You Shall Not Pass: Non-Intrusive Feedback for Virtual Walls in VR Environments with Room-Scale Mapping

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Abstract

Room-scale mapping facilitates natural locomotion in virtual reality (VR), but it creates a problem when encountering virtual walls. In traditional video games, player avatars can simply be prevented from moving through walls. This is not possible in VR with room-scale mapping due to the lack of physical boundaries. Game design is either limited by avoiding walls, or the players might ignore them, which endangers the immersion and the overall game experience. To prevent players from walking through walls, we propose a combination of auditory, visual, and vibrotactile feedback for wall collisions. This solution can be implemented with standard game engine features, does not require any additional hardware or sensors, and is independent of game concept and narrative. A between-group study with 46 participants showed that a large majority of players without the feedback did pass through virtual walls, while 87% of the participants with the feedback refrained from walking through walls. The study found no notable differences in game experience.

Keywords: Virtual reality; virtual walls; tactile feedback; haptic feedback; visual feedback; auditory feedback; locomotion; game design.

Index Terms: K.8.0 [Personal Computing]: General – games; H.5.2 [Information interfaces and presentation]: User Interfaces. – Interaction styles

1 Introduction

VR technology has improved greatly over the last years and has various applications, ranging from multiplayer gaming in arcade centers to training simulations for professionals. Strong immersion is a key advantage of VR [20] and VR applications can transport users into worlds that they would otherwise never experience. However, the large degree of immersion raises player expectations regarding moving and interacting freely and naturally. One of the most popular current VR systems is the HTC Vive. It features a room-scale user movement tracking system. Here, physical walking has proven to be a natural and uncomplicated means of locomotion [27]. Other locomotion modalities, such as teleportation or using the touchpad on hand controllers as a gamepad entail the risk of motion sickness, limit flexibility of the movement, or restrict the freedom in game design.

By physically walking in a room which is mapped linearly into the virtual world, the player has precise control and does not need an input device for moving, allowing for convincing reality-based interaction [12]. However, this approach also leads to design challenges, since the explorable space with the HTC Vive is limited to about 12 m^2 to ensure that the tracking works correctly [8]. In many games, a clear structuring or segmentation of the valuable space using walls or other boundaries is required. This raises the issue of how the application can prevent users from crossing virtual boundaries if the game design requires that these are respected.

In traditional video games, setting up barriers for the player avatar is easily achieved by stopping avatars from moving further when approaching a collider. In VR environments with room-scale mapping there are no dynamic physical borders to prevent the player from moving through walls. Also, it is not an option to stop the virtual camera from moving further ahead while the player continues walking, since this would result in the user's viewpoint being placed non-correspondingly in the virtual space in relation to the physical tracking area. This could break immersion or induce motion-sickness. Consequently, if players walk through a virtual wall, the virtual camera must go through as well.

We encountered this challenge when developing a VR game with room-scale mapping. In its evaluation, we observed that some players tended to ignore walls. Since related work and literature do not provide an established standard on how to implement virtual walls as boundaries in VR, we were motivated to design and evaluate a possible feedback system.

While a growing body in recent research considers electrical muscle stimulation (EMS) for enforcing movement boundaries for the player [15][16], such techniques require additional hardware and are not comfortable or safe to use for many potential users. This issue motivated the research question *whether non-intrusive sensory feedback can prevent players from walking through virtual walls* in VR environments with room-scale mapping. Our approach to sensory feedback is based on features available through standard game engines paired with VR devices that include a head-mounted display (HMD) and hand controllers. Our research contributes a feedback method that is effective, yet easy to implement in any application and well-suited for the current VR market. We report on the implementation and on a comparative study of this solution for feedback for virtual walls in VR.

2 Related Work

Today, sensory feedback for virtual walls is uncommon in VR games. The technical and game design challenges in locomotion are often avoided by using non-natural locomotion techniques, such as teleporting [22][28]. To gain a better understanding of common feedback modalities for walls in current VR games, a selection of popular applications was tested.

2.1 State of the Art for Feedback for Walls in Games

Nvidia VR Funhouse [14] is the only one of the tested games that provides vibrotactile feedback when interacting with big game elements. However, it features neither auditory nor visual feedback.

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In other high-quality games, such as *Trials on Tatooine* [10], *The Lab* [28] or *Portal Stories: VR* [22], there is no sensory feedback when interacting with walls. Furthermore, in all the games that were tested – except for *The Lab* – the walls and bigger objects consist of simple one-side rendered planes. Once players stick their head through a wall, it becomes invisible.

Instead of providing sensory feedback, most state of the art VR games either (1) stop the game progress and limit rewards or otherwise punish the player using game mechanics when crossing walls, (2) are designed in a way so the players cannot get close to the walls at all, or (3) simply avoid walls completely within the play area. As an example of the prior, the teleportation device in *Portal Stories: VR* gets deactivated. While this allows for free movement within the game and attempts to prevent players from cheating by walking through walls, the immersion will arguably suffer when players walk right through paper-thin walls and see only empty space and a skybox on the other side. As an example of the second, *The Brookhaven Experiment* [21] scales down the players' horizontal movement so that it is impossible to move around much in the virtual space and approach a wall. The world remains somewhat consistent, but scaling the movements limits the freedom in game design significantly and is no natural or reality-based interaction [12]. Moreover, this approach is not applicable for VR environments with room-scale mapping. An example for the third approach is *Space Pirate Trainer* [9], in which the walls are out of reach while players remain mostly stationary.

