Conveying the Perception of Kinesthetic Feedback in Virtual Reality using State-of-the-Art Hardware

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ABSTRACT
Including haptic feedback in current consumer VR applications is frequently challenging, since technical possibilities to create haptic feedback in consumer-grade VR are limited. While most systems include and make use of the possibility to create tactile feedback through vibration, kinesthetic feedback systems almost exclusively rely on external mechanical hardware to induce actual sensations so far. In this paper, we describe an approach to create a feeling of such sensations by using unmodified off-the-shelf hardware and a software solution for a multi-modal pseudo-haptics approach. We first explore this design space by applying user-elicited methods, and afterwards evaluate our refined solution in a user study. The results show that it is indeed possible to communicate kinesthetic feedback by visual and tactile cues only and even induce its perception. While visual clipping was generally unappreciated, our approach led to significant increases of enjoyment and presence.

ACM Classification Keywords
H.5.2. User Interfaces: Interaction styles; H.5.2. User Interfaces: Haptic I/O

Author Keywords
kinesthetic feedback; pseudo haptics; virtual reality.

INTRODUCTION
Virtual reality (VR) has made its way to the homes of end users. Current VR headsets are tracked by sensors and allow direct interaction using controllers which are as well tracked in the 3D space. This way, users can move freely in the tracking space and interact in a more natural way. However, along with this natural interaction, raised expectations of consumers are coming along – especially regarding feedback. In comparison to other interaction techniques such as mouse and keyboard or gamepads interaction with tracked controllers enables the illusion of virtual body ownership [44, 15]. If users interact with their real hands, users may tend much more to expect haptic feedback. The increasing advance in display technology and rendering lets the virtual world become some kind of true alternative reality. The real visual information is fully overridden by the virtual one. However, the same does not apply to other human senses. Due to the mismatch between virtual and real world, it is rather difficult to enable true haptic feedback. If a user pushes a virtual object, there is no restriction perceived or touch felt, because no real counterpart exists.

The feeling of touch is often represented using vibration, which is though not matching the real expectation, some kind of substituting tactile stimulus. The feeling of kinesthetic feedback (i.e. the resistance when physically pushing an object) is more difficult to display, since it depends on a physical directional force which is hard to realize without a matching real world counterpart. Though different solutions for providing *kinesthetic* haptic feedback in VR were presented by researchers, none of them is used in consumer hard- or software for facilitating kinesthetic feedback. These approaches require additional hardware, making it difficult to be included in consumer grade VR systems. In addition, most of the presented kinesthetic feedback devices are too big and expensive (e.g. exo-skeletons) to be integrated into consumer products.

The current state-of-the-art solution in today's VR games (e.g. [5, 21]) frequently is to let virtual hands clip through virtual objects. Since the real hand is not really colliding with the virtual object, there is no physical barrier to prevent the hands from penetrating a virtual object. In order to mitigate the effects thereof, i.e. breaks of immersion and presence, an approach to provide haptic feedback with current consumer-grade hardware is desirable. Further, such haptic feedback can provide benefits for developers of VR experiences, by offering new interaction possibilities currently limited by hardware. In general, two output channels can be used with the current consumer VR hardware: tactile haptics (in form of vibration) and visual (in form of pseudo-haptic feedback).

We hypothesize that it is possible to combine the tactile haptics and visual manipulations in a way to facilitate kinesthetic feedback for VR applications. By employing a user-elicited approach, we developed a first prototype using the available channels and let users interact with virtual objects. In a semi-structured interview we collected qualitative feedback on how to improve and design the respective channels. After updating the software prototype, we conducted a second study with the aim of getting insights on the effect of the different channels regarding immersion and enjoyment, but also on how realistic and sufficient the feedback was perceived. Finally,

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we contribute guidelines on how the feedback part of software should be designed to improve the VR experience.

We found that vibration can be combined with perceivable pseudo haptic effects to communicate kinesthetic feedback and even induce its perception to a certain degree. In addition, we found the current state-of-the-art using clipping is not appreciated by users. The presented solution, though, significantly increased immersion and enjoyment.

RELATED WORK

There are several object properties associated with haptics in general – such as pressure, temperature, size or weight. Considering kinesthetic feedback, the bone structure of the human body additionally forwards the resistance of a stationary object to be felt in larger parts of the body (e.g. pressing a hand against a wall can be felt in the shoulders). Researchers have presented a variety of solutions ranging from physical-only to software-only solutions to include such sensations inside VR. Since this paper is focused on tactile but most of all kinesthetic perception, the work presented in the following also is focused on these aspects.

Physical solutions

Tactile

The most common haptic feedback channel is vibration, as respective actuators are small and lightweight enough to fit in all kinds of wearables or controllers. It can also be found in the state of the art VR controllers (e.g. HTC Vive or Oculus Touch), was used in various kinds of wearables (e.g. [17, 28]) or was used in VR research projects (e.g. [34, 35]) to enhance tactile feedback.

Tactile feedback can also be applied by stretching the skin (e.g. [7, 2]), using physical shape displacement (e.g. [3]) or airflow (e.g. [43, 48]).

Weber et al. compared different ways of communicating collisions by visual, vibration and force feedback by a robotic arm [52]. They found that substituting force feedback with vibro-tactile cues increased the cognitive load, while visual feedback only was perceived as less ambiguous but increased the task completion time.

Kinesthetic

Those tactile interfaces do not allow displaying directional forces as needed to simulate kinesthetic feedback. Grabbing objects can for example be realized by using layer jamming (e.g. [47]). Another way of displaying directional forces is the use of tethers, which can be held (e.g. [33]) or stationary mounted around the user (e.g. [16]). Exoskeletons were also used to simulate forces or restrictions either on the hands [4, 6, 10, 13], an whole arm (e.g. [36]) or just attached between two body parts (e.g. [51]).The kinesthetic feedback of exoskeletons was also combined with tactile feedback (e.g. [20]).

Another way to provide directional kinesthetic feedback is the use of EMS (e.g. [11, 29, 30, 37, 50]) where single or groups of muscles are actuated. Lopes et al. used this approach to simulate even weight by actuating opposing muscles [31].

Using the real physical world

The physical mismatch between virtual and real world can be compensated by creating a physical world around the user. This was done using robots (e.g. [12, 32, 53]) or by other humans [8]. A similar idea is passive haptic feedback or the substitution of virtual objects with similarly shaped objects [14, 19, 46].

