Exploring Interaction Fidelity in Virtual Reality: Object Manipulation and Whole-Body Movements

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Figure 1: In two user studies, we explored player experiences with varying degrees of interaction fidelity in VR. One study explored object manipulation (a & b), while the other focused on whole-body movements (c).

ABSTRACT

High degrees of interaction fidelity (IF) in virtual reality (VR) are said to improve user experience and immersion, but there is also evidence of low IF providing comparable experiences. VR games are now increasingly prevalent, yet we still do not fully understand the trade-off between realism and abstraction in this context. We conducted a lab study comparing high and low IF for object manipulation tasks in a VR game. In a second study, we investigated players' experiences of IF for whole-body movements in a VR game that allowed players to crawl underneath virtual boulders and "dangle" along monkey bars. Our findings show that high IF is preferred for object manipulation, but for whole-body movements, moderate IF can suffice, as there is a trade-off with usability and social factors. We provide guidelines for the development of VR games based on our results.

CCS CONCEPTS

• **Applied computing** → **Computer games**; • **Software and its engineering** → **Interactive games**;

KEYWORDS

virtual reality; interaction fidelity; games; whole body interaction; virtual objects; player experience.

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1 INTRODUCTION

In recent years, increasing progress in the domain of virtual reality (VR) has reached the consumer market, to widespread popularity. Many games are being ported or developed specifically for VR, and there are an increasing number of VR arcades and installations [39, 47]. While VR applications achieve a remarkable degree of display fidelity, they vary widely in the implementation of interactions [18, 24, 35].

Research on precursors to modern VR (e.g., 3D user interfaces) have long explored how much realism should be featured by VR systems. This realism, i.e., the exactness with which VR resembles the real world, is named fidelity; research in this domain generally differentiates between display fidelity (DF) and interaction fidelity (IF). The results of that literature show that increasing DF coincides with an improvement in user experience (UX), particularly presence. Yet for auditory DF in particular, recent work with modern VR has shown little impact on users in a game context [38]. In terms of IF, research has yielded evidence that there may be an uncanny valley for IF: moderate IF can negatively impact UX, but both low and high IF can reach comparably good results. This has been described as an effect of familiarity: high degrees of IF remind the user of the real world, while low degrees of IF are associated with also familiar computer interfaces. Modern VR, since the widespread adoption of head-mounted displays (HMDs) and corresponding systems such as the Vive or Oculus Rift, has reached a good level of DF, however IF is implemented in more varied ways. Whether the uncanny valley of IF also applies to modern VR remains has not yet been explored.

In this work, we focus on IF in VR, and explore it from a player experience (PX) perspective. Games are a particularly interesting domain for exploring IF, as realism is often not the dominant goal, yielding instead to abstractions for ease of use, aesthetics, or game mechanics that facilitate enjoyment [40, 41]. We empirically explored effects of IF for object manipulation tasks on PX, yielding first evidence that high IF improves PX in VR compared to low fidelity implementations for this kind of task. Further, contributing to the discourse on benefits of physicality on game engagement and human-computer interaction, we investigated effects of IF for whole-body movements in VR games through a qualitative mixed-methods study. In a VR prototype, we approximated several real-world movement metaphors with moderate IF: crawling, dangling, and multi-object interactions (e.g., using a virtual item like a sword to cut down a virtual spiderweb). Our findings point to trade-off considerations between high IF for realistic whole-body movements, and the purposeful use of lower or moderate IF for increased usability and convenience. Based on this, we offer guidelines to inform design of IF in future VR games with regards to object manipulation tasks as well as whole-body movements, thereby further extending research on playful bodily experiences in VR games.

2 RELATED WORK

A prominent aspect of VR development and research has focused on fidelity (also naturalism, or realism): the degree of accuracy with which a system recreates real-world experiences. This area of research distinguishes between display fidelity (sensory realism, referring mainly to auditory and visual qualities) and interaction fidelity (action realism, i.e., the degree of exactness with which user actions in VR resemble real world actions in terms of biomechanical similarity, input, and control) [29, 30].

Fidelity in VR. In terms of display fidelity, prior research has shown that high fidelity VR display systems (e.g., graphics and audio quality) facilitate immersion and presence [6, 11, 33, 51]. However, there are indications that the addition of ambient noises to VR game audio does not improve PX (including immersion) [38]. This suggests that bodily and sensory experiences may override effects of audio fidelity in VR; similar effects have been observed for music in the exercise context [23].

