Virtual Travel Collisions: Response Method Influences Perceived Realism of Virtual Environments

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Travel methods are the most basic and widespread interaction method with virtual environments. They are the primary and often the only way the user interactively experiences the environment. We present a study composed of three experiments that investigates how virtual collisions methods and feedback impact user perception of the realism of collisions and the virtual environment. A wand-based virtual travel method was used to navigate maze environments in an immersive projective system. The results indicated that the introduction of collision handling significantly improved the user's perception of the realism of the environment and collisions. An effect of feedback on the perceived level of realism of collisions and solidity of the environment was also found. Our results indicate that feedback should be context appropriate, e.g. fitting to a collision with the object; yet, the modality and richness of feedback were only important in that traditional color change feedback did not perform as well as audio or haptic feedback. In combination, the experiments indicated that in immersive virtual environments the stop collision handling method produced a more realistic impression than the slide method that is popular in games. In total, the study suggests that feedback fitting the collision context, coupled with the stop handling method, provides the best perceived realism of collisions and scene.

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1. INTRODUCTION

Virtual environments (VEs) are experienced solely through the programmed stimulation of the user's senses in an attempt to create an impression that they are in a virtual place. Although much is known about the technical aspects of simulating an environment and about creating the sensory information that leads to the perception of that place, less is known about the subjective experience of that place.

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In most cases, the VE creators desire to produce the feeling of a real place; therefore, most of what is known about the experience of VE compares it with the experience of reality. Questions of the "realism" of an environment are a critical portion of presence questionnaires (Slater et al. [1998, 2009b], Witmer and Singer [1998]), under the assumption that perceiving the VE as real means a better experience. Most of our current formal knowledge about perceived realism is formed by the straightforward questions used in those contexts. Other research, discussed in more depth in the following section, investigates specific differences between reality and VE—for example, spatial awareness and distance compression—or the suitability of VEs for learning something later applied in reality.

We are interested not in the differences between reality and VEs, but whether we can methodologically affect the user's perception of the realism of a VE. A limited set of work has attempted to do this by manipulating the render quality, although with mixed results [Yu et al. 2012; Slater et al. 2009a; Vinayagamoorthy et al. 2004]. We believe that interaction methods may provide a stronger impact on the perception of realism of VEs. Interactions form a critical portion of the experience of the environment and are likely to shape how we perceive that environment. In this initial research, we elected to study virtual travel, which is the most commonplace form of interaction with a VE. The study presented investigated how realistic users perceived collisions with virtual objects to be during virtual, wand-based travel interactions in an immersive virtual environment (IVE) and the effect that it had on perception of the environment.

Virtual travel collisions have been only narrowly studied; yet, it is widely held that virtual collisions are important. They are thought to effect presence, realism of the environment, and help in tasks such as wayfinding [De Barros et al. 2011; Hoffman 1998; Ryu and Kim 2004; Whitton et al. 2005]. Typical virtual collision responses consist of simply not allowing users to travel through walls. In the standard setup, this means that translational movement is stopped at the point of contact of a simulated "virtual body" with the virtual object. Beyond this *stop* response, another common approach from the gaming community is the *slide* response, where the "momentum" along the object's surface is maintained. In the study presented, we investigate these two responses and compare them with no response. To enrich the experience, additional feedback, such as audio cues, may also be added. Various feedback methods have been used and suggested and are described in the section that follows. Generally, the feedback is designed to simulate or substitute for the visual, audio, and haptic feedback that naturally occurs in collisions in the physical world. In Blom et al. [2012], we report on the impact of such methods on user performance. The impact of these different responses and feedback methods on environmental perception has not yet been systematically investigated.

We present a study composed of three mixed between/within subjects experiments. The initial experiment tested the stop collision response coupled with a broad spectrum of feedback methods; it also compared them with having no collision response. This experiment investigated several feedback methods that have been used previously without formal investigation in this context (e.g., color changes or notification sounds). The results provide insight into which methods are effective and informed the method selection in the following experiments. The second experiment investigated in a more controlled manner whether expected effects by modality and cue richness are present, with the hypothesis being that richer, multimodal feedback will improve the realism of collisions and the environment. These two experiments used the stop collision response. A third experiment using the slide method was additionally undertaken, since it provides such a different experience than the stop response.

In the following section, we provide background information on relevant research in the experience of the VE and on virtual collision handling. We detail the experimental methods in Section 3. The results of the three experiments are presented in Sections 4 through 6, followed by a general discussion of the results in Section 7.

2. BACKGROUND

2.1 Experience of Virtual Environments

Historically, most of the perception work in virtual reality has been focused on the phenomena of presence—the feeling of being in the virtual place. A review of presence topics can be found in Slater et al. [2009b]. Typically, presence is measured by one of various scales, consisting of various lines of direct subjective questions about the participants' perceptions and experience. An alternative, but related, measurement methodology suggested by Slater et al. [2009b] is to consider whether the participants react to events in the environment as if they were real.

Perhaps the most relevant work in this line of investigation to our study is of Davis et al. [1999], who investigated whether adding ambient sounds effected the visual perception of the VE. They reported that the inclusion of ambient sounds within virtual rooms increased the user's sense of presence, as determined by two unreported questions. The users also reported a higher degree of realism in the ambient sound condition over the no sound condition, although this was not a significant difference. Another series of studies have investigated whether render quality improves experience [Yu et al. 2012; Slater et al. 2009a; Vinayagamoorthy et al. 2004; Zimmons and Panter 2003], with mixed results. These studies have generally not found evidence of differences with presence questionnaires and similar questions. The most recent study from Yu et al. [2012] found some evidence that the inclusion dynamic illumination impacts physiological responses to an event involving an avatar but finds no differences in questionnaire-based presence measures.

The realism of an environment can alternatively be investigated in a similar manner as Slater's real responses hypothesis. Various research avenues have investigated differences between virtual reality and "real" reality. Albrecht et al. [2009] found that affordances of virtual objects were similar to those in reality but noted differences that may be important. A bigger set of research has looked at where virtual reality seems to be differently perceived than reality. Tichon and Burgess-Limerick [2011] provide a recent overview. Well-known areas with differences include navigation and wayfinding [Wallet et al. 2009; de Kort et al. 2003], spatial awareness [Mania et al. 2010; Ruddle 2001], and estimation of distances and sizes [Mohler et al. 2010; Ries et al. 2008; de Kort et al. 2003]. Another area that considers the connection of virtual and real is learning transfer, where a task is learned in a VE for use in the real world. Most recent works indicate that successful transfer can occur [Tichon and Burgess-Limerick 2011; Wallet et al. 2009; Mania et al. 2010].