On the other hand, it was also suggested to visually redirect users' movements to match the virtual world with real world counterparts. This was done for touching static surfaces (e.g. [18, 45]) or objects [1].

Software solutions

Another way of communicating haptic feedback is by using pseudo-haptics, which can be applied using software-only solutions. The idea is to provide haptic feedback without the real stimulus, but by *faking* it via vision [22]. Visual stimuli are presented synchronized to interaction, like e.g. touching an object. Pseudo-haptics were most of all used for tactile feedback, such as friction [24, 25], stiffness [49]. Other works proposed to use pseudo-haptic effects to simulating forces [26, 23], the subtle resistance of airflow ([39, 40]) or weight [9]. On the other hand objects may react or deform as a reaction of touch (e.g. [38]).

These works show that it is possible to communicate directional forces by visual feedback only. Though, most of the presented works were not designed for the application in VR. The illusion of body ownership as well as the strong feeling of proprioception when directly interacting with a controller cannot be compared to on-screen-experiment using a mouse as input device (e.g. [23, 26]). Other approaches, which were tested and implemented for VR, use such effects in a very subtle way, without breaking with proprioception. It was shown, that virtual body motion can be manipulated to communicate special feedback (such as slow-motion) [42] and that perceivable tracking offsets are accepted as a metaphor for weight [41]. In contrast, we assumed that even obviously breaking with proprioception would still be more appreciated then the alternative of using clipping. We also expected that with increasing intensity of such effects the respective induced level of perception of kinesthetic feedback will increase.

PERCEIVABLE VISUAL MANIPULATIONS

Although different solutions to introduce haptic feedback in VR were presented, none of them was realized in consumer hardware. Even pseudo haptic effects which could be realized by a software-only solution are rarely found in applications. One problem of current pseudo haptic approaches is their expressiveness. This is due to limiting the design of visual manipulation in a way a user does not perceive breaking with proprioception. Though one could argue that this is of great importance to keep presence and immersion, we assume that perceivable manipulation can even enhance these feelings due to the additional feedback. Virtual reality does not have to be a one-to-one match of the real world. VR consumers already accept interaction metaphors as part of the virtual world (e.g. using teleportation for moving around). We therefore argue, that users may also accept perceivable visual manipulation as a metaphor of communicating kinesthetic feedback. On the other hand, the lack of perceivable manipulation has some drawbacks, too. When for example pushing against a virtual object that cannot be moved, the virtual hands have to penetrate it (clipping). We argue however, that such clipping effects are not less unrealistic than breaking the proprioception by applying stronger visual manipulations in form of tracking offsets.

With this paper, we aim at answering whether users prefer breaking with proprioception to enable the communication of kinesthetic feedback or dislike such a concept and prefer effects such as clipping. Further we strive to optimize such pseudo-haptic effects with the available haptic feedback channel (vibration).

We built our work on an approach based on user-elicitation and expert interviews. First, we conducted a workshop with VR researchers to discuss relevant aspects of haptic perception and the associated interaction, then we implemented a prototypical system that communicates kinesthetic feedback with perceivable tracking offsets as visual manipulation as well as vibration feedback. Based on the results of semi-structured interviews we improved the software prototype and conducted a second user study, in which we evaluated different combinations of channels for haptic feedback with respect to immersion, enjoyment and the perception of tactile and kinesthetic feedback. Finally, a second workshop with VR researchers was conducted to discuss the findings of the user study and their implications.

EXPERT WORKSHOP

The presence of natural haptic feedback in the real world is self-evident. A metric to describe the quality of haptic feedback is therefore not trivial. Since there is no questionnaire on measuring the quality of induced haptic perception, we invited five researchers working in the field of virtual reality to discuss the topic of haptic perception in VR. The experts were researchers with a focus on VR including three focused on interaction, one focused on perception and one working in the field of serious games.

Discussing the Quality of Haptic Perception

We motivated the discussion with the discordance of real and virtual space which prevents direct kinesthetic feedback.

It was first discussed that realism in terms of virtual reality might not be the same as in the real world. The consensus was that whether a certain feedback is actually realistic or not, it can be interpreted as realistic as long as it is perceived accordingly. Feedback should therefore conform to expectations. This should be represented by both, objects' behavior as well as the provided feedback. Expectations were divided into two main parts. The first was the presence of feedback or the respective stimulus. This implies, that e.g. a feeling of restriction, texture, touch or temperature, should be perceived at all. The second part of expectation conformity was seen as the realism of the respective feedback. The same two metrics could also be applied on objects' behavior, since objects should first of all react to user interaction, but also behave in a natural way.

Another important factor was seen in the ability of communicating objects properties in a way a user can compare two objects based on the respective feedback. This could be for example that one object is perceived as heavier, since it induces a stronger kinesthetic feedback.

The last topic was about direct manipulation. Haptic feedback should support the feeling of being in control of manipulating objects in the virtual world.

Though not relevant for our evaluation of kinesthetic feedback, two additional items were considered as relevant for special applications: (1) If there is kinesthetic feedback, it may be relevant how exhausting it was to interact with a virtual object. This effort could on one hand be interpreted as positive, if desired by the application e.g. in the simulation domain, or negative if too exhausting e.g. during casual gaming. (2) Some gaming scenarios could have an entirely different focus on haptic perception, since it may be more useful to communicate boundaries of interaction considering elements of game play, than to provide the most realistic feedback.

Deriving Questions

In the second part of the workshop the participants derived questions based on the discussion. This process was guided by the study conductor. The first two questions were based on the two discussed parts of expectation conformity. The first question, targeting towards measuring the presence of a stimulus was stated as *I could feel [a stimulus].* The second one, targeting to measure the perceived realism, was formulated as *The representation of [the stimulus] felt realistic.* The matching items for measuring the object behavior were *I could manipulate the behavior of objects with my actions* and *I had the feeling of manipulating real objects*. To measure the ability of communicating haptic properties to allow a discrimination on the basis of feedback was formulated as *I could perceive a different [object property] when interacting with the objects*.