Altogether, the state of the art approach to interaction with walls in VR can be summarized as making design decisions that bypass the challenges. So far, most developers appear to accept that a sizable percentage of players may cheat, at the peril of their own immersion, or they avoid interactions with walls completely. We agree with the *Oculus Rift Best Practices Guide*, that further "experimentation and testing will be necessary to find an ideal solution" [19].

2.2 Research on Collisions in Virtual Environments

Investigations on collision feedback in VR are a growing topic in human-computer interaction research. To simulate physical impact, Lopes et al. designed a small wireless device using magnetic coils and EMS [15]. Subjects in a respective study reported that they experienced a realistic feeling of getting hit. In a more recent study, Lopes et al. used EMS again to simulate haptics of walls and heavy objects by using electrodes that create a counterforce when the user touches virtual walls or objects [16]. User studies showed that their approach adds realism to heavy virtual objects and prevents the participants from both touching and reaching through the objects better than vibrotactile feedback alone. However, this solution works best with a so called repulsive wall design in which the walls or objects are visually surrounded by an electric field visualized by lightning between virtual Tesla coils. Additionally, the EMS is accompanied by a white flash and a loud sound. This limits the design of objects and environments, is critical for epileptics and requires calibration for every use. Moreover, Lopes et al. deal with EMS solely for the arms and do not address the problem of the HMD passing through walls.

Similarly, Pamungkas and Ward designed an electrotactile feedback glove to create a more immersive VR environment with positive results [20]. However, electrical stimulation carries a certain risk and may not be suitable for every user due to health concerns nor practical for daily use in the private sector. The possibility of providing force feedback has also been explored in a study investigating its effect on task performance in a collaborative environment using the PHANToM 3D force feedback input device but remained without significant results [23]. Another approach to tactile feedback is vibration for which Sziebig et al. designed a glove, focusing on vibration feedback for each finger and the palm individually [26]. While this solution could be applicable in a room-scale mapping environment, it still requires additional hardware.

The same applies to the approach of passive haptics (PH): the use of physical objects to provide haptic feedback for virtual objects. Insko et al. showed that the use of even low-fidelity physical objects to augment high-fidelity virtual objects significantly improves the sense of presence for users as well as cognitive mapping and effectiveness of spatial knowledge training [11]. Kohli et al. combined PH with redirected walking, which allowed for the same physical object to provide haptic feedback for several virtual objects [13]. Also, the idea of Robotic Graphics by McNeely [18] reduces the number of necessary props. He suggested to use robotic props that physically imitate various virtual objects in different locations depending on where the user is currently walking. Similarly, Cheng et al. use human actuators handling reusable generic props to simulate the environment [3]. Still, all approaches using PH cannot be employed in consumer applications for today's VR mass market as they require proprietary equipment, as well as a precise setup and calibration for every use.

The *simulated surface constraints technique* requires no additional hardware and works by stopping the movement of the virtual hand before it penetrates an object. As shown by Burns et al. [2], users are more sensitive to noticing hand-object penetration than discrepancy between real and virtual hand. However, as described earlier, a discrepancy of the user's virtual viewpoint to the real-world tracking area is problematic whereby this technique cannot simply be adopted for the HMD.

The related research is mostly concerned with haptic feedback systems, and we are not aware of studies that explicitly and formally evaluate other, more common sensory feedback, such as visual or auditory modalities. Overall, the existing research mainly focuses on feedback systems in general and is not directed specifically towards preventing users from walking through walls in environments with room-scale mapping.

3 Feedback Design and Study Rationale

As elaborated above, current VR games frequently do not provide sensory feedback for virtual wall collisions. Related research has not considered feedback for virtual walls specifically or requires special hardware, additional sensors, or employs intrusive technologies. While some related work on interaction with 3D objects exists, there is a lack of research on virtual boundaries - such as walls - and on how feedback on virtual interactions with these influences the user's behavior.

3.1 Sensory Feedback

We approached the issue of walls in VR using a combination of sensory feedback that builds on existing feedback modalities in VR development environments (here Unity 5). This led to a combination of visual, auditory and tactile feedback. We chose to employ a broad selection to address multiple senses and increase the possibility of preventing users from walking through walls.

Unlike solutions that use proprietary gloves [20][26], electrodes [15][16], harnesses [29] or physical props [11], this solution does not require any additional hardware, sensors or accessories besides the VR headset and controllers that support vibration as feedback. Furthermore, we consider it non-intrusive as it does not physically restrict or impair the user, features only non-invasive audiovisuals, and was designed to not affect the gaming experience. The feedback bundle is deliberately restricted to types of feedback that can be applied for almost any VR application, concept, genre, and narrative, aiming to maximize applicability and practicality.

