Vibrollusion: Creating a Vibrotactile Illusion Induced by Audiovisual Touch Feedback

MARCO KURZWEG, Berlin University of Applied Sciences and Technology, Germany
MAXIMILIAN LETTER, Berlin University of Applied Sciences and Technology, Germany
KATRIN WOLF, Berlin University of Applied Sciences and Technology, Germany

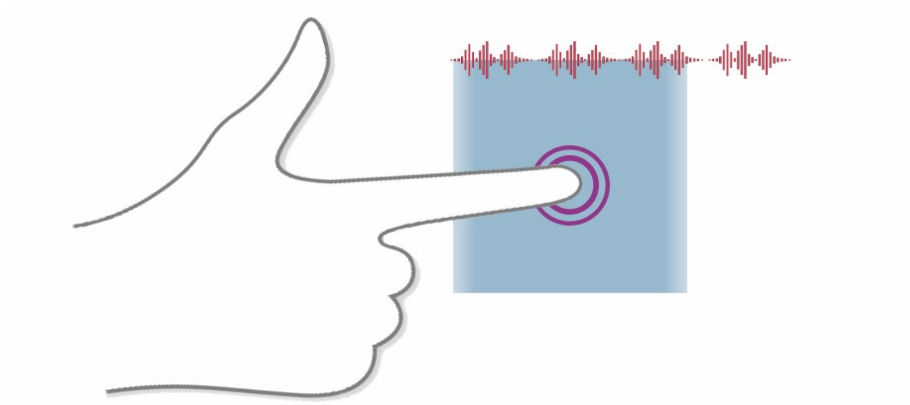

Fig. 1. Vibrollusion is a concept that uses a vibrotactile illusion instead of haptic actuators to provide touch feedback when interacting with surfaces. While the illusion is neither perceived when a virtual object is only visually vibrating (drawn as a motion blurred object in blue here) nor when a vibration sound (visualized as a soundwave in red here) is played, a vibration is felt when both modalities are presented at the same time in a specific range of intensities. That tactile illusion is visualized as purple circles here.

Vibrations are the dominant way to create haptic feedback for interactive systems and are most often induced by vibrotactile actuators. However, virtual content created for augmented reality usually does not support that modality, instead relying mainly on visual and auditive output. Aiming to provide haptic feedback for augmented reality in cases where real vibrations cannot be used, we explore how vibrations can be felt using vision and audio only. In a user study, a virtual 10 x 10 cm white square-shaped cuboid was influenced by animation and/or sound to induce a haptic illusion when being touched. We were able to identify a specific range where the perception of vibration was significantly stronger and more realistic compared to all other values. This was the case if the virtual object's edges were blurred up to a range of 0.4 cm or 0.6 cm, correspondingly accompanied by sounds, where the spectrum was cut off at a frequency of 256 Hz (for 0.4 cm) or 966 Hz (for 0.6 cm). With that, we aim to enrich augmented reality systems.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; **Empirical studies in HCI**; **Interaction design**.

Additional Key Words and Phrases: visual, illusion, haptic feedback, vibration, vibrotactile

Manuscript submitted to ACM

ACM Reference Format:
Marco Kurzweg, Maximilian Letter, and Katrin Wolf. 2023. Vibrollusion: Creating a Vibrotactile Illusion Induced by Audiovisual Touch Feedback. In *International Conference on Mobile and Ubiquitous Multimedia (MUM ’23), December 3–6, 2023, Vienna, Austria.* ACM, New York, NY, USA, 21 pages. https://doi.org/10.1145/3626705.3627790

1 INTRODUCTION

Vibrations generated by different hardware components (i.e., vibrotactile actuators), which are embedded into smartphones and game controllers, are commonly used to induce various kinds of haptic feedback. This ensures high usability, e.g., in mobile computing, virtual reality, and gaming using controllers. However, integrating haptic feedback is challenging in ubiquitous computing, where walls and surfaces can become interactive.

Embedding actors (and possibly also sensors) into walls and surfaces while aiming at “a physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements” serves as interface [57], is technically difficult and would change the way our environments are built. While examples of smart furniture, as presented in InFORM by Follmer et al. [16], can provide promising interaction and feedback possibilities, they are often very costly, can create much noise, and are not as recommended by Weiser as “calm” interface concept [57, 58]. Thus, it is not always feasible to embed hardware into every object and surface.

Even if integrated into massive objects like walls, floors, or wardrobes, vibrotactile actuators would hardly let such objects vibrate. In addition, because of the lifetime of the hardware, the effort of maintaining these would be immense, as components (actuators, batteries) have to be replaced from time to time. In IllumiRoom from Brett R. and al. [24], the furniture is instead only visually vibrating using projector-based AR, providing quite realistic vibrations using audiovisual stimuli. However, users cannot feel the furniture vibrations as they are placed out of hands’ reachability.

The alternative of providing vibrotactile feedback through object vibrations is a remote sensation, e.g., using wearables, such as haptic gloves that simulate touching a vibrating object through vibration motors placed directly underneath the fingertips [15, 34], or EMS that can move limbs which can create the sensation of resistance and touching surfaces [35]. However, these approaches have the drawback that wearables would encumber hands [62].

Therefore, an alternative approach has to be found to support natural interaction with smart environments, e.g., where haptic feedback could be perceived on large, solid, smart objects. For example, touch interaction with a button or keyboard projected on a table or wall in front of us through AR glasses would benefit from haptic feedback. Aiming to avoid as much hardware as possible, we propose using haptic illusions instead of haptic actuators.

Haptic illusions are widely investigated to induce several haptic sensations. Actuator-generated vibrations were investigated to indicate several object properties or haptic sensations (weight [50], stiffness [23], texture[9], or skin sensations via funneling [28], Stimulus-Onset-Asynchrony (SOA) [21], or saltation [18]). In addition, a broad spectrum of haptic sensations can be created by stimulating several senses. For example, the sense of sight can be used to induce several object properties through haptic illusions (i.e., weight [41, 44], size [61], texture [13, 33], or stiffness [2, 59]), as well as the sense of sound (i.e., [14, 31, 55]). These works demonstrate the possibility of haptic illusions as a robust non-tech alternative for creating haptic sensations. Nevertheless, research is still lacking knowledge if senses used for creating illusionary haptic sensations can also be used to induce the feeling of vibrotactile touch feedback.

To reduce this research gap, this paper explores whether vibrations can be haptically perceived by only stimulating the visual and/or auditory sense (RQ1). Further, if such a haptic sensation is possible, we aim to identify the limits of this haptic illusion, which means exploring the beginning and breaking point of the illusion (RQ2).

In a user study, participants had to interact with a virtual 10 x 10 cm white virtual square and to judge if they perceived the haptic sensation of feeling a vibration. We systematically changed the cutoff frequencies of auditory feedback and the intensity of visually perceived object vibration. Our results clearly show that a single modality in our setup could not create a vibrotactile illusion, but specific multimodal combinations (a cutoff frequency of 265 Hz combined with a 0.4 cm amplitude edge blurring effect and a cutoff frequency of 966 Hz combined with a 0.6 cm amplitude edge blurring effect) indeed made people feel a tactile illusion, while no haptic technology was used.

2 RELATED WORK

This work explores if a tactile sensation of feeling a vibration can be created using an illusion that utilizes visual and aural stimuli. Therefore, we reviewed how haptic sensations can be induced by stimulating the sense of sight, Section 2.1, the sense of hearing, Section 2.2, and multisensory feedback, Section 2.3.

2.1 Haptic Sensations induced through Visual Stimuli

Using vision to provide and simulate haptic feedback without requiring haptic devices is also known as pseudo-haptic feedback [32, 39]. Hachisu et al. combined pseudo-haptic feedback with visual and tactile vibrations to enrich the overall haptic sensation [20]. This is partly in line with our work, as the visual presentation of vibrations is used to create haptic sensations. Conversely, it was not researched if the tactile sensation of feeling a vibration can be induced. Lécuyer studied how pseudo-haptics are understood and investigated how different object properties (i.e., stiffness, weight, texture, and shape) can be created with pseudo-haptic feedback [32]. Speicher et al. investigated pseudo-haptics to provide feedback for hands-free mid-air interactions on VR user interfaces [46]. They tested a planar UI similar to common 2D desktop UIs and a pseudo-haptic UI based on physical metaphors. The study results show that the pseudo-haptic approach performed better regarding workload, user experience, motion sickness, and immersion.

2.1.1 Shape. One object property that can be created through visual stimuli is the shape of an object. Former research looked into different methods like 3D deformation [3], or manipulation of the C/D ratio (Control/Display ratio) [6]. Ban et al. investigated how the perceived shape of an object can be influenced through the visual sense [3]. In their study, participants touched a cylinder placed behind a screen as a physical stimulus. They saw their hands and a visual representation of that cylinder on that screen. The visual appearance of the cylinder could be changed on the screen, and based on the visual appearance, the perception of the felt shape differed. Bickmann et al. created the illusion of grasping objects of a cylindrical shape by influencing the C/D ratio in a VR application [6]. This was achieved by using a custom haptic illusion glove where a power circuit is closed when the finger of a hand touches the balm of the same hand, as done in a grasping gesture. If the power circuit is closed, the user's hand is accordingly grasping in VR to the point where the hand fully encloses the cylinder. This approach created the illusion of grasping a cylindrical object, further assessing the device's usability.

2.1.2 Weight. Another haptic sensation that can be created using vision is weight perception. This illusion can be created by using the size-weight illusion [22] or by taking advantage of influencing the C/D ratio [42]. Hashiguchi et al. investigated how the perceived weight of a rod can be influenced by using the visual sense and taking advantage of the size-weight illusion [22]. In AR, users saw a real rod they were holding in one hand in front of a black background. The rod could be shortened and extended visually by using augmented or diminished reality. They found that the shorter the rod looked, the heavier it was perceived by the participants, and vice versa. Samad et al. also used the visual sense and researched how manipulation of the C/D ratio can influence the perceived weight of an object [42]. Users were lifting a small physical cube while lifting a virtual representation of that cube in VR. By influencing the height of the virtual cube, the users perceived the cube as heavier the lower the virtual cube was lifted compared to the real one.