USER STUDY I

We designed a simple VR application, in which participants had to interact directly with the virtual surrounding. By using state-of-the-art hardware we designed different feedback modalities using a common VR controller (Oculus Touch), as well as vibration and visual feedback in form of pseudo-haptics. We presented the different feedback modalities and measured immersion, enjoyment and our own items as discussed in the workshop. The focus of the first iteration was on collecting qualitative data regarding the perception of touch, how the stimuli should be presented and enhanced as well as how sufficient such haptic feedback would be for VR applications.

Participants

We recruited 12 participants (3 female) with an average age of 25.0 (*SD* = 2.3). They were mostly university students and employees. They had an average experience with VR of 9.4 months (*SD* = 11.6), ranging from none to 25 months. We aimed at recruiting very experienced but novice users (without any prior VR experience) as well to get as much variety of feedback as possible.

Design

This study was conducted as a 2x2 within-subjects design with the vibration of the controller and the visual redirection as variables. We did not use auditory feedback, except music to block out ambient noise and the sounds of the vibrating controller. We decided to exclude sound under the assumption, that the auditory channel does not play a major role when creating kinesthetic feedback. We consider auditory reactions of objects (e.g. objects falling to the floor) to be unrelated to the touch itself. We decided to exclude such sounds to prevent uncontrolled side effects, since such effect sounds assumedly only contribute to general presence and enjoyment.

Vibration

The vibration variable consisted of two states *vibration on* or *vibration off*. We implemented the controller to provide a short term vibration feedback of 200Hz for the duration of 50ms each time the virtual hand collided with an object. In the *vibration off* state there was no vibration at all.

Pseudo Haptics

The second variable was related to visual manipulation as pseudo-haptic feedback with two states (*pseudo-haptics on* and *pseudo-haptics off*). Both concepts are illustrated in Figure 1. In the common state-of-the art, the virtual representations of user's hands follow the tracked controller with the most possible accuracy. While the physics engine considers differences regarding weight and resistance between objects that are only virtually present, the controller (having also a real world representation) is treated differently, and is not influenced by virtual objects. While, for example, pushing a virtual object, there is no difference between heavy and light objects during the interaction. Objects, like walls, that are designed to be stationary in a scene and thus cannot be moved have to be clipped by the virtual representation of hands if they follow the tracked controller as close as possible. This state, which we consider as state-of-the-art, is further on referred to as *pseudo-haptics off*.

The second state (*pseudo-haptics on*) uses pseudo-haptic feedback without perceptual limitations and thus allowing a perceived conflict between proprioception and visual input. We designed the virtual hand to be detached from the tracked position of the controller and moved it by translating it each frame to match the real position. The virtual hands more or less modeled like any other physical object present in the virtual scene, but followed the tracking as close as possible as long as there was no barrier. When the hand collides with a virtual object, the kinesthetic force of the virtual hand presses against the virtual object. Depending on the virtual weight of the object, the required force to move it has to be greater or smaller. The euclidean distance between the tracked position and the virtual representation, which is applied as translation, is such a force. The applied force therefore depends on the offset between the virtual hand's representation and the tracked position of the controller. Depending on the object's resistance, the user perceives an increasing offset between visual and real position of the hands. Since a user has to stretch her hands farther for moving heavier objects, such a visual manipulation even leads to a higher effort. In the case of a static unmovable object, there is conceptually no offset limit and the unmovable object as well as the virtual hands keep their position.

Apparatus

As VR headset we used the Oculus Rift CV1 and the Oculus Touch controllers. Our application software was developed with Unity. The virtual environment contained four tasks that were implemented to be representative for different direct interactions with virtual objects (see Figure 2).

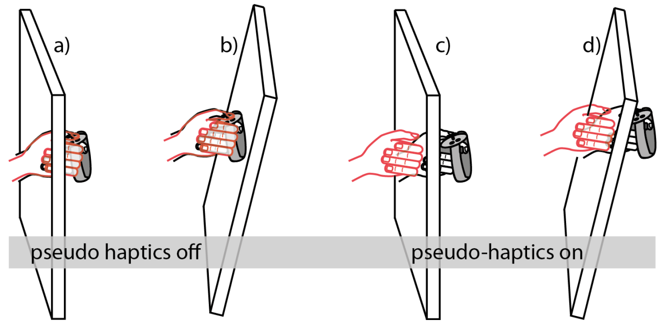

Figure 1. The visual effects present in both visual conditions (red hand represents the virtual one): a) Clipping: if an object cannot be moved, the virtual hand follows the tracked one and penetrates the object. b) when an object can be moved, there is no representation of physical resistance. c) using pseudo haptic feedback, the virtual hand does not penetrate the unmovable object, but the offset between tracker and virtual hand increases. d) An object communicates the resistance by no longer following the exact tracking position (the offset depends on the strength of physical resistance).

Heavy or static objects:

The first task consisted of three walls. The participants were instructed that they could overturn one of them, while the others would be solid. The walls were set to be unmovable until the first two were touched, to make sure that the participants have to try each wall. This condition was used to compare clipping with high pseudo haptic offsets. Depending on the condition, the hands clipped through the unmovable walls or suffered an increasing offset while pressing. The third wall did not resist when being pushed in the *pseudo-haptics off* state, though the visual appearance suggested a heavy weight. In the *pseudo-haptics on* state the wall *resisted*, which led to an offset between tracked controller and the visual position of the hands. This implies that the hands had to reach farther to overturn the wall.

Light objects:

The second task aimed at interacting with smaller and lighter objects. Three vases were placed on a base and the participants had to throw them down. Due to the low weight of the objects, there was only little difference between the *pseudo-haptics on* or *off* state. The pseudo-haptic manipulation only led to little offsets and therefore only little more effort to move the objects. The base was unmovable when touched which led to the already described effects.

Different weights:

As discussed in the workshop, a feedback modality should allow the comparison of object parameters. The third task was therefore to press three stone cubes into a slot in the wall. All cubes had a different weight and therefore resulted in a different strength of kinesthetic forces. In the *pseudo-haptics on* state the differences were represented offsets.

Heavy round object:

The first task involved short pushing of heavy objects, but with the focus on investigating effects of clipping. We therefore included a second task on interacting with heavy objects, though for a longer time. The last task was to roll a heavy stone sphere. Due to the heavy weight and strong friction of the sphere, both visual states differed strongly. In the *pseudo-haptics on* condition the resistance lead to large offsets which aggravated to get the stone rolling. There was no visual communication of resistance in the *pseudo-haptics off* state.

