Assignment of a Vibration to a Graphical Object Induced by Resonant Frequency

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Abstract. This work aims to provide tactile feedback when touching elements on everyday surfaces using their resonant frequencies. We used a remote speaker to bring a thin wooden surface into vibration for providing haptic feedback when a small graphical fly glued on the board was touched. Participants assigned the vibration to the fly instead of the board it was glued on. We systematically explored when that assignment illusion works best. The results indicate that additional sound, as well as vibration, lasting as long as the touch, are essential factors for having an assignment of the haptic feedback to the touched graphical object. With this approach, we contribute to ubiquitous and calm computing by showing that resonant frequency can provide vibrotactile feedback for images on thin everyday surfaces using only a minimum of hardware.

Keywords: Assignment, Illusion, Haptic Feedback, Resonant Frequency

1 Introduction

Nowadays, touch is the dominant way to interact with computers. Haptic feedback, given during touch interaction, for example, when pressing a button, increases users' performance [5].

In the case of interacting with smartphones, tablets, or game controllers, small embedded vibration motors provide users with haptic feedback. Designing haptic feedback for augmented environments and everywhere displays [33] in comparison is challenging. Following Weiser, who envisioned that future technology should be calm and interwoven into everyday materials [44], raises the question of how future smart environments and objects, including required haptic feedback, might look and feel.

Research on haptic feedback explored a wide range of technologies, such as vibrotactile actuators [18, 23, 3], peltier elements [32, 14], and electrotactile devices [50]. In addition, the interaction of the visual and the aural sense has been explored [41, 52] as well as how audio itself can influence haptic experiences to create haptic sensations [42, 43]. While everyday materials and surfaces are promising candidates for future interaction [17], it remains unclear how to provide haptic feedback when interacting with them.

We are inspired by a physical phenomenon called Eigen- or resonant frequency, which can be used to bring, for example, wooden boards into vibration using sound from an external speaker somewhere in the room [28]. Creating haptic feedback for interactions with surfaces in our environment via audio has the advantage of using existing objects, as surfaces can be found everywhere, and speakers are present in most households. Another advantage of using resonant frequency through a speaker is that the speaker does not have to be attached to the surface to stimulate it. Instead, it can be placed anywhere in the environment. Therefore, one speaker could energize different surfaces and create haptic feedback to various images presented at them. This makes the approach scalable to create haptic feedback for several objects of different sizes presented on various surfaces with one sound source. It has to be kept in mind that the use of speakers results in hearable sounds, which might disturb the illusion. However, this effect could be eliminated with speakers able to play infrasound frequencies.

But how can we facilitate vibrating boards for interface design? Imagine a keyboard drawn on a thin wooden board, and a camera or attached capacitive sensors detect when and where the board is touched. If the touched board vibrates using resonant frequency and a user assigns that vibration to the key they press, we could use the board's vibration as haptic feedback when interacting with smart materials and surfaces without thinking about how to embed space-consuming technology into them.

In this work, we introduce the idea of using resonant frequency for haptic feedback when interacting with everyday surfaces. We further examine a proof-of-concept evaluation and show that vibration can be associated with graphical objects on a surface that vibrates when touched. Moreover, such vibration is associated with the graphical objects and is not assigned to the entire surface. As an example, in this work, the image of a fly is placed on a surface, leading to the image being perceived as a fly while the fly undergoes an embodiment process (in this work referred to as fly-embodiment). As a surface, a wooden board was excited by its resonant frequency, which was examined in a technical evaluation. Furthermore, we empirically explore the impact of additional auditive feedback on the perceived fly-embodiment of the touched graphical object. Finally, we look at the effects of feedback duration and timing on the fly-embodiment.

2 Related Work

This paper investigated whether sound can be used to activate haptic feedback for user interfaces. Therefore, we have reviewed (1) work on vibrotactile feedback, (2) research on how audio can create haptic feedback, and (3) how resonant frequency can be used for haptic feedback creation.

2.1 Vibrotactile Feedback

A commonly popular method to induce haptic sensations is using vibrotactile feedback. This is known from devices using small vibrators to create haptic sensations, like VR controllers, smartphones, or other touch displays, but also for illusionary haptic feedback like phantom sensations (e.g., Funnel illusion [7], Saltation [13], and Stimulus-Onset-Asynchrony (SOA) [6]).

Several works investigated if haptic feedback can be felt anywhere between the hands out of the body [3, 23, 38]. Berger et al. took advantage of virtual environments and used vibrations of VR controllers to create haptic sensations [3]. In their study, participants had to hold a virtual object in their hands, which could be seen in the virtual scene as a wooden stick. Participants perceived an illusory sense of touch in the space between their hands, induced by several strength vibrations of the controllers. Kim et al. investigated phantom sensations between the participants' hands using a mobile device [23]. They fixed vibrotactile actuators in a row at the back of a mobile device. Depending on active actuators, a resulting phantom sensation should be located. Participants had to figure out the location of this resulting vibration on the mobile device screen. They showed that the phantom sensations were perceived between the hands in a 2D space at different locations depending on which actuators were used. Seo et al. used a mockup of a mobile device made of acrylic resin and fixed a vibrotactile actuator on each end [38]. By varying the frequency of each actuator, a resulting haptic sensation should be felt on the mockup somewhere between the hands. In a study, they elicited that participants perceived haptic sensations at different locations depending on the frequency of each of the two actuators.

