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Comparing Auditory and Haptic Feedback for a Virtual Drilling Task

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Abstract

While visual feedback is dominant in Virtual Environments, the use of other modalities like haptics and acoustics can enhance believability, immersion, and interaction performance. Haptic feedback is especially helpful for many interaction tasks like working with medical or precision tools. However, unlike visual and auditory feedback, haptic reproduction is often difficult to achieve due to hardware limitations. This article describes a user study to examine how auditory feedback can be used to substitute haptic feedback when interacting with a vibrating tool. Participants remove some target material with a round-headed drill while avoiding damage to the underlying surface. In the experiment, varying combinations of surface force feedback, vibration feedback, and auditory feedback are used. We describe the design of the user study and present the results, which show that auditory feedback can compensate the lack of haptic feedback.

Categories and Subject Descriptors (according to ACM CCS): Information Interfaces and Presentation [H.5.1]: Multimedia Information Systems —Artificial, augmented, and virtual realities; Information Interfaces and Presentation [H.5.1]: Multimedia Information Systems —Evaluation/methodology; Multimedia Information Systems [H.5.2]: User Interfaces—Auditory (non-speech) feedback Multimedia Information Systems [H.5.2]: User Interfaces—Haptic I/O

1. Introduction

One key aspect of Virtual Reality (VR) is the support for natural, multi-modal interaction. The use of multiple modalities increases immersion and provides different types of feedback, which can increase the quality of the interaction. Since the visual sense is dominant for humans, many VR-applications focus on the graphical representation. Still, other modalities like haptics and acoustics are important to create a more realistic impression and to provide additional feedback.

Haptic feedback addresses the human's sense of touch by simulating forces or surface textures. To use haptics in Virtual Environments (VEs), haptic devices can produce forces to convey information about contacts, material properties, etc. Especially for medical simulators, e.g. robot-assisted surgery [vdMS09], palpation or needle insertion [URK11], haptics is an important aspect, and often even the dominant modality of the simulators (see [CMJ11] for a survey). However, the use of haptic feedback in VEs is restricted by the hardware. Current devices, like the Sensable PHANTOM series, are usually mounted at fixed locations and have a limited workspace. Furthermore, the displayable force is limited, and is often transmitted via a stylus that has to be held in the hand. This makes it difficult to use haptics in many VR scenarios, especially if the user can move around freely or if the interaction exceeds the limitations of the device. In these cases, other modalities may help to compensate for the lack of haptics. For example, Brogni et al. [BCS11] have shown that participants visually touching a virtual object reported feeling haptic properties although no haptic feedback was present.

Audio is another modality available in VEs. Sounds are reproduced to enrich the environment or convey information. In contrast to haptics, auditory feedback can be reproduced using either headphones or speakers, and thus can be used in most VEs. Integrating virtual sound sources can increase the feeling of presence and aid with interaction tasks [LVK02]. Ambient sounds are commonly used to increase the richness and believability of a virtual scenery, but can also be used as feedback channel. However, the use of auditory feedback of-

Figure 1: *A participant uses a virtual drill to remove material from a surface.*

ten only employs artificial sounds, like alarms or trigger indicators, resembling their use in 2D GUIs. For believable VEs, however, the use of realistic sound is preferable to maintain the immersion [CM02].

In this paper, we present a study to examine the possibility of substituting haptic feedback with realistic audio. Auditory feedback is compared to two different haptic feedback types: one that is designed to be very similar to the auditory channel, and one that provides different feedback.

We chose an interaction task using a mechanical precision tool where the haptic feedback is of importance and can still be simulated in a VE. In the presented user study, the participants use a virtual drill to remove material from a surface (see Fig. 1). Apart from the visual representation, a combination of different feedback channels is provided: auditory feedback, haptic vibration feedback, and force feedback of the surface. In reality, a drill rotates and produces vibrations and sound based on its rotation frequency, which changes when the drill comes into contact with a material. Thus, it is well suited as a scenario for investigating the different impact of auditive and vibrational haptic feedback. Both modalities are based on the same physical basis, and thus have comparable quality. Additionally, surface contact forces provide another form of haptic feedback for comparison.