Procedure

The participants were welcomed and introduced to the topic of the study. The introduction included the problem definition of having no direct haptic feedback due to the mismatch between real and virtual world. They were also informed that they could pause or cease the test at any time. The participants were also instructed what to do in the respective tasks. Before starting with the first condition, each participant signed a consent form and completed a demographic questionnaire.

We tested four conditions based on the 2x2 study design (*vibration on, pseudo-haptics on*, *vibration on, pseudo-haptics off*, *vibration off, pseudo-haptics on* and *vibration off, pseudo-haptics off*). Participants played each condition in a different order balanced by a Latin square. After each condition the participants completed the E^2I questionnaire [27] to measure immersion and enjoyment. In addition, we used our own the questions as reported in the workshop.

The participants should state for each task separately how they agree to some statements on a scale from 1 (=strongly disagree) to 6 (=strongly agree). These statements were *"I had the feeling to touch the walls/vases/cubes/sphere"*, *"I could feel a resistance"*, *"The representation of physical constraints felt realistic"*, *I had the feeling of manipulating real objects* and *"I could manipulate the behavior of objects with my actions"*. For task 3, which involved different strength of kinesthetic feedback we also asked *I could feel a difference regarding the resistance of the cubes.* In addition to the items stated by the participants of the workshop, we included two more questions: *"The representation of physical constraints was sufficient for VR applications"* and *"I liked this representation of physical constraints"*.

After completing all tasks, we conducted a semi-structured interview. The topics of interest mostly considered how the participants perceived the different tasks and conditions and which conditions they preferred for each tasks. We also discussed how the respective feedback channels could be designed to increase the desired perception.

A session lasted around 40 minutes and each participant was compensated with 5 Euro.

Results

We first analyzed the difference between the tasks for each condition separately using Friedman's variance analysis. If there was a significant difference, we compared the tasks pairwise adjusting the significance values with the Bonferroni correction. Here we tested only our individual items, since they were the only ones that were gathered for each task separately.

Though the Friedman test showed significant differences, there was no post-hoc difference between the tasks. We therefore calculated a mean of all tasks and used this mean for further comparisons.

In the next step, we examined the influence of visual and vibration feedback comparing the"*vibration on, visuals off*" and "*vibration off, visuals on*" conditions to the ground truth (*vibration off, visuals off*), using Wilcoxon's signed rank test. Vibration significantly enhanced immersion and the approval about whether the representation was sufficient for VR applications. Giving visual feedback significantly improved all scores and items (see Table 1).

	Vibration			Pseudo-haptics		
Score/Item	$\delta\varnothing$	*SD*	*p*	$\delta\varnothing$	*SD*	*p*
Immersion	0.52	0.80	.04*	0.40	0.62	.04*
Enjoyment	0.17	1.20	.53	0.70	0.97	.03*
Touch	0.57	1.45	.15	1.40	1.20	.003*
Resistance	1.00	1.80	.07	1.75	1.56	.003*
Sufficient	0.59	1.50	.01*	1.20	1.31	.007*
Realistic	0.67	1.50	.10	1.60	1.39	.004*
Like	0.90	1.60	.20	1.35	1.30	.001*

Table 1. Overview of the change of the scores compared to the ground truth without vibration and pseudo-haptics: $\delta\varnothing$ is the mean change of the scores when being treated with vibration or pseudo-haptics (positive implies an increase of the respective score).

The recordings of the semi-structured interviews were transcribed in note form. Two researchers performed an open coding on the interviews. All codes were compared and conflicts resolved by discussion. By axial coding, based on the codes, themes and concepts were identified.

Vibration was seen as a supporting channel enhancing the visual feedback of touch (four mentions). If there was only vibration feedback, it was seen as disturbing (three mentions) or irrelevant (one mention). On the other hand, participants saw greater potential for vibration feedback to communicate kinesthetic and tactile feedback when combined with visual pseudo-haptics. Five participants emphasized the interaction between vibration and offsets. They saw vibration as a supportive channel, enhancing the feeling of kinesthetic forces when combined with pseudo-haptics, but not when presented alone. For one participant, vibration was enough tactile feedback.

Pseudo-haptic feedback was most of all described as realistic (eight mentions) while four participants stated a physical feeling of restrictions. Four participants commended the greater design space, since they could identify different levels of restrictions. One of them saw great potential for interactions. Besides this, the redirection metaphor was described as logical and playful. Participants also associated the offsets with pressure between hand and object. One participant criticized offsets of static objects when fully stretching the arms. Another participant stated **clipping** would be more realistic, since there is no matching real counterpart to touch. All other participants, however, were opposed to clipping. Some stated it felt like an error of the game while others just described it as unrealistic or that it would destroy the immersion.

Another topic of interest was **missing haptic feedback**. Two participants stated that it would destroy the immersion to get no real haptic feedback. The other participants did not miss haptics that much. Some stated that they just do not expect a true haptic feedback due to the nature of virtual reality. Eight participants stated that the representations were enough, while two emphasized the importance of vibration and five