Other researchers also investigated phantom sensations felt in the space between hands but without additional devices, like smartphones, mockups, or controllers. Instead, they fixed the vibrotactile actuators directly at the users' fingertips [27, 26, 30]. Lee et al. fixed one vibrotactile actuator on the fingertips of each index finger [27]. Participants had to judge the position of the phantom sensation (with the help of an augmented ruler) between their fingertips. The results showed that the phantom sensation was localized differently depending on the frequency of each actuator. In a separate study, Lee et al. investigated the same haptic sensation. This time the vibrotactile actuators were fixed at the index finger and thumb of the same hand while participants performed a pinch gesture [26]. In their experiment, they were able to elicit that a phantom sensation is felt between the fingers, with no physical object connected to the participants' bodies, using different stimulation methods of the actuators.

Further, other works investigated haptic sensations felt on the own body using vibrations [18, 21]. Israr et al. investigated different patterns and amounts of vibrotactile actuators placed on various parts of the body [18]. They aimed to explore if different movement patterns can be felt on the skin. Their results showed participants felt varying movement sensations using a large grid of vibrotactile actuators. Kim et al. placed actuators on opposite sides of body zones, like the back of the hand and palm or back and front of the upper body [21]. They showed that haptic sensations could be felt if tactile stimulation was performed through body parts. Further, they presented that the frequency of the actuators is important, and duration and direction are less crucial. Bau et al. used electrovibrations when people moved fingers across a touch surface [2]. In four different experiments, they investigated the potential of these electrovibrations to induce tactile feedback. They found electrovibration can be used for various tactile sensations, like the perception of textures, or for different interactions, like dragging or the alignment of an object.

Another research interest is investigating the movement of felt haptic sensations from one hand to another induced by vibrotactile actuators [35, 34, 54]. Therefore, different devices for creating vibrational feedback were used. Pittera et al. made a custom vibrotactile device for each hand and investigated how the moving vibrations are perceived [35]. In their experiment, they varied the frequency and duration of the stimulation. They showed that illusionary movement was perceived while holding separate objects with non-contiguous parts of the body. In another study, Pittera et al. used ultrasound speakers to stimulate the palm of participants' hands with vibrational feedback [34]. They showed that illusionary movement is also perceived by using midair technology. Zhao et al. used a tablet with fixed vibrotactile actuators on each end [54]. A moving sensation was created by activating the actuators with different asynchronous stimuli over different durations. This sensation was supported through a moving graphical illustration. They presented that the graphical representation enhances the perceived haptic feedback.

While most related works used actuators and devices directly attached to the users or placed in their hands, we used sound to create the vibration. Further, the speaker is not directly attached to the user or the surface.

2.2 Haptic Feedback Using Audio

Our approach relies on the assignment of the haptic feedback using sound. Hence, we looked at related work investigating haptic sensations with additional sound.

Cho et al. investigated the sound of a pencil writing on paper in combination with vibrotactile feedback [9]. The sound, as well as the vibrotactile feedback, was coupled with the writing speed and pressure. They elicited that users perceived the haptic sensation of writing on a sheet of paper when writing with a pen on a tablet screen. The effect was most intense for the combination of audio and tactile feedback, compared to one modality alone. Etzi et al. created haptic sensations of pleasantness and roughness of materials by using the sound of paper and sandpaper combined with the visual sense by presenting images of different surfaces. [12]. While participants explored the same surface within the study, they perceived sounds and saw images of different materials. These sounds let the participants feel different pleasantness and roughness of the same material.

Won et al. examined how the perceived tactile intensity can be changed by auditory feedback [51]. In a study, they were able to show that the presence of audio influenced the perceived tactile intensity. Besides, the frequency of the auditory feedback was not significant and did not have to coincide with the tactile feedback. The perceived duration of haptic feedback was researched by Villanueva et al. by investigating interference of audio and touch [43]. Both auditory and tactile stimuli were used as distractors to the other modality. They found incongruent conditions influenced each other modality in terms of duration perception by decreasing performance. Further, congruent auditory feedback did not enhance tactile perception performance. Lai et al. elicited if audio feedback can influence the perceived physicality when applying force with a finger on a rigid surface [25]. Therefore, in an experiment, participants had to press on the same rigid surface while perceiving various auditory feedback in each condition. The auditory feedback was based on real-world material, object, or phenomenon. The results indicated that audio, as an interaction channel, enriched the perceived physicality when pressing a rigid surface.

When audio is used to create haptic sensations, it is usually done by using material or other real-world sounds. In contrast, we used a special frequency to stimulate a real-world surface and bring it into vibration, but we did not use hearable sounds.

2.3 Haptic Feedback using Resonant Frequency

As we use resonant frequency of an object to create haptic feedback, we also looked at research on the resonant frequency to create haptic sensations.

Using resonant frequency to improve haptic sensations is a conventional method to increase the perceived haptic feedback on a maximum value for linear resonant actuators or piezoelectric actuators [39, 53]. Silva et al. investigated different technologies to create haptic feedback [39]. They found the linear resonant actuator operating with a voice coil to drive the mass as energy efficient and powerful when operating at resonant frequency. The actuator requires little power to reach the resonant frequency, is small, and can provide powerful vibrations and haptic sensations. Yeh et al. used piezoelectric actuators to create a working abstraction of a haptic feedback system where users can feel the stiffness of an object [53]. They investigated the setup number and stimulation possibilities of the piezoelectric actuator. They showed that the piezoelectric actuator yields better efficiency if it has a resonant frequency.