In the following, we will first discuss related work in this area (Section 2), and then describe the design of the user study in section 3, outlining the procedure and different conditions. Section 4 will provide details about the modeling and realization of the auditive and haptic feedback. The results of the study are presented section 5, followed by a discussion and concluding remarks in section 6.

2. Related Work

Prior research has been performed on sensory substitution and multimodal feedback. Some studies already compared interaction tasks supported by sound and haptic feedback. Many of these use simple tasks like target acquisition, and utilize artificial feedback. In 1994, Richard et al. examined the influence of haptic force feedback and artificial sound feedback on task performance when grabbing and moving a virtual ball [RBGC94], showing that haptic feedback is better for hard balls and sound better for soft ones. Kim et al. [KK07] found that using artificial acoustic or haptic signals as depth cues can enhance pointing precision along the depth direction. Others utilized abstract feedback for target acquisition [MPKB10], concluding that haptics was in general more helpful than acoustics. Lécuyer et al. [LMB*02] chose a scenario where a ball had to be guided through apertures, and used different feedback conditions including alarm sounds, vibrations, and directing forces. However, they found no effect of haptic or auditory feedback on the error rate, while the task completion time was best without any feedback. A study using a simple virtual maze and haptic and auditory collision feedback [DHM*06] indicated a strong benefit of haptics, but only a minor benefit of sound. In another experiment, it was shown that either visual or auditory feedback can partially substitute one of the feedback axes of a 3-DOF torque haptic wrist device [MSD*08]. When combining haptics and audio, it has been shown that auditory feedback can enhance haptic realism, e.g. by making a contact appear stiffer [AC06]. A study of the virtual assembly of clockworks showed that haptic feedback was more beneficial than audio or visuals [PZF*04]. Edwards et al. [EBN04] also used an assembly task, but found that audio had little influence and that depending on gender, haptic feedback could have no impact (females) or be detrimental (males).

Most of the prior studies rely on artificial auditory feedback or only display collision events. Their results vary greatly, which may be attributed to the different quality of the feedback which depends on its design, implementation, and the used harware. To overcome this problem, we designed the auditory and vibrational haptic feedback to be of comparable quality. To achieve this, they are both based on the same physical property and parameters, and show the same reaction to user interactions.

3. User Study Design

The study compares the influence of haptic and auditory feedback on an interaction task similar to dental drilling. In the used scenario, a patch of soft material is located on a slightly curved surface made of hard material. While both materials are non-deformable, the material patch is softer than the surface material so that it can be removed faster with the drill. The task of the user is to remove as much as possible of the soft material in a fixed amount of time using a drill with a spherical head, while taking care not to remove any of the underlying surface.

During the trials, combinations of three feedback types are provided to support the task (see section 4 for details):

- *Auditory feedback* (A) reproduces the sound of the virtual tool. Depending on the kind and amount of material being removed, the sound's frequency and volume change, providing feedback about the removed material.
- *Vibration feedback* (V) produces a haptic vibration of the interaction device to simulate the vibration of the virtual tool. It is based on the same frequency and amplitude as the auditory feedback, thus also giving feedback about the type of removed material.
- *Surface force feedback feedback* (S) provides haptic force feedback when the user touches a surface with the tool, allowing him to feel the shape of the remaining material. The surface is modelled to be non-deforming except for the material abrasion, and force computation does not depend on the material type. It thus helps to detect a contact between tool and surface, and how strongly one pushes. However, it does not provide any feedback about the material type.