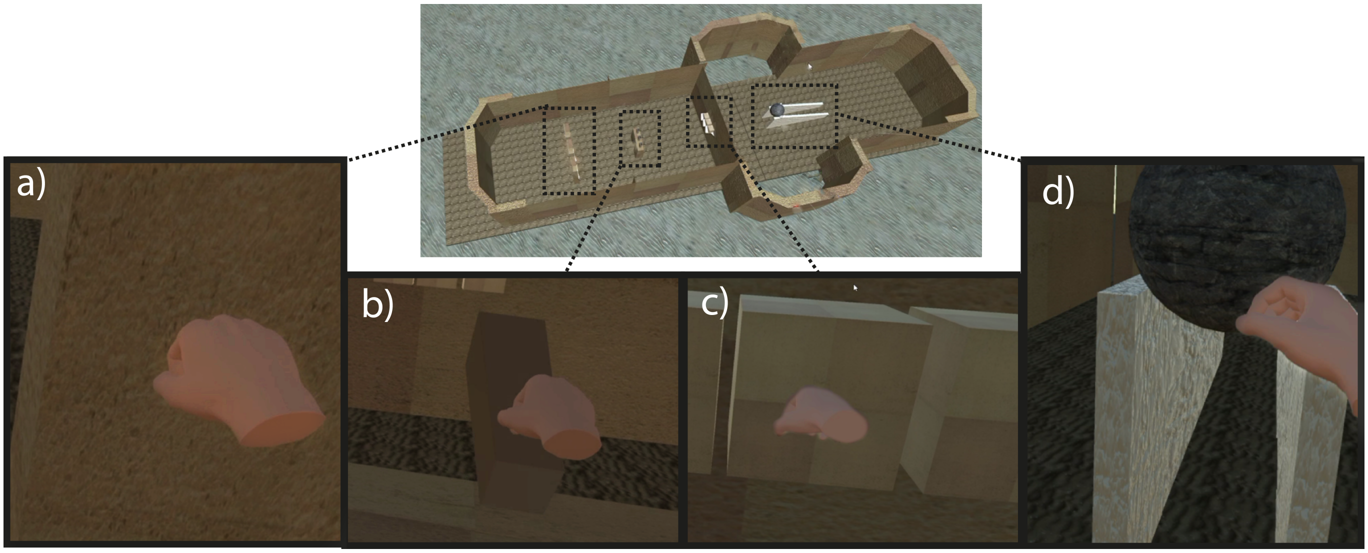

Figure 2. The different tasks as implemented for the study: a) one of the three stone walls which should be overturned, b) a vase on the base which should be thrown down, c) the cubes which should be pressed into the wall and d) the heavy stone sphere which should be rolled.

the pseudo-haptic. Another participant stated that visual and vibration is enough, but only compared to no feedback.

Finally, we identified potential **improvements** regarding the design of the available feedback channels. One half of the participants stated a desire for constant vibration while touching objects, while others wanted the vibration to be designed more subtle. Eight participants wished to couple the vibration with the visual feedback in a way that vibration increases with the pressure which was visualized by increasing offsets. Three participants desired the visual hands to react on the touch. This could for example be done by forming a fist, or if the hands are open prior to the touch, by stretching fingers. Two participants also talked about auditory feedback when manipulating objects. The participant who struggled with too high offsets when pressing against a static object with fully stretched hands suggested to use clipping as a fall back strategy in such cases.

USER STUDY II

We implemented the participants' suggestions for improving the feedback channels and conducted a second user study to further evaluate our research question. The same conditions were used as in the first study, i.e. vibration (on-off) and pseudo-haptics (on-off). Since some participants complained about missing auditory feedback we designed another condition (*full feedback*). This condition included all feedback channels with additional effect sounds. These effects were crashing sounds when the wall or vases drop to the ground, scratching when the cubes were pressed into the wall and a sound of a rolling ball while the sphere of the last task was moving. Besides the demand of the participants for heaving sound effects, we were also interested to test our solution in a condition which is more related to a common application, where sound effects are most likely part of.

Participants

We recruited another 20 participants (10 female) with an average age of 24.3 (*SD* = 2.3). They had 2.6 months of VR experience on average (*SD* = 6.4), ranging from none (10 participants) to 24 months. In this study, we aimed at recruiting most of all novice VR users, since we expected them to provide the most neutral feedback without being influenced by existing representations.

Apparatus

The same hardware setup was used as in the first user study and the virtual environment and tasks remained the same as well. However, we implemented a couple of software improvements we derived from the interviews.

Visual feedback: Since the participants hands were holding a controller, their hands already formed a fist (real and virtual). We therefore decided to visually close the hands more when an object was touched. This feature was implemented as an animation changing the finger angles as soon as the hand's collided with an object.

Vibration feedback: Most of the participants comments were about the vibration. They desired a constant feedback which should be coupled with the visual feedback. We therefore implemented vibration in two different ways. In the *vibration on, pseudo-haptics off* condition, vibration was changed to be lasting as long as an object was touched. We also decreased the frequency to 150Hz according to the wish of some participants.

In the *vibration on, pseudo-haptics on* condition, we increased the frequency of the vibration with the euclidean distance between the tracked position of the controller and the visually displayed hand. Since the increasing offsets were associated with pressure, the increasing frequency should also be used as the same metaphor as desired by some participants.

Procedure

The second study was designed equal to the first one, including the same introduction and questionnaires. The tested conditions remained the same in general except the described modifications. The order of conditions was again balanced by Latin square. After each task, participants completed the questionnaires known from the first study. After the last iteration, the participants were asked to fill in a final questionnaire containing more general questions. Participants stated their agreement on a scale from 1 (=strongly disagree) to 6 (=strongly agree) to several statements. The first statements regarded the different feedback channels and included the items *"The resistance of an object should be represented by vibration"*, *"The resistance of an object should be represented by visual offsets"* and *"My hands should penetrate objects that cannot be moved"*.

After this final questionnaire the participants were presented the last condition with additional effect sounds. This condition was always played last, since we refer effect audio not to be directly contributing to kinesthetic perceptions, but though most likely influencing some of the scores. We therefore did not compute any statistical test on this condition and only used it as hint towards how compelling a real application could be with the proposed combination of vibration and pseudo-haptic feedback. Here we also measured immersion, enjoyment as well as our own items.

A session lasted for about 45 minutes and each participant was compensated with 5 Euro.

Results

We split the description of results in four main parts. Starting with the difference between the tasks, we compare the influence of the different feedback channels as well as the differences between the first and second iteration. We conclude with the results of the final questionnaire.

Tasks

As a first step, we compared the tasks of each condition for differences regarding the scores with Friedman's variance analysis for dependent variables. There was no significant difference, so we calculated a mean score over all tasks as score for the whole condition.

Feedback Channels

The results of presence and enjoyment is illustrated in Figure 4, the individual items are shown in Figure 6 and Figure 5. The ratings for the rating whether the representation was sufficient are illustrated in Figure 3.

We compared the conditions having only one feedback channel being in the *on* state to the ground truth (all states *off*) using Wilcoxon's signed rank tests to get insights on the influence of the different feedback channels.

While immersion and enjoyment was not influenced significantly by vibration, we could find a significant increase of the feeling of touch (*p=.028; Z=2.0; r=.45*) and resistance (*p=.021; Z=2.4; r=.54*).