2.2 Virtual Collision Handling

Dealing with the nonphysicality of virtual objects involves two major steps when simulating collisions in VEs: collision detection and collision response. A large body of work exists on collision detection—that is, knowing when a collision will occur. Readers are referred to Thomas and Torras [2001] for a review of the field. A virtual collision response is composed of two components, handling the collision with regard to movement and making the user aware of the collision. The most basic approach is not to do anything, which we refer to as *no collision*. The user just travels through the collided object, with no feedback. We will use the term *collision response* for the movement reaction to the virtual collision, which may stop and/or modify the virtual movement. The two common methods are the stop and slide methods, which were previously compared by Jacobson and Lewis [1997] in a study performed in a desktop environment using a mouse-based movement. They found a significant difference in task completion time between methods but investigated neither feedback nor user impression of the collision and environment. In Blom et al. [2012], we found that virtual collision response did not have a large impact on performance in IVEs.

The other component that should be considered is how to notify the user of the collision. We will refer to this as *collision feedback*. Probably the most common notification is the playing of a sound on collision. This may be an abstract alert, like a beep, or something more fitting to the situation. For instance, while investigating spatial awareness, Suma et al. [2007] used a buzzing sound to notify the user of collision in a comparison of travel methods.

Haptic responses for travel are less common in IVEs but arguably are more appropriate, because the physical haptic response is replaced using the same sensory channel. Whitton et al. [2005] report having used rumble packs as feedback devices in addition to "clunk" sounds as substitutions for missing haptics in travel method studies. Ryu and Kim [2004] showed that users were able to discriminate the direction of a collision based on localized vibration feedback on a vibro-tactile belt. They also compared their results with spatial sound feedback, showing improvements for the haptic feedback.

A more classical method in virtual reality is indicating collisions visually. This is often done by coloring the object involved in the collision. Bloomfield and Badler [2008] compared visual (color change) and vibro-tactile notification for collision awareness on reaching tasks. Similar research on arm movement has included comparisons with auditory feedback [Herbst and Stark 2005; Lécuyer et al. 2002; Richard et al. 2006]. These works have all found that including additional feedback influences performance, although with varying results. A meta-analysis of visual-auditory and visual-tactile feedback effects by Burke et al. [2006] shows that augmentation generally improves user performance.

3. EXPERIMENTAL METHODS

The study presented exposed participants to different virtual collision handling methods in order to investigate whether method choice impacts the user perception of the realism of collision and the VE. The study consisted of three experiments. The independent variable was the collision handling method, controlled across two variable spaces: the collision response and the collision feedback. The dependent variables were different measures of realism and subjective experience, detailed in Section 3.1. Our expectations, based on the literature and prevailing community expectations, were that:

H 1. *providing a collision response would increase perceived realism of the environment.*
H 2. *improving feedback (see H4) would increase perceived realism of virtual travel collisions.*
H 3. *improving feedback (see H4) would increase perceived realism of the VE.*
H 4. *feedback would be improved though context appropriateness and feedback richness. We expected an ordering to feedback cues as: haptic+auditory > haptic > auditory > no feedback.*

H4 is based on prevailing attitudes within the community and existing literature. The addition of multimodal input is widely thought to improve feedback and make it more realistic [Burke et al. 2006; Davis et al. 1999; Hoffman 1998; Lécuyer et al. 2002; Ryu and Kim 2004]. Richness indicates this multimodal nature as well as the qualities of the cues provided. We also expected the appropriateness of feedback method to moderate the effectiveness of collision feedback methods. For instance, a sound that is similar to a real sound caused in a collision is expected to be preferable to an alert-type sound, such as a beep.

Collision response and collision feedback were manipulated across the three experiments with a mixed within/between subjects design. The experiments all followed the same design to allow comparisons between experiments. In each experiment, the order of conditions was randomized and balanced for initial condition to permit between subjects comparisons without carryover effects. The first experiment investigated a larger number of feedback methods, combined with the stop response, to determine which methods were worth perusing. As seen in Section 2.2, various feedback methods have been suggested, but no data exist; therefore, seven feedback methods were compared. Additionally, the no collision response was compared to the stop collision response, in the absence of feedback. Early, partial results of this first experiment were reported in Blom and Beckhaus [2010] and are superseded by the full results and analysis published here. The second experiment focuses on the effect of feedback richness and modality. The third experiment explores feedback with the slide response.

After experimentation and pretests, we chose the following feedback methods to use with the stop response:

visual	The collided object was modulated with a red color.
buzz	A 1.9s-long buzzer sound was played.
thump sound	A thump sound was played; the sound approximated something running into a wall.
rumble sound	A rumble sound was played; the 0.7s-long sound approximated the vibrating of something tumbling along the wall.
floor thump	A thump of the floor was performed (using the same sound as thump sound).
floor rumble	A rumble of the floor was performed (using the same sound as rumble sound).
bass thump	The same thump sound was played with extra bass through a subwoofer; the sound level was similar to the floor thump.
wand rumble	The wand device rumblepack was activated for the length of colliding movement plus 0.1s.

The *visual* and *buzz* methods are alert-style messages; they were chosen to be similar to those reported in existing works. The buzz sound was derived from electric hair clippers and can be imagined as similar to sounds used for mistaken answers in some competition TV shows. The last three methods are haptic/tactile methods. The floor-based methods use a special flooring setup, described briefly in Section 3.2 and in depth in Blom et al. [2012]. The *floor thump* method can be imagined as the feeling that someone is hitting the wooden riser with a hammer from the other side. The *floor rumble* is similar, but with a vibrating movement. It is analogous to the *wand rumble* but delivered over the flooring to the feet instead of to the hand. In order to compare the effect of modality, *thump sound* and *rumble sound* methods were introduced in Experiment II. They used the exact same sounds that drove the floor in the floor thump and floor rumble methods but were played over speakers at approximately ear level. This created the possibility to compare the haptic and audio modalities in a controlled manner. In order to provide more exact comparisons of modality, the method *bass thump* was introduced. It uses a richer bass sound that included the low-frequency tones produced by the floor thump method, thereby differing primarily in the haptic component. Additionally, two audio sounds of different tonal richness could be compared directly.