Further, research on the resonant frequency investigated the use of speakers to create haptic sensations [46, 47]. Wi et al. used resonant frequency to prototype a haptic feedback assistive device for visually-impaired drivers [46]. They created a haptic device with pins of different diameters and lengths and resonant frequencies ordered in a square layout. They were connected to the voice coil of a speaker. The results showed slight differences in the pins' structure were enough to stimulate specific pins with a resonant frequency, which resulted in a high-resolution haptic display. Withana et al. researched if audio can create haptic sensations in the own body by using the resonant frequency [47]. They used a custom chair on which four acoustic actuators were placed under the seat. These actuators played sounds with different frequencies. Participants had to judge where inside the body they perceived haptic sensations. They found that they can provide haptic sensations to multiple body parts via just one contact point.

Fig. 1. Left: Wooden board with the graphical representation of a fly. **Right**: Rear of the wooden board with copper tape at the same position as the fly and copper wire connected to an Arduino, detecting resistance change when the fly is touched.

Previous works that investigated resonant frequency used different actuators, like piezoelectric or linear resonant actuators, and attached them to objects or surfaces. Our approach differs from these by not attaching a speaker to a certain object or surface but using a speaker placed anywhere in the room. Thus, we can use one single speaker to add vibrotactile feedback for different surfaces or objects remotely.

2.4 Summary

Due to space, weight, and other limitations, not every object can be equipped with hardware, such as a vibrotactile motor. One alternative solution for this might be using haptic illusions, which can, for example, be created through a sound source. Existing works utilizing audio to create haptic illusions investigated the phantom sensations of a localization or a movement. While these works investigated if the feedback can be perceived at another location than it is produced, it remains unclear how to understand such haptic illusions or what mental models they create. A first step towards understanding the interpretation of sound-induced haptic feedback could be if it will be assigned to the entire vibrating surface or to a graphical representation placed on the surface.

3 Concept & Prototyping

Calm Computing: Aiming to contribute to calm computing, we explore if sound can be used to create haptic feedback and, in particular, if such haptic feedback could be assigned to a graphical object. The term calm computing was introduced by Weiser [45]. Calm technology should stay out of the focus when it is not needed but has to be there with all powers and opportunities when the user wants to interact with it. Hence, we turned a wooden board into a touch interface that provides vibrotactile feedback while using minimal technology. We merely used three components: (1) a wooden board, which is a common material and used for furniture, doors, floors, and device cases, (2) a speaker, in our case, an off-the-shelf Bluetooth box, while speakers can also be found in phones, TVs or media systems, and (3) a copper tape, which can make surfaces touch-sensitive when being part of an electrical circuit with a capacitance measuring unit. The copper tape can even be attached to the rear of a wooden board and still allow for touch detection. This retains the touch and feel of the wooden board, and the technology will stay out of sight but is able to create haptic sensations; see Figure 1. Therefore, our work contributes to the basic idea of calm computing.

Resonant Frequency: The phenomenon we rely on to bring a surface into vibration is described as resonance frequencies. Resonance frequencies are the frequencies with which an object, in our case, a wooden board, vibrates when it is stimulated, e.g., through a hammer hit or, for our planned interface, through sound. The benefit of using a hammer instead of sound during the technical evaluation to identify the resonance frequency for our interface is that the hammer excites a struck board with all possible resonance frequencies. We used a hammer to determine the most practical of these frequencies and later recreated this resonant frequency using sound. This resonant frequency, when played, stimulates the entire board so that the vibration can be felt wherever the board is touched. The resonance frequencies of a board depend on the size, thickness, and material of the board. We tested four wooden boards, all made out of chip wood of different thicknesses, 1 mm, 3 mm, 6 mm, and 10 mm, all having the same size (26 cm x 53.5 cm). The four boards were struck ten times with an impulse hammer (Dytran 5800SL) by hand in the center of the board. Each time, the impulse response of the board was recorded at a different position close to the board's edges using a piezoelectric sensor. Then, the average of the ten recorded signals was calculated to analyze the frequency-dependent mobility of the board, see Figure 2. Mobility refers to the relative velocity with which the board vibrates after being hit with the hammer [36]. This is given in decibels relative to full scale ($dBFS$), which can be a maximum of zero decibels [1].

Selection of the Board: Figure 2 shows the averaged frequency measures of the thinnest board, which was selected later for our apparatus. The thinnest board was selected as it is more likely to vibrate when excited with low-frequency signals, see Figure 2, left. High mobility is of interest to us because it will create a well-perceivable haptic sensation. With commercially available speakers as we used in this study, this approach has the drawback of producing unwanted hearable sounds. An alternative would be the use of infrasound resonant frequency. Since off-the-shelf speakers do not allow this, our goal was to reach a resonant frequency as low as possible. Therefore, we used the thinnest wooden board; as the resonance frequency increases with board thickness, more energy is needed to excite it.

Latency: We connected an Arduino that detects touch and gives acoustic feedback in the form of playing the resonant frequency at that moment. As latency of different feedback modalities informing about the same action affects user experience [19], we had to determine the exact latency of the system precisely. Therefore, we measured the round trip latency of the analog-digital and digital-analog conversion of the used computer, which was 91 ms. As this is