Table 1. The feedback combination used in the experiment.

collision type / feedback	visual feedback	auditory feedback	tactile feedback
HMD-wall collision	black vision	muffled background music	–
controller-wall collision	–	knocking sound	vibration

The virtual wall feedback consists of two different components: (1) feedback for collisions between wall and hand controller, and (2) feedback for collisions between wall and HMD (Table 1). For the former, we set the controllers to continuous vibration for the whole duration of a collision. Additionally, a single authentic knocking sound is played as auditory feedback. When the HMD collides with a wall, an acoustic dampening effect muffles all sounds and the background music. To achieve this, we apply a lowpass filter with an adjusted cutoff frequency to fit our ambience sounds. At the same time, the player receives visual feedback. The screen turns black while the head is inside a wall to simulate the vision being concealed by a solid object. We want to emphasize that the combination of feedback in our experimental setup does not render it impossible to move through walls. Thus, the vision is reactivated when the HMD leaves the wall again and the participants can still choose to ignore the walls if our feedback did not convince them.

The research question driving the study design is: *Can non-intrusive sensory feedback prevent players from walking through virtual walls in VR environments with room-scale mapping?*

Based on previous reports of players and their behavior in our pretests, we developed the following hypotheses:

H1: More subjects who received no wall-feedback pass through walls than participants who receive feedback.

H2: Subjects receiving feedback take more time before walking through walls than those without in scenarios that encourage moving through walls.

H3: There are more hand controller collisions with walls from participants who do not receive feedback.

H4: Subjects receiving feedback feel more discomfort being inside of a wall than subjects who receive no feedback.

4 Study Design

The between-groups experiment included an *experimental* or *treatment group* that received enhanced sensory feedback on collisions with virtual walls as described above, while a *control group* received no feedback when touching or walking through walls, akin to the current state of feedback in many popular VR titles. Apart from the feedback mode, the setup was identical for the two groups. The results presented in this paper are based on tracking data and observations from the play sessions, underlined by questionnaires and a semi-structured interview per participant.

4.1 Experiment Setup

The participants start in a menu scene providing some time to get used to VR while receiving further instructions about the features in the test setup, learning how to walk around freely in the room, how to interact with buttons, and how to use teleporters.

All rooms are solely built of uniform, 15cm thick tile walls to prevent confounding factors such as differences in visual design. The only exception is a window in room 2. However, this window is small and situated so low that the players must bend down to look through it, hence the head passes through the wall above it when walking through in an upright position.

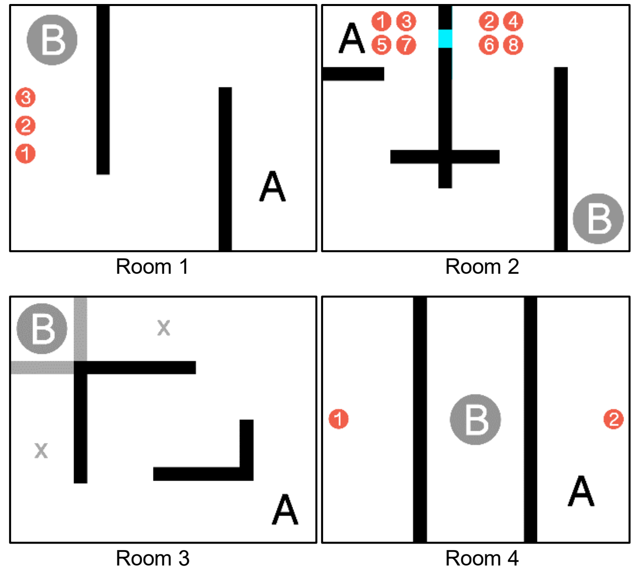

Figure 1: Room layouts for the study indicating starting locations (A), destinations (B), and button locations (red circles).

During development it was observed that most users rarely attempt to walk through walls in brief play sessions (cf. [25]). Therefore, the test environment was designed to quickly provide players with gradually increasing incentives to walk through walls. Play sessions consisted of four rooms. The layouts are illustrated in Figure 1. The participants were asked to move from the starting point (A) to the teleporter (B) in each room.

Room 1 introduces the participant to the room design and interaction principles. The red buttons on the walls are numbered and must be pushed sequentially to activate the teleporter (destination). The player receives a visual and auditory indication when pressing a button or when the teleporter activates. Since the teleporter is right next to the buttons, the participant can see the effect right away and learns this essential game mechanic for the next rooms. No differences in the behavior between the groups were expected in this room.

Room 2 provides a clear incentive to the participants to walk through a wall to solve a repetitive and time-consuming task faster. The participants are tasked to push eight buttons in the right order. To activate them sequentially, players must walk back and forth between two locations that are spatially close but separated by a wall. This requires walking a notable distance between every button push. To make the situation transparent to users the wall has a small window so that the players clearly see that the two groups of buttons are right next to each other. Figure 2 shows a screenshot of room 2 with the first button group being visible through the window. The buttons are far enough from the window, so that the participants would have to walk through the wall to reach them.

Figure 2: Window to emphasize the potential shortcut of walking through the wall in room 2.