Comparing the *pseudo-haptics* with the ground truth, immersion (*p=.025; Z=2.50; r=.56*) and enjoyment (*p=.048; Z=1.95; r=.44*) were significantly increased. We also observed a significant increase of the feeling of touch (*p=.002; Z=3.03; r=.68*) and resistance (*p=.001; Z=3.23; r=.72*). There was also a significant difference regarding the rating whether the haptic feedback would be sufficient (*p=.001; Z=3.27; r=.73*). The participant also reported a significant higher feeling of touching real objects (*p=.002; Z=3.10; r=.70*) and the feeling of being more in control of the manipulations (*p=.033; Z=2.14; r=.48*).

The item whether participants could distinguish between different strengths of kinesthetic feedback was only asked for the third task and was therefore not averaged over all tasks. While vibration did not increase the ability to differentiate kinesthetic feedback (*p=.63; Z=.74; r=.17*). The pseudo-haptics though significantly increased this ability (*p=.007; Z=2.72; r=.06*).

The condition where vibration was coupled with pseudo-haptic feedback increased the immersion (*p=.012; Z=2.5; r=.56*) and enjoyment score (*p=.031; Z=2.16; r=.48*) as well as the single items regarding the feeling of touch (*p=.00; Z=3.70; r=.83*), restriction (*p=.00; Z=3.75; r=.84*), realism (*p=.001; Z=3.21; r=.72*) as well as the feeling of interacting with real objects (*p=.001; Z=3.19; r=.71*) and being on control (*p=.003; Z=3.02; r=.68*). Participants also liked the condition more (*p=.004; Z=2.90; r=.65*) and rated it to be more sufficient (*p=.00; Z=3.49; r=.78*). The ability to differentiate different strengths of kinesthetic feedback was also judged as significantly higher (*p=.00; Z=3.66; r=.82*).

We also compared the three feedback modalities (vibration, pseudo-haptic and the combination of pseudo-haptic feedback and vibration) using the Friedman's analysis of variance.

While immersion and enjoyment did not differ significantly, our individual items did all show significant differences. Pairwise comparisons with Bonferroni corrected significance values showed that the combined feedback provided a better feeling of touch (*p=.002; Z=3.41; r=.76*) and resistance (*p=.003; Z=3.32; r=.74*) than vibration only. It was also liked more (*p=.028; Z=2.60; r=.58*) and rated more sufficient (*p=.001; Z=3.72; r=.83*) and realistic (*p=.003; Z=3.33; r=.74*) than vibration only. The use of pseudo-haptic feedback only also provided a stronger feeling of resistance compared to vibration only (*p=.027*).

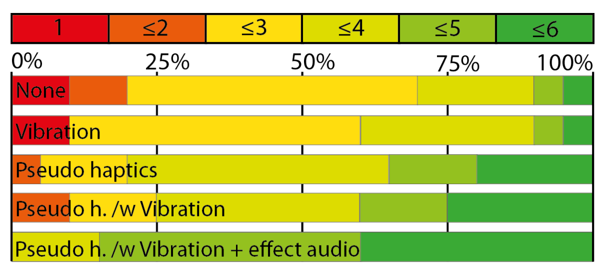

Figure 3. The ratings of the item whether the feedback modality was sufficient to communicate kinesthetic feedback.

Study I vs Study II

We also compared both iterations using the Mann-Whitney-U test. The only condition that was the same in both iterations was the ground truth with all states *off*. Here we found no significant difference between both iterations.

There was also no significant difference comparing the pseudo-haptics and vibration only conditions. The "*pseudo-haptics on, vibration on*" condition though was significantly different in the first and second iteration regarding immersion (*p=.048*) and enjoyment (*p=.043*) as well as the single items whether the

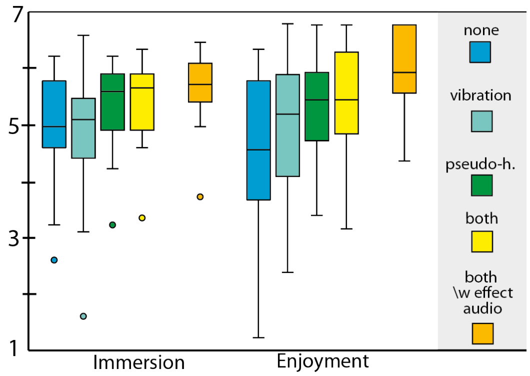

Figure 4. Box plots of the immersion and enjoyment scores.

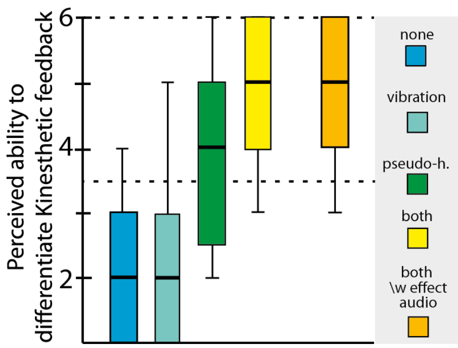

Figure 5. Box plots of the ratings whether the participants could distinguish different kinesthetic feedback. Note: Scores are only based on task 3.

feedback was sufficient (*p=.008*) and realistic (*p=.050*). We also found a significant increase on the perception of touching real objects (*p=.025*) and the perceived ability to manipulate them (*p=.025*). Participants also liked the second iteration significantly more then the first one (*p=.002*). An overview of the results is presented in Figure 7.

Final Questionnaire

After all conditions (except the separate condition including effect sounds) were played and all questionnaires were completed, the participants answered one last questionnaire containing items concerning their general preferences. The participants were asked to answer whether they agree to statements about the use of the respective feedback channels. Most participants agreed that vibration and pseudo-haptic feedback should be used to represent kinesthetic feedback, while clipping should be avoided. The results are shown in Figure 8.

EXPERT DISCUSSION

We presented the results to the same VR researchers, that were involved in the initial workshop. We discussed implications, as well as limitations in general. Before the discussion, all participants tested the different conditions.

The item whether the haptic representation was sufficient was discussed a lot. All agreed that sufficient has to be distinguished from more positive adjectives (e.g. good). On the other hand, they discussed that VR consumers have low expectations on haptic feedback which could also lead to higher scores. The item *sufficient* should as well be interpreted in the context of the application. A representation may be sufficient for gaming but not for simulations.

