is in the real world nor was the non-matching one strong enough to convince them of the opposed characteristic. But when both modalities matched, we are indeed able to manipulate users' perception again.

Our results are a small but important step towards creating a richer, more multimodal augmented reality environment that are not just focused on visual stimuli but embrace all our senses. Alternative applications of our research include a scenario where a single 3D-printed object is presented to users with different characteristics, such as hollow or solid by purely manipulating the multimodal haptic and acoustic feedback. Important areas to explore in future research include studying further characteristics of different materials and utilizing richer and more complex audio and haptic signals. Furthermore, one could explore how adding visual cues could further help in creating these augmented experiences; promising examples include visualizations of different materials, such as wood, marble, porcelain, and combining them with different audio cues or haptic feedback.

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