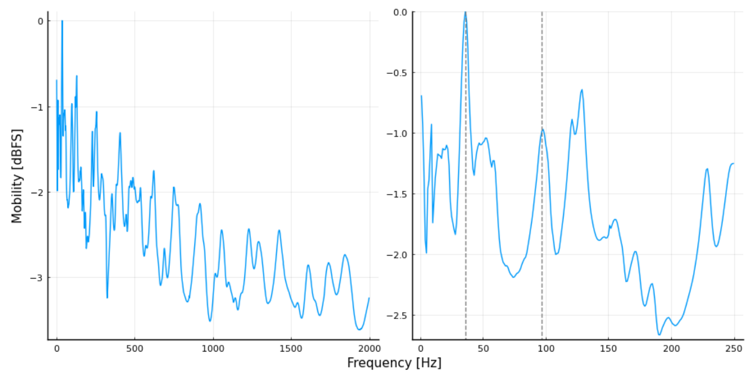

Fig. 2. Mean mobility per frequency triggered through 10 hammer strikes on the thinnest wooden board of 1 mm thickness and 26 cm x 53.5 cm size. The left diagram shows that mobility decreases with increasing frequency. An enlarged presentation of the most promising lowest frequencies on the right shows that the main resonant frequency at 35 Hz would be most suitable for our apparatus, as the board here vibrates with the highest intensity. As the highest excursion of the measured resonant frequency at 35 Hz can hardly be radiated by most of today's commercially available speakers, the next-higher resonant frequency at 96 Hz was chosen for our apparatus. Although the peak value for the resonant frequency 130 Hz was higher than the peak value for 96 Hz, we chose the latter because it was the lowest resonant frequency with a high excursion that the speaker could reproduce.

a comparable high delay, we added an external audio interface to the existing system and reached a round trip latency of 33 ms. Combined with the minor latency of the Arduino (2 ms), the overall latency was 35 ms. Even though this latency might be an issue in certain musical and rhythmic tasks, it is suitable for most multimedia applications [24, 19]. Nevertheless, this is still a critical value that can only be reached with dedicated hardware. As this can not be assumed in all real-world scenarios, we decided to investigate the possible impact of a delay, too.

Noise-cancelling Headphones: The speaker is placed underneath the wooden board to play the resonance frequency. However, while it could be placed anywhere in the room, the closeness of the speaker to the board allowed for lower sound volume. Despite this, some sound was still audible, possibly disturbing the illusion. To isolate the stimuli during the empirical evaluation, participants listened to white noise via noise-canceling headphones.

4 Empirical Evaluation

A user study was conducted to explore if vibrotactile feedback could be assigned to a passive graphical object displayed on a wooden board vibrating with a resonant frequency. Further, the goal was to understand how such an illusion would work best.

4.1 Experiment Design

It is commonly accepted that coherent and consistent multimodal feedback increases realism [48]. Moreover, the latency of vibrotactile feedback influences the haptic experience and perception of an object's attributes [19].

Independent Variables: We chose feedback modality and feedback latency as our independent variables. Our controlled experiment had a 2x3x2 within-subjects design with the independent variables MODALITIES *(*touch only (T) and touch plus audio (TA)), LATENCY (direct (35 ms latency), smallLatency (100 ms latency), and largeLatency (200 ms)), and DURATION (3 seconds (which was also the touch duration) and 0.5 seconds). The three-second touch duration was chosen in alignment with the work of Wolf et al. [50] and the 0.5 seconds touch duration was chosen related to the work of Schönauer et al. [37].

Dependent Variables: Our dependent variables were SIMULTANEITY JUDGMENT (as a test to measure if the feedback latency was perceived), FLY-EMBODIMENT (to measure to what extent the graphical image — using a fly picture as an example — would be perceived as realistic fly), FLY-EMBODIMENT INFLUENCING PARAMETERS (to identify the reasons for an increased fly-embodiment), and QUALITATIVE FEEDBACK (to possibly better understand our quantitative and qualitative results).

4.2 Measurements

To measure the SIMULTANEITY JUDGMENT, we followed the design of Kaaresoja et al. [19] and asked the following question for each condition: "*Was the received feedback simultaneously to the touch interaction?*" Participants could answer Yes or No.

For the FLY-EMBODIMENT, a standardized embodiment questionnaire [31] was taken as a reference to measure under what conditions the fly image might be more or less perceived as a real fly. This questionnaire was chosen as it contains questions related to multisensory feedback and some questions directly asked for the assignment of feedback, both important for this work. As these questions relate to different subscales within the questionnaire and the questionnaire itself is designed to compute a final score [31], all questions were kept for our study. Nevertheless, we slightly adjusted the questions to the physical context of this study. To maintain the meaningfulness of the questionnaire, we replaced the phrase *my body* with *a real fly* or *my finger*, and the phrase *virtual body* with *a graphical fly*. To stay consistent with the initial embodiment questionnaire's rating, we had to negate the first question to be consistent for later analysis. The altered questionnaire can be found in the appendix. All questions were answered using a 7-item Likert scale.

Afterward, to investigate FLY-EMBODIMENT INFLUENCING PARAMETERS, we asked semi-structured questions about reasons for creating or breaking the fly-embodiment illusion:

- What helped to create the illusion that it was a real fly?
- What broke the illusion that it was a real fly?

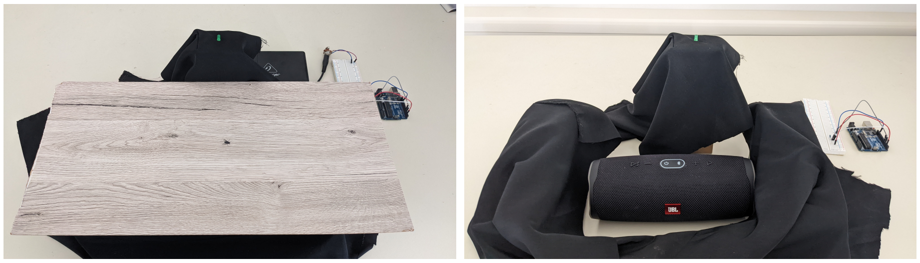

Fig. 3. This figure shows the study setup, once like the participants saw it during the study with a covered speaker (left) and once, the setup without the covered speaker (right).