The slide collision response includes two phases: the moment of impact and while “sliding” along the contact surface. Feedback can be applied to either or both parts. Whereas stimuli sources are derived from those used previously, the rumble is only applied here in a context appropriate manner to the sliding component; earlier, it was applied to an impact action. The following feedback methods were used with the slide response:

rumble	The rumble sound as described previously was played during sliding contact. It played when the transformed movement was greater than a small threshold.
thump/rumble	The thump sound at the moment of contact and the rumble was played as described previously.
floor thump	The thump sound drove the sound floor at the moment of contact.
floor rumble	A rumble of the floor was performed for length of contact, as in the rumble method.
floor thump/rumble	The thump and rumble sounds drove the sound floor.

3.1 Measures

The primary measures used were subjective questions. Custom questionnaires were developed or adapted from the literature. All questionnaires were asked in the native language of the test country. Questions pertained to realism, method preference, and demographics.

3.1.1 Realism. The main measures accessed any impact on the realism of the environment and the collision itself. The six-question SUS questionnaire was used to ascertain the level of presence [Slater et al. 1998] as an indicator of general acceptance of the environment (see Section 2.1). Presence questionnaires, such as the SUS, are partially based on questions of the environment realism but draw on other concepts and are quite nonspecific. Therefore, we drew questions from other research to investigate more specific effects. The realism questions were:

collision	How realistic did the collision feel?
solidity-walls	How solid did the walls seem to be?
solidity-item	How solid did the X seem to be? X = plant, teapot, etc.
material	Out of which material were the walls of the environment made?
weight	Would you say that it weighs less, the same, or more than a similar X from your daily experience? (significantly less, same, significantly more)
drop	If you were to pick the X up and drop it, what would you expect to happen?

The question *collision* was adapted from Ryu and Kim [2004], who investigated collision perception with a vibro-tactile belt. The questions about the solidity of the environment and item weight were adapted from Hoffman [1998].

Inspired by Hoffman, we placed objects in the environment, where no direct interaction could occur (see Section 3.3.2 for details of placement). Thereby, the properties they take on should reflect how the user perceives the environment as a whole. Questions *solidity-item*, *weight*, and *drop* were about these objects.

A series of different objects were used, one per exposure; the X in questions *solidity-item*, *weight*, and *drop* were replaced by the name of each item. The question responses were given on a five-point Likert scale (not at all to very), excepting *material* and *drop*, which were open questions. Questions *material* and *drop* were asked only after the first exposure.

3.1.2 Method Preference. A summary questionnaire was used to ascertain user preference for collision response methods. The questionnaire explained that they had experienced various different collision methods and listed a descriptive name for each method. The following summary questions were asked:

realistic	With which method did the maze seem the most realistic?
solid	With which method did the walls seem the most solid?

The participants were also asked to rank the methods from those they least preferred to those they most preferred. The result is a ranking, with 1 being most preferred and with decreasing preference for increasing numbers.

3.1.3 Demographics. Standard demographic information was collected from all participants. In the first experiment, a standard question as to the level of gaming experience, based on hours per week playing, was asked. However, there was much confusion, as many reported informally that the answer depended on when. Generally, they reported playing less now than previously. In response, we split the question into two, specifying times as "currently" and "previously." We also introduced a self-report "gamer-type" measure, first reported in Blom et al. [2012]. The Immersive Tendencies Questionnaire (ITQ) of Witmer and Singer [1998] was administered to investigate whether the participants' ability to immerse themselves in an experience influenced the effectiveness of the feedback methods.

3.2 Equipment

The experiments were performed in our "L-shape" immersive projective display system. This was a projected active stereoscopic display system with two cojoined surfaces (floor and a single wall) that form an L. The floor projection was 3m × 2.25m, and the wall projection was 3m × 2m. The projectors were driven at a resolution of 1400 × 1050. The user was tracked using an ART ARTrack2 optical tracking system with eight cameras. The L-shape had a surround sound system for spatial sound with speakers at the four corners of the display at approximately ear height and a subwoofer. A Wiimote equipped with a tracking target for the ARTrack system was used as a wand for the interactions.

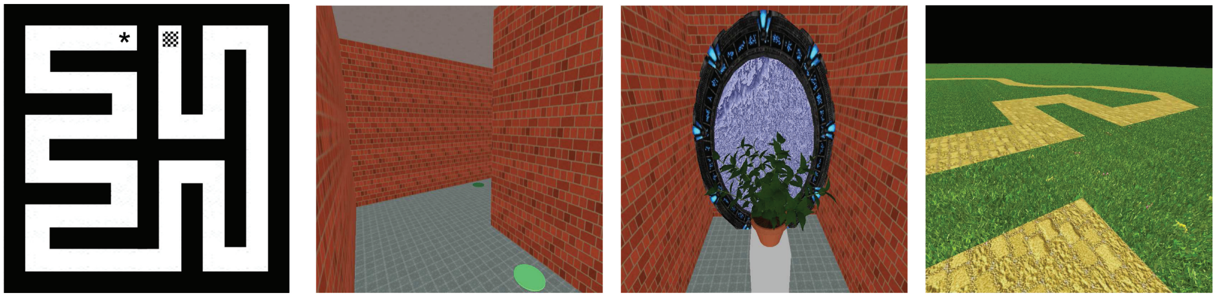
The floor of our L-shape was a specially prepared device that we referred to as the sound floor [Blom et al. 2012]. The sound floor is technically similar in design to the haptic floors developed by Visell et al. [2008, 2009]. The critical difference for this study was that the surface is contiguous, providing an artifact-free surface for the projection. Such artifacts may impact perceived realism of the VE and presence. The floor of the L-shape sat upon a wooden riser construction. Attached to the underside of the platform were a number of linear actuators with good low-frequency response. The actuators were driven as bass channels by a spatial audio system. This means that any sound sample could be played through the floor, giving unique effects. When driven by a single impulse bass sound, a haptic impulse was felt through the flooring by the user standing in the display. Likewise, oscillating sounds led to vibrations of the floor surface in the same frequency. This allowed us to easily experiment with different haptic responses. Although greatly dampened, it must be noted that the floor itself acted as a speaker when driven.

The VEs were generated using the VR Juggler libraries with OpenSceneGraph(OSG) for rendering. The interaction code was written using the ACTIF framework [Hess et al. 2008]. The mazes were generated from files generated by the Daedalus maze software [Pullen 2013]. The file format was lightly extended for placement of the starting and ending points as well as waypoint placement. The geometry of the mazes was generated at runtime by a custom C++ loader, and several custom shaders were written in GLSL.