Another interesting part of the discussion was about the context. Pseudo-haptic feedback was described as a good way to communicate kinesthetic feedback, but in some gaming scenarios this may not be in focus. Sometimes it is of greater importance to communicate simple object states. In case of static or movable objects it may therefore be useful to use clipping, since it is faster in communicating whether the user can or cannot interact with an object. On the other hand, most of all the pseudo-haptic effects were largely appreciated since they do not only provide some kind of haptic information, but can also be used as part of the game play. Displaying different resistances by tracking offsets could lead to playful effects, such as needing both hands to push an object. According to the experts, the pseudo-haptic feedback also leads to a more natural behavior of objects (e.g. a heavier object moves slower). The experts emphasized the importance of the suggestion raised in the first iteration using an escape strategy, such as clipping, when offsets increase too high. The experts saw a great importance of including stronger effects like the used deformation of the hands to communicate touch or pressure. It was suggested to deform the fingers and change their color to simulate accumulation of blood while pressing.

DISCUSSION

Our questionnaire consisted of two standardized scores (immersion and enjoyment) and some individual items as discussed in the initial workshop. The following discussion will be divided in three main categories: *expectation conformity, game play* and *participants preferences*.

Expectation Conformity

As discussed in the initial workshop, four of the own items were related to expectation conformity and realism. We also associate the immersion score to be contributing towards realism.

Regarding the different feedback modalities, the pseudo-haptic feedback proved to have the greatest effect on the perception of kinesthetic feedback. While we expected that vibration would have a greater effect on the feeling of touch, and pseudo-haptics being more suitable to communicate kinesthetic feedback, pseudo-haptics proved to be as suitable as vibration to communicate the touch.

Interestingly, the combination of pseudo-haptics with vibration increased immersion, as well as the other scores the most. This matches the results of the semi-structured interview of the first study. Here participants rated vibration as a support channel for visual offsets.

In general, though there were significant differences the rather large variances have to be considered when interpreting the data. The single feedback modalities (vibration only or pseudo-haptics only), as well as the ground truth, all resulted in very diverse judgments, while the combination of vibration and pseudo-haptics seemed to be more consistent. We interpret these variances as result of different expectations. While some participants may be used to vibration as general feedback

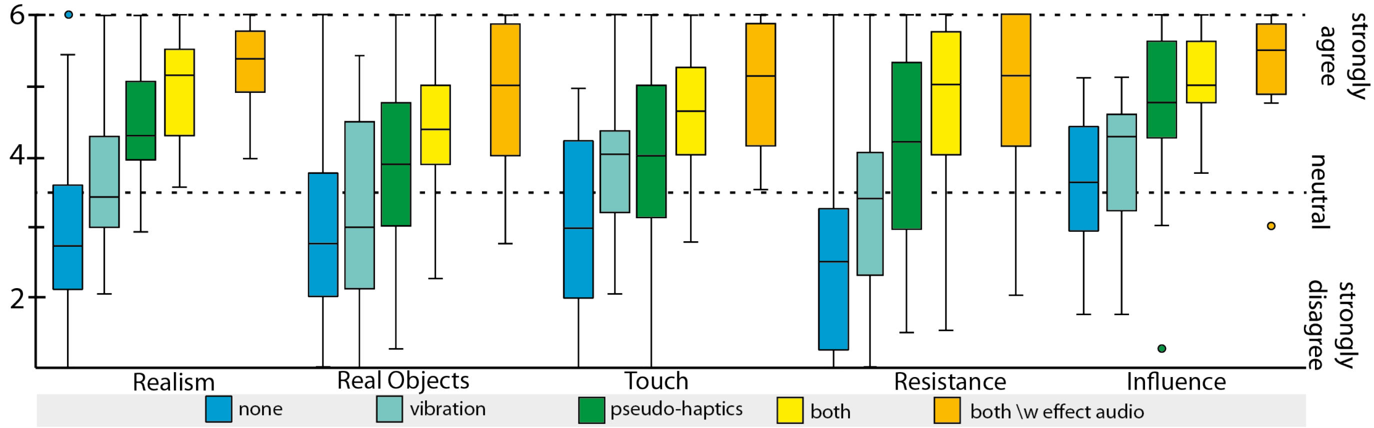

Figure 6. Box plots of the own items.

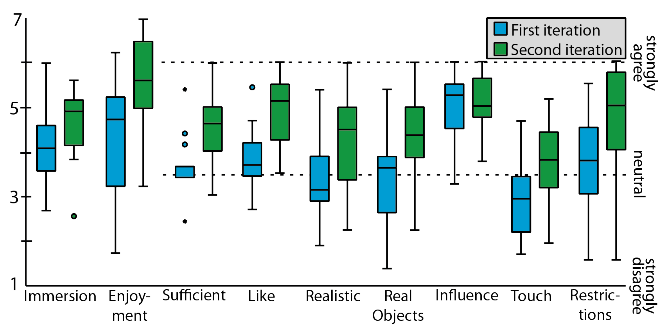

Figure 7. Results of the first and second iteration of the *vibration on, pseudo-haptics on* condition. Note: Immersion and enjoyment scores are on a scale from 1 (minimum) to 7 (maximum), while other items are on a scale from 1 (strongly disagree) to 6 (strongly agree)

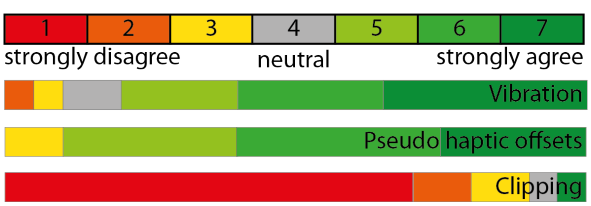

Figure 8. Participants desired the use of vibration and most of all pseudo-haptic effects, while they most of all disagreed with the use of clipping.

channel – which is common in many video games – others may be not.

The use of effect audio: The additional use of effect audio showed interesting effects. While some scores were influenced stronger than others, most of all the variances in the ratings decreased (see Figures 4 and 6). This is a hint towards the importance of auditory effects on the perceived realism. Objects should not only react visually but also via audio to user interactions.