In *room 3*, the players see a timer counting down from two minutes. It is impossible to complete this level in time without walking through a wall. Participants are not informed about this. There are no buttons and the teleporter is already activated. The two walls marked grey in Figure 1 are sliding doors, which close when the participants cross the points marked 'x' (the points are not marked in the actual setup). Even if running, the participants cannot make it through before the doors close. They open again when the participant steps back. If the timer runs out, the doors open and stay open, so the participant can move on. Figure 3 shows how the sliding doors close when being approached. The doors are designed the same way as the other walls.

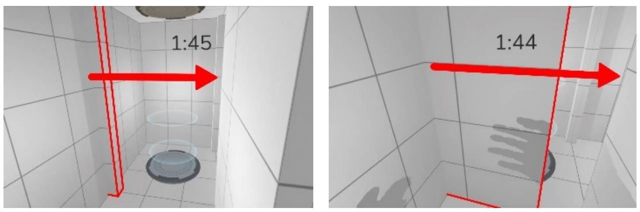

Figure 3: The sliding doors in room 3 close when the player approaches (red markings for illustration only).

Room 4 cannot be completed without passing through walls of which the participants were informed. This room assured that all participants experienced walking through walls. The room is divided by two walls. The buttons and teleporter are located in such a way that the participants have to cross the walls at least five times.

The procedure of a test session was structured in a carefully controlled manner. Following informed consent, the participants were asked to fill out a questionnaire with demographic elements, gathering basic information about their gaming habits and possible prior experience with VR. After putting on and adjusting the HMD and headphones, the test subjects were instructed to find the teleporter in every room and activate it by pressing the buttons. Rooms 1 to 3 were played without interruption or communication. Subsequently, the participants were asked to complete a questionnaire about their game experience and immersion, including elements of the validated scales from TLX [7] and IMI [17]. Afterwards, the participants completed room 4, receiving explicit instructions to walk through walls to solve this level. Lastly, they were asked to fill out a final questionnaire regarding their experience of walking through walls including the validated PANAS [5] scale followed by a short semi-structured interview.

The participants were free to decide whether to complete all questionnaires and the interview in German or English. We used validated translations where available [1] and otherwise employed own translations that were subject to pre-testing and careful adjustments following pilot runs of the study.

4.2 Participants

The study was conducted with 46 convenient subjects, split evenly between experiment and control group. The participants were assigned randomly after controlling for gender distribution and distribution of prior experience with VR. The experimental group consisted of seven female and 16 male participants, 14 of whom had tried VR before, while nine had not. The control group consisted of eight female and 15 male participants; 12 with prior VR experience and 11 without prior VR experience. It was decided to sample for participants with both basic and no experience with VR to avoid distortion effects. Most participants were German nationals and students from the University of Bremen.

Player types were also included in the pre-study questionnaire, since they could potentially affect the behavior of the participants. We included the player types *free spirit*, *achiever*, *player* and *disruptor* from the terminology of Diamond et al. [6]. The *socializer* and the *philanthropist* were excluded since those player types did not appear relevant in a single player setup without non-player characters. Analysis showed only minor imbalances regarding player types between the test groups, and we observed no difference in the behavior between the player types regarding our research question and hypotheses.

5 RESULTS

5.1 Participant Behavior

Since room 1 was a brief introduction, no considerable differences in behavior were expected and none were observed. Only one participant in total walked through the walls in this level.

5.1.1 Room 2

In room 2, nine of the 23 participants in the control group walked through a wall while none of the participants in the experimental feedback group did (cf. Figure 4). This difference between the two groups is significant (X^2 (1, N = 46) = 11.189, p = .001, φ = .493), indicating a medium to large effect size.

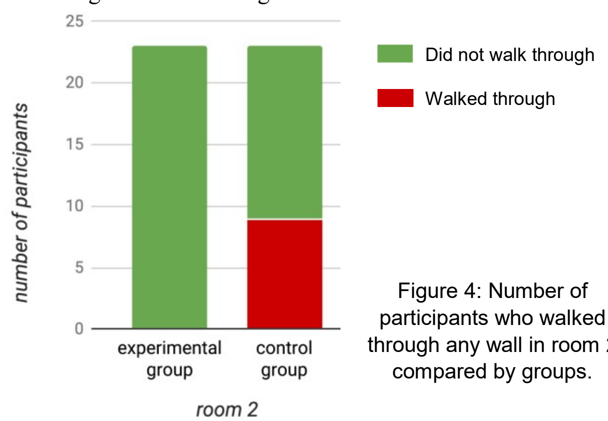

Figure 4: Number of participants who walked through any wall in room 2 compared by groups.

The typical behavior of the participants in room 2 is illustrated with two examples in Figure 5. As it appears, the participant in the experimental group (A) walked the long way around the wall between the buttons once, touched it numerous times with the hands and even had head-wall contact, but never walked through. The participant in the control group (B), on the other hand, walked around the wall once but took the shortcut through the wall for pushing the remaining buttons.