2.1.3 *Size.*

Influencing the C/D ratio was also used to influence the perceived size of an object [4]. Bergstrom et al. affected the visually perceived size of an object by resizing the grasping in a VR application [4]. By manipulating the displayed distance between thumb and index finger, the users perceived a grabbed cube in different sizes, which was always of the same physical size outside of VR.

2.1.4 *Texture.*

The visual sense was also used to create haptic feedback of perceived textures through different methods (i.e., superimposing texture [63], interactor displacement [36], and using C/D ratio [54]). Yokoyama et al. investigated how the visual sense can be used to tactile perceive a very small ridge [63]. Therefore, they used a real-life object with a small ridge under the perception threshold that participants could not feel and made it perceptible by adding a visual cue to the ridge as a painted line. Van Mensvoort et al. displaced the mouse cursor on a desktop computer screen to investigate if this will influence perceived force feedback and create a perception of different textures [36]. By increasing or decreasing the speed of the mouse cursor movement on specific areas of the screen, participants had the feeling of hovering over bumps or holes with the mouse. Ujitoko et al. manipulated the C/D ratio on a tablet to create a feeling of perceiving specific textures [54]. In their study, participants should use their index and middle fingers to "walk" on the screen, on which different images (i.e., a snowy ground) were shown. Depending on the image, the scroll speed of the tablet changed while the finger walk speed was constantly the same. They found that this influence successfully created the feeling of walking on different grounds.

2.1.5 *Stiffness.*

A last object property created through pseudo-haptics is the perceived stiffness. Kokubun et al. researched the creation of stiffness through visual stimuli on a custom mobile device [29]. Participants could push on the back side of the device, and depending on how hard they pushed, they saw a texture deformation on the front screen. Using this illusion, the perceived stiffness of the device was influenced, as it was a rigid object but was perceived as soft.

2.2 Haptic Sensations induced through Auditory Stimuli

Illusionary perceived haptic feedback was not only created by visual stimuli but also by using audio as a stimulus.

2.2.1 *Stiffness.*

Turchet et al. investigated how aural stimuli can be used not only to perceive a particular shape but also to perceive a specific stiffness of the ground a person is walking on [52]. They used different material sounds (snow, gravel, wood) of undergrounds a person could walk on. Participants wore sandals with integrated pressure sensors. A footstep sound of one material was played by detecting when a step was made. The results showed that the walking pace of the participants was affected by the sound they perceived when doing their steps.

2.2.2 *Texture.*

Not only the haptic sensation of stiffness can be created through material-related sounds, but also the perceived texture of an object [9]. Cho et al. researched how haptic feedback for writing on a tablet can be increased by recreating the feeling of writing on a physical piece of paper [9]. They modified a pen with an accelerometer, a vibrotactile actuator, and a small speaker. The accelerometer detected the writing and sent the data to a computer. With this information, the vibrotactile actuator was activated with a frequency similar to moving a pencil on a piece of paper to simulate occurring vibrations. At the same time, the speaker was activated and played a sound equal to moving a pencil in the same way on a piece of paper. They found that combining both (tactile feedback and sound) created the sensation of writing on a real piece of paper while writing on a tablet screen.

2.3 Multisensory Feedback

The previous examples have only stimulated a single sense to generate tactile feedback. Nevertheless, multisensory integration can be employed by integrating multiple senses to create tactile feedback [11, 12].

2.3.1 Texture. Multisensory feedback was used to create different haptic sensations, like texture perception. Turchet et al. modified different properties of a camera in a virtual scene displayed on a desktop monitor to investigate if these modifications can influence the perception of the ground a user is walking on [51]. The visual sense made participants think they were walking over bumps, through holes, or on flat ground by changing the camera's height, orientation, and/or velocity. They also used aural stimuli (standalone or in combination with visual stimuli) to investigate if haptic feedback can be created through auditory input. Therefore, the footstep sounds were played at different temporal intervals (shorter intervals when going down and longer intervals when going up). They found visual and auditory input to be possible factors in creating haptic feedback for perceiving the shape of the ground a user is walking on.

2.3.2 Skin Sensation. Multisensory feedback was also used to create skin sensations. Won and Altinsoy investigated how auditory feedback can affect the intensity perception of tactile stimuli [60]. For their study, they mounted a touchscreen on top of a shaker. When participants pressed a virtual button on the touchscreen, the shaker vibrated with different frequencies and amplitudes. In addition to this tactile stimulus, the participants heard different frequencies as an auditory stimulus. A user study showed that auditory feedback is an important factor in tactile intensity perception. However, the different frequencies of the auditory feedback did not show any significant differences.

2.3.3 Stiffness. Another property created through pseudo-haptics is the perceived stiffness of an object [25, 59]. Wolf and Bäder also used texture deformation to investigate the perceived stiffness of different materials [59]. Therefore, different material images were projected on a rigid surface. When the participants touched the surface, a visual texture deformation of different levels was made, so the material seemed to be deformed. They showed that visual stimuli could influence the perception of object properties regarding stiffness. Besides, they showed that the perception could be reached using electro-tactile stimuli. Further, combining both stimuli did not significantly increase the results compared to a single stimulus. Kang et al. examined the perceived stiffness of a virtual object placed on the palm of users' hands and the perceived roughness of a virtual object in mid-air [25]. For stiffness, they used a virtual cube that was visually vibrating in combination with the sound of a vibrating smartphone. They found the perceived stiffness of a virtual object for passive touch to be significant for auditory cues but not for visual cues or their interaction. For the perceived roughness of a virtual object, they found the auditory and visual cues as significant factors but not the interaction of both.

2.4 Summary

It can be concluded that different haptic sensations and several object properties could be created or influenced by stimulating the visual or aural sense or the combination of the two. The works mentioned in this section show how versatile visual and auditory stimuli can generate various feedback modalities. The most related approaches to this work are the research of Kang et al. [25] and Hachisu et al. [20], as they used a similar setup as well as the same stimuli conditions of visual and auditory vibrations. On the opposite, they investigated how these stimuli influenced the perceived stiffness of a virtual object [20, 25], but not if the haptic sensations feel like tactile perceived vibrations. Therefore, it remains unclear if also the haptic sensation of perceiving vibrations as tactile feedback can be created by using the visual and/or aural sense as input.

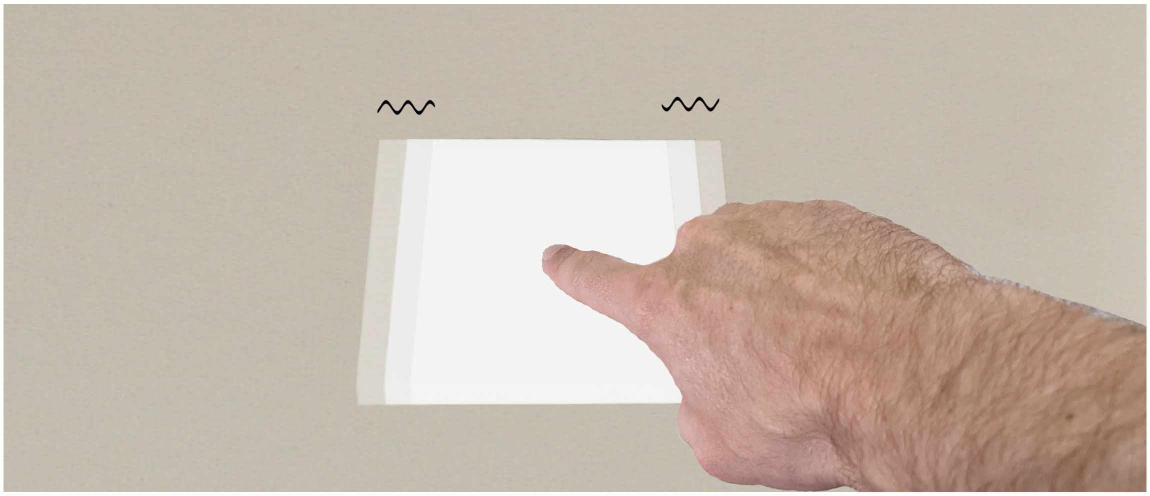

Fig. 2. Visualization of the participants' view when wearing the HoloLens 2. In the center, the white virtual object is displayed. When touched, it vibrates using auditory, visual, or audiovisual feedback (highlighted with black waves to show movement).

3 IMPLEMENTATION

We aimed to explore if the sensation of tactile perceiving a vibration can be created through stimuli by the visual sense, aural sense, or a combination of both. To create such a haptic illusion, our concept is based on the principles of multisensory illusion: If information about the environment is received from different sensory channels like vision, touch, or auditive, there might be a discrepancy between what we expect and what feedback we receive through the different channels [11]. The brain then trusts the input which is nearest to our expectations.

Baseline. Following that idea, creating the tactile sensation of feeling vibrations might be possible with realistic visual and auditory stimuli. Therefore, visual and auditory stimuli were chosen, as the visual sense is the most dominating sense of all [45], and auditory feedback as vibrations usually have a specific sound connected to them, known from our everyday life (i.e., vibrating smartphone). As this work aims to explore the creation and perception of vibrotactile feedback in situations where real vibrotactile feedback cannot be present, we implemented a baseline for all different stimuli, where no feedback could be perceived and integrated that as our control condition.

Physical Laws. To choose the different values with equally perceived changes for the visual and auditory stimuli, we used the Weber-Fechner law and Steven's power law [37, 47]. These laws investigated how much a stimulus must be increased to perceive the resulting feedback more strongly. Regarding these two laws, the values for the visual stimuli were increased linearly. This is because a doubling of the distance is also visually perceived as a doubling of the distance [47]. To achieve the same for the auditory stimuli, the values were increased logarithmically [37].