Under all conditions, visual feedback is available, showing the surface as well as the soft material in distinguishable colors (grey and dark yellow), and by showing a model of the drill. The visualization of the drill is not co-located with the haptic device, but shifted backwards to fit on the screen area and to prevent occlusion. A stereoscopic projection system with head tracking is used to provide a better depth impression of the environment. This was further enhanced by casting a shadow from the tool onto the material. Furthermore, the noise of the haptic device (see section 4.4) made it necessary to play a constant sound even during non-auditory conditions. This sound was equal to the auditory condition when the drill has no contact with any material.

The scenario was chosen because drilling is a task for which visual, haptic, and auditive feedback are of importance and can be reproduced in a virtual environment. Additionally, it is a common task so that no extensive training is required to use the simulation. We chose a drill with a spherical head so that users do not have to consider its exact orientation, and it allows a visual estimation of its penetration into the surface. With a drill diameter of $32mm$ and a target material size of about $10cm \times 15cm$, the scale was comparatively large in order to make the task easier and to utilize the full interaction space of the haptic device. The amount of target material and the task duration were chosen based on pre-studies such that one could not remove all material in the given time, which would have lead to a large error. However, the time was long enough so that one had to work close to the boundaries of the target material.

3.1. Procedure

The study uses a within-subject design with three independent variables: *auditory feedback* (A), *vibration feedback* (V), and *surface force feedback* (S). Every combination of feedback types is tested, resulting in eight conditions: Ø (only visual feedback), A, V, VA, S, SA, SV, and SVA. Each condition is repeated three times by all participants, resulting in a total of 24 trials. The trials form three blocks, in which the order of the conditions is counterbalanced using Latin Squares. The dependent variables that are measured during the study are the actual amount of removed target material (RTM) and the amount of erroneously removed surface material (ERR).

The visual representation of the scenery is not shown until a trial is explicitly started. For this, the user has to hold the virtual tool inside a spherical region for 3 seconds, ensuring that it always starts at the same location.

Participants are seated on a table before the projection display and wear headphones (see Fig. 1). The haptic device is placed at the center of the table, so that the setup is symmetrical for both left- and right-handed people. At the start of a session, the participant receives written instructions explaining how to use the system, and explaining the task. The goal is to remove as much of the target material as possible in the given time, with focus on avoiding damage to the original surface.

The study begins with a training task that lasts 60 seconds and provides full auditory, vibration and surface force feedback. Afterwards, five more training trials follow (conditions Ø, S, V, A, and SVA) with 25 seconds duration each. Prestudies showed that there is a strong training effect during the first few trials, but is low after the initial training block. After a 60 second break, the participants then perform the 24 actual trials, each lasting 25 seconds. After every sixth trial, breaks of 30 seconds were enforced during which the user puts down the haptic device in order to reduce fatigue.

After the study, participants fill out a post-study questionnaire. In addition to general data (age, sex, computer and VR experience, etc.), they are asked to rate several items on a 5-point Likert scale, covering the realism and involvement, the helpfulness of feedback modalities in comparison to one another, and the ease of tasks under different conditions.

The whole test takes about half an hour, of which the actual task performance takes around 17 minutes.

4. Technical Realization

For the user study, we developed a prototype application using the ViSTA Virtual Reality Toolkit [AK08]. The application provides a visual representation of the scene, handles input and output of the haptic device and calculates the material abrasion and haptic feedback. The sound synthesis component is connected by a network interface.

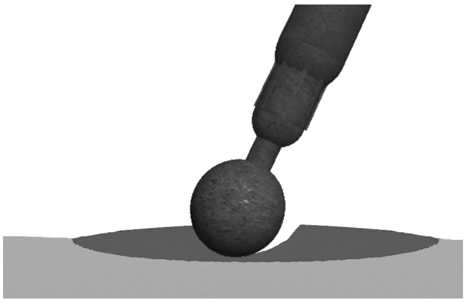

Figure 2: *Cross section of the scenario, showing the original surface (bottom), the target material that should be removed (center), and the drill.*

4.1. Hardware

The study was performed on an imsys flip150 system with a 60" back-projection screen (1400x1050 resolution) providing stereoscopic images using passive stereo technology. The application runs on a Windows 7 PC with an Intel Xeon 5530 (2.4GHz), 4GB RAM, and an nVidia Quadro FX 5600 graphics card, providing frame rates of at least 30Hz. An ART TrackPad opto-electronic tracking system is used for head tracking in order to provide user-centered projection. A Sensable PHANTOM Omni is used for 6-DoF input and 3-DoF haptic output, and sound is reproduced by closed Beyerdynamics DT 770 headphones.