4.3 Apparatus

For our apparatus, we used a Razer Blade 15 Laptop and an external Behringer UMC22 sound card. Via the audio software Waveform, we played the sounds (resonant frequency of the wooden board and sound of a fly), created latencies (between the sounds and for the start of playing the sounds), and generated the white noise for masking the sound of the resonant frequency.

Through noise-canceling headphones (Sony WH-1000XM4), we covered frequencies not masked by the white noise. Both methods, also in combination, are commonly used to mask sounds and frequencies [16, 20, 22, 29]. We used both to make sure all external sounds were masked.

A LATENCY of 35 ms was chosen as the value for the *direct* MODALITY as it is the internal latency of the hardware and the minimum latency possible with our technical setup. With a value under 50 ms, it is still perceived as synchronous for auditory feedback, and no latency should be recognized [19]. 100 ms was chosen as the value for the *smallLatency* condition because it is not perceived as synchronous regarding Kaaresoja et al. [19], but still in the cognitive range of the human processor model [8]. 200 ms was chosen as the value for *largeLatency* as we doubled the previous value of 100 ms to have a value that should be perceived as latency regarding Kaaresoja and the human processor model [19, 8].

The selected wooden board was sufficiently thin (1 mm) that even sound with lower volume provided adequate vibrationThe board was placed on four small wooden cubes, damped with felt pieces on the bottom to ensure its vibrational behavior remained unaffected. The board was placed on two cardboard boxes, hiding the speaker underneath it; see Figure 3.

On top of the board, a sticker with the appearance of a fly was placed at the point where the participants had to touch the board to receive the haptic feedback. A graphical representation of a fly was chosen as an object where people could anticipate a reaction the moment it is touched. When interacting with a real fly (e.g., capturing or covering it), we expect to feel an object's vibration and hear a fly's sound. While another graphical object that produces feedback by touching it could alternatively be used, a representation of an object that creates feedback before touching it would break that metaphor (i.e., a smartphone).

To detect when the fly is touched while at the same time having a "natural" look of the everyday life surface and no additional hardware on the participants' fingers, we used an Arduino UNO and the "CapacitiveSensor library". The copper tape as an electrical conductor was mounted on the rear of the wooden board. When adjusting the size of the conductive area, the contact is recognized when the fly is touched but not at other parts of the wooden board. This should raise the illusion that the origin of the haptic feedback is at that exact point.

The speaker (JBL Charge 4) was directly placed under the wooden board with a distance of $3cm$ and could not be seen because, in front, it was covered by black fabric. While the white noise and the sound of the fly were played via the headphones, the speaker was used to excite the board with its resonant frequency. The sound signal was not restricted to a pure sine wave to perceive a strong vibration at low volumes. Instead, a sawtooth wave was used, which also excited the plate with higher frequencies due to the upper partials. To match the partials to the plate, they are weighted with the related mobility (shown in Figure 2) according to their frequency. To ensure that all participants' time of touch is the same over each condition, we had a second LED light behind the wooden board that lighted up when the fly was touched, see Figure 3. After three seconds, the light went out, and the exploration time was over.

4.4 Participants, Task, and Procedure

We recruited 24 participants (9 female, 15 male) with an age range from 23 to 53 years and an average of 31,79 years (SD = 8,26). The experiment was conducted as a lab study. First, the participants were welcomed and asked to agree to a consent form. They were informed that participation in the study was voluntary and that taking a break was possible. After filling in a demographic questionnaire, participants started with the study. Our 12 conditions were counter-balanced using a Latin square design [4]. In each condition, the participants wore noise-canceling headphones and touched the graphical fly with their right index finger, which let them perceive feedback according to the experimental conditions. This procedure could be repeated as often as the participants wanted. No time limitation was given. The participants were also allowed to explore other areas of the wooden board where no feedback was provided. After each condition, participants filled in the questionnaire on a dedicated computer and answered the semi-structured questions. Finally, we showed all participants the setup, how the haptic feedback was created, and where it was present. Then we recorded the general statements about the interface.

5 Results

We first analyzed our quantitative data to learn if LATENCY, DURATION, or SOUND affected the FLY-EMBODIMENT (assignment of the haptic feedback). Further, we analyzed if there were any interaction effects between our independent variables. We then evaluated the qualitative data to gain a better understanding of the quantitative results.

5.1 Quantitative Results

In our quantitative analyses, we used the aligned rank transformation (ART) to perform an ANOVA with our non-parametric results [49, 10]. The ART also allows performing post-hoc analysis with pairwise comparisons.

Simultaneity To explore if the latency between touching the graphical object and the perceived haptic feedback is relevant for an assignment of feedback, we began the questionnaire with a simultaneity judgment, see Section 4.2.

The results showed that in 245 out of 288 cases (85 percent), the haptic feedback was perceived simultaneously to the point of touching the fly, independent of the present latency. Looking at the different latencies individually, most often, feedback was perceived simultaneously for a latency of 100 ms (87 out of 96 cases) and least often for 200 ms (75 out of 96 cases). For 35 ms, it was perceived as simultaneous in 83 out of 96 cases.

Assignment of Haptic Feedback In line with the results of the simultaneity judgment, we could not find any statistically significant results for LATENCY, performing an ANOVA on the fly-embodiment questionnaire scores [31]. On the opposite, the ANOVA revealed statistically significant differences for the two remaining variables, DURATION ($F_{(1,\ 253)} = 63.2$, $p < .001$) and SOUND ($F_{(1,\ 253)} = 27.86$, $p < .001$).