Visual Stimulus. For visually presenting a virtual object's vibration, we blurred the edges of the virtual object between specific widths; see Figure 2. This visualization technique was selected based on its superiority in representing vibrations visually compared to other methodologies documented in prior work [30]. In each frame, the strength of the blur effect was varied by randomly setting the width of the blurred edges to a random value up to the maximum value of one of the six different strengths we are examining. This effect was used solely on the sides of the virtual object and was

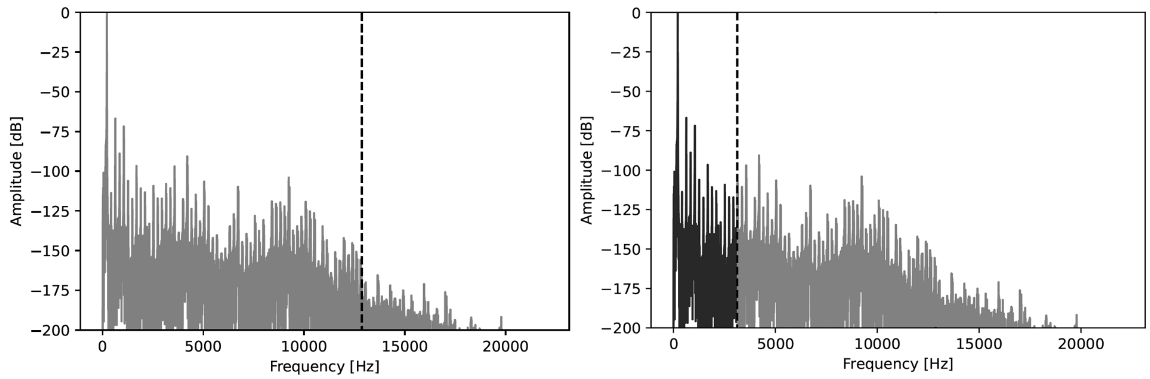

Fig. 3. *Left:* To determine the maximum cutoff frequency of our vibration sound, we calculated at which point the frequency is in an area where changes are not recognizable anymore. This point was reached at -165 dB and a frequency of 12866 Hz. The vertical dashed line represents the cutoff frequency. *Right:* A presentation of the cutoff frequency. It can be seen that the sound is the same over each condition. Depending on the cutoff frequency, all tones in the spectrum of the sound above the cutoff are not present (grey), just the ones below (black). This example is for the cutoff frequency of 3525 Hz.

seen identically on both sides. The values to present the different strengths of the vibrations started at 0 cm and were increased linearly in 0.2 cm steps, following Steven's power law [47]. The maximum value was 1 cm. While a value of 1 cm initially seems very large in terms of representing a vibration, there are different reasons why this value was chosen. One reason is that there is no experience about which range is suitable for the visual representation of vibration, as visual feedback is not known from vibrations. Choosing a too small range, essential values and thus findings could be lost. Another reason is that small values would not be perceived in the display of vibrations. Therefore, we have chosen the model of non-photorealistic rendering [17]. This model proposes a cartoon-inspired model of vibration, which is not realistic but seems to enhance the interaction experience. We applied this approach to ensure the visibility of the vibration. This was also done in other works [20]. For the same reason, we have chosen 0.2 cm as the step size for the visual strength values. This value was found to be small but still noticeable in a pre-study conducted with a team of 6 researchers. The visual vibration effect was achieved using a shader that erratically blurs the edges of a virtual object. It performed better than traditional sine wave movement for displaying virtual vibrations on a HoloLens 2 headset [30].

The frequency of the visual vibrations was limited to 40 Hz. This was due to the limitations of the hardware, which is discussed in Section 6.3.

Auditory Stimulus. The sound used for our prototype was a familiar vibrational sound of a smartphone. Unlike other studies where the sound was altered permanently to correspond with an object's interaction and resulting haptic feedback, we consistently played the same sound (but with distinct cutoff frequencies) as long as the touch lasted. To set the different values for our conditions, we used a Low-Pass filter to filter out/cutoff higher frequencies. This means that the filter modified only the spectrum of the sound. The sound itself, as well as its base frequency, was the same for every condition. For better fitting of visuals and sound, the volume of the different cutoff frequencies has been slightly adjusted. A higher amplitude is known to be connected to a higher sound [1]. As this effect is naturally created through the different cutoff frequencies (higher cutoff frequencies are louder than smaller ones), we made it more noticeable by increasing the volume differences to a constant difference of 3 dB from one cutoff frequency to the next. Accordingly, the cutoff frequency was decreased to a lower value for simulating a weaker vibration. Therefore, in the first step, the highest and lowest values were defined. The lowest value was set by having a cutoff at a frequency of 20 Hz, the lower limit of the human hearing range [64]. It was impossible to take 0 Hz as the lowest value as the two values were used to calculate all other logarithmic values, and a $\log(0)$ can not be calculated. The maximum cutoff frequency was investigated by analyzing the frequency spectrum of the stimulus used in this study. The intensity is negligibly small above a frequency of 12866 Hz ($< -165dB$), and a higher cutoff frequency than 12866 hardly affects the perceived sound. Above 12866 Hz, only very small peaks up to $-175dB$ are reached, which are not or only with difficulty perceived by the ear, see Figure 3. In addition, the spectrum was visualized and tested with music applications [1] to see if higher cutoff frequencies and present sounds could be heard. Therefore, 12866 Hz is assumed as the maximum cutoff frequency; see Figure 3. By having the upper and lower borders, we then were able to determine six different cutoff frequencies for the sound (20 Hz, 72 Hz, 265 Hz, 966 Hz, 3525 Hz, 12866 Hz) in equal logarithmic steps, following the Weber-Fechner law [37], and have the same amount of values as we had for the visual stimuli. If these six cutoff frequency values are listed or mentioned in the further course of the work, they are always to be understood as cutoff frequency unless described otherwise. The sound in the study was applied using an HRTF (Head-Related Transfer Function) to make the sound appear originating from the virtual object [43].

Combination of Both Stimuli. The visual stimuli were combined with the auditory stimuli in ascending order (i.e., 0 cm with 20 Hz or 0.6 cm with 966 Hz). This was done because vibration can be assumed as nonlinear movement [8, 26, 56]. This is based on the correlation of a greater supply of energy resulting in a greater amplitude (in our case, the width of the blurring effect) and a higher cutoff frequency (more overtones). This is one reason why combining all different visual and auditive stimuli would lead to unnatural combinations far from expectations. In addition, a higher amplitude is connected to a higher sound [1]. In addition, it is known that a higher cutoff frequency also means a higher sound volume compared to a lower cutoff frequency, and smaller cutoff frequencies sound more muffled [1]. This also shows that combining the different stimuli in ascending order is more natural. For these reasons, we did not combine every value of visual and auditive stimuli, as the values should fit together to have the best possible stimulus, which we perceive as meaningful for creating the best illusion. This is important because the perceived stimulus has to be believable and should seem as real as possible linked to real-life experiences that the discrepancy of missing haptic feedback can be overwritten by the visual and aural sense, as mentioned at the beginning of this section. As this approach aims to enrich scenarios and environments where no feedback can be present, we had a control condition for each stimulus where no feedback was present (width of 0 cm, cutoff frequency of 20 Hz, and a combination of both). This is due to the study design and calculation of various strengths for each stimulus. However, we believe this does not impact the outcome of perception but indicates that perception occurs only when stimuli are present.

[1] https://www.steinberg.net/cubase/

Strength \ Stimulus	Audio	Visual	Audio and Visual
1	20 Hz	0 cm	20 Hz/0 cm
2	72 Hz	0.2 cm	72 Hz/0.2 cm
3	265 Hz	0.4 cm	265 Hz/0.4 cm
4	966 Hz	0.6 cm	966 Hz/0.6 cm
5	3525 Hz	0.8 cm	3525 Hz/0.8 cm
6	12866 Hz	1 cm	12866 Hz/1 cm

Table 1. Overview of all different conditions used in our study.

4 USER STUDY

To explore if the illusion of feeling vibrations can be created and which modalities are suitable for creating the illusion, we determined the following research questions: (RQ1) "Can vibrotactile perception be induced by auditory, visual, or audiovisual stimuli?" and (RQ2) "Where is the illusion's beginning and breaking point?".

4.1 Experiment Design

As we aimed to explore which stimuli could lead to the perception of feeling vibrations and if there is a specific range in which the illusion takes place for the different stimuli, we varied the input stimuli within our study and the input value. We designed a controlled experiment with a 3x6 within-subjects design and the independent variables STIMULUS (*auditory*, *visual*, *audiovisual*) and INPUTSTRENGTH with 6 different strength levels. The creation and choice of the values used for the INPUTSTRENGTH of the different STIMULI were described in Section 3.

The dependent variables were PERCEIVEDSTRENGTH (to explore if tactile feedback was perceived and in which strength), REALISM (to figure out how realistic the feedback was perceived), COMPOSITION (as a possibility to explore which stimulus influenced the perception of feedback), and FEEDBACKIMPROVEMENT (as qualitative feedback on points that helped or prevented to perceive tactile feedback).

4.2 Measurements

To explore if the haptic illusion of feeling a vibration can be created through visual and/or aural stimuli, we asked the participants for the PERCEIVED STRENGTH and the REALISM of the felt haptic feedback. Therefore, we used two single-item questions, like done by prior work investigating haptic illusions [25, 40, 41, 48]. In addition, such questions were found to be mainly used when visual and audio-related haptic feedback is investigated [10]. Following the aforementioned work, this resulted in the following questions:

- To what extent was a vibration perceived tactile?
- To what extent was realistic tactile feedback perceived?