For the degree of interaction fidelity, results are further divided. Researchers have suggested that full realism may not always be necessary, pointing out that there are benefits to VR experiences beyond realism [5]. Further, there is work pointing towards an uncanny valley in interaction fidelity: while moderate degrees of IF negatively impact user experience in VR, low degrees of IF have reached comparable user experience to high degrees of IF [29, 30]. McMahan et al. have speculated that this occurs as an effect of familiarity: user experiences in high fidelity VR leverage associations with the real world, while low fidelity VR builds on associations born from familiarity with existing computer interfaces. However, research in this area is mostly or partially based on precursors to modern VR (e.g., CAVE systems), extending an opportunity to explore how these findings apply to modern VR game experiences. Further, studies have focused on a wide range of tasks ranging from object manipulation to navigation. Research on physicality in games suggest that whole-body movement is a significant factor in engagement and sensory immersion [21], suggesting that effects of IF may differ for more stationary tasks as opposed to tasks focusing on full-body movements.

In modern VR, there are few studies on effects of interaction fidelity. One notable example by Nabiyouni et al. [33] showed evidence for the theory that moderate IF leads to worse user experience than both high and low IF. However, this study focused only on locomotion tasks and featured a small sample size. The results also showed that some measures yielded no difference for any degree of fidelity (e.g., no effect on perceived precision in the initial phase of the VR experience). To our knowledge, there is no other empirical work exploring IF in modern VR.

VR Player Experience and Whole-Body Movements. The growing market of VR applications contains a large number of games, prompting a surge in research on PX in VR. In comparison to traditional video games, players in VR can experience less control, but increased flow in VR; in general, the intensity of experiences are heightened [46]. Further, specific interactions affect players differently, particularly passive game elements such as exploration should be emphasized in VR game design [38]. In games, many other aspects beyond realism constitute "good" player experience, e.g., enjoyment, engagement, immersion, challenge or relaxation [13, 16, 25, 52]. For many game elements and genres, realism is thus not the utmost goal: developers and researchers alike have pointed out uncanny valley phenomena, and suggested reduced realism in favour of other aspects of PX, as well as adherence to conventions of the medium/genre [17, 40, 41, 48].

VR games potentially build on a range of HCI and games research that increasingly explores effects of physicality [21, 31]. Physicality and whole-body movements correlate with enjoyment, intensified experience, and more affective game experiences [4, 14]. Thus it has been suggested that the proprioceptive experience should be included in the concept of sensory immersion [3, 13]. Although previous research on movement in VR has studied aspects such as locomotion techniques or perception of exertion [15, 44, 53], VR games can feature a wide range of movements, including crouching, jumping, and reaching. How players experience these movements in VR as part of an immersive VR game is not well understood.

In non-VR exergames, focus on the body is encouraged, however too much realism can be too difficult, particularly for novice players [3, 21]. The degree to which players execute full body movements realistically depends on player motivations (i.e., wanting to win leads players to optimize their movements, whereas players aiming to relax may perform fully realistic movements regardless of score impact) [3]. Guidelines for movement-based games have also stated that movement mappings need not be fully realistic [21, 32].

3 RESEARCH QUESTIONS

In this work, we explore several research questions (RQs) on effects of IF in VR. Research has shown mixed results for IF; sometimes high IF is more immersive and enjoyable, while sometimes low and high achieve comparable results. Our first question focused on a basic VR tasks, object manipulation: *RQ1*: *Does high IF in object manipulation tasks improve player experience in VR?*

Our second main RQ targeted whole-body movements in VR: *RQ2*: *How does IF in whole-body movements affect player experience in VR?*

Finally, we explored whether indications that audio fidelity may be less prominent in visually complex commercial VR games [38] also apply to a less visually focused game. We chose ambient noises as the audio type for this secondary research question, as they facilitate presence in traditional games, as does their combination with sound effects in precursors to modern VR [9, 12]: *RQ3*: *Does ambient noise affect player experience in a visually minimalistic VR game?*

We explored *RQ1* through a within-subjects study using a VR game with two fidelity variants. Subsequently, we explored player experiences with whole-body movements (*RQ2*, interaction fidelity), as well as ambient noises (*RQ3*, display fidelity), in a mixed-methods study.

4 STUDY 1: FIDELITY OF OBJECT INTERACTION

In this study, we compared IF in object manipulation tasks in VR through a study with within-subjects design.

Stimuli

We implemented a VR shopkeeper game as a test stimuli (Fig. 1a & b), with a low (*LF*) and a high fidelity (*HF*) variant. The game loop consisted of fulfilling tasks assigned by a customer by finding the item they wanted in the virtual shop, and giving it to the customer. The game environment was implemented as room-scale to minimize potential simulator sickness issues.

Tasks. The game tasks were designed to ensure that players interacted with the objects in the game environment.

In the first task (*T1*), players were asked to find a red gem that was hidden in a chest to ensure that players manipulated the container object. In the second task (*T2*), players handled virtual items that required a lot of interaction (e.g., physically grabbing and carrying them in high fidelity). They were asked to mix a red and green potion, i.e., collecting potion vials of those colours, mixing them together in a cauldron, and bottling the result in a new vial. The final task (*T3*) asked players to look up an item in the shopkeeper's book, i.e., using a virtual book laid out on a pedestal for stationary use.