Post-hoc pairwise comparison revealed a better assignment of the feedback to the graphical object if the perceived feedback is as long as the touch, compared

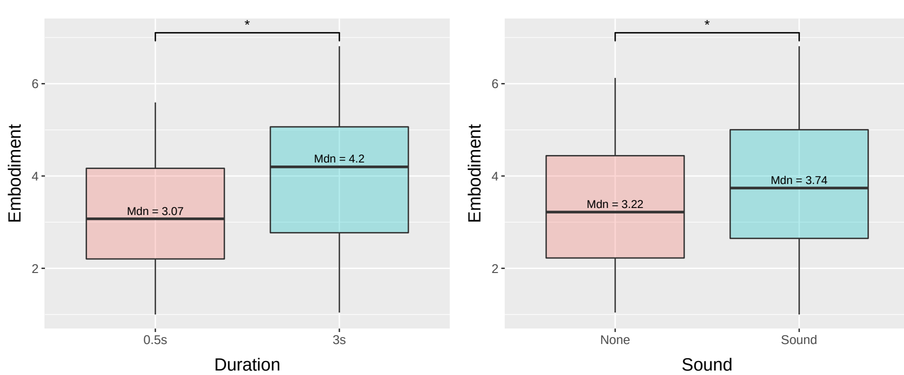

Fig. 4. Box plots showing significant differences for the assignment of the haptic feedback to the graphical object based on the score of the fly-embodiment questionnaire. **Left**: Box plot of the fly-embodiment score for DURATION. **Right**: Box plot of the fly-embodiment score for SOUND.

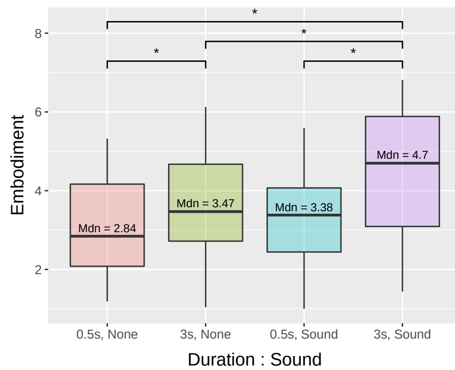

Fig. 5. The box plot shows the assignment of the feedback to the graphical object based on the fly-embodiment questionnaire score. The figure presents significant differences in the interaction effects of DURATION and SOUND.

to a short impulse ($p < .001$) and a better fly-embodiment for additional sound (related to the touched object) compared to no sound ($p < .001$), see Figure 4.

Further, the results showed an interaction effect between DURATION × SOUND ($F_{(1,\ 253)} = 9.08$, $p = .003$). Post-hoc pairwise comparison revealed a statistically significant better assignment of the feedback for a long duration with additional sound (3s, sound) compared to an impulse without additional sound (0.5s, none) ($p < .001$), compared to an impulse with additional sound (0.5s, sound) ($p < .001$), and compared to a long duration without additional sound (3s, none) ($p < .001$), see Figure 5. Also, a significantly better assignment for a long duration without additional sound (3s, none) compared to an impulse without additional sound (0.5s, none) ($p = .001$) could be measured, see Figure 5.

5.2 Qualitative Results

The qualitative data were coded using Grounded Theory [40]. Axial and selective coding was applied by building categories according to the questions that asked for positive or negative perceived aspects of a system [40]. Two researchers did the coding independently of each other and discussed their results afterward to develop common codes. The goal was to gain possible explanations for the quantitative findings through qualitative analysis. Also, we observed the participants' reactions after we revealed how the haptic feedback was created and where it took place. The qualitative results are separated into Reactions to the haptic feedback as well as into factors that supported an assignment and factors which prevented an assignment, which was pre-structured by the semi-structured interview questions, see Section 4.2.

Reactions to the Haptic Feedback After the last condition for every participant, we revealed the setup and functionality of the prototype to the participants and recorded their reactions. We aimed to get insights if the illusion worked as intended and if the haptic feedback matched the functionality of the setup. Most participants were surprised and mentioned that they had not expected such a setup (18 out of 24 participants). Many of them stated that they did not expect the whole wooden board to vibrate (13 out of 18 participants): ("*I would have never believed that the whole board is vibrating. It did not feel like a "real" fly, but also definitely felt like the feedback just directly came from the fly*", P.16) In addition, some participants mentioned that they were surprised that the feedback was created by a speaker (5 out of 18 participants): ("*I never thought that feedback is produced by a speaker. I believed there was an actuator connected at the other side of the board producing the feedback, as the feedback was very strong*", P.24)

Supporting an Assignment As the participants were not forced to answer the questions of the semi-structured interview, we have a total number of 216 answers for reasons that helped to create an illusion and a total of 122 answers as reasons for a break of the illusion. Our results showed three factors supporting the assignment of the haptic feedback to the graphical fly. First, the graphical representation of the fly was named as increasing factor 23 out of 216 answers. All participants mentioned that the realistic look of the sticker helped to think they were touching a real fly, as exemplary in the following statements: ("*The image creates a perception that is in line with known experience and gives a connection to a real fly*", P.10) and ("*The realistic image of the fly*", P.15)