Both answers had to be answered on a 7-item Likert scale. For PERCEIVED STRENGTH, the Likert scale lasted from *not at all (1)* to *very strong (7)*, and for REALISM, from *not at all (1)* to *completely (7)*. For the COMPOSITION, the participants were asked:

- To what extent did the following stimuli characterize the perceived feedback?

This question was answered via three sliders, lasting from 0 to 100, representing three different stimuli (visual, auditory, and tactile). Further, we asked two semi-structured interview questions about reasons supporting or limiting the perceived feedback of feeling a vibration:

- What supported perceived feedback of a vibration?
- What limited perceived feedback of a vibration?

4.3 Participants

For the study, we recruited 18 healthy participants (6 female and 12 male) aged 21 to 32 years (mean = 25,83 years, SD = 2,62) via mailing lists. The participants were from different scientific areas and had no AR experience.

4.4 Apparatus

For the study system, a HoloLens 2 AR headset was used. A virtual 10 x 10 cm white square-shaped plate was placed on a physical flat table and had to be touched to start the different conditions. The touch interaction was realized using colliders in Unity in conjunction with MRTK (Mixed Reality ToolKit) functionalities.

After finishing one condition, the participants could use a virtual button in the right periphery of the scene to switch to the following condition. To ensure that all participants' time of touch is the same over each condition, we had a virtual progress bar in the upper periphery of the HoloLens 2 screen. The participant should lift their index finger again if this bar was completely filled. In addition, we also added an acoustic signal at the end of the task time. A visualization of the apparatus can be found in Figure 4. The questionnaires were completed on a separate computer.

4.5 Task and Procedure

The experiment was conducted as a lab study. First, the participants were introduced to the study's purpose and then were asked to agree to a consent form. Participants were not informed whether real feedback was available or not to avoid influencing responses. After filling in a demographic questionnaire, participants started with the actual study. In each condition, the participants touched the virtual object with their right index finger for 3 seconds, as this duration was used in other haptic illusion studies (i.e., [59]). The order of the different conditions was counterbalanced, following a balanced Latin square design [7]. After each condition, participants filled in the questionnaire and answered the semi-structured question. Participation in the study took approximately 30 minutes for each participant.

5 RESULTS

We first analyzed our quantitative data to learn how the different STIMULI conditions *auditory*, *visual*, and *audiovisual* affected the PERCEIVED STRENGTH, REALISM, and COMPOSITION of the feedback. Subsequently, we analyzed the qualitative data to understand our quantitative results better.

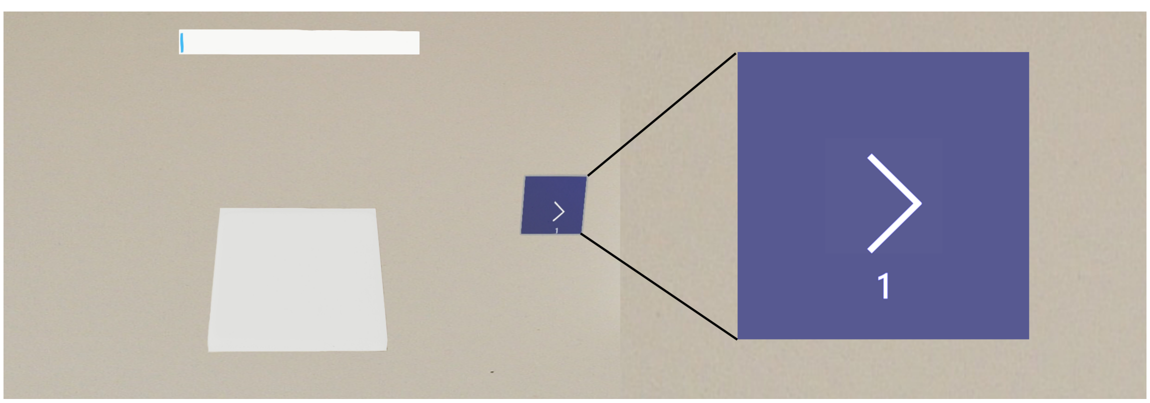

Fig. 4. A representation of the scene the participants have seen, with the progress bar indicating the virtual object was touched and when to lift the finger with which the object was touched. The button on the right was for the participants to switch to the next condition after answering the questionnaire. A number on the button helped them to recognize if they went one condition further.

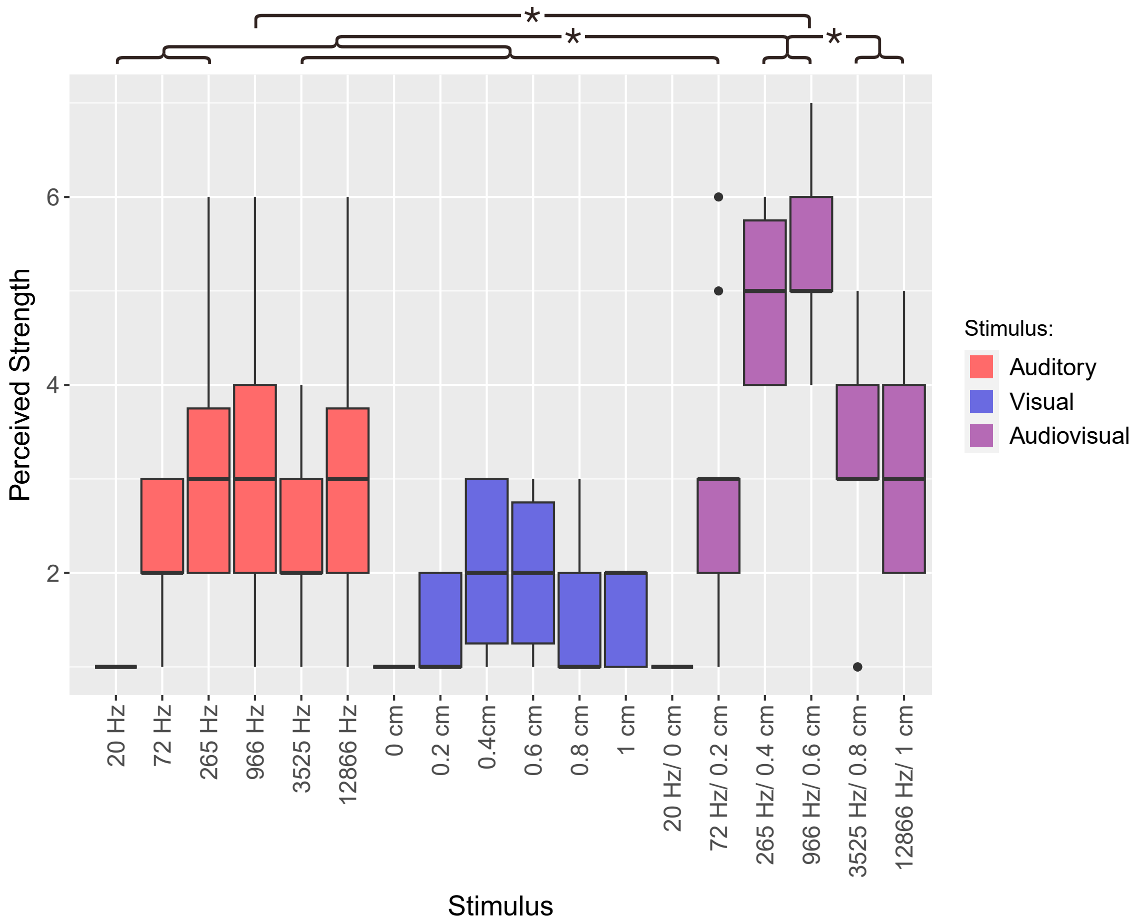

Fig. 5. Box plot representing the results for the question *"To what extent was a vibration perceived tactilely?"*. Only the most prominent significant differences are present here to ensure better clarity.

5.1 Quantitative Results

For analyzing the quantitative results of the PERCEIVED STRENGTH and REALISM, we used a Friedman test to identify significant differences. Post-hoc analysis with Wilcoxon Signed-Rank tests was conducted with a Bonferroni correction applied for the p-value, resulting in a significance value of 0.0028. For the quantitative results of the COMPOSITION of the feedback, we used an ANOVA as the data collected by the sliders can be understood as ordinal data [27].

5.1.1 Perceived Strength. For detailed results, we took a look at the PERCEIVEDSTRENGTH considering the STIMULI, as well as the INPUTSTRENGTHS, to compare all 18 conditions. A Friedmann test indicated significant differences for the PERCEIVED STRENGTH, ($\chi^2(17) = 208.62$, $p < .001$).