4.2. Material Abrasion

In this scenario, the surface is modeled as an evenly spaced height map, where for each 2D cell the current height and the amount of soft material is stored. The surface has a size of $350mm \times 350mm$ and a cell size of $1mm$. The target material that is to be removed is located in the center of the surface, and has an elliptical base area and a thickness that decreases towards the border (see Fig. 2). To reduce training effects between trials, the orientation and aspect ratio of the elliptic area is randomized, while keeping the surface area ($17500mm^2$) and volume constant. Furthermore, while the maximum thickness of the ellipse is always $8.5mm$, the ratio of elevated material to indented material is varied slightly. The drill is modeled with a spherical head of $18mm$ radius.

The user controls the drill with the haptic device and uses it to remove material from the surface when getting in contact with it. To model the interaction, the input position of the haptic device is used as *haptic interaction point (HIP)*. While it is possible to use this point directly as position for the virtual tool, this would allow a deep penetration into the surface, as the haptic device is not able to display the necessary forces for a stiff contact. Therefore, we followed a common approach by distinguishing between HIP and the virtual interaction point (VIP) that defines the position of the virtual tool. The behavior of the tool can then be simulated under consideration of high contact stiffness values and *virtual coupling* [CSB95]. This approach tries to align the VIP and HIP, while preventing a deep penetration of the VIP. In this experiment, we used the *static virtual coupling* approach [WM03] [BJ08] where the virtual tool receives penalty contact forces based on Hooke's law, and is coupled to the HIP by a generalized spring. In each haptic cycle, a linear approximation of the forces and torques acting on the tool is computed. The tool is then moved to the location where the linear system predicts an equilibrium of contact and coupling forces.

The material abrasion is determined by calculating the intersection of the displaced drill's head with the material. For each cell of the height map that lies in this intersection, the penetration depth p is calculated. The amount of removed material for this cell is then calculated as $min(p \cdot s_M, l_M)$, where s_M and l_M are material parameters that describe the penetration-dependent increase and the maximal allowed abrasion. The parameters were chosen such that the soft material can be removed five times faster than the hard material.

4.3. Frequency Modeling

To avoid that a different quality of haptic and auditory feedback reduces their comparability, both feedback types were designed to work similarly. This was a main reason to choose a vibrating tool – the feedback can be defined by a frequency and an amplitude, which works as input to both the vibration feedback and the acoustics synthesis.

The frequency and amplitude of the tool's rotation is computed based on the interaction. In each time step, the frequency is calculated from the amount of removed soft material Δv_s and hard material Δv_h by a weighted combination of base frequencies:

$$f = \frac{f_n + w_s \cdot \Delta v_s \cdot f_s + w_h \cdot \Delta v_h \cdot f_h}{1 + w_s \cdot \Delta v_s + w_h \cdot \Delta v_h} \quad (1)$$

Here, $w_s = 100$ and $w_h = 500$ are relative weights, and f_n, f_s, and f_h are the frequencies for states with no contact, full contact with the soft target material, and full contact with the hard surface, respectively. The amplitude is derived analogously from corresponding values a_n, a_s, and a_h.