3.3 Scenario

In order to investigate differences in perception due to the choice of virtual collision responses, the user has to experience each. Ideally, we would control all aspects of the collisions, including the number of collisions experienced. However, to do this would reduce the experience to a passive viewing instead of an immersive interaction, severely reducing the participant's sense of agency. We felt that it was very important to maintain the travel interaction. Because of this, the exact number of collisions with each method differs per participant. The scenario was designed to reduce the probability that the participant would not collide at all.

Two VEs were developed for the experiments: the experimental environment and a specially developed warm-up environment, created for learning the virtual travel method. The virtual travel method is outlined next, followed by descriptions of the experimental and warm-up environments.



(a) (b) (c) (d)

Fig. 1. The VEs used in the study: (a) The layout of the initial maze for the tests. The asterisk (*) represents the start, and the checkered field represents the end. (b) View of the maze with waypoints around a corner. The nearest is triggered. (c) The end of a maze with a plant and the portal. (d) The practice environment with a yellow brick road in a grass field.

3.3.1 Interaction Techniques. Virtual travel was performed using wand-based pointing methods. A constant velocity (1.4m/sec) movement in the direction the wand pointed was performed while the "trigger" was pressed. A scaled virtual rotation was performed, while the "A" button of the wand was pressed. The zero direction was pointing directly into the L-shape screen. Travel and rotation could be combined at the same time. Participants were free to move physically within the display system.

Virtual collision detection used a classical ray-casting method. Because a single ray creates difficulties with approaches to walls at angles, we extended the collision detection to include multiple rays at angles. The user's body was not tracked, but instead their bodily volume was simulated by a constant distance in the direction of travel. The rays were placed at a height that ensured intersection with the walls and the pedestal (explained in the next section). Collisions of the head were also determined and recorded, but no action was taken.

3.3.2 Experimental Environment. An environment that fulfilled two main criteria was needed for the study; it had to provide a high potential for collisions and be valid if applied multiple times for the repeated measures design. We selected a maze-based environment, as mazes are commonly used in similar studies [Jacobson and Lewis 1997; Suma et al. 2007] and they meet both main criteria. In order to keep the participants' interest and avoid learning effects, we used different maze layouts for each exposure. The mazes were unicursal, having exactly one path through the maze without any junctions. Each maze had the same cell distance, and the traveled distance was approximately 53m. The mazes all consisted of similar percentages of straightaways and turnings (either 44/56% or 50/50%). An example layout can be seen in Figure 1(a). The hallways were 1.5m wide and were textured as red brick walls with a tiled floor. The walls, floor, and ceiling were all rendered using a parallax normal mapping shader to improve the believability of the environment.

In early tests, participants frequently navigated the mazes without colliding, even with the speed of the travel quite high. To increase the probability of collisions, without increasing a risk of simulator sickness, a waypoint task was added. Five waypoints, seen in Figure 1(b), were place in each maze, positioned such that they where close to walls and at corners. The waypoints decreased the number of zero collision occurrences to an acceptable level.

In order to transport the user from one maze to the next, a method based on the work of Steinicke et al. [2009] was introduced. They showed that user presence was increased when a portal was used to move from a virtual reproduction of the physical environment to a novel virtual world. We applied their portal idea to make transitions between environments more seamless and less disorienting. To use the portals, the user was required to physically move through the portal; virtual movement did not "activate" the portals. Figure 1(c) shows a portal. The "worm hole" portion of the portal was dynamic and viewpoint dependent, driven via a modified water shader.

An independent method of testing the perception of the environment was introduced, in the form of additional objects, inspired by Hoffman [1998] and Suma et al. [2007]. In each maze, objects were placed on a pedestal, similar to those used for display in museums (Figure 1(c)). The user could not collide with the objects, as they were smaller than the pedestal. This provided an interaction-neutral object, for which we could ask about the realism of the environment. The pedestal was positioned roughly 1m in front of the portal so that the object would be seen. The objects used were a plant, a teapot, a lamp, a hammer, a fruit bowl, an electric kettle, a book, a laptop, and an iron. The object and maze order were held constant between participant and experiment.

3.3.3 Warm-Up Environment. An extra environment was developed for participants to learn the virtual navigation method. A planar world was used, as it was neutral to the independent variable, collision response. To make it somewhat more interesting and to give users a task that ensured they used the travel method similarly to test conditions, we developed a "follow the yellow brick road" world. The plane was covered with an animated grass and a road that was made of worn yellow bricks, rendered with a parallax normal mapping shader. The warm-up environment can be seen in Figure 1(d).

3.4 Procedure

The same procedure was used in all three experiments; only the independent variable was changed, with differing methods and number of trials in each experiment. The mazes and objects were presented in the same order in each experiment. The independent variable was randomized and counterbalanced for the starting maze. Participants were welcomed and briefly told that they would be taking part in a virtual reality study using the L-shape display that was in the room. They were asked to fill out the prequestionnaires—a demographic data questionnaire, ITQ, and pre-SSQ—and gave informed consent. At this point, the display was started in the warm-up environment. The participants were reminded that they could, at any moment and without repercussion, end the session. Participants were invited into the display system and briefed on how the interaction worked. They were tasked with becoming comfortable with the virtual travel method and left to explore the grass world for as long as they liked. This typically took between 2 and 5 minutes.

The experimental task was explained to the participants in the physical space of the L-shape using printed pictures of the maze environment to explain the waypoint sensors and the portal as the end point. The speed of completion was indicated as being important, and timing was mentioned. The VE was then changed to the test environment, with the first test method in use. After participants had successfully navigated to the portal, they were asked to step out of the L-shape to a desk, just in front of the display, to fill out the first round of questionnaires. These were the SSQ, post-SUS, and the realism questionnaire.

Participants were then invited to return to the L-shape. They were informed that a number of runs through mazes would be performed. The use of the portal was explained to them. When they were prepared, they physically moved through the portal. After each run, the shorter realism questionnaire was administered via aural questioning by the conductor of the study. The participant did not leave the display system, although several removed the active stereo glasses when turned to the study conductor.

After completion of all conditions, the summary questionnaire was administered in written form. If the participants expressed confusion on which methods were which, they were allowed to reenter the environment to experience the methods. In cases where the participants had not experienced all methods (i.e., by not colliding with the walls), they experienced the others in a post session, where each activated separately.