Post-hoc analysis performed with Wilcoxon Signed-Rank tests indicated various significant differences between STIMULI for PERCEIVEDSTRENGTH regarding a perceived vibration when touching the virtual object. As it would be incomprehensible to present all individual significant differences, we focus on the most prominent ones. Considering all

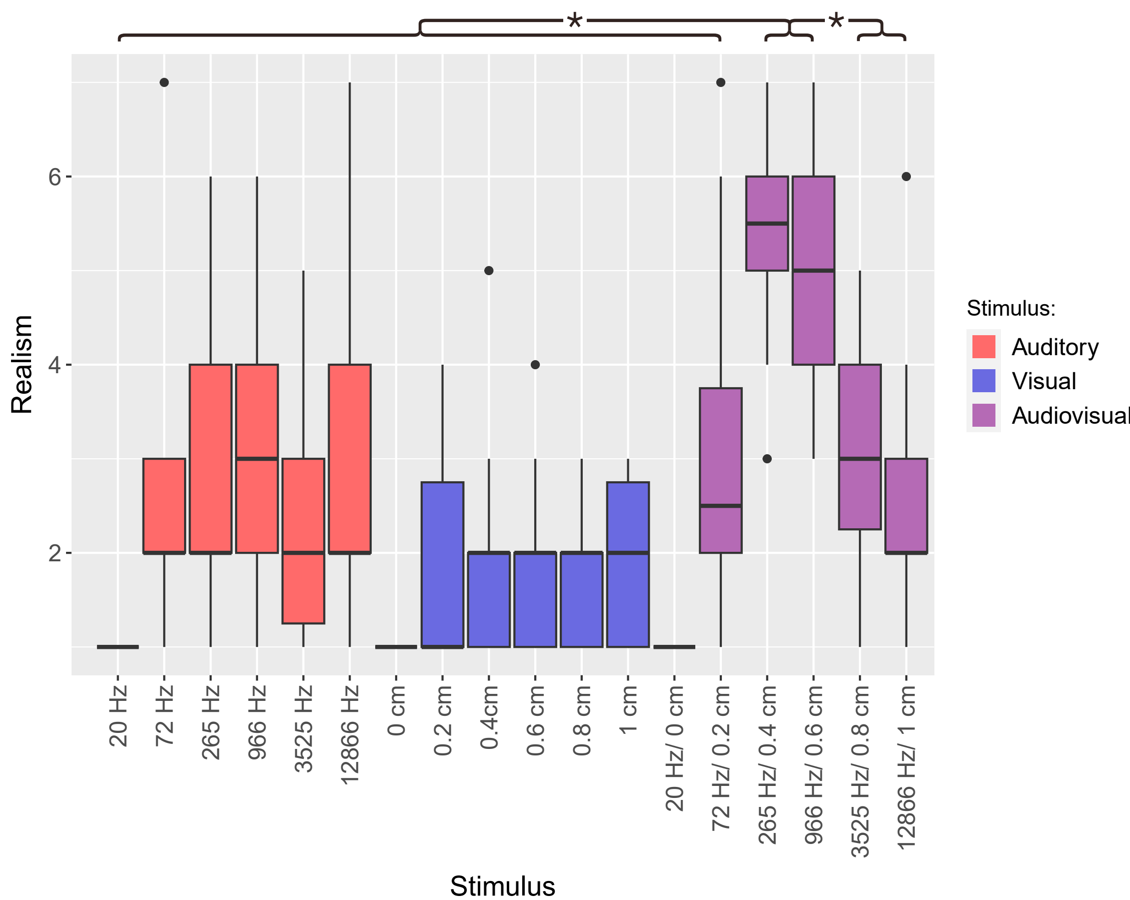

Fig. 6. Box plot representing the results for the question *"Did the perceived feedback feel real?"*. Only the most prominent significant differences are present here to ensure better clarity.

statistically significant differences, the conditions 265 Hz/ 0.4 cm (cutoff frequency/ amplitude) and 966 Hz/ 0.6 cm of the STIMULUS *audiovisual* were most often perceived as statistically significantly stronger than most of the other conditions, see Figure 5. Further, nearly all conditions were perceived as significantly stronger than the control conditions (no feedback to be perceived). For a detailed presentation of all significant differences, see Appendix Table 1.

5.1.2 Realism. For the comparison of the REALISM considering the different STIMULI and INPUTSTRENGTHS, a Friedman test indicated statistically significant differences ($\chi^2(17) = 163.08$, $p < .001$). The post-hoc analysis results of Wilcoxon Signed-Rank tests again indicated various significant differences. For the REALISM, the conditions 265 Hz/ 0.4 cm (cutoff frequency/ amplitude) and 966 Hz/ 0.6 cm of the STIMULUS *audiovisual* were perceived as statistically significantly more realistic than all other conditions, see Figure 6. In addition, nearly all conditions were perceived as significantly more realistic than the control conditions where no feedback was present. A list of all significant differences, including control conditions, can be seen in detail in Appendix Table 2.

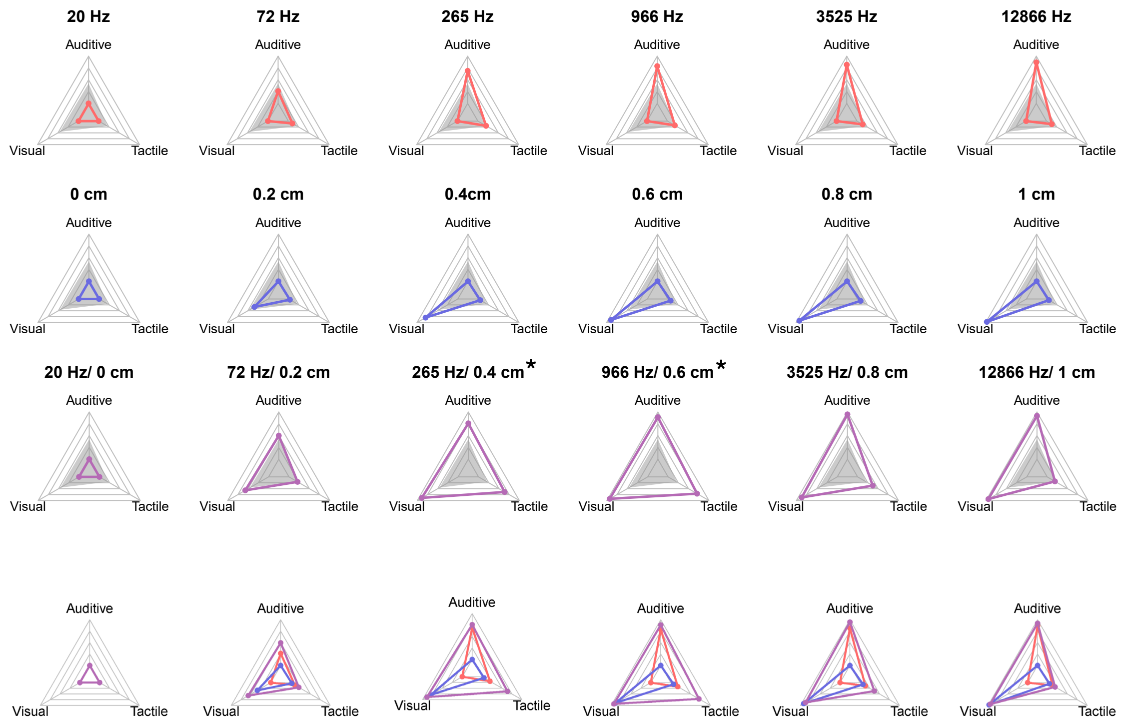

Fig. 7. Radar charts representing results for the perceived composition of feedback. The gray triangles in the top three rows show the mean overall conditions. The colored triangles represent the three different stimuli (red for auditory, blue for visual, purple for audiovisual). The two conditions marked with an $*$ showed significant results in perceiving tactile sensation than all other conditions. In the bottom row, the three results of comparable conditions are overlaid onto one radar chart for each step.

5.1.3 Composition. An analysis of the dependent variable COMPOSITION was made by investigating only the results for the tactile slider, even if there were also the sliders for auditory and visual feedback. This is because the answers for the visual and auditory characterization of the perceived stimuli differ by nature, since just one feedback modality (visual or audio) was present for some conditions, and therefore the results for these two modalities are not expressive. The perception of the single modality was recognized correctly in all respective cases; see Figure 7. Further, the absent modality was consistently rated with 0. An ANOVA revealed statistically significant differences for the variable COMPOSITION regarding the perceived tactile feedback ($F_{(1,\,306)} = 55.23$, $p < .001$).

Post-hoc pairwise comparison (performed with Tukey-test) revealed a better characterization of the feedback by a tactile stimulus for the conditions 265 Hz/ 0.4 cm (cutoff frequency/ amplitude), 966 Hz/ 0.6 cm, and 3525 Hz/ 0.8 cm, compared to all other conditions ($p < .001$). In addition, the feedback was found to be characterized significantly more by a tactile stimulus for the conditions 265 Hz/ 0.4 cm (cutoff frequency/ amplitude), 966 Hz/ 0.6 cm compared to 3525 Hz/ 0.8 cm ($p < .001$).

5.2 Qualitative Results

The qualitative data were coded using Grounded Theory [49]. Axial and selective coding was applied, building categories according to the questions that asked for positive or negative perceived aspects of a system [49]. Two researchers did the coding independently of each other and discussed their results afterward to develop common codes. That procedure aims to gain explanations for our quantitative findings through qualitative analysis. The qualitative results are separated into factors that supported or limited the perceived feedback of a vibration, which were pre-structured by the semi-structured interview questions. As both questions were answered after each condition, we gained a total of 726 answers, split into 377 answers for supporting and 349 answers for limiting factors. The total number of answers exceeded the maximum of 648 possible answers, as some participants mentioned more than one point.

5.2.1 Supporting Factors. Overall, three different factors could be identified to support the perception of feeling a vibration, resulting in 377 answers. In 193 of the 377 answers, it was mentioned that the presence of auditory feedback or visual feedback at all was a supporting factor:

- The fact that sound was present at all (P.6, 966 Hz)
- The movement of the object (P.13, 0.2 cm)
- The presence of auditory and visual feedback (P.3, 265 Hz/0.4 cm)

Further, in 90 out of the 377 cases, it was mentioned that not only the presence of the feedback supported a perception but also that the perceived feeling seemed realistic and was perceived as how the participants would expect it. 42 of these 90 answers were given for the two statistically best performing conditions where auditory and visual stimuli were presented with a strength of 256 Hz combined with 0.4 cm and 966 Hz combined with 0.6 cm:

- The volume and the type of sound seemed realistic. It felt like a movement (P.11, 966 Hz)
- The finer movement makes it more realistic (P.10, 0.4 cm)
- It just felt very good. Very real. The interplay of the 3 elements was very coherent (P.9, 966 Hz/0.6 cm)

Another supporting factor was the good interaction of visuals and sound, as stated in 19 out of the 377 answers. 15 times, this was the case for the two conditions 256 Hz combined with 0.4 cm and 966 Hz combined with 0.6 cm:

- The sound combined with the visual was very good, creating a resonance in the ear which actually made it feel like a vibration (P.14, 265 Hz/0.4 cm)

Lastly, in 75 out of the 377 answers regarding supporting factors, it was mentioned that there was no supporting factor at all. This was every time the case for the control conditions (54 answers).