Low vs. High Fidelity. Each game variant offered a different type of IF. In the *LF* variant, players interacted with objects via widgets. By pointing at objects, players could activate widgets that offered interaction functionality. For example, the widget of the chest object in Fig. 2c shows that the chest (*T1*) contains two potion vials, each of which can be selected to transfer them into the player's inventory. The inventory was limited to holding two items at a time, to keep variants

Figure 2: Task *T1*: In the *HF* condition, users had to physically use each buckle ⓐ and then push open the chest's lid ⓑ, while the low-fidelity version offered clicks and a widget ⓒ to allow users to interact with the chest and its contents.

comparable; in HF, players had no inventory and could only carry one item in each hand at a time. In the *HF* variant, players had to grab and undo the chest's buckles, and lift the lid (Fig. 2 a & b). The potion vials in the chest were represented as virtual objects that could be grabbed and moved, rather than abstracted in a widget.

Similarly, the cauldron (*T2*) was implemented via a drag and drop widget in *LF*; in *HF*, players uncorked the potion vials, poured the liquids into the cauldron, and scooped up the result in a new vial (Fig. 3). For the shopkeeper's book (*T3*), in *LF*, players used buttons to navigate between pages (triggering an animation of the turning page). The *HF* version required players to lift and turn individual pages.

Tutorial. Both game versions were preceded by a tutorial (in the same game world, with objects appearing one by one as needed) to teach players the upcoming interaction techniques. To help players with little or no VR experience, both versions began with selecting dialogue window buttons by pressing the trigger button on the game controller. Afterwards, the tutorial versions diverged to show players how to use the current interaction techniques to pass an item from their inventory to the in-game customer, collect a potion vial into their inventory, peruse the chest's contents, and mix a potion via the cauldron.

Measures

We used common and standardized questionnaires after each game variant to assess player experience. Affective state was operationalized through SAM [7]. SAM uses manikin images on a 9-point scale to assess emotional valence, arousal, and dominance. Intuitiveness of the interactions was assessed via INTUI (subfactors effortlessness, gut feeling, magical experience, and verbalizability through 17 items on a 7-point semantic differential scale) [49]. Immersion was operationalized through the IEQ [22]: 31 items on 7-point Likert scales, measuring five immersion factors: challenge, control, real world dissociation, and emotional as well as cognitive involvement. Engagement was measured via GEQ (19 items on a 7-point Likert scale) [8]; we also used the E2I's enjoyment (5 items) and presence (9 items) scales [26].

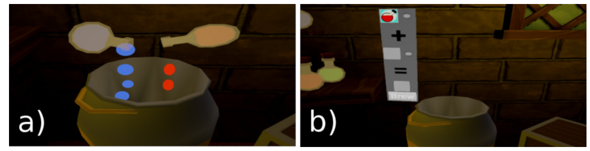

Figure 3: Potion brewing (*T2*) in *HF* involved physically pouring potion vial contents into the cauldron ⓐ. In the *LF* variant, players dragged potion vials from their inventory to the activated cauldron widget ⓑ.

The post-game questionnaire also included custom 7-point Likert scales that asked participants how much they liked the individual interactions with the chest (*T1*), the cauldron (*T2*), and the book (*T3*). These items were phrased to avoid mentioning *HF* or *LF*, as this could potentially already cause bias. Instead, depending on the game variant, they were asked how much they agreed with a statement such as "*I liked moving the individual pages to interact with the book*" in the *HF* condition, as opposed to "*I liked clicking through the pages to interact with the book*" in the *LF* condition. Additionally, we employed one survey for participants' demographic background, and one to compare the game variants. The comparison questionnaire asked which of the two experiences the participant had preferred (prompted via screenshots from each game version, to avoid priming by naming them as *HF* or *LF*), and offered a text field for participants to describe reasons for their preferences.

Participants and Procedure

A total of 26 participants (20 male, 6 female) were recruited from a university context, with a median age of 26 (*SD*=5.24). Participants were mainly students of varying backgrounds (7.6% non-university participants). Twenty (76.92%) had no prior experience with VR. For the others, the extent of their experience in months was limited (*Mdn*=1, *IQR*=1–4.75).

Each study session (~1hr) began with an introduction and consent forms, followed by the demographic questionnaire. The study was split into two parts. Each half consisted of the interactive tutorial for the upcoming variant of the prototype, followed by the prototype game with the three tasks described above, and the surveys. Participants played the game once in *HF* and once in *LF*; the order was counterbalanced across participants. Finally, participants completed the questionnaire comparing the two experiences, and were then thanked for their time and given 10 EUR as compensation.

Results of Study 1

Participants took longer to complete the *HF* variant (*M*=274.38 sec, *SD*=196.95) than the *LF* variant (*M*=246.15, *SD*=109.09), however, a Wilcoxon signed rank test showed that this difference in duration was not significant. For the surveys, we used dependent t tests and Wilcoxon signed rank tests to compare participants' responses after each condition; the descriptive data are listed in Table 1.