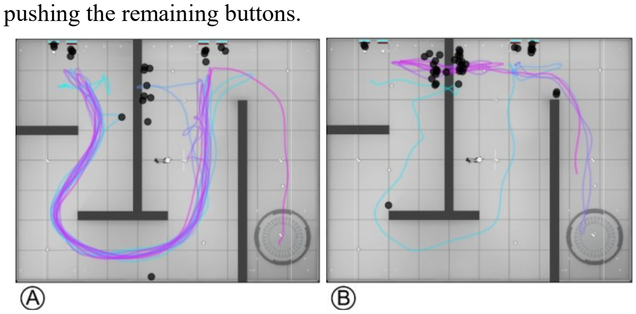

Figure 5: Example data visualizations showing the walking paths of two participants tracked via the HMD position in room 2 for the experimental (A) and control (B) group. The beginning of the paths is colored in turquoise and transitions into pink. Black dots illustrate collisions with both HMD and hand controllers.

Although none of them walked through the wall, seven participants in the experimental group had head-wall contact in room 2 (cf. Figure 6). In the control group, head-wall collisions were registered for 10 participants, of which only one participant refrained from walking through. The difference between the groups in room 2 regarding not walking through a wall despite having head-wall collision is significant (X^2 (1, N = 46) = 13.388, p < .001, φ = .887).

In room 2, we measured the reverse effect regarding collisions between hand controllers and walls. There was no significant difference between the groups (t (37) = -1.942, p = .060), but a tendency that the participants who did not receive feedback touched the walls more often (mean = 12.36, SD = 9.75, N = 22) than those who did receive feedback (mean = 7.50, SD = 6.56, N = 22).

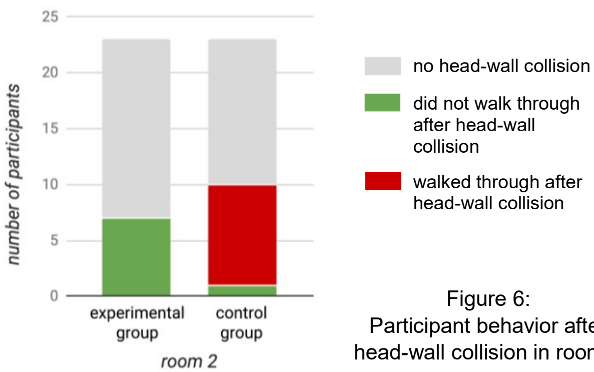

Figure 6:
Participant behavior after head-wall collision in room 2

5.1.2 Room 3

Similarly, in room 3, fewer participants in the experimental group walked through walls compared to the participants in the control group (cf. Figure 7). Only three participants in the experimental group (13%) walked through a wall in room 3, while 19 (82.6 %) in the control group did. This difference is significant (X^2 (1, N = 46) = 22.303, p = .000, φ = .696), indicating a large effect size.

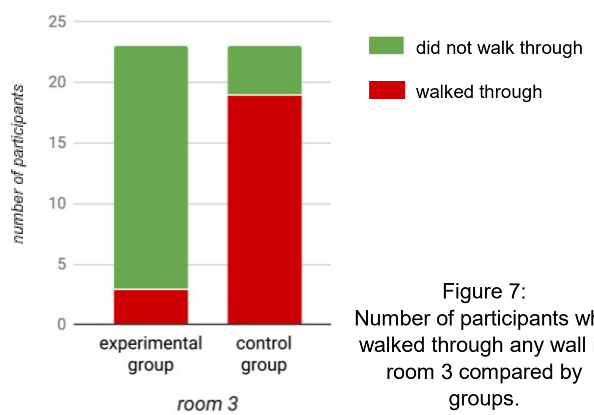

Figure 7:
Number of participants who walked through any wall in room 3 compared by groups.

The three participants in the experimental group who walked through a wall in room 3 did so after 106 seconds on average and they only went through shortly before the timer ran out. Of the 10 participants in the control group, who walked through a wall without having done so already in room 2, only two waited more than 90 seconds before crossing. On average, they waited 57.7 seconds (SD = 33.05, N = 10), which is just over half of the average 106 seconds (SD = 11.98, N = 3) for which the participants in the experimental group waited. This shows a significant difference between the two groups (t (11) = 2.419, p = .034). The effect size is d_{Cohen} = 1.943 as defined by Cohen et al. [4], which corresponds to a large effect according to Sawilowsky [24]. This difference should be interpreted cautiously, however, since one group consisted only of three people after applying the selection criteria.

We found a significant difference between the groups when comparing the time until the participants first put their head into a wall. Those who received feedback waited on average 74.2 seconds before the first head-wall contact in room 3, while the participants without feedback waited only 46.2 seconds on average. The participants in the experimental group took significantly longer (t (30) = 2.605, p = .014). This finding also showed a large effect size (d_{Cohen} = .938). We observed no similar effect in room 2.

In room 3, 10 out of 13 participants with head-wall contact in the experimental group refrained from walking through a wall, whereas none of the 19 participants in the control group who had head-wall contact did so (cf. Figure 8). This difference between the two groups is significant (X^2 (1, N = 46) = 21.259, p = .000, φ = .815) with large effect size.