5.2.2 Limiting Factors. For the semi-structured interview question about limitations for perceiving vibrational feedback, two different factors were mentioned in a total of 349 answers. One of the two factors was the absence of visual or auditory feedback depending on the conditions in 120 out of 349 answers:

- A motion was missing completely (P.13, 966 Hz)
- Visual feedback felt bad because there was no sound (P.5, 0.8 cm)

Further, it was mentioned that the strength of the feedback limited the feedback perception as it was not appropriate because the stimuli were either too weak (60 out of 349 answers) or too strong (60 out of 349 answers):

- The sound was too loud (P.7, 12866 Hz)
- Motion too strong. Seems like a graphical error. (P.14, 0.6 cm)
- Sound and motion were too extreme. Causes discomfort when using (P.18, 12866 Hz/1.0 cm)

Lastly, it was mentioned by many participants that no limiting factors have been perceived (110 out of 349 answers). This was mainly the case for all control conditions (54 out of 110 answers), followed by the two multimodal conditions 256 Hz combined with 0.4 cm and 966 Hz combined with 0.6 cm (24 out of 110 answers).

6 DISCUSSION

Aiming at exploring if we can create the feeling of a vibrotactile illusion, we investigated which STIMULI (*visual* and/or *auditory*) and in which strength/range can be used to create such a haptic sensation. Our results indicated a significantly better haptically *perceivedStrength* and *realism* for a combination of visual and auditory stimuli than both stimuli solely. Regarding perceived tactile feedback, two combinations of sound and visual stimuli (256 Hz combined with 0.4 cm and 966 Hz combined with 0.6 cm) outperformed the other conditions. Both quantitative and qualitative results are discussed here. Based on this, considerations are given on how visual and auditory feedback can be used to create tactile, irrational feedback in cases where real feedback cannot be provided. We lastly regard the limitations of our design and implementation and how these might be addressed by future research.

6.1 Tactile Perception Supporting and Limiting Factors

Within our study, we tested the influence of two different senses. The visual sense, as it is the most dominant sense of all, see Section 2.1, and the sense of sound as this sense also can be used to create haptic sensations, see Section 2.2. In addition to researching both stimuli alone, the combination of the two was also investigated. This section discusses the factors that supported and limited the perception of vibrational tactile feedback of each STIMULUS.

6.1.1 Visual and Auditory Stimuli Combined. The combination of both stimuli achieved the best results regarding the PERCEIVEDSTRENGTH, REALISM, and for perceived tactile feedback found in the COMPOSITION of the feedback. That the combination of feedback modalities increases the results compared to the feedback modalities solely is known and was shown in other publications, see Section 2, and also takes place in the present work.

The best results were achieved for 256 Hz combined with 0.4 cm and 966 Hz combined with 0.6 cm. These were conditions where the participants mentioned not only the visual and auditory feedback being present as a supporting factor but also the strength of the feedback modalities to be adequate and in a range where they would expect it. This is in line with the principles of multisensory illusions [11]. The perceived visual and auditory feedback was so close to the participants' expectations that they were able to overwrite the tactile perception and let them feel vibrations, see Sections 3 and Figure 8. This might also be why these two conditions performed better than the other visual and auditory feedback combinations. For the other combinations, the perceived feedback was too weak and sometimes not even recognizable or too strong and, therefore, themed unnatural and not appropriate for inducing a vibration. The other conditions could not overwrite the other senses in the same way. In addition, these two were the conditions with feedback actually being present, where, most often, no limiting factors were perceived.

Partially, our results confirm the findings of related work with a similar setup, like the research of Kang et al. [25]. They found auditory cues to be a significant factor for perceiving stiffness, while visual cues are not. On the opposite, we found the combination of auditory and visual stimuli as performing significantly better compared to one sense alone regarding illusionary perceived vibrations, while this was not significant for perceiving stiffness in their work [25].

6.1.2 Visual and Auditory Stimuli Solely. Besides the combination of visual and auditory stimuli, both modalities were investigated alone and performed worse than in combination. The quantitative and qualitative results showed no differences between the visual and auditory conditions, considering the dependent variables REALISM and COMPOSITION.

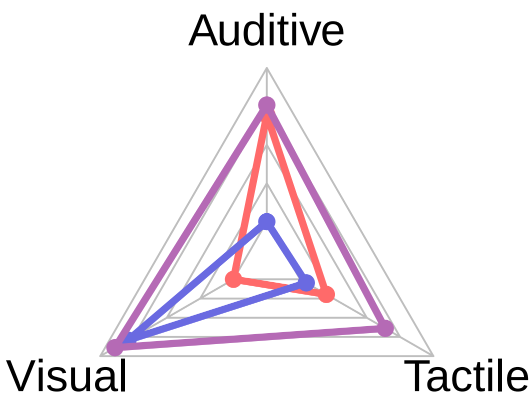

Fig. 8. Radar charts of the conditions (256 Hz / 0.4 cm and 966 Hz / 0.6 cm) that show significant differences in perceived tactile sensation compared to all other conditions, as shown in Figure 7. While the other conditions of combined feedback basically add the two sensations (auditory and visual), these two create a measurable outbreak toward perceived tactile sensation.

Only the visual conditions with a range of 0.2 cm performed significantly worse than the auditory conditions in terms of PERCEIVEDSTRENGTH. This might be because this visual stimulus was hard to perceive and often missed. Besides, for this dependent variable, no differences could be found.

Overall, the qualitative results indicate that one of the modalities solely was perceived as unnatural and unrealistic without the other. The absence of one modality in each case broke the illusion. Therefore, both modalities alone could not create the illusion of feeling a vibration. However, both still performed significantly better than the control conditions, with no feedback. While in other research, visual or auditory stimuli alone were able to create haptic sensations [3, 4, 9, 22, 52, 54], we could not support such findings in terms of creating a vibrotactile illusion. One reason might be that some haptic illusions (deformation) are easier to achieve than others. It appears reasonable to assume that illusionary creating a vibrotactile sensation without directly using haptic modality is difficult to accomplish.

6.2 Applicability of Vibrollusion in HCI

Vibrollusion is related to haptic illusions and psychophysics and aims to enrich ubiquitous environments by providing a tactile sensation induced through the auditory, visual, and audiovisual senses. We can see a growing interest in using haptic illusions to provide haptic sensations in the field of HCI [5, 19, 53].

Our work aims to enrich ubiquitous AR environments where attaching hardware to the environment, objects, or users would be laborious, impossible, and unfeasible. We see three application areas in ubiquitous computing that could benefit from the Vibrollusion concept: (1) walls, (2) surfaces, and (3) furniture:

(1) Providing vibrotactile feedback to make walls interactive would enable to feel feedback when pressing buttons that might be projected at walls using AR glasses, which has been, for example, done by Lopes et al. [35, 53]. While they used EMS for providing haptic feedback when interacting with smart walls, which is laborious and requires the user to carry hardware, including recharging the device's battery occasionally, Vibrollusions would be a zero-weight and not hurting alternative to EMS.

(2) Stiff surfaces have been perceived as soft and flexible using distortion projections when pressing the projected material by Wolf and Bäder [59]. This approach is easily combinable with Vibrollusion, which would allow rich and computable material perception through augmenting analog surfaces and turning everyday surfaces into user interfaces with the support of haptic feedback.

(3) Furniture can be visually brought into vibration, as shown in the IllumiRoom project, and smart furniture using physical modules can be easily built, as presented through Foxels [38]. While both approaches integrate furniture into smart room interaction, the furniture cannot provide haptic feedback due to the lack of embedded technology. Vibrollusion could easily add vibrotactile feedback to both approaches and enrich the interaction with the furniture.

As the described possible application, Virollusion contributes to the idea of ubiquitous computing and aims at helping to create low-cost natural interactive environments with just a minimum of hardware. Everyday life objects could be augmented with HMDs or projectors and provide the user with haptic feedback through sensory illusion, while users' hands could stay unencumbered while interacting [62], and the interactive environment could be kept calm [57].

6.3 Limitations & Future Work

As we can see in our results, the visual presentation alone performed worse in terms of PERCEIVEDSTRENGTH and REALISM, see Figure 5 and 6. Especially for higher ranges of the blur effect, see Figure 7, could have two possible limitations. The first limitation might be that users are not used to perceiving a vibration only visually. In everyday life, we are more used to hearing a vibration together with seeing a lighting display or other indicators. To still provide an experience that is as close as possible to a visual representation of a vibration, we chose the visualization as it performed best out of five possible ones in our pre-study [30]. The second limitation is that we used a neutral object without connection to users' experiences. Using a texture or another shape, like a smartphone, might have increased the results as this is more related to a vibration. Nevertheless, we decided to take a neutral shape and color to not bias the ratings.

Besides the visuals, one limitation can be seen in the presentation of the vibrational sound. Three participants mentioned that the duration of the sound was long and monotone. While 3 seconds was found to be used in related work [59], in the future, when this illusion is investigated further, impulses should be examined for auditory feedback.

The combinations of sound and visuals were mainly perceived as coherent; see Section 5. However, this should be further investigated in the future. One limitation of our study might be the step size between the different conditions, which came up through the laws to set the conditions, and that a number of 6 strengths was chosen for each feedback modality. A higher number of steps and more conditions would have extended the study time, which might have resulted in exhaustion. The goal of this work was firstly to figure out if we can create the illusion of feeling a vibration, and if so, in which range. Now, with having a range and only focusing on the combination of visual and auditory feedback, the values around the range that were found to work best can be investigated in more detail in the future.