To determine suitable values for these three pairs of frequency and amplitude, we started by analysing sounds of real tools that fit the scenario of the task, like drills, grinders, and dental drills. Sounds from online databases and own recordings showed that this group of tools has a primary frequency in the range of $50Hz$ to $200Hz$. To find the three basic frequencies and amplitudes in this range, we performed pre-studies with several participants. Based on their subjective impression, we finally chose suitable values that were well distinguishable and also matched the visual appearance of the virtual device. The frequency-amplitude-pairs for the three states are: no contact ($f_n = 90Hz, a_n = 0.2$), drilling soft material ($f_s = 85Hz, a_s = 0.5$), and drilling hard material ($f_h = 59Hz, a_h = 0.8$). These proved to be suitable for both the auditory and the vibration feedback. The selected values represent a rather low choice in the available spectrum, which was motivated by different reasons. First of all, high-frequency sounds would be straining over a longer period. Additionally, the haptic device can only reproduce a limited spectrum of vibrations, and also produces more noise for higher frequencies.

4.4. Haptic Feedback

The haptic feedback consists of two separate parts: surface force feedback and vibration feedback. Surface force feedback produces a force if the tool penetrates the surface, indicating the contact to the user. Its direction and amplitude is determined by the displacement between HIP and VIP, producing a force of up to $1.2N$. Vibrations are reproduced by adding a force with amplitude-dependent magnitude (max. $0.9N$) and a direction that rotates circularly around the drill's axis. While the circular force vector provides a good reproduction of vibrational forces, the amplitude had to be kept rather small due to force limitations of the haptic device. In order to increase the actual vibration strength felt by the users, we had to remove the detachable handle of the PHANTOM device because it introduced a strong dampening. By gripping the underlying metallic rod of the handle, the produced vibrations had sufficient strength.

Initially, we had concerns that the PHANTOM Omni used in this study might not be able to reproduce vibrations with sufficient accuracy. However, measurements with a laser doppler vibrometer showed that the device reproduces frequencies in the desired range with an error of less than one Hertz.

One problem was a considerable noise produced by the haptic device when displaying vibrations. Since this sound can provide feedback similar to the auditory condition, it could influence the results. To prevent this, we chose closed headphones and also played a constant, interaction-independent sound even for the non-auditory conditions to cover the device's noise.

Since haptic feedback requires update rates of $1kHz$, the material abrasion and the corresponding forces were computed in a separate thread, and results were transmitted to the visualization thread and the audio interface.

4.5. Auditory Feedback

As auditory feedback, a sound synthesis generates an audio signal that corresponds to the noise a vibrating tool would produce. It was modeled to sound similar to a drill and varies based on the same frequency and amplitude as the vibration.

The sound modeling was realized with *pureData*, a real-time graphical programming environment for audio synthesis that combines signals using dataflow-like networks. It receives interaction information from the main application over a network interface, and calculates the corresponding audio output in real-time. For the sound output of pureData, *ASIO4ALL* drivers were used, causing an output delay of $40ms$.

The frequency and volume of the reproduced sound is based on the same parameters as the vibration feedback. However, simply reproducing the input frequency and amplitude would not create a plausible drilling sound, but would sound very artificial and monotonous. Thus, the sound was enriched with additional overtones. Furthermore, instead of sine signals, it turned out that sawtooth signals produced sounds that more closely resembled the desired tools. The effect of beats and modulation as well as the implementation of minor random functions further enhanced the realism of the sound, and made it appear less synthetic. Additionally, applying a set of bandpass filters attenuated certain frequency regions to achieve a more harmonic impression. For all these adjustments, we took care that they only affect frequencies above $200Hz$. The Frequency range containing the base interaction frequency was not altered in order to maintain the comparability to the vibration.

After the sound synthesis, a short room reverberation was added to the signal because an acoustical free field environment without any reflections and reverberation would appear unnatural. Furthermore, the sound source was spatialized using binaural synthesis using the tracked position of the user's head. By convolving the audio signal and a generic head-related impulse response and by attenuating it by distance, the generated sound appears to come from the visual position of the virtual drill in order to make it appear more realistic.