3.5 Analysis

In a first step, the data were encoded and cleaned. Occasionally, a participant did not collide during a particular exposure. The data for that condition were excluded in the statistical analysis. This never happened on the first exposure for any participant.

The data analysis was performed using the R statistical system. All analyses were performed at the .05 significance level. The main analyses of the nonparametric questionnaire data were performed using the Aligned Rank Transform (ART) method [Higgins et al. 1990]. Custom R code was implemented following Wobbrock et al. [2011]. The ART method was elected over the more traditional Friedman's ANOVA, because it enables two-way repeated measures ANOVAs (referred to as RM ANOVA in the results sections). This allows controlling for effects of order, individual mazes, and interaction effects in the analysis. PostHoc Tukey HSDs were performed with Bonferroni's correction. Kruskal-Wallis tests were used for between subjects analysis of variance, and Fisher's Exact Text (FET) for test of fit. The FET test was used in place of χ-square, since not all cells had observations. Kendall's coefficient of concordance was used for interrater agreement of ranking data. Logistic regression analysis was performed using the Cumulative Link Mixed Models (CLMM) method of the ordinal package. Cumulative link logistic regression permits both the ordinal response and the repeated nature of the data to be taken into account. An adaptive Gauss-Hermite quadratic approximation was used in fitting the maximum likelihood estimation with nine control points. All models were checked for violation of the proportional odds assumption by comparing the likelihood of the model with a multinomial logistic regression model [Fox 2002].

4. EXPERIMENT I

This experiment served two purposes: investigating the impact of having a collision response and investigating a broad variety of feedback methods. The *no collision* and *stop collision* responses without feedback were compared. Additionally, a broad set of feedback methods were tested. The methods, in their expected ascending order of effectiveness, were *no collision*, *stop*, *visual*, *buzz*, *rumble*, *thump*, *wand rumble*, *floor rumble*, *floor thump*.

Fifteen participants were recruited from campus and were naive to the purpose of the study before participating. Of these, 73% were male. The mean age was 26.5 years (SD 3.2). Excepting one participant, all reported normal or corrected to normal vision, color vision, and stereo vision. One participant reported not having stereo vision. In addition, 60% reported having no experience with VEs. In equal thirds, the participants reported their time spent gaming as "none," "up to 3 hours per week," and "3 to 14 hours per week."

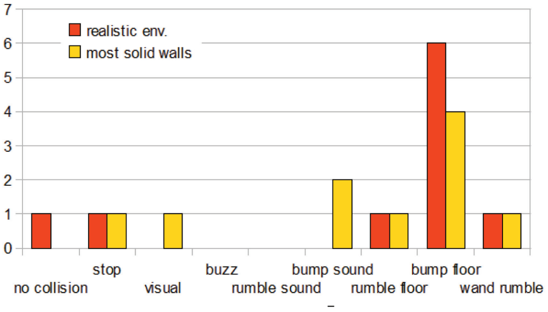
4.1 Results

The RM ANOVA of the ART data showed a highly significant main effect of condition on perceived realism of the collisions [F(8) = 11.8, $p < .001$]. The results of PostHoc Tukey tests can be seen in Table I. A planned Mann Whitney U test showed a highly significant difference between *no collisions* and *stop* [U = 145, Z = −3.77, $p < .001$].

The RM ANOVA of the ART data for the perceived solidity of the walls showed a main effect of method [F(8) = 17.0, $p < .001$]. PostHoc analysis is presented in Table I and shows that the no collision method drove most of the effects, producing less solid impressions of the walls than all other methods. Likewise, a main effect of method was found for the solidity of the item [F(8) = 5.6, $p < .001$]. The PostHoc analysis indicates that the effect was driven by the no collision and buzz methods, which produced less solid impressions.

Table I. PostHoc Tukey HSD Comparisons of Main Effect of Response Method of the ART Data in Experiment I
This shows which of the nine conditions differed significantly from each other on the main realism questions. The questions were Collision Realism (cr), Solidity of Walls (sw), Solidity of Item (si). '$-$' indicates the column response is greater compared to the row. Significance codes: $p < .001$ **, $p < .01$ *, $p < .05$ *, $p < .1$ $^{+}$

stop	cr*** sw*** si**							
visual	cr^{+} sw***							
buzz	cr* sw* si***							
thump sound	cr*** sw*** si**		cr**	cr*				
rumble sound	cr*** sw***			si^{+}				
floor thump	cr*** sw*** si***		cr***	cr***		cr*		
floor rumble	cr*** sw***			sw^{+} si**			$-$cr^{+}	
wand rumble	cr*** sw* si^{+}						$-$cr** $-$si^{+}	$-$sw*
	no collision	stop	visual	buzz	thump sound	rumble sound	floor thump	floor rumble



(a) Counts for best method for questions *realistic* and *solid*.

	MODE	MEDIAN	IQR
no collision	9	9	3.8
stop	7	7	2.5
visual	6	8	2
buzz	8	7	2.5
rumble sound	5	5	1.8
thump sound	3	3	1.8
rumble floor	2	2	1
thump floor	1	1	0.8
wand rumble	4	5	2

(b) Ranking of Methods: 1=best, 9=worst.

Fig. 2. Experiment I: Postsession ratings (a) and rankings (b) of methods.

Realism of collision and the solidity of walls were moderately correlated [$\rho = .42, p < .001$]; realism of collision and the solidity of the item were similarly correlated [$\rho = .33, p < .001$]. The solidity of the item was only weakly correlated with the solidity of the walls [$\rho = .28, p < .01$].

Regression analysis revealed that the perceived realism of the collision was explained by method, gender, gaming experience, and prior VE experience. Males were 19 times more likely to rate the collision realism one point higher than females. Those without VE experience were four times more likely to rate the collision realism one point higher than those with experience. People who reported playing games up to 3 hours per week were 18.8 more likely to report collision realism one point higher than those who did not play. People who reported playing 3 to 14 hours per week were 3.3 times more likely to report collision realism one point higher than those who reported not playing games. Both solidity responses were explained only by method. Comparative weight responses were not explained by any factor.

Users generally preferred methods that were multimodal and appropriate to the impact. Figure 2 shows the results of the summary ratings and rankings. The choice of best method for realistic collisions and for solidity of walls were significantly different than random choice [$\chi^2(8) = 22.8, p < .01$] and [$\chi^2(8) = 18.0, p < .05$], respectively. The best method was not significantly different between the two questions [$\chi^2(8) = 18.5, p = .1$]. Kendall's coefficient showed strong interrater agreement on the rankings of the methods [$W = .59, p < .0001$].