Our results are associated with the study setup in which an interactive virtual object of 10 x 10 cm is placed on a physical table. Future research can explore if different textures, sizes, and positions affect the perception. When interacting with a virtual object on an everyday surface, our results showed participants preferred the combination of two stimuli (256 Hz / 0.4 cm and 966 Hz / 0.6 cm) as it meets their expectations.

Our findings indicate a specific multimodal stimuli range in which audiovisual feedback can induce a vibrotactile illusion for touch interactions on everyday objects using haptic actuators.

7 CONCLUSION

This work aims to explore if auditory, visual, or audiovisual stimuli can induce a vibrotactile perception without using haptic actuators. If this is possible, ubiquitous computing could be designed calm, in a sense with a minimum of hardware. This would be appropriate, particularly when haptic feedback technology is not feasible. To investigate that, we used HoloLens 2 to display a 10 x 10 cm virtual white square on a physical table directly in front of the users. When touching this square, it was visually vibrating, and/or a vibration sound was played.

Our results show that two combinations of auditory and visual feedback were haptically perceived as significantly stronger and more realistic than all other conditions:

- a vibration sound with a cutoff frequency of 265 Hz combined with a 0.4 cm amplitude edge blurring effect
- a vibration sound with a cutoff frequency of 966 Hz combined with a 0.6 cm amplitude edge blurring effect

The concept of creating vibrotactile touch-feedback through visual and auditory stimuli could be proven in this work and can help to enrich interaction with ubiquitous computers while keeping the required hardware simple.

ACKNOWLEDGMENTS

This project is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 425869442 and is part of Priority Program SPP2199 Scalable Interaction Paradigms for Pervasive Computing Environments.

REFERENCES

[1] Florian Anwander. 2000. *Synthesizer: so funktioniert elektronische Klangerzeugung-erklärt am Beispiel modularer Synthesizer.* PPV, Presse-Project-Verlag-GmbH, Feldgeding, Germany.

[2] Ferran Argelaguet, David Antonio Gómez Jáuregui, Maud Marchal, and Anatole Lécuyer. 2013. Elastic Images: Perceiving Local Elasticity of Images through a Novel Pseudo-Haptic Deformation Effect. *ACM Trans. Appl. Percept.* 10, 3, Article 17 (aug 2013), 14 pages. https://doi.org/10.1145/2501599

[3] Yuki Ban, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2014. Displaying Shapes with Various Types of Surfaces Using Visuo-Haptic Interaction. In *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology* (Edinburgh, Scotland) *(VRST '14)*. Association for Computing Machinery, New York, NY, USA, 191–196. https://doi.org/10.1145/2671015.2671028

[4] Joanna Bergström, Aske Mottelson, and Jarrod Knibbe. 2019. Resized Grasping in VR: Estimating Thresholds for Object Discrimination. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 1175–1183. https://doi.org/10.1145/3332165.3347939

[5] Carlos Bermejo and Pan Hui. 2021. A Survey on Haptic Technologies for Mobile Augmented Reality. *ACM Comput. Surv.* 54, 9, Article 184 (oct 2021), 35 pages. https://doi.org/10.1145/3465396

[6] Raoul Bickmann, Celine Tran, Ninja Ruesch, and Katrin Wolf. 2019. Haptic Illusion Glove: A Glove for Illusionary Touch Feedback When Grasping Virtual Objects. In *Proceedings of Mensch Und Computer 2019* (Hamburg, Germany) *(MuC '19)*. Association for Computing Machinery, New York, NY, USA, 565–569. https://doi.org/10.1145/3340764.3344459

[7] James V Bradley. 1958. Complete counterbalancing of immediate sequential effects in a Latin square design. *J. Amer. Statist. Assoc.* 53, 282 (1958), 525–528.

[8] Antoine Chaigne, Cyril Touzé, and Olivier Thomas. 2005. Nonlinear vibrations and chaos in gongs and cymbals. *Acoustical science and technology* 26, 5 (2005), 403–409.

[9] Youngjun Cho, Andrea Bianchi, Nicolai Marquardt, and Nadia Bianchi-Berthouze. 2016. RealPen: Providing Realism in Handwriting Tasks on Touch Surfaces Using Auditory-Tactile Feedback. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 195–205. https://doi.org/10.1145/2984511.2984550

[10] Fabien Danieau, Anatole Lecuyer, Philippe Guillotel, Julien Fleureau, Nicolas Mollet, and Marc Christie. 2013. Enhancing Audiovisual Experience with Haptic Feedback: A Survey on HAV. *EEE Trans. Haptics* 6, 2 (apr 2013), 193–205. https://doi.org/10.1109/TOH.2012.70

[11] Marc O. Ernst. 2005. The "Puzzle" of Sensory Perception: Putting Together Multisensory Information. In *Proceedings of the 7th International Conference on Multimodal Interfaces* (Torento, Italy) *(ICMI '05)*. Association for Computing Machinery, New York, NY, USA, 1. https://doi.org/10.1145/1088463.1088464

[12] Marc O Ernst and Martin S Banks. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 415, 6870 (2002), 429–433.

[13] Roberta Etzi, Francesco Ferrise, Monica Bordegoni, Massimiliano Zampini, and Alberto Gallace. 2018. The Effect of Visual and Auditory Information on the Perception of Pleasantness and Roughness of Virtual Surfaces. *Multisensory Research* 31, 6 (2018), 501 – 522.

[14] Roberta Etzi, Francesco Ferrise, Monica Bordegoni, Massimiliano Zampini, and Alberto Gallace. 2018. The Effect of Visual and Auditory Information on the Perception of Pleasantness and Roughness of Virtual Surfaces. *Multisensory Research* 31, 6 (2018), 501 – 522.

[15] Emma Fallows, David White, and Neil Brownsword. 2022. Design and Development Approach for an Interactive Virtual Museum with Haptic Glove Technology. In *Proceedings of the 25th International Academic Mindtrek Conference* (Tampere, Finland) *(Academic Mindtrek '22)*. Association for Computing Machinery, New York, NY, USA, 242–255. https://doi.org/10.1145/3569219.3569382

[16] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. InFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 417–426. https://doi.org/10.1145/2501988.2502032

[17] Brian Gleeson and David E. Johnson. 2010. Expressive haptic rendering with cartoon-inspired effects. In *2010 IEEE Haptics Symposium*. IEEE, Waltham, MA, USA, 191–194. https://doi.org/10.1109/HAPTIC.2010.5444656

[18] Mar Gonzalez-Franco and Christopher C. Berger. 2019. Avatar Embodiment Enhances Haptic Confidence on the Out-of-Body Touch Illusion. *IEEE Transactions on Haptics* 12, 3 (2019), 319–326. https://doi.org/10.1109/TOH.2019.2925038

[19] Monica Gori, Sara Price, Fiona N Newell, Nadia Berthouze, and Gualtiero Volpe. 2022. Multisensory Perception and Learning: Linking Pedagogy, Psychophysics, and Human–Computer Interaction. *Multisensory Research* 35, 4 (2022), 335–366.

[20] Taku Hachisu, Gabriel Cirio, Maud Marchal, Anatole Lécuyer, and Hiroyuki Kajimoto. 2011. Pseudo-haptic feedback augmented with visual and tactile vibrations. In *2011 IEEE International Symposium on VR Innovation*. IEEE, IEEE, Singapore, 327–328.

[21] Taku Hachisu and Kenji Suzuki. 2019. Representing Interpersonal Touch Directions by Tactile Apparent Motion Using Smart Bracelets. *IEEE Transactions on Haptics* 12, 3 (2019), 327–338. https://doi.org/10.1109/TOH.2019.2929810

[22] Satoshi Hashiguchi, Shohei Mori, Miho Tanaka, Fumihisa Shibata, and Asako Kimura. 2018. Perceived Weight of a Rod under Augmented and Diminished Reality Visual Effects. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology* (Tokyo, Japan) *(VRST '18)*. Association for Computing Machinery, New York, NY, USA, Article 12, 6 pages. https://doi.org/10.1145/3281505.3281545

[23] Seongkook Heo and Geehyuk Lee. 2017. Vibrotactile Compliance Feedback for Tangential Force Interaction. *IEEE Transactions on Haptics* 10, 3 (2017), 444–455. https://doi.org/10.1109/TOH.2016.2604305

[24] Brett R. Jones, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2013. IllumiRoom: Peripheral Projected Illusions for Interactive Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 869–878. https://doi.org/10.1145/2470654.2466112

[25] Namkyoo Kang, Young June Sah, and Sangwon Lee. 2021. Effects of visual and auditory cues on haptic illusions for active and passive touches in mixed reality. *International Journal of Human-Computer Studies* 150 (2021), 102613.

[26] Wilfried Kausel. 2018. *Vibrations and Waves*. Springer, Berlin,Heidelberg, 29–47. https://doi.org/10.1007/978-3-662-55004-5_2

[27] Patty Kero and Daniel Lee. 2015. Slider Scales and Web-Based Surveys: A Cautionary Note. *Journal of Research Practice* 11 (09 2015).