All SAM factors showed significant differences. Arousal (V=199.5, p<.01, r=-.41), valence (V=0.78, p<.001, r=-.47), and dominance (V=178, p<.05, r=-.31) were all significantly higher in *HF* compared to *LF*. There was also a significant difference in GEQ mean values, with higher engagement in *HF* than in *LF*, $t(25)$=2.99, p<.01, r=.51.

The IEQ questionnaire showed significant differences for most factors (see Fig. 4). Wilcoxon signed rank tests showed that the *HF* condition yielded a higher cognitive involvement than the *LF* condition, V=228.5, p<.05, r=-.31, as well as significantly higher control, V=276, p<.001, r=-.50. Similarly, dependent t tests showed significantly higher real world dissociation for *HF*, $t(25)$=2.60, p<.05, r=.46, and also significantly higher emotional involvement, $t(25)$=3.04, p<.01, r=.52. There was no significant difference for challenge.

The two E2I factors also showed significant differences in favour of *HF*. Presence values were significantly higher for *HF* than *LF*, V=268.5, p<.001, r=-.55. The same applied to enjoyment, V=295.5, p<.001, r=-.50. In terms of the INTUI, two intuitiveness factors showed a significant difference between conditions: Effortlessness (V=258, p<.01, r=-.43) and magical experience (V=272.5, p<.001, r=-.48) were rated significantly higher for *HF* than *LF*. There was no significant difference for gut feeling or verbalizability.

In the final questionnaire, players were asked to rate the individual tasks (with the chest, the book, and the cauldron) on a 7-point Likert scale. Participants preferred interacting with the chest by physically grabbing items from within (*Mdn*=6, *IQR*=5.25–7) compared to using the widget (*Mdn*=5, *IQR*=3–6), V=210, p<.001, r=-.46. This was mirrored in their significantly higher rating for turning over pages (*Mdn*=6, *IQR*=5–6) as opposed to clicking on the arrow widgets (*Mdn*=3, *IQR*=2.25–5), V=198, p<.01, r=-.40. Further, participants much preferred to physically grab and carry potion vials (*Mdn*=7, *IQR*=7–7) compared to using their inventory (*Mdn*=4.5, *IQR*=2–6), V=263, p<.001, r=-.53.

Finally, participants were asked about their preference between the two VR experiences. Here too, the *HF* experience was preferred by the large majority of participants (84.62%), with three participants listing no preference between the two, and only a single participant preferring the *LF* variant. Reasons for preferring the *HF* version emphasized the greater degree of immersion ("*more interesting and immersive*"–P11) and realism ("*much more natural*"–P20; "*closer to reality*"–P17). The results also reflected enjoyment of playful interaction with virtual objects ("*it's fun to twist objects around [...] satisfying to be able to do that*"–P19), which is a theme that we explore further in the second study: "*I enjoyed it and had fun trying out other actions and took all items into my hand and tried to destroy items in the game, or to combine them, completely separate from the actual task*"–P1.

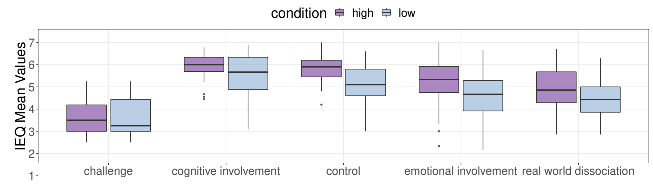

Figure 4: The higher fidelity condition resulted in significantly higher values for all IEQ factors except challenge.

Participants with no preference saw advantages to both variants, mentioning greater ease with the *LF* inventory; for scale reasons (e.g., preferred for larger inventories: "*searching in a huge inventory (with a window) is easier*"–P25), and to keep hands free ("*I didn't have to hold the item all the time [...] much easier to operate*"–P22). The participant who preferred the *LF* variant emphasized its familiarity: "*in other video games there is also an inventory, so its intuitive*"–P18.

Discussion of Study 1

The results show that the *HF* variant yielded higher scores for almost all player experience factors. Participants' affective state was more positive, and engagement, presence and enjoyment were all higher after interacting with the *HF* game variant than after the *LF* variant. The *HF* experience was also rated as more immersive in terms of cognitive and emotional involvement, control, and real world dissociation. These dependent variables showed not only significant differences in comparison to the *LF* version, but also medium to large effect sizes. Further, when asked about the overall variants and individual tasks directly, participants significantly preferred the *HF* variants. The reported reasons for these preferences indicate that *HF* object manipulation is perceived as more immersive, reminiscent of real-world interaction, and more enjoyable. We thus conclude that for object manipulation tasks, high IF provides better PX than low IF in VR.