5. Results

The study was conducted with 30 participants (age 20-33, average 25.5 years). 20 were male and 10 female, and all of them had normal hearing and normal or corrected-to-normal vision.

5.1. User Performance

The main measurements during each task were the amount of removed target material (RTM) and the error (ERR) measured as the amount of erroneously removed surface material. However, these values depend on the overall performance of a participant, which varies significantly. Some people were more careful in general, and thus removed less material and made a smaller error than others, while others worked faster and made a larger error. To allow a comparison of the measured values among participants, the results were normalized by a participant's average RTM and ERR over all trials, resulting in the normalized removed target material (nRTM) and normalized error (nERR). After this adjustment, the distribution of the measurements resembles a normal distribution. To examine learning effects, the average

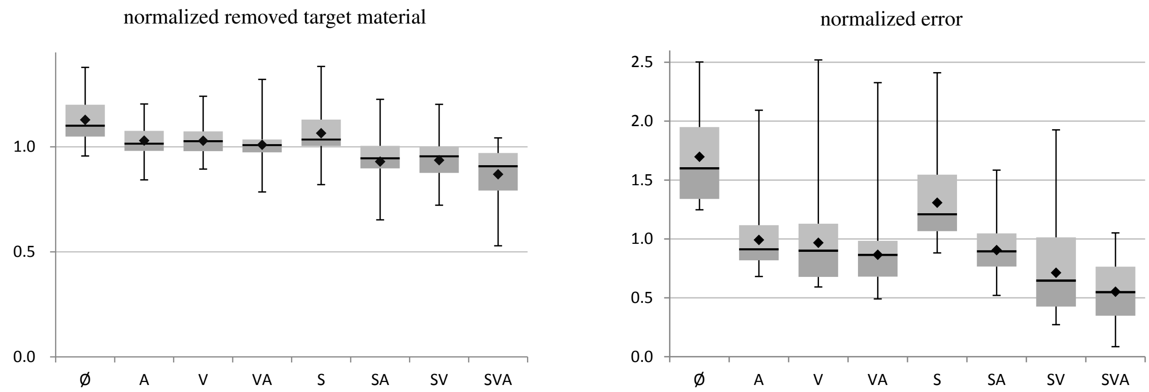

Figure 3: *Box plots of the normalized removed target material (left) and the normalized error (right) under different feedback conditions ([S]urface×[V]ibration×[A]uditive), showing the mean (diamond), median, .25- and .75-percentiles (box), and minimum and maximum (whiskers).*

RTM and ERR in the three sequential blocks were examined. They showed no significant deviation and varied by less than 5%.

The results of the nRTM and nERR for the eight different conditions are plotted in Fig. 3. As the results show, adding feedback slightly reduces the amount of target material that is removed, while strongly reducing the error. For both measures, the trends are similar: when adding either A, V, or both to the conditions Ø or S, the values drop by a similar amount. A MANOVA was performed to find significances of the differences between the conditions. The p-values for each combination of conditions are shown in Table 1, and significant differences are highlighted.

The results show that conditions A, V, and VA have significantly lower nRTM and nERR than the condition without any feedback (Ø). At the same time, none of A, V, and VA significantly differ from one another. Similarly, condition S shows highly significant differences to either SA, SV, or SVA, while there is again no significant difference between any of SA, SV, and SVA except for a decrease of nERR from SA to SVA.

When comparing conditions with S to the corresponding condition without S, the results vary. If at least one other feedback type is present, the nRTM shows a significant decrease when adding surface force feedback, but the decrease in nERR is not significant. On the contrary, when comparing Ø to S, the nRTM shows no significant decrease while nERR is now significant.

5.2. Questionnaire

In the post-study questionnaire, participants rated several questions about involvement, helpfulness and easiness on a 5-point Likert scale. The results for selected questions are shown in Fig. 4.