[28] Jinsoo Kim, Seungjae Oh, Chaeyong Park, and Seungmoon Choi. 2020. *Body-Penetrating Tactile Phantom Sensations*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376619

[29] Arata Kokubun, Yuki Ban, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2013. ARAtouch: Visuo-Haptic Interaction with Mobile Rear Touch Interface. In *SIGGRAPH Asia 2013 Emerging Technologies* (Hong Kong, Hong Kong) *(SA '13)*. Association for Computing Machinery, New York, NY, USA, Article 2, 3 pages. https://doi.org/10.1145/2542284.2542286

[30] Marco Kurzweg, Maximilian Letter, and Katrin Wolf. 2023. Increasing Realism of Displayed Vibrating AR Objects through Edge Blurring. In *Proceedings of Mensch Und Computer 2023* (Rapperswil, Switzerland) *(MuC '23)*. Association for Computing Machinery, New York, NY, USA, 16–26. https://doi.org/10.1145/3603555.3603570

[31] Chi-Hsia Lai, Matti Niinimäki, Koray Tahiroglu, Johan Kildal, and Teemu Ahmaniemi. 2011. Perceived Physicality in Audio-Enhanced Force Input. In *Proceedings of the 13th International Conference on Multimodal Interfaces* (Alicante, Spain) *(ICMI '11)*. Association for Computing Machinery, New York, NY, USA, 287–294. https://doi.org/10.1145/2070481.2070533

[32] Anatole Lécuyer. 2009. Simulating Haptic Feedback Using Vision: A Survey of Research and Applications of Pseudo-Haptic Feedback. *Presence: Teleoper. Virtual Environ.* 18, 1 (jan 2009), 39–53. https://doi.org/10.1162/pres.18.1.39

[33] Anatole Lécuyer, Jean-Marie Burkhardt, and Laurent Etienne. 2004. Feeling Bumps and Holes without a Haptic Interface: The Perception of Pseudo-Haptic Textures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vienna, Austria) *(CHI '04)*. Association for Computing Machinery, New York, NY, USA, 239–246. https://doi.org/10.1145/985692.985723

[34] Shang Ping Lee, Tran Cong Thien Qui, Shing Chuan Loy, and William Russell Pensyl. 2009. Haptic Interaction in Augmented Reality. In *Proceedings of the 17th ACM International Conference on Multimedia* (Beijing, China) *(MM '09)*. Association for Computing Machinery, New York, NY, USA, 975–976. https://doi.org/10.1145/1631272.1631475

[35] Pedro Lopes, Sijing You, Alexandra Ion, and Patrick Baudisch. 2018. Adding Force Feedback to Mixed Reality Experiences and Games Using Electrical Muscle Stimulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174020

[36] Koert Van Mensvoort, Peter Vos, Dik J. Hermes, and Robert Van Liere. 2010. Perception of Mechanically and Optically Simulated Bumps and Holes. *ACM Trans. Appl. Percept.* 7, 2, Article 10 (feb 2010), 24 pages. https://doi.org/10.1145/1670671.1670674

[37] Forrest W Nutter Jr. 2010. Weber-Fechner Law. *Encyclopedia of research design* 3 (2010), 1612–1615.

[38] Florian Perteneder, Kathrin Probst, Joanne Leong, Sebastian Gassler, Christian Rendl, Patrick Parzer, Katharina Fluch, Sophie Gahleitner, Sean Follmer, Hideki Koike, and Michael Haller. 2020. Foxels: Build Your Own Smart Furniture. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 111–122. https://doi.org/10.1145/3374920.3374935

[39] Andreas Pusch and Anatole Lécuyer. 2011. Pseudo-Haptics: From the Theoretical Foundations to Practical System Design Guidelines. In *Proceedings of the 13th International Conference on Multimodal Interfaces* (Alicante, Spain) *(ICMI '11)*. Association for Computing Machinery, New York, NY, USA, 8 pages. https://doi.org/10.1145/2070481.2070494

[40] Michael Rietzler, Florian Geiselhart, Julian Frommel, and Enrico Rukzio. 2018. Conveying the Perception of Kinesthetic Feedback in Virtual Reality Using State-of-the-Art Hardware. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174034

[41] Michael Rietzler, Gabriel Haas, Thomas Dreja, Florian Geiselhart, and Enrico Rukzio. 2019. Virtual Muscle Force: Communicating Kinesthetic Forces Through Pseudo-Haptic Feedback and Muscle Input. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 913–922. https://doi.org/10.1145/3332165.3347871

[42] Majed Samad, Elia Gatti, Anne Hermes, Hrvoje Benko, and Cesare Parise. 2019. Pseudo-Haptic Weight: Changing the Perceived Weight of Virtual Objects By Manipulating Control-Display Ratio. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300550

[43] Carl Schissler, Aaron Nicholls, and Ravish Mehra. 2016. Efficient HRTF-based Spatial Audio for Area and Volumetric Sources. *IEEE Transactions on Visualization and Computer Graphics* 22, 4 (2016), 1356–1366. https://doi.org/10.1109/TVCG.2016.2518134

[44] Jonas Schmidtler and Klaus Bengler. 2018. Influence of Size-Weight Illusion on Usability in Haptic Human-Robot Collaboration. *IEEE Transactions on Haptics* 11, 1 (2018), 85–96. https://doi.org/10.1109/TOH.2017.2757925

[45] Scott Sinnett, Charles Spence, and Salvador Soto-Faraco. 2007. Visual dominance and attention: The Colavita effect revisited. *Perception & Psychophysics* 69, 5 (01 Jul 2007), 673–686. https://doi.org/10.3758/BF03193770

[46] Marco Speicher, Jan Ehrlich, Vito Gentile, Donald Degraen, Salvatore Sorce, and Antonio Krüger. 2019. Pseudo-Haptic Controls for Mid-Air Finger-Based Menu Interaction. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3290607.3312927

[47] Stanley S Stevens. 1960. The psychophysics of sensory function. *American scientist* 48, 2 (1960), 226–253.

[48] Patrick L. Strandholt, Oana A. Dogaru, Niels C. Nilsson, Rolf Nordahl, and Stefania Serafin. 2020. Knock on Wood: Combining Redirected Touching and Physical Props for Tool-Based Interaction in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376303

[49] Anselm Strauss and Juliet M Corbin. 1997. *Grounded theory in practice.* Sage, Thousand Oaks, CA, USA.

[50] Takeshi Tanabe, Hiroaki Yano, and Hiroo Iwata. 2018. Evaluation of the Perceptual Characteristics of a Force Induced by Asymmetric Vibrations. *IEEE Transactions on Haptics* 11, 2 (2018), 220–231. https://doi.org/10.1109/TOH.2017.2743717

[51] Luca Turchet, Maud Marchal, Anatole Lécuyer, Rolf Nordahl, and Stefania Serafin. 2010. Influence of Auditory and Visual Feedback for Perceiving Walking over Bumps and Holes in Desktop VR. In *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology* (Hong Kong) *(VRST '10)*. Association for Computing Machinery, New York, NY, USA, 139–142. https://doi.org/10.1145/1889863.1889893

[52] Luca Turchet, Stefania Serafin, and Paola Cesari. 2013. Walking Pace Affected by Interactive Sounds Simulating Stepping on Different Terrains. *ACM Trans. Appl. Percept.* 10, 4, Article 23 (oct 2013), 14 pages. https://doi.org/10.1145/2536764.2536770

[53] Yusuke Ujitoko and Yuki Ban. 2021. Survey of Pseudo-Haptics: Haptic Feedback Design and Application Proposals. *IEEE Transactions on Haptics* 14, 4 (2021), 699–711. https://doi.org/10.1109/TOH.2021.3077619

[54] Yusuke Ujitoko, Yuki Ban, Takuji Narumi, Tomohiro Tanikawa, Koichi Hirota, and Michitaka Hirose. 2015. Yubi-Toko: Finger Walking in Snowy Scene Using Pseudo-Haptic Technique on Touchpad. In *SIGGRAPH Asia 2015 Emerging Technologies* (Kobe, Japan) *(SA '15)*. Association for Computing Machinery, New York, NY, USA, Article 29, 3 pages. https://doi.org/10.1145/2818466.2818491

[55] Lia Villanueva and Massimiliano Zampini. 2018. Reciprocal Interference Between Audition and Touch in the Perception of Duration. *Multisensory Research* 31, 5 (2018), 351 – 371.

[56] Chris Waltham and Shigeru Yoshikawa. 2018. *Construction of Wooden Musical Instruments*. Springer Berlin Heidelberg, Berlin, Heidelberg, 63–79. https://doi.org/10.1007/978-3-662-55004-5_4

[57] Mark Weiser. 1991. The Computer for the 21 st Century. *Scientific american* 265, 3 (1991), 94–105.

[58] Mark Weiser and John Seely Brown. 1996. Designing calm technology. *PowerGrid Journal* 1, 1 (1996), 75–85.

[59] Katrin Wolf and Timm Bäder. 2015. Illusion of Surface Changes Induced by Tactile and Visual Touch Feedback. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 1355–1360. https://doi.org/10.1145/2702613.2732703

[60] Hong-In Won and M. Ercan Altinsoy. 2020. Effect of Auditory Feedback on Tactile Intensity Perception in a Touchscreen Application. *IEEE Transactions on Haptics* 13, 2 (2020), 343–353. https://doi.org/10.1109/TOH.2019.2947553

[61] Jackie (Junrui) Yang, Hiroshi Horii, Alexander Thayer, and Rafael Ballagas. 2018. VR Grabbers: Ungrounded Haptic Retargeting for Precision Grabbing Tools. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association

for Computing Machinery, New York, NY, USA, 889–899. https://doi.org/10.1145/3242587.3242643

[62] Y. Yokokohji, R.L. Hollis, and T. Kanade. 1996. What you can see is what you can feel-development of a visual/haptic interface to virtual environment. In *Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium*. IEEE, Santa Clara, CA, USA, 46–53. https://doi.org/10.1109/VRAIS.1996.490509

[63] Maki Yokoyama, Taku Hachisu, Michi Sato, Shogo Fukushima, and Hiroyuki Kajimoto. 2012. Control of Ridge by Using Visuotactile Cross-Modal Phenomenon. In *Proceedings of the 2012 ACM International Conference on Interactive Tabletops and Surfaces* (Cambridge, Massachusetts, USA) *(ITS ’12)*. Association for Computing Machinery, New York, NY, USA, 335–338. https://doi.org/10.1145/2396636.2396694

[64] HP ZENNER. 2013. *Die Kommunikation des Menschen*. Springer-Verlag, Berlin,Heidelberg, 259–277.