Further, the sound of the fly was named in 80 out of 216 answers as a supporting factor to create an illusion of touching a real fly. The participants mentioned it was helpful that there was a sound of a fly at all, sounding like a flying fly (66 out of 80 times). Also, some participants noticed that the sound has many variations and seems to come from the fly spatially (14 out of 80 times): ("*The sound helps to perceive it like a representation of a fly*", P.2), ("*Variations in the sound of the fly*", P.23), ("*The fly was moving as long as it touched the fly. Thus I noticed the sound was coming from the image of the fly a little more*", P.9), and ("*The sounds created the illusion as if a fly had flown away from the place I touched and, after a short time, sat down again somewhere*", P.10),

At last, participants stated the felt vibration at their fingertips reminded them of touching a fly and helped to create good illusional feedback in 113 out of 216 answers. This stemmed from the fact that there just was a vibration (87 out of 113 times), that the vibrations, just like the sound, were felt as they had variations (3 out of 113 times), and the feedback was common to known experiences (19 out of 113 times). Further, the vibration slightly created a feeling of touching a three-dimensional object (4 out of 113 times): ("*The vibration helped me to create the illusion*", P.3), ("*The vibrations felt similar to that when touching a fly. The frequency of vibrations was well chosen*", P.9), and ("*The vibration on the finger felt 3D. The light buzzing made it realistic*", P.14),

Preventing an Assignment In line with the factors for creating the illusion of touching a real fly, we also found three factors preventing the participants from assigning the haptic feedback to the graphical object. One of the three factors mentioned by the participants here (21 out of 122 answers) is sound, similar to previously stated points. Besides participants noticing completely missing sound as the breaking point of the illusion (12 out of 21 cases), they also mentioned the short sound to be too monotone (9 out of 21 cases): ("*There was no sound*", P.7) and ("*The sound was too short: It was too monotone*", P.11),

In addition, the participants were disappointed by the felt vibrations (mentioned before as a supporting factor) when it was just a short impulse (16 out of 40 times) and complained about the unnatural feeling of the vibrations when the feedback just had a short DURATION (24 out of 40 times): ("*The intensity of the vibration was very weak*", P.4) and ("*The abrupt stop of the motion. A real fly would continue to move since I touched it slightly and not too hard*", P.3).

As a final reason for breaking the illusion, the non-existing shape of the graphical object was given in half of the answers (61 out of 122 answers). It was answered that the haptic (three-dimensional shape) of the object is missing (50 out of 61 times) and the feeling of touching a board is higher than touching a fly (11 out of 61 times): ("*The feeling of touching the board was higher than touching the fly*", P.1) and ("*The fly had no haptic or real body*", P.17).

5.3 Summary

In summary, our qualitative results reflect and substantiate the quantitative findings. Our results show that haptic feedback created through an audio source would be assigned to a graphical object when touching the latter. When doing so, participants perceived the graphical object as the source of the felt feedback and not the surface that was actually vibrating. We found sound and perceived haptic feedback as important factors for having an assignment of the feedback to the graphical object, as well as preventing such an assignment. A short impulse of haptic feedback is perceived differently from a long duration in terms of intensity, naturality, and expectations compared to real-life experience. Further, not only the duration of the sound is important, but also if there is sound at all. The assignment of feedback to a graphical object requires the appearance of suitable sound, or the assignment will not be made. In addition, the qualitative results indicate a good visual representation to be important. The illusion of touching a three-dimensional shape could increase the perceived haptic feedback and the feeling of touching a real fly, as it further matches our expectations.

6 Discussion

We investigated which factors are important to assign haptic feedback created on an everyday life object to a graphical object and if consequently the graphical object is perceived as the source of the haptic feedback. Further, we looked at the limitations of our design and the current technology and how these could be solved by future research or improved hardware.

6.1 Assignment of Haptic Feedback

Overall, our findings indicate that the graphical object (in this case, the graphical representation of the fly) was perceived as the source of the haptic feedback. This was further supported by the participants' reactions after revealing the setup and telling them about the prototype's functionality. This is in line with the answers to question 13 of the questionnaire ("*It seemed as if I felt the motion of a real fly in the location where I touched the graphical fly*"), where the overall median is 5.0. The conditions, with additional sound and a feedback duration as long as the touch, have a median of 6.0. This supports our concept that speakers can provide haptic feedback for graphical objects on surfaces that vibrate in resonance frequency through a sound played by the speakers. In the following, we discuss in more detail factors that are important to create such an assignment illusion, the mental modal that this illusion relies on, and limitations of the current prototype that should be considered and addressed for future work.

Mental model As mentioned before, several factors (sound, duration of the haptic and auditive feedback, look & feel of the embodied object) influence the assignment of the haptic feedback to the graphical object. All these aspects have in common that users can build the mental modal of a real fly being touched. Through the multimodal feedback – the seen graphical fly, which they also feel through resonant frequency, and hear through sound feedback when touching the graphical object – users' expectations when touching a real fly are fulfilled. Hence, to a certain extent, they believe the illusion of touching a fly. Multisensory perception and the human ability to integrate information from different senses into one unified illusionary concept is possible if all senses coherently and consistently fulfill humans' expectations or the information of one sense is overwritten with expected information that fits the information of another sense [11].

Important factors Several questions of the fly-embodiment questionnaire target the kind of assignment by asking for the source of the feedback, see Section 4.2. Therefore, fly-embodiment-increasing factors have been identified that influence the assignment level of the perceived haptic feedback.

For assigning the haptic feedback to the graphical object, we identified different factors to be important. The duration of the vibration feedback has to be perceived over the entire touch duration. The sound a user perceives when touching the graphics must be played when and as long the graphical object is touched. The look of the graphical object determines the mental model built by the user and the expectation of any other feedback when touching the image. If the image had a corresponding elevated shape, the fly-embodiment could become stronger. The factors of sound and duration of the haptic feedback were also relevant for the level of perceived haptic feedback, as shown in quantitative results. The importance of a realistic look and felt shape was identified through the answers of the semi-structured interview, see Section 5.2.