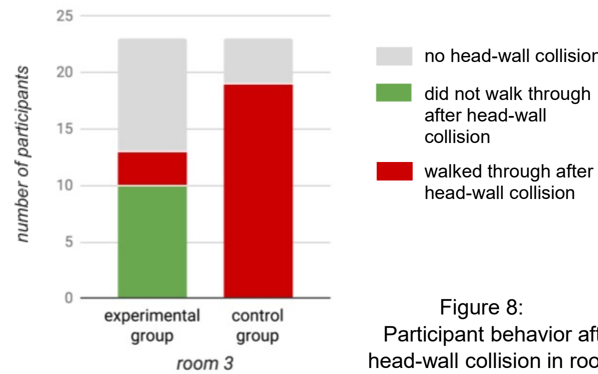

Figure 8:
Participant behavior after head-wall collision in room 3

The participants in the experimental group had significantly more collisions between hand controllers and walls (t (42) = 2.034, p = .048) in room 3 than in the control group (cf. Figure 9 top). The participants with feedback had contact with the walls on average 11.64 times (SD = 14.57, N = 22), while the participants without feedback touched the walls on average 4.95 times (SD = 5.03, N = 22). The effect size is moderate with d_{Cohen} = .614.

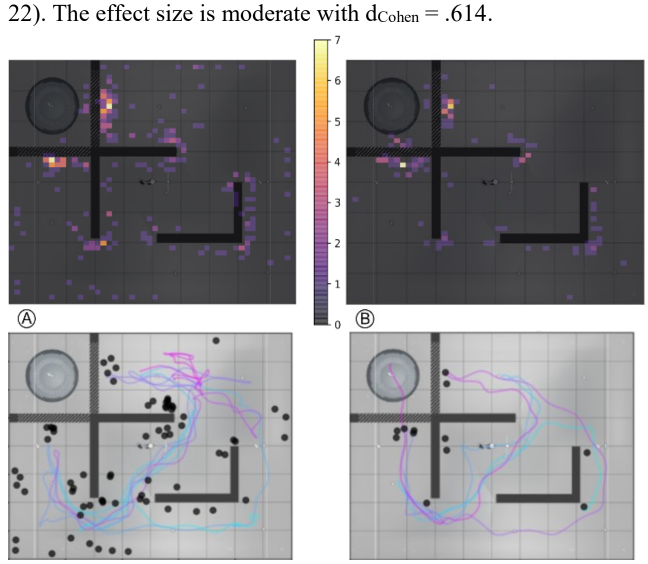

Figure 9: *Top:* Aggregated heat maps for HMD and hand controller collisions with walls, floor or ceiling in room 3 for experimental (A) and control group (B).
Bottom: Example data of two individual trajectories of each group. The beginning of the walking paths is colored in turquoise and transitions into pink. Black dots illustrate collisions with both HMD and hand controllers.

Two test sessions with incomplete tracking were excluded in these calculations. As we learned in the interviews, many participants in the feedback group thought it was impossible to walk through the walls and therefore touched the walls in search of hidden buttons or other solutions to proceed in the level (cf. Figure 9 bottom).

5.1.3 Room 4

In both groups, all 23 participants walked through the walls in room 4. However, seven participants who received feedback stepped back after the first head-wall contact and only walked through on the second attempt, whereas everyone except one participant in the control group walked straight through the walls without hesitation. This difference is significant with a medium effect size (X^2 (1, $N = 46$) $= 5.447$, $p = .020$, $\varphi = .344$) and is shown in Figure 10.

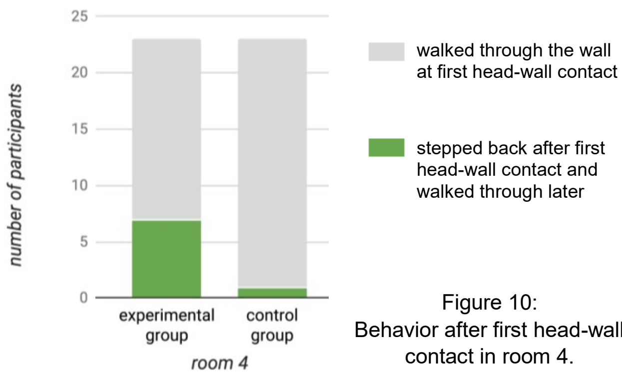

Figure 10: Behavior after first head-wall contact in room 4.

5.1.4 Cross-rooms Results

We also compared the number of participants who had head-wall contact at some point *before* room 4, that is before they were explicitly instructed to walk through. 14 participants (60,9%) in the experimental group had head-wall contact before room 4, while 20 (87,0%) in the control group did. This difference is significant with a medium effect size (X^2 (1, $N = 46$) $= 4.059$, $p = .044$, $\varphi = .297$). When considering collision frequencies in all four test rooms there were no notable differences between the two groups.

5.2 Game Experience

After playing the first three rooms, the participants completed a user experience questionnaire that included the *NASA Task Load Index* (TLX) [7] and the two sub-scales *interest-enjoyment* and *tension-pressure* from the *Intrinsic Motivation Inventory* (IMI) [17]. We adjusted the Likert scales to keep our questionnaires more uniform. Thus, we used a 10-point Likert scale for TLX and a 5-point Likert scale for all other dimensions. Neither TLX nor IMI showed any significant difference between the two groups. The results are summarized in Table 2.