In terms of the debate surrounding the uncanny valley phenomenon with regards to IF, the literature has suggested that low IF may be as good as high IF in terms of PX, while moderate IF performs worse in comparison. While we cannot definitively address this hypothesis with our study, our results do provide some evidence to the contrary. As our study had no moderate IF condition, we cannot make any claims about effects of moderate IF for object manipulation tasks. However, the results show that for the presented fidelity variants, the higher IF outperformed the lower IF. As VR improves further with regards to IF (e.g., through passive haptic feedback and weight perception [2, 37]), we expect our version of high IF to become moderate IF, and to provide comparably worse PX.

	Dependent variables	HF				LF			
		Mdn	*IQR*	*M*	*SD*	*Mdn*	*IQR*	*M*	*SD*
SAM	arousal*	5	3–6	–	–	3	2–5	–	–
	valence*	7	6–7	–	–	6	5.25–6.75	–	–
	dominance*	6	5–7	–	–	5	4–6	–	–
GEQ	engagement*	–	–	4.15	1.07	–	–	3.63	0.88
IEQ	cognitive involvement*	6	5.69–6.33	–	–	5.67	4.89–6.33	–	–
	dissociation*	–	–	4.87	0.97	–	–	4.42	0.99
	emotional involvement*	–	–	5.33	1.14	–	–	4.51	1.30
	challenge	3.5	3–4.19	–	–	3.25	3–4.44	–	–
	control*	5.9	5.45–6.2	–	–	5.1	4.6–5.8	–	–
E2I	presence*	5.31	5.25–5.84	–	–	4.63	4.28–5.13	–	–
	enjoyment*	6.5	6–6.75	–	–	5.5	4.75–6.44	–	–
INTUI	effortlessness*	6.2	5.6–6.8	–	–	5.2	4.25–6.35	–	–
	magical experience*	5.63	5.25–6.5	–	–	4.75	3.81–5.94	–	–
	gut feeling	3.88	2.56–4.94	–	–	3.13	2.31–3.69	–	–
	verbalizability	5.83	4.75–6.92	–	–	5.17	4.67–6.5	–	–

Table 1: Almost all player experience factors were significantly higher (*) after the *HF* variant.

While the difference in duration between the two variants was not significant, participants took slightly longer to complete the tasks in low fidelity. For games or VR experiences where speed is an issue, users might thus prefer *LF* interactions. Yet the comments of participants who did not prefer the *HF* variant instead point towards scenarios with larger numbers of objects, and hands-free interaction as the main benefits of the *LF* variant. Overall, the results are in favour of high degrees of IF for object manipulation in VR applications, although future work may have to explore trade-offs with usability for specific use cases.

Limitations. It should be noted that while *HF* performed significantly better for almost all PX measures, the *LF* scores were also not overly poor as a whole. While not superlative, the *LF* variant still yielded ratings that skewed neutral to positive. This may imply that PX in VR is generally acceptable regardless of IF, merely by virtue of being in VR (i.e., novelty bias, matching the sparcity of VR experience reported by participants). It may also imply general enjoyment of the implemented game. Whether IF influences PX differently in a less enjoyable game, or how it affects players with extensive VR experience is difficult to answer at this stage.

We also point out that our results could be influenced by the prototype itself (e.g., usability issues of either variant). Yet as mentioned there was no difference in terms of reported challenge between the two variants, and while the *HF* condition was perceived as more effortless and a more magical experience, there was no difference for gut feeling and verbalizability. As such, both versions seem to have met a general degree of usability and familiarity.

5 STUDY 2: WHOLE-BODY INTERACTION IN VR

In this second study, we explored how players experience IF of whole-body movements in VR. As we consider high fidelity still difficult to achieve for many whole-body movements in modern VR, we instead focused on a more exploratory study design featuring varying degrees of moderate IF. We designed a VR prototype featuring whole-body movements implemented with varying IF through game elements that combined whole-body movement with manipulation of virtual items, but also only whole-body movements such as crawling, and dangling (described in detail below). Our goal was not to compare *HF* and *LF*, but instead to explore player experiences of varying moderate fidelity (dependent also on how participants enacted movements) in a context where the extremes of IF (entirely *LF* or *HF*) make little sense or are still beyond reach. In a mixed-methods lab study, participants experienced all game elements (within-subjects). We investigated their experiences (*RQ2*) based on the analysis of post-gameplay semi-structured interviews.

As a secondary inquiry, we explored effects of audio fidelity, by comparing conditions with or without ambient noises (between-subjects), as the literature reports mixed results (i.e., facilitating presence [9, 12], vs. making no difference to PX [38]). We used standardized surveys to assess these effects (*RQ3*).

Stimuli

A prototype VR game was developed in Unity for the HTC Vive HMD and corresponding controllers. The game consisted of a tutorial for participants to become acquainted with all four implemented game elements, and a prototypical game level in the form of a labyrinth that confronted players with the four elements in counterbalanced order.