While previous work used resonant frequency to create haptic feedback through speakers directly mounted on a specific object [46] or for haptic feedback provided on different body parts [47], we used remote speakers to serve as haptic feedback devices. In addition, we investigated if images could serve as a mental model to create illusionary objects to which the feedback can be assigned. Previous work used capacitive touch and investigated haptic sensations when touching a flat surface [2]. While the work of Bau et al. used a touch screen and investigated the perception of textures, this approach is about the assignment of haptic feedback when touching a graphical object placed on an everyday life surface, like a table. Thus, analog materials could be used as an interface and provide realistic touch experiences useful in ubiquitous computing.

In summary, the discussed factors were identified to influence the level of fly-embodiment, which represents the assignment of the feedback coming from the graphical image (and neither from the speakers nor from the entire vibrating board). Our results indicate that a higher level of the fly-embodiment will more likely result in an assignment of the haptic feedback to the graphical object and vice versa.

Limitations & future work One limitation of our setup is that there always will be a specific latency between the point of touch and the creation of the haptic feedback. In our study, we measured the round trip latency of the AD and DA conversion of the used computer, audio interface, and microcontroller. We reached a latency of 35 ms, which should be recognized as no latency regarding the human processor model and other related work [8, 19]. With other hardware and additional devices, the latency might be higher. Within our study, we used latencies up to 200 ms, which still were perceived as synchronous. Therefore, the effect can be recreated at home with simple hardware and devices which are not computationally powerful computers.

Another limiting factor might be the creation and use of sound frequencies to let the surface vibrate. While using a single audio source to create haptic feedback on different real-life objects is an advantage, the frequency needed to achieve that also brings disadvantages. A disadvantage is that the frequency to let real-life objects vibrate mostly is in a range that the users will hear, and the sound would be annoying and might disturb the illusion. This disadvantage probably will not be an issue in noisy environments, but when silence is appreciated. While we could determine the heard frequency by using noise-canceling headphones and white noise, as we did in the study setup, this might neither be practical nor comfortable in later applications. Alternatively, future research could further look into how to utilize infrasound frequencies for this use case.

The sound used as resonant frequency could be modified by filtering and deleting certain frequencies that are not needed [15]. Depending on the targeted surface, the resonant frequency might be very high. Thus, it should be investigated in the future, until which point this solution will work.

Future research might investigate if the assignment of the feedback will also work for multiple objects placed on the same physical object. This would be of interest because the feedback induced through resonance frequency is coupled to the surface and, therefore, the same for all objects that are placed on it, even though these could differ in size and look. For this case, a ubiquitous solution for a practical implementation has to be found. It would not be a ubiquitous approach to have multiple sensors detecting capacitive touch beneath the surface.

For this work, a speaker activated a single surface. In the scenario of using a single speaker to stimulate an arbitrary amount of surfaces in an environment, it has to be researched how feasible and scalable such an approach is. This includes evaluating which materials can be addressed, what frequencies can be supported, or what distances can be reached.

7 Conclusion

This work aimed at exploring if and under what conditions touch feedback can be assigned to a graphical object illustrated on an everyday surface using resonant frequency. A user study showed that haptic feedback induced through resonant frequency is assigned to a passive graphical object if (1) the duration of the feedback lasts as long as the touch and (2) additional auditive feedback is provided. On the contrary, the feedback assignment (fly-embodiment) fails if (1) the duration of the feedback is shorter than the touch on the graphical object and (2) no additional sound is played when the graphical object is touched.

Qualitative results suggested additional factors that might influence an assignment of feedback to the graphical object: (1) The realism of the graphical representation of the object seems to support the assignment. Therefore, a realistic design of the graphical object is recommended, and (2) the fly-embodiment of the graphical object could be enriched when touching an elevated shape.

It can be stated that it is important to fulfill users' expectations about the touched object in order to cause an assignment of feedback towards that object. Overall, we showed that vibrotactile feedback for images applied on surfaces can be provided due to resonant frequencies of the corresponding surfaces. This was achieved for surfaces of rather thin thickness (1 mm) using only a minimum of hardware. Thus, we not only contribute to the research domain of haptics and multimodal feedback but also to ubiquitous computing as our approach can be considered to be interwoven into everyday material and, therefore, is what Weiser called "calm".

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8 Appendix

The questions from the original embodiment questionnaire [31] were slightly adjusted for our study as follows:

1. I did not believe it was a real fly.
2. It felt as if the graphical fly was slightly becoming real.
3. It felt as if the movements of the graphical fly were influencing my tactile perception.
4. It felt as if the graphical fly was turning into a real fly.
5. At some point, it felt as if a real fly was starting to move simultaneously with the graphical fly.
6. It felt as if there was one more fly in the room from when I came in.
7. It felt as if the fly had changed.
8. I felt a motion at my fingertip when I touched the fly.
9. It felt as if the fly's body could be affected by my touch.
10. It felt as if the graphical fly was a real fly.
11. At some point, it felt that the graphical fly resembled a real fly in terms of shape, color, and motion.
12. I felt that a real fly was located where I saw the graphical fly.
13. It seemed as if the felt motion came from the fly.
14. It seemed as if I felt the motion of a real fly in the location where I touched the graphical fly.
15. It seemed as if the motions I felt were caused by the movement of the graphical fly.
16. It seemed as if my finger was touching a real fly.