After completing the fourth room, where every participant had walked through at least five walls, the participants were asked to report about their experience of walking through the walls using the *Positive and Negative Affect Scale* (PANAS) [5] in a directed manner. Again, there was no significant difference between the two groups. Due to a minor issue concerning the German translation of the PANAS, the negative emotion 'upset' was excluded. This was compensated for by linearly scaling up the remaining nine negative emotions. While this may slightly impact the reliability of that subscale, the two group means appeared nearly identical, giving reason to assume that this error should not have an impact on the overall result. The participants were also asked how disoriented they felt walking through the walls on a 5-point Likert scale. There was no significant difference between the groups (feedback: M = 2.48, SD = 1.16; no feedback: M = 2.74, SD = 1.32).

Table 2. There are no significant differences in the results of the TLX, the abridged version of IMI, and the PANAS.

		Group	Mean	(SD)
TLX		Experimental	32.54	(11.41)
		Control	30.58	(9.37)
IMI	**Interest-Enjoyment**	Experimental	3.71	(0.76)
		Control	3.83	(0.78)
	Tension-Pressure	Experimental	2.14	(0.86)
		Control	2.01	(0.81)
PANAS	**Positive Affect**	Experimental	30.17	(9.55)
		Control	29.17	(7.28)
	Negative Affect	Experimental	16.47	(5.41)
		Control	17.29	(6.63)

6 Discussion

The repeated finding that significantly more participants in the control group walked through walls in rooms 2 and 3, where this was voluntary, indicates that the feedback did indeed prevent participants from walking through walls. This confirms our hypothesis **H1**: *More subjects in the test setup without wall feedback pass through walls than participants who receive feedback*. The player behavior in room 2 (cf. Figure 5) suggests a strong effect of our feedback, since it appears that many participants initially did approach the wall between the buttons.

The finding that fewer participants in the experimental group had head-wall contact before being directly asked to walk through a wall can be related to the fact that a part of the feedback, which the participants in the treatment group received, was triggered by collisions between hand controllers and walls: the knocking sound and the vibration. Based on the interview sessions, we can corroborate with further evidence for an effect of the vibrating controllers, as nine participants pointed out that the vibration prevented them from going through walls. One of them said that he *"touched [the wall] at some point with my hand and then it vibrated and then I thought 'okay, this is the feedback from the game now, that this is not working'"* (translated from German). In addition, half of the participants in the treatment group said the vibration added physical presence and a more realistic feeling when touching the walls. This can be linked to the additional observation that more than half of the treatment group participants reported that they did not notice the other feedback, i.e. the knocking sound, at all, leading to the assumption that the vibration was crucial regarding hand controller feedback.

The effect of the hand controller to wall collision feedback is further supported by the observation that the participants receiving feedback waited much longer before attempting to walk through a wall in room 3; that is, until having the first head-wall collision. This finding, however, might also be an effect relating to the fact that many participants in the feedback group had already tried putting their heads through the wall in the previous room and simply did not try again that quickly, conceivably assuming that walking through walls would not be tolerated. In other words, the feedback may already have had convinced them.

The time it took before the participants walked through a wall for the first time in room 3 further corroborates the effect of the hand controller collision feedback. These results support the effect of our feedback and our hypothesis **H2**: *Subjects receiving feedback take* *more time before walking through walls than those without in scenarios that encourage moving through walls.*

The participants in the control group touched the walls more often in room 2 due triggering three collisions (two hand controllers and one HMD) every time they crossed the wall in the middle of the room. Assuming this effect, we postulated hypothesis **H3**: *There are more hand controller collisions with walls from participants who do not receive feedback*. In room 3, however, the experimental group touched the walls significantly more often despite having more participants crossing walls in the control group. Apparently, the feedback for touching walls with the hands already deterred many test subjects from attempting to pass through the walls. As described in the interviews, the participants assumed it was impossible to cross walls and instead searched for hidden buttons triggering a collision each time (cf. Figure 9 bottom). Since overall, there is no difference between collision frequencies in all four test rooms, we cannot confirm the hypothesis H3.

For those who attempted going through walls despite the controller feedback, we found the feedback for HMD collisions to be effective as well, since most of those who put their head into a wall and received feedback stepped back and decided not to pass through. This was especially clear in room 2, where every participant with head contact in the experimental group did not walk through the wall after all.

The results from the fourth test room, where seven participants in the experimental group hesitated after first head-wall contact, also show an impact of the feedback for head-wall collisions. It made the participants hesitate although they were explicitly instructed to walk through the walls.