Table II. Encoded Responses to the Between Subjects Question *Drop*, with Percentages of Responses and Methods the Participants Experienced

falls & breaks	falls & earth spills out	falls, nothing happens	too heavy to pick up	nothing
35.7%	21.4%	28.6%	7.1%	7.1%
floor rumble	floor thump	stop	no collision	wii rumble
wii rumble	floor thump	stop		
thump	thump	buzz		
visual		rumble		
rumble				

4.2 Discussion

The results of this experiment show that the addition of a collision response does positively effect the perception of the realism of the collision and environment, supporting H1. Although it is fairly obvious that collision realism should be more realistic when collisions are handled, the user regardless experienced the "collisions" in the no collision method, in the form of visual feedback of moving through the walls. Similarly, the solidity of the walls is greatly improved when one cannot move through them. Although that seems likely a priori, the same improved perception of solidity was found for an object with which the participant had no direct contact. This indicates that there is a positive effect of having a collision response in terms of overall environment realism. This experiment is the first to verify that the presence of a travel collision response positively effects collision realism.

Evidence that differences between feedback methods existed was found, as hypothesized in H2 and H3. Collision responses for notification methods were significantly lower than those of the thump sound–based feedback methods. Similarly, the rumble-based feedback methods produced less realistic collision perceptions than the thump sound–based feedbacks. The extent of the effect of feedback on perceived solidity of the environment was limited. The buzz created lesser impressions of solidity than thump methods, and wand rumble performed worse than the two floor-based methods for solidity measures.

The between subjects, open subjective responses provided further support for differences between feedback methods. All but one of the participants responded to the open subjective question *material* that the walls were composed of bricks. This answer could indicate acceptance of the visual cue but could also be reporting what they think the experimenter wants to hear. The other participant responded that it was made of pixels, looked like bricks, and felt more like wood (*wii rumble* method). Stronger support of differences is found in the responses to question *drop*—What would happen if you were to pick up the plant and drop it? The results were encoded into five categories and are summarized in Table II. These responses show a tendency for the environment to be interpreted as real when provided with more realistic feedback and as virtual with more abstracted feedback.

5. EXPERIMENT II

This experiment investigates more closely whether there is an effect of feedback modality, comparing audio and audio-haptic feedback. The experiment focuses on three methods from the prior experiment - *stop*, *thump sound*, *floor thump* - and an additional method, *bass thump*, in a smaller controlled study to see if differences do exist. The three feedback methods are driven by the same sound. *t*hump sound and *bass thump* differ in the tonal quality of the sound, the latter being a much richer sound. *b*ass thump is very similar to *floor thump* from tonal quality, but it does not include the haptic feedback via the feet, allowing better comparison of the inclusion of the haptic modality. For this experiment, our hypothesis was that the methods in ascending order should be stop, thump sound, bass thump sound, and floor thump.

Sixteen users participated in this study. They were recruited on campus and were naive to the purpose of the study. The mean age was 28.8 years (SD 9.2), and 25% were female. All participants reported normal or corrected to normal vision, color vision, and stereo vision. Self-report gamer type were 43.8% nongamer, 18.8% casual, 25% core, and 12.5% hardcore. Of the participants, 63.5% reported having VE experience.

5.1 Results

The RM ANOVA of the ART data revealed a trend for the main effect of method on the realism of collision responses [$F(3) = 2.9$, $p = .05$]. No significant effects were revealed in the PostHoc analysis. The solidity of the walls was not significantly impacted by method; however, there was an effect by method for the perceived solidity of the item [$F(3) = 6.9$, $p < .01$]. PostHoc analysis revealed that the item was perceived more solidly with bass thump than either stop [$z = 2.9$, $p < .05$] or thump sound [$z = 2.5$, $p = .05$]. The floor thump method showed a trend compared to the stop method [$z = 2.6$, $p = .05$].

Inspection of the raw collision realism data showed a slight trend for stop to be less realistic than the others. To detect any differences between stop and having feedback, the feedback methods were pooled and Wilcoxon rank sum tests were run. Collisions were perceived as significantly more realistic with feedback [$W = 375$, $p < .05$].

Regression analyses showed that the only explanatory factor for the realism of collision and solidity responses was the method. The comparative weight response was significantly predicted by the gamer type and score on the SUS presence questionnaire. Increasing SUS scores increased the probability of a point higher response by 80%. Gamer types casual, core, and hardcore were more likely to respond one point higher than nongamers by factors of 5.9, 11.1, and 4.9 times, respectively.

The rankings given to the methods was clearly as hypothesized: *stop* < *thump sound* del< *bass thump sound* < *floor thump*. Kendall's coefficient showed strong interrater agreement on the rankings of the methods [$W = 63$, $p < .01$]. The most realistic collision was always reported as either the floor thump (12) or bass thumpsound (4). The most solid walls were produced by floor thump (13) or bass thump sound (3) methods. Both were highly significantly different than random [$\chi^2(3) = 24.0$, $p < .001$] and [$\chi^2(3) = 28.5$, $p < .001$], and they were not significantly different from each other.

5.2 Discussion

This experiment was designed to take a closer look at the effect of feedback and at any effect of modality, using the best methods from the first experiment. The findings provide some support to the notion that the addition of feedback improves the perceived realism of the collisions over the same response without feedback. The perceived solidity of the walls was not significantly effected by choice of feedback; however, the solidity of the item was. We saw evidence that the richer cues of floor thump and bass thump improved the impression of solidity over the no feedback case. However, we did not find evidence of the hypothesized improved realism for richer feedback.

During the experiment, there was ample anecdotal evidence indicating that the realism would be improved. For instance, two of the participants reacted to collisions in particularly interesting ways. One exclaimed "Oh God" with the base thump method. Another made a comment about having a "bump on my forehead." Several participants avoided all collisions after having experienced the floor thump method. When asked afterward, they indicated that they were "afraid" to collide after the experience of the floor.

Most of the participants identified the walls as being made of bricks, regardless of which feedback they experienced. One participant in the thump sound condition identified the walls as "rubber"; however, the same participant also said that the flower pot would break when dropped.

Upon falling, 62.5% said the pot would break. Four participants expected that the pot would fall and they would hear the collision. One participant, who experienced bass thump, said nothing would happen, and one, who experienced the floor thump, said he did not expect it could move. Further questioning revealed that the participant thought it was too heavy to be moved.