Game Play

We associate the scores of influencing objects as well as the enjoyment score to be contributing to game play issues. The application was not designed as a game, since we did not want to distract the participants from the provided haptic feedback. We therefore want to emphasize that enjoyment scores could vary strongly depending on the context of the application. Since enjoyment was not the focus of the experiment, it was not unexpected that the scores did not vary strongly over the different conditions. Yet most of all, pseudo-haptics did positively influence the enjoyment score (besides effect audio). We assume, that introducing larger visual offsets also introduces new challenges such as judging the required strength to set objects in motion. Interestingly, the perceived ability to influence objects was strongest improved by pseudo-haptic effects. Though the presented offsets did aggravate the manipulation of objects (since they visually resisted) participants had the impression of being more in control.

Participant's Preferences

The participants agreed on simulating haptic feedback with both, vibration and pseudo-haptic offsets. In contrast, the participants did refuse the use of clipping. This emphasizes the importance of introducing even perceivable offsets in virtual reality. The avoidance of clipping requires the introduction of offsets, since unmovable objects cannot be displayed in another way.

Interestingly, the current feedback modalities were seen as sufficient for VR applications. In the condition combining vibration and pseudo-haptics with auditory effects there was no participant stating the feedback was insufficient. But as already discussed by the experts, this item has to be interpreted with care. Though haptic feedback can be displayed in a kind of sufficient way – if designed well – we argue, that this does not imply that there is no need for better haptic devices.

Limitations

Since we only used state-of-the-art hardware, we had no condition involving real and natural haptic feedback. We believe, that some judgments of the participants would differ when comparing the haptic metaphors like vibration and pseudo-haptics to the interaction with real objects. Most of all the item regarding whether the kinesthetic feedback as sufficient has to be distinguished from more positive adjectives, and could also be influenced by the low expectations of participants towards receiving kinesthetic feedback in VR (see Section *Expert Discussion*).

Measuring the quality of haptic feedback in VR is not trivial, as was discussed in the initial workshop. We believe that many of our items are strongly related to expectations and the application itself. While some participants accept haptic metaphors like vibration and pseudo-haptic feedback, others did not. This led to huge variances regarding the results, which aggravates the interpretation. Though, we found a significant trend that even obvious offsets were preferred over clipping or the complete absence of kinesthetic feedback, as it is the current state-of-the art.

Regarding the comparison of study I and II it should be considered that a different amount of users with a different distribution of experience was tested.

IMPLICATIONS

Our results indicate that it is possible to communicate kinesthetic feedback with the current state-of-the-art hardware. Most of all the stronger visual manipulation using offsets proved to be of great importance. However, such effects are currently either not used at all, or used too subtle in VR applications. We could show that offsets can be used far beyond the limits of not conflicting with proprioception.

While the perception of kinesthetic feedback as well as most of the scores about realism and even enjoyment was increased by introducing such pseudo-kinesthetic feedback (most of all when combining visual and vibration feedback), we argue that there is a huge potential – even beyond immersion and presence. We showed that by using stronger visual manipulation by offsets, objects can be compared regarding the strength of resistance. Further, users have to exert more intensely to compensate the offsets and move objects with higher friction or weight. Kinesthetic feedback can therefore also be used as part of the game play, where users can explore objects more closely and where kinesthetic forces even lead to higher exertion. We therefore suggest the following to improve the perception of kinesthetic feedback:

Avoid clipping: Our results show a huge impact of pseudo-haptic effects on the perception of kinesthetic feedback as well as immersion. Along with that finding, the common state of the art of using clipping for static objects was very much unpopular. Our results indicate that offsets are a desired feature, and not perceived as disturbing. Most of all, realism was increased by introducing tracking offsets, since objects behave differently depending on their properties, even during direct manipulations.

Synchronize vibration with visual pseudo-haptics: Vibration as a standalone feature was less expressive and suitable for communicating haptic features and was seen as a supportive channel for visual pseudo-haptic effects. In our tests, the coupling of vibration with pseudo-haptic offsets (and therefore the pressure a user exerts on an object) provided the best haptic (tactile and kinesthetic) perception using the state-of-the-art hardware. Combined with effect audio, there was no participant stating this kind of feedback was insufficient for VR applications.

Use pseudo-haptic effects – but with care: We argue, that perceivable pseudo-haptic feedback is a very promising approach for VR applications, since it is able to communicate kinesthetic feedback. We therefore suggest to pay greater attention to higher degrees of visual manipulation as it was done prior. Our results show that even larger offsets, breaking obviously with proprioception, were accepted and appreciated as metaphor for kinesthetic feedback. However, there is a limit of such effects that should be considered for static objects, where offsets conceptually can increase unlimited. Participants and experts suggested to use clipping as escape strategy, when offsets increase too much.

Kinesthetic Feedback as a Game Mechanic: Our approach is able to create the perception of kinesthetic feedback and allows its comparison. With regard to games, however, it even enables new types of play experiences. The possibility to create different types of object properties can be used in various types of exploratory game experiences. For example, players could have to find hidden switches in walls by searching for differences in resistance. Communicating these object properties would be difficult with regular button interaction.

CONCLUSION

VR got to a point, where most of all the visual consumer hardware has made huge steps. On the other hand, there is a tendency towards direct interaction using tracked controllers, where users stand or even walk in reality. This additional degree of freedom also leads to new challenges concerning the mismatch of real and virtual world. Compared to the use of indirect interaction, like playing with a gamepad, users expect haptic or kinesthetic feedback when touching virtual objects. The current hardware is very limited displaying haptic features while the controller in the user’s hands as well as vibration is the only available haptic modality.

We used the state-of-the-art-hardware, implemented different haptic representations using vibration and pseudo-haptics. Our pseudo-haptic manipulation go much farther than prior reported ones, and can lead to obvious breaks with proprioception, but thereby increase their expressiveness. We measured the influence on immersion, enjoyment and perception related items, which were determined in a workshop with VR researchers. We also collected qualitative feedback on how the available channels should be designed and improved. Improving the software implementation based on the suggestions, we found a strong influence of pseudo-haptic effects, while vibration was most of all seen as a supportive channel for visual effects. In addition, we found a very promising interaction between visual and vibration feedback for the communication of kinesthetic feedback.

According to our participants, the combination of visual and vibration feedback is sufficient to communicate kinesthetic feedback. We therefore argue, that when being implemented well, kinesthetic feedback can not only be used to increase immersion, but also to increase enjoyment by becoming part of the game play.

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