Guidelines for movement-based games emphasize the importance of designing for focus on the body, i.e., not distracting too much with visuals [21, 32]. To minimize visual distractions and keep players focused on the physical movements, we designed the game in a minimalistic style, using visualized sonar waves for orientation in a dark game world.

Sonar Waves: Orientation and Exploration. The main game element for orientation consisted of visualized white sonar waves in an otherwise dark game world (see Fig. 1c)—a game mechanic used in existing games, both VR and non-VR (e.g., *Dark Echo* [36] vs. *Scanner Sombre* [20]). Players could send out these waves from their controller by pressing the touchpad button; where the waves hit a surface (i.e., the floor, a wall, or an object), they bounced back. The waves stayed visible for 2 seconds, allowing players to orient themselves. The game featured teleportation (~3 m) for navigation [15]. Players were warned of walking through virtual walls or obstacles via a red-tinted screen overlay and a warning tone. If they persisted, they were reset to the level start. In this manner, they were able to explore a virtual labyrinth, throughout which they encountered obstacles that required whole-body movement to be overcome.

Whole-Body Movement. The game featured four elements with whole-body movements: (1) Finding a key and using it to unlock a door. (2) Finding a sword and using it to cut down a spiderweb. (3) Crawling underneath an obstacle. (4) Dangling from monkey bars.

All obstacles (door, spiderweb, boulder, monkey bar) were visible as grey shapes even without the sonar waves, but virtual items (key, sword) had to be found via the wave mechanic. These items were placed on the floor so that players had to crouch down to pick them up. By touching the item with a controller and pressing the trigger button, players could pick them up; items were then fixed to the controller until the button was released. These two elements were thus fairly realistic in terms of their whole-body movement (crouch and pick up item), but otherwise were implemented with some abstraction: players merely touching the item to the correct location (the door lock / the spiderweb as a whole) made the obstacle disappear (with a sound effect for both, and an animation of falling threads for the spiderweb).

The crawling obstacle consisted of a large grey boulder at a height of ~135 cm (Fig. 5). Players had to crouch down to look underneath; because the obstacle was curved and surrounded by walls, teleportation was limited while traversing it (minimum of four teleportation steps across a curved distance of ~8 m). As such, this interaction was represented with a moderately high degree of realism, in that players had to physically crouch and move forward through teleporting and/or crawling.

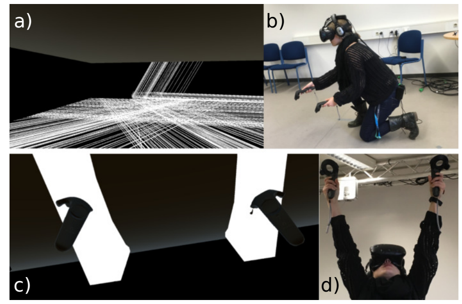

Figure 5: The player (b) and their view (a) while crawling, compared to the player (d) and their view (c) while dangling along two bars.

The obstacle in the dangling interaction consisted of a large grey pipe (~3 m) on the ceiling (Fig. 5), calibrated to the user's height and arm length prior to gameplay. Seven bars were attached to it; by pushing the controller into this bar and keeping the trigger pressed, players could "hold on" to that bar (highlighted as feedback when the controller actively grabs them). By always keeping one controller within one of these bars, players move safely across the floor (also highlighted grey) underneath this obstacle. Thus, this game element required carefully holding one hand to a virtual bar, while the other hand reached for the next one, i.e., "dangling" along monkey bars. If the player lost their grip by releasing the trigger or moving both hands away from the bar, they were considered to have "fallen", and reset to the beginning of the level. Trying to simply walk across was thus not possible, and teleporting along the floor under the obstacle disabled. Prior to this element, players had to position themselves within the area carefully to traverse the obstacle without exiting the physical VR space; this was indicated in VR via a blue rectangle. Thus, while dangling had a moderately high degree of IF in that the users had to strain to reach up to the bars, and had to keep the triggers pressed to hold on, they were also still walking along the physical floor.

Game Audio. To expose participants to game audio, they were instructed to wear headphones. All conditions had basic sound effects as feedback for user actions, e.g., when teleporting or interacting with items. An audio signal warned players traversing into a forbidden area, i.e., a wall or obstacle. Additionally, there were three sound conditions for ambient noise:

one without any ambient noises (*no-ambient*), one with continuous ambient noise (*permanent-ambient*), and one where ambient noise was only audible while sonar waves were active (*wave-ambient*). The last condition was added as tying audio to game mechanics could increase player attention to audio and thus impact effects thereof on PX. The ambient noise consisted of distant industrial factory noises (audio sources attached to the wall objects).