6. EXPERIMENT III

This experiment focuses on a different class of collision handling—the slide response. The slide response is very popular in games and adopted in some IVEs. It generates very different responses at angles and has a large potential to change solidity and realism perceptions. The slide method has two components to it: the impact and sliding phases. This experiment uses different combinations of the thump impact and rumble sliding effects. The methods tested, in the expected ascending order, are slide, rumble, floor rumble, floor thump, thump/rumble, floor thump/rumble. All sounds were played with the additional bass component.

Sixteen users took part in this study. All but two were naive to the purpose of the study. Those two had taken part in Experiment II. The mean age was 27.9 years (SD 4.5), and 68.75% were male. All participants reported normal or corrected to normal vision, color vision, and stereo vision. Self-report gamer types were 25% nongamer, 31.3% casual, 37.5% core, and 6.3% hardcore. Of the participants, 69% reported having VE experience.

6.1 Results

RM ANOVA analysis of the ART data found a significant main effect by method for the perceived realism of the collision $F(5) = 3.6, p < .01$. PostHoc Tukey HSD indicated that collisions with the slide (without feedback) method were perceived as less realistic than with every other method, all significant to at least $p < .05$. A significant main effect by method was found for the perceived solidity of the walls [$F(5) = 4.2, p < .01$]. PostHoc analysis indicated that perceived solidity of the walls was improved by the floor rumble/thump [$z = 3.7, p < .01$], floor thump [$z = 3.1, p < .05$], and rumble/thump [$z = 4.1, p < .001$] methods over the slide method. No effects were found for the solidity of the item.

Planned analyses of the no feedback condition against the pooled feedback methods on the raw data was significant only for the solidity of the walls [$W = 915, p < .01$]. Analysis of the between subjects condition revealed no significant effects by method.

Regression analysis of the perceived collision realism showed that method, gamer type, and gender were explanatory factors. In comparison to the nongamers, the other types were likely to report one point less realism by factors of 31.6 (casual), 82.8 (core), and 34.4 (hardcore). The gender factor did not fulfill the proportional odds assumption. Individual binary logit regressions showed that in the transition from realism scores 1 to 2, there was no difference between genders. At higher scores, males were more likely to respond one point higher by odds of 4.3 (2|3), 21.7 (3|4), and 15.8 (4|5).

The solidity of the walls was explained by method and VE experience. Those with no VE experience were 18.8 times more likely to report one point higher solidity of the walls than those with VE experience. No factors significantly explained the perceived solidity of the items. The comparative weight was explained by method, gender, and VE experience. Males were 10.1 times more likely to perceive the virtual item heavier by one point than females. Those with no VE experience were 3.6 times more likely to perceive the virtual item heavier by one point than than those with VE experience.

The selections of the best methods were more spread than in Experiment II. Participants selected either the floor thump/rumble (7 and 7 times for realistic collision and wall solidity, respectively) or thump/rumble(7,6 selections) methods. The methods that created the most realistic collisions and most solid walls were different from random choices [$\chi^2(5) = 14.0, p < .016$] and [$\chi^2(5) = 17.8, p < .01$], respectively, and not significantly different from each other. The interrater agreement of rankings of

Table III. Statistics on the Rankings Given to the Methods, 1 (Best) to 6 (Worst)

	Mode	Median	IQR
floor thump/rumble	1	2	1
thump/rumble	1	2.5	2.3
floor rumble	3	3	1
rumble	5	4	2.3
floor thump	5	4	3
slide	6	6	0

the methods was only moderate in this experiment [W = .43, $p < 0.01$]. Table III shows results of the rankings of the methods. The slide was the lowest rated, and two methods that combined the impact thump and the sliding rumble were preferred.

6.2 Discussion

The additional qualitative measures provide further insight into participant perceptions. Most participants responded that the material of the walls was brick. Interestingly, two of the four participants who experienced no feedback responded with different answers: “paper or plastic” and “not real.” Only one of the participants who experienced a method with feedback answered something other than brick; that participant responded “hard plastic” and had experienced the floor thump method. The spontaneous responses to some methods are of interest. Having experienced floor thump/rumble, one participant expressed the rough equivalent of “hey,” and another physically jerked back on contact twice. The participant who said “hey” also jerked back on the floor thump method, said it was “totally frightening,” and swore loudly. This carried over to the next maze—no feedback—where that participant also jerked back on initial contact.

7. GENERAL DISCUSSION

The most basic of our hypotheses, H1—that having a collision response increases the realism of the environment—was supported by the experimental results of Experiment I. When using the stop response in comparison to no response, measures of realism for both the collision and environmental realism were significantly different. However, there was no effect on the self-report level of presence on the SUS scale. There may be several reasons for this. It may be due to the relatively small sample size of the between subjects measure. It may be that the SUS scale is too general to be sensitive enough to detect the differences. However, this may also be attributable to how strongly immersive virtual reality works, regardless of the collision response.

To investigate the relative effect of the collision handling method selected, we also compared the three handling methods without feedback (no collison, stop, and slide) in a between subjects test. Kruskal-Wallis tests found significant differences in collision realism [$\chi^2(2) = 8.7$, $p < .05$], solidity of walls [$\chi^2(2) = 17.3$, $p < .001$], and solidity of item [$\chi^2(2) = 7.2$, $p < .05$]. PostHoc comparisons with Bonferroni’s correction are indicated in the plot in Figure 3 . The slide method produces impressions of the environment that were between those of no collision and stop method and tended to be closer to the no collision responses. Our interpretation, based on this data and user comments, is that the slide method tends to produce a “spongy” feeling instead of the more solid impression that the stop method produces.