Considering all findings, the outcomes clearly indicate that the feedback combination for head-wall collisions was very effective in preventing the participants from walking through the walls, which is also supported by the interviews. Especially the visual feedback seemed to have a great impact on the participants. As an example, one participant in the experimental group explained: *"I tried once to walk into the wall and when it turned black I thought 'oh, I guess that doesn't work' and then I didn't do it."* Another participant stated that *"when it blackened I thought there is a border, I can't go there anyway and therefore I did not go further"* (translated from German). In the interviews, none of the participants mentioned negative aspects regarding the hindered vision. It was generally accepted as *"fitting"* and *"a good idea."*

We suppose that the vision turning black had a more notable effect than the muffled sound as 13 of 23 participants stated during the interviews that they did not even notice that the sound was dampened when they stepped into a wall. However, it is possible that the sound had an effect without the participants consciously realizing it. One participant pointed out how the sound adjustment was probably a good thing, since it appeared *"just natural"*. Due to the combined feedback treatment in the experimental setup, we cannot isolate how strong the impact of the audio dampening or any other individual feedback measure was exactly, but we can conclude that the combination as such is effective.

Our findings also indicate that the effect of our feedback does not affect the game experience to a notable degree since there were no significant differences between the two groups in the IMI and TLX questionnaire. The results from the PANAS questionnaire indicate that the feedback also did not cause notable discomfort for the participants. While we feared that the black vision might cause participants to feel disoriented, the according questionnaire item indicates that this was not the case. Hence, the hypothesis **H4**: *Subjects receiving feedback feel more discomfort being inside of a wall than subjects who receive no feedback* was not confirmed. While we cannot exclude – with statistical certainty – the possibility that the feedback might have a slight negative effect on some players, or interact with certain game mechanics, our results consistently do not indicate the presence of notable effects that would be of considerable relevance to game design.

6.1 Lessons Learned for Game Design

The results of the study show that the interplay of sensory feedback at hand-wall and head-wall collision in VR has a significant impact on the willingness to walk through virtual walls. The applied feedback does not appear to notably influence the game experience nor cause discomfort. Additionally, the feedback added a more realistic feeling to the VR experience, as interview statements of the participants have indicated. This indicates that an immersive and realistic experience of touching walls in VR can be created even without additional hardware or forcing rules onto the player with game mechanics. In contrast to related research with a focus on implementing realistic haptic feedback when touching virtual objects, our results strongly suggest that simple feedback already has a large and reliable effect on player behavior regarding the interaction with - and respecting of - virtual walls.

While our feedback implementation drastically decreases the number of players who would walk through a virtual wall, it does not absolutely prevent every player from doing so. Thus, it might be advisable to combine the feedback implementation with additional, physically non-intrusive ways to prevent crossing walls if cheating prevention is crucial to the application. This might be by means of game penalties as some of our participants suggested in the interviews.

While most current games do not apply any feedback or inhibitor to prevent players from passing through walls, our research suggests that a comparatively simple feedback solution, building on established modalities, can play an important role in creating more realistic VR environments, and in preventing most players from even attempting to cross virtual walls. This further increases the potential of room-scale mapping with physical locomotion through natural walking in VR.

6.2 Future Work

Future studies on this topic are needed to further investigate the possible influence of player types on the behavior of the participants. Although we did not find any significant effects, it would be interesting to employ a more detailed questionnaire to get a better impression of the participants' player types in following studies.

Also, a careful differentiation between the individual components of the combined feedback solution in this study would be important to analyze in future work. Thereby, it could be determined in how far all three feedback types are needed to achieve the same level of an effect. The data from the semi-structured interviews provided first hints regarding the amount of influence provided by tactile, auditory, or visual feedback respectively. However, a clear quantitative distinction between the individual components cannot currently be provided.

In addition, we assume that different behaviors may be observed with different virtual wall materials, such as glass walls, fences, paper-thin walls or mirrors, which could be studied in another comparative experiment.

Lastly, while we only considered feedback methods that are independent of application design and narrative in our experiment, future studies could consider the effect of narrative reasoning and semantics for walls as boundaries in VR, e.g. by assigning logical danger to the walls, such as electro shocks, lava, or spiders.

7 CONCLUSION

We presented a combination of sensory feedback for VR applications and games which helps preventing users from walking through virtual walls. This is crucial to allow for free game design choices when using physical locomotion through natural walking in VR applications with room-scale mapping. Our goal was to apply physically non-intrusive feedback in a way that measurably convinces users that it is not possible, advisable, or desirable to walk through walls. To this end, we created a feedback solution for hand-wall collisions (vibrating controllers and a knocking sound) and head-wall collisions (blackened vision and dampened surrounding sound). We verified the hypothesis that users receiving this feedback are less likely to walk through walls than users who do not receive feedback for wall collisions. The study was implemented using a simple game-like VR environment that seduces players to walk through walls by giving them incentives. Additionally, we tested the experience and effect when explicitly asking players to walk through virtual walls. The results show a significant impact of the simple combination of established feedback modalities. The solution can be put into practice without any additional devices or sensors, was not found to harm the player or the game experience, and is applicable for a broad range of potential VR applications and narrative scenarios.

ACKNOWLEDGMENTS

We thank all the volunteers who participated in our experiment, the staff of the project *Adaptify*, Christine Jacobsen, Benjamin Gallagher and our supervisors at the University of Bremen. This project was partially funded by the BMBF (Federal Ministry of Education and Research, Germany). This project was partially funded by the DAAD (German Academic Exchange Service) through the FITweltweit program.

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