Participants

A total of 36 participants were recruited through flyers and mailing lists at the university. Of these, 25 were male (69.44%), 10 were female (27.78%), and one reported something else (2.78%). Participants were 25 years old on average (*IQR*=23–28). On average, participants had some VR experience, however there was a large variance (*Mdn*=5, *IQR*=1.75–6 on a 7-point Likert scale; 1=*strongly disagree*, 7=*strongly agree*); 9 participants (25%) strongly refuted having VR experience. They were divided into audio conditions equally; gender was mostly balanced between them (*no-ambient*: 9 male, 3 female; *wave-ambient*: 8 male, 4 female; *permanent-ambient*: 8 male, 3 female, 1 something else).

Measures and Method

Participants' demographic background (age and gender) was assessed through a survey, as was their prior VR experience and VR enjoyment (7-point Likert scale). Game durations were logged by the VR application. A second survey was used as a post-game questionnaire to measure affective state (operationalized via SAM [7]; 7-point scale), immersion (IEQ [22]; 7-point scale), curiosity and autonomy (PEI [50]; 5-point scale), and presence and enjoyment (E2I [26]; 5-point scale) Finally, participants were asked to take part in a semi-structured interview focusing on their experience with each of the game elements (key, sword, crawling, and dangling), as well as their audio perception.

The interviews were transcribed and then rated by three of the authors as part of an iterative thematic analysis approach. The first fifteen interview transcriptions were used to build a codebook in five iterations: Based on three interviews at a time, all raters individually built a codebook using an open coding scheme. These emerging themes and codes were discussed among the three raters to create a merged codebook, until agreement was reached regarding coding scheme. The final operational codebook represents the result of the fifth iteration of this process. This codebook was used to code the remaining 21 interview transcriptions. As a measure of inter-rater reliability for this final coding step, we calculated an intraclass correlation coefficient (ICC, using two-way mixed, consistency, and single measures as parameters [19, 28]), ICC(C,1)=0.82, 95% CI [0.75, 0.87]. This ICC is classified as within the good range [10], indicating a high level of agreement across coders.

Procedure

Each session (~1 hr) began with a consent form and written introduction to the study procedure. Participants then completed the survey on their demographic background. As we expected a majority of participants to have little or no VR experience, participants were first introduced to the VR system and controllers. They were then given a written game description, and asked to complete the tutorial. Once participants reported that they felt comfortable proceeding, they played the game (in a randomly assigned audio condition). The order of game elements was counterbalanced across participants. The study was framed as a prototype evaluation, inviting participants to become acquainted with all game elements and provide feedback.

After playing, participants were asked to fill in the post-game survey to assess affective state, immersion, curiosity and autonomy, as well as presence and enjoyment. They then participated in a semi-structured interview on their experience of the game elements, as well as their perception of the game audio (~15 minutes). The semi-structured interview first asked players to recount their personal experience of each game element, and then asked them whether and how they had perceived ambient noises in the game. Finally, we thanked participants for their time, and gave them 10 EUR.

Results of Study 2

We found the following themes through our analysis of the interview transcriptions, resulting from the process described above (quotes translated from original language).

Orientation and Exploration. Some participants had difficulties with understanding the game world layout or interpreting how far away they were from objects: "*the model of where I actually am didn't build itself*"–P28. For some, this was caused by visual clutter inherent to the wave mechanic implementation: "*it partially came bouncing back directly towards you, so that you sometimes couldn't see anything*"–P10. For others, the confusion was rooted in the teleportation ("*it makes me lose orientation*"–P26). The mismatch between being allowed to teleport widely in the general game and being limited during obstacles was also pointed out. However, others found it an easy learning curve to assemble a mental model of the game environment: "*exploring the room with sonar waves worked real well [...] in the beginning it was confusing, but then at some point you sort of had a, essentially a spatial image in your head*"–P21.

Sonar waves were enjoyed as a mechanic of orientation and exploration. For some, this was rooted in an appreciation of challenge ("*it wasn't easy and that's why it was so* *interesting*"–P15). Others described this enjoyment in terms of increased immersion ("*it gave the feeling [...] yeah, diving into another world*"–P19). Some participants also indicated this was facilitated by the visually minimalistic design: "*that you can't see [...] it's very exciting, because I find that the absorption in the game was much much stronger through this, compared to when you could actually see*"–P30.

Whole-Body Movement. The participants often commented on the novelty of the physical interactions, which led to an increased focus on the experience: "*the interaction was so new to me that in the end I was so focused on it*"–P18. For most, this was positive, but a few found it disconcerting: "*at first totally, totally unfamiliar [...] having to actually move yourself, I found that pretty difficult*"–P7. We noted minor usability issues in interacting with virtual items, inducing one participant to request an inventory: "*a mechanism, to put it away somehow, and then immediately hold it in your hand again, that might be a bit easier*"–P10. However, the majority of participants displayed enjoyment of object interaction, in terms of searching for the key or sword, teleporting with items, and using items on obstacles: "*yeah that you had to collect something and do something actively with the controllers, like wielding the sword or the key [...] I found that very interesting*"–P19; "*Picking up these things and doing something with it, I think I liked that the best*"–P11.