We had hypothesized in H2 that perceived collision realism would be greater for improved feedback. In particular, we expected that the addition of haptics through the sound floor device would greatly

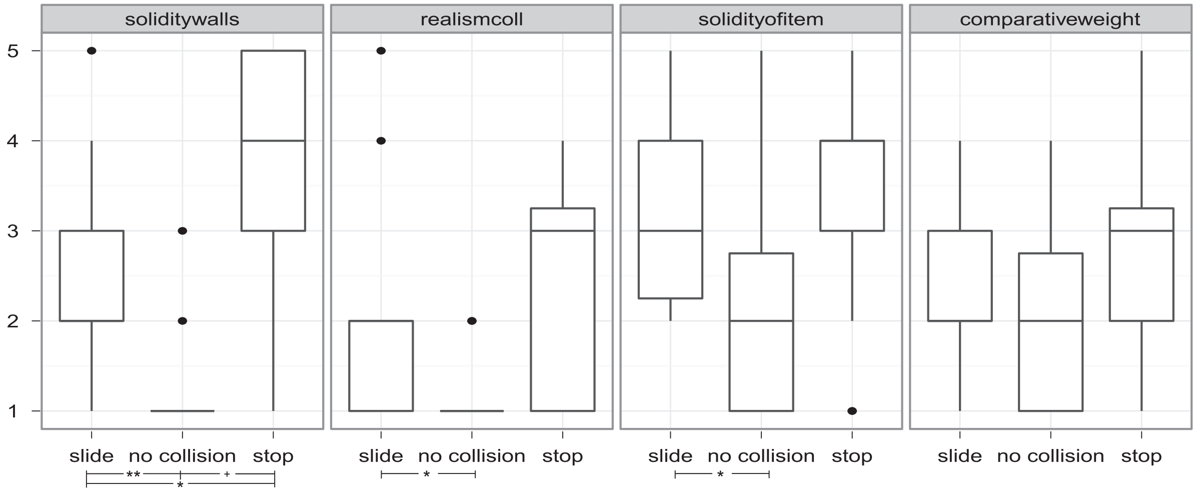


Fig. 3. Comparison of the collision response methods without feedback. Standard box plots of user responses to each question (five-point Likert scaled) are provided. Significant differences between methods are denoted below with significance levels: $^+$, <.1; *, <.05; **, <.01.

improve those perceptions, as it couples directly with our standard locomotion devices, our legs. However, the experiments indicate only limited effects in these regards. Experiment I provided statistically significant evidence that the thump-based feedback was better than both the notification-style feedback and the rumble feedback coupled with a stop response. However, Experiment II, which investigated the effect of feedback richness more closely, found no effect within a set of context-appropriate, thump-based feedback methods that varied only in richness of the cues. In Experiment III, we found no evidence of an effect by feedback with the slide response. Therefore, the results from Experiment I should be interpreted as indicating the importance of context appropriateness of the feedback rather than modality or feedback richness.

H3 proposed that the realism of the environment would be greater with improved feedback. The experiments provided limited evidence of this. Across all experiments, the SUS presence scores did not differ by method. Experiment I produced evidence that perceived solidity of the environment was improved by using context-relevant feedback with the stop response. In particular, thump sounds were better than rumble sounds, rumbling of the floor was better than rumbling of the wand, and the buzz method was worse than thump-based methods. Experiment II found only weak support in the case of the thump sound versus the richer floor thump and bass thump methods in relation to perceived solidity of the item. Experiment III found no statistical difference between the feedback methods. In total, we see that the inclusion of appropriate collision feedback improves the perception of solidity of the environment, but further enriching of the cues through haptics does not significantly impact the perceived solidity of the environment.

H4 proposed that feedback richness would be a factor of modality and context. That context is important is supported by Experiment I; notification types of feedback that are commonly used (e.g., Bloomfield and Badler [2008], Suma et al. [2007], and Whitton et al. [2005]), and even the rumble pack in the wand created perceptions only slightly better than no feedback and were liked less by some. Although the sound floor– based methods were preferred, they created only limited differences in the perceptions of the VE. Experiment II was designed specifically as a controlled experiment of this factor and found no differences by modality. However, reactions of participants to the floor-based haptic methods with both response types indicated that the methods worked strongly. Spontaneous exclamations and avoidance of collisions after using a method happened almost exclusively for the sound floor–based methods.

When designing the experiment, we expected to find a number of relationships between explanatory factors such as immersive tendencies, presence, and gaming experience. Following conventional wisdom from the community, these factors should be explanatory factors of variables such as the realism of the environment or the experience. However, in our analyses, we found that neither ITQ scores nor SUS presence scores were explanatory factors of any measure. ITQ scores did correlate with SUS scores, as would be expected. Similarly, the traditional question of "how much time per week do you spend gaming" was not an explanatory factor. Instead, only the gamer-type measure introduced in the later experiments was a significant explanatory factor. Even then, effects were limited to nongamers versus gamers.

The results of our study indicated that the inclusion of a collision response positively impacts the user's perception of the interaction and environment. Although our study used a single, specific scenario, we believe that these results generalize to other scenarios and applications that are not as collision intensive. However, from this initial study, it is yet unclear to what extent the addition of collision responses may impact any given application. For instance, in the Introduction, we discussed several areas of perceptual research within VEs (e.g., learning transfer, spatial awareness); the impact of inclusion of collision responses in those contexts needs to be verified in future work. We also believe that the results of our study are generalizable across many standard display setups and travel methods. We have used a fairly standard wand-based virtual travel method and expect that for most abstract virtual travel methods, similar results would be found. For travel methods that are more physically based, like "walk in place," results may differ. We suspect that when physical body movement is a critical component of movement, the simplistic, global feedback we provided may be too limited. In cases such as this, the participant may desire more localized feedback, as in Ryu and Kim [2004]. We have also used a very simplified environment for collisions, where only large surfaces existed for collisions. If collisions can occur with specific body parts due to objects of various sizes and protrusions, the global feedback performed may be too coarse. This global versus local feedback question is an interesting avenue for future exploration. In both of these cases, we believe that the general findings of the studies will still apply: the use of a context-appropriate feedback style coupled with some sort of collision handling will improve realism.

8. CONCLUSION

Collisions in VEs have to be explicitly programmed in order for them to occur, and various methods can be selected. In this article, we have presented a study composed of three experiments that investigated the effect of collision response methods and feedback methods on the user's perception of the environment and collisions. The results indicate that the presence of a collision response significantly impacts the perception of the realism of the interaction and environment. The stop response method leads to the highest levels of realism of the collision and impressions of the solidity of the VE; the slide method also significantly improves the improved solidity of the walls but has a less pronounced global effect. The coupling of feedback with the responses only made statistically significant improvements to the impressions in limited cases. We found evidence that the context appropriateness of the feedback is important, suggesting that traditional notification-style feedback should be replaced with cues that are collision appropriate. Notification-style feedback was not significantly better than no feedback and often liked less. Context-appropriate feedback coupled with the stop response produced significantly stronger impressions of the collision and solidity of the environment. Surprisingly, little evidence of an effect was found for different feedback richness and modality. However, users consistently rated methods involving our floor-based haptic method as the best method for realism and solidity of the environment as well as general preference. In total, we conclude that a collision response with a context-appropriate feedback should be used for virtual travel, regardless of the modality.

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