The answers indicate that all components of the virtual environment – visual, audio, vibration and surface haptics – work well and involve the users. Furthermore, each of the three feedback variants were regarded to be of similar helpfulness. In direct comparison, most participants preferred one feedback type over the others – however, these preferences were distributed evenly so that on average, no feedback type was regarded distinctively more helpful than oth-

normalized removed target material

	Ø	A	V	VA	S	SA	SV	SVA
Ø	+	**.012**	**.011**	**.001**	.319	**<.001**	**<.001**	**<.001**
A	**.012**	+	.999	.997	.914	**.011**	**.023**	**<.001**
V	**.011**	.999	+	.997	.905	**.012**	**.025**	**<.001**
VA	**.001**	.997	.997	+	.506	.089	.157	**<.001**
S	.319	.914	.905	.506	+	**<.001**	**<.001**	**<.001**
SA	**<.001**	**.011**	**.012**	.089	**<.001**	+	.999	.385
SV	**<.001**	**.023**	**.025**	.157	**<.001**	.999	+	.253
SVA	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	.385	.253	+

normalized error

	Ø	A	V	VA	S	SA	SV	SVA
Ø	+	**<.001**	**<.001**	**<.001**	**.005**	**<.001**	**<.001**	**<.001**
A	**<.001**	+	.999	.927	.052	.991	.132	**.001**
V	**<.001**	.999	+	.977	**.026**	.999	.221	**.002**
VA	**<.001**	.927	.997	+	**.001**	.999	.821	.055
S	**.005**	.052	**.026**	**.001**	+	**.003**	**<.001**	**<.001**
SA	**<.001**	.991	.999	.999	**.003**	+	.584	**.017**
SV	**<.001**	.132	.221	.821	**<.001**	.584	+	.778
SVA	**<.001**	**.001**	**.002**	.055	**<.001**	**.017**	.778	+

Table 1: *p-Values of the difference in normalized removed target material and normalized error between feedback conditions. Light grey cells indicate significant results, dark grey highly significant results.*

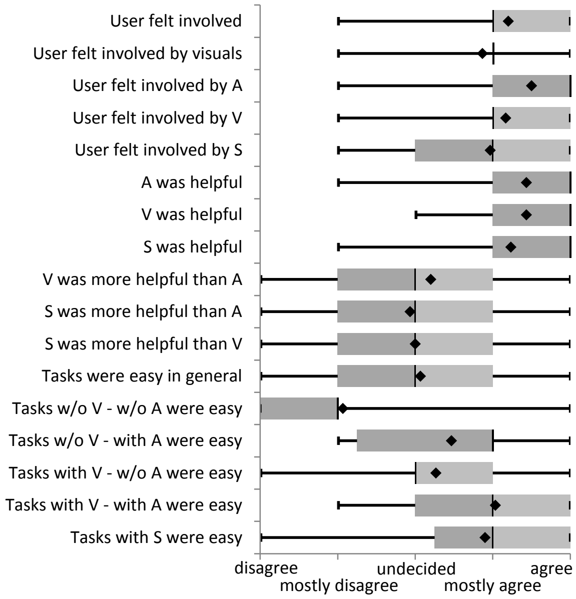

Figure 4: *Post-study questionnaire results, showing the mean (diamond), median, .25- and .75-percentiles (box), and minimum and maximum (whiskers).*

ers. Considering the easiness of tasks under different conditions, it can be seen that tasks with neither acoustic nor vibrational feedback are regarded as most difficult, A and V are considered to be of similar helpfulness, and AV-tasks are the easiest. Surface force feedback is considered nearly as helpful as having both vibrational and haptic feedback.

6. Discussion and Conclusion

With this study, we intended to show that for the drilling scenario, auditory feedback can help compensating the lack of certain types of haptic feedback. For this, we test the following four hypotheses:

H1 *Adding feedback enhances user performance.* Since auditory and vibration feedback allow users to notice when they start removing the wrong material, they should be able to correct mistakes sooner. When surface force feedback is present, the response forces allow for a better control of the drilling speed. The results show that the addition of any of the three feedback types leads to a slight reduction of the amount of removed target material, as well as a more pronounced reduction of the erroneously removed material. In general, **H1** can only be confirmed for nERR, but not for nRTM. A possible explanation for the reduction in nRTM is that the additional feedback makes users more careful even before they make an error, thus reducing their speed. Still it can be concluded that the overall performance increases because nERR is reduced by a larger amount than nRTM, and the participants were particularly instructed not to remove any material from the original surface. This is further supported by the results of the questionnaire that show a better rating for ease and helpfulness when feedback is present.

H2 *Auditory and vibrational feedback have a comparable influence on user performance.* This hypothesis is assumed because both A and V provide the same information – namely the type of material that is currently drilled – and are based on the same physical property. Comparing the relative influence of acoustic and haptic feedback, one can see that conditions A and V have very similar nRTM and nERR values. Furthermore, the participants rated the helpfulness and ease of A and V very similar. Thus, **H2** has been confirmed.

H3 *Combining auditory and vibrational feedback does not increase performance further.* Both feedback types provide the same information, and thus their combination should not provide a notable increase in performance. When comparing conditions VA to A and V as well as SVA to SA and SV, no significant difference can be found except for the change of nERR between SA and SVA. However, the participants rated condition VA better than A and V. Because of the user evaluation and the one significant deviation, **H3** cannot be fully confirmed. However, the results still indicate that both types interact with one another since the differences are very small.

H4 *The impact of surface force feedback is independent of other feedback types.* Unlike A and V, S does not provide information about the removed material type, but about surface contact and force. Thus, its influence on the user's performance should not be influenced by the other feedback types. **H4** can be confirmed due to the difference in nRTM and nERR when comparing S with SA, SV, and SVA, and furthermore because the decrease in nRTM from Ø to A, V, and AV is very similar to the decrease from S to SA, SV, and SVA. Although the nERR results do not differ significantly between either A, V, and VA and the corresponding variants including S, this can be attributed to the dominance of the other feedback types.

The results of the study show that auditory and vibration feedback have a similar influence on user interaction because both lead to similar changes, while combining them only leads to a slight improvement over the separate conditions. A main focus during the design of the study was to make those feedback types as comparable as possible. Both provide information about the same interaction state – i.e. the type of material that is currently drilled – and are based on the same physical properties.

Surface force feedback, however, provides information about contacts with the surface, but not about the material type. Thus, its influence on nRTM and nERR differs from that of A and V, so that a combination of feedback types further influences the interaction. The influence of S on the interaction performance is lower than A and V, although it was rated almost as well as the condition AV in the questionnaire.

Additionally, when another feedback type is present, adding surface feedback does not lead to a significant reduction in nERR while at the same time reducing nRTM. Thus, in these cases the addition of surface force feedback is actually detrimental. This might be explained by a dominant influence of direct error feedback from the other modalities.

From the results of this study, one can conclude that for this scenario, vibrational and auditory feedback lead to a similar improvement in performance, whereas combining both does not lead to a significant improvement over the individual conditions. At the same time, the comparison with surface force feedback shows that the auditory or vibrational condition can still be combined with another feedback type. Thus, the vibrational and auditory feedback have very similar influence on the user performance. This indicates that it is possible to compensate the lack of a haptic feedback by the auditive modality.

While the study investigated a drilling task, the results should be applicable to similar scenarios with feedback that resembles a vibration, for example sawing or grinding. Further studies should determine to what degree the results translate to less similar scenarios as long as they depend on feedback that is simultaneously transmitted by the haptic and auditory modalities. For example, car and flight simulators – where information about the motor state is transmitted by sound and haptics – are other scenarios where auditory feedback could substitute haptics.

Apart from an investigation of additional scenarios, future work may be conducted to compare vibrational and auditory feedback in the absence of visual feedback. Without a graphic representation, the other feedback modalities gain importance, potentially showing a more significant difference.

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