Several participants mentioned social considerations, i.e., the awkwardness of physically moving in VR with an onlooker (i.e., the study investigator). For some, this was described as a stray thought ("*it was somehow strange, this image of me in this room, well I thought to myself what I must look like in this real room that I'm in*"–P3), for others it impacted the experience: "*I think if I had played it alone it wouldn't have been so bad [..] it would have been, well, embarrassing if people watched [...] you have the feeling that you're being observed when you're crawling on the floor even though you're just in a room*"–P12 and "*I occasionally thought about how stupid I look in that moment*"–P15.

The most dominant theme in the interviews was the trade-off between realism and abstractions in the whole-body game elements. In the following, we report how realism or unrealness of these game elements was perceived.

Sword-Wielding and Door-Unlocking. For these two game elements, participants tended to appreciate existing realistic aspects and wished for more realism. Participants enjoyed wielding the sword to make the spiderweb fall apart ("*I found it cool, hacking at it to get through it*"–P19). This is reflected by the full execution of movements; even though they did not have to swing the sword (a brief touch would have sufficed), most participants did so. Perceptions of its realism ranged from "*understandable and appropriate*"–P28 to "*the sword didn't feel like a sword [...] but it still felt intuitive*"–P30. Aspects where most would have enjoyed more realism included haptic feedback from the spiderweb ("*I feel no resistance*"–P28), and requiring multiple hits of the sword to make the spiderweb fall apart. However, one participant liked that the spiderweb fell apart at a single hit: "*it was super – you touched it once with the sword and then it fell down. I found that funny [...] gave it a bit of character*"–P33.

Participants also enjoyed the door-unlocking obstacle; this enjoyment was mostly mentioned in the context of searching for the key, and having a literal gate as an obstacle. Many mentioned that the task should require more precise movements (e.g., inserting the key and turning it in the lock), as well as animation of the door swinging open and creaking noises. Again, only few participants seemed to want less realism. One speculated that more realism might feel aggravating: "*I'm not sure if I wouldn't experience that as a kind of harassment, having to precisely put it in and turn it*"–P28. Another wanted the key to disappear after its use, to indicate that it was no longer needed ("*like in adventure games*"–P30). Overall, having physical interactions in VR was unfamiliar, but appreciated: "*you know you're not really doing it. But otherwise I found it cool [...] you're actually doing something*"–P8.

Crawling. This element was perceived as fairly real, making several participants worry about hitting the obstacle: "*really felt like if I were to stand up or not duck enough, I would bump my head*"–P35. It also gave participants a sense of space and distance ("*the feeling of covering distance*"–P28), as well as physical exertion ("*it was a little strenuous*"–P32).

The degree to which participants appreciated the realism differed. Some cited annoyance of the cable and fear of injury (e.g., "*[while walking] I'm more stable than if I bump into something head first*"–P34). These participants expressed a preference for teleporting through the obstacle in small steps while crouching: "*I'm a bit claustrophic [...] it was dark, I had to make myself small, there were only walls around me, so I felt a little uncomfortable ... and quickly teleported out*"–P36; "*it was maybe a lazy approach [...] but I just crouched down and then teleported through, so I never had to really crawl and that's why I liked it*"–P29. Others enjoyed the realistic crawling and disliked teleportation because they felt it was a half measure ("*you're basically only doing half the activity*"–P25). A few suggested that teleportation should be disabled for the obstacle: "*if the passages under which you had to crawl were shorter but then you really had to crawl, that would be cool, and then you really couldn't teleport there*"–P30.

Dangling. This element yielded varied responses; many participants found it very interesting and exciting (" *it felt cool [...] fun and generally well implemented*"–P30). In terms of realism, most considered it not comparable to the crawling ("*less convincing than for example the crawling*"–P35, or even “*the least realistic of all*”–P17). Several participants remarked that the difference in exertion to real-life dangling or climbing stood out to them, although many still mapped the lower degree of exertion to an approximation of realism: “*it just wasn’t as tiring physically, but because I had to hold my hand up and basically statically in that position, that made it close enough*”–P30. This game element also induced several moments in which players were convinced by the movement: “*I really had a little vertigo, like, oh god oh god I’m falling [...] there I was the most excited*”–P19.

There was a clear trend that the concentration required by this element, and the challenge it posed (mentally and physically) facilitated a suspension of disbelief, which made players perceive it as more realistic: “*even though the feet didn’t leave the ground, you’re kind of willing to buy it in that moment to focus on the hands so much that you forget that you’re walking and can’t actually fall*”–P24, “*because I was so concentrated, I didn’t at all think of me standing on the floor, instead it was really, okay, I have to dangle across this now*”–P31, “*I was very very concentrated [...] I didn’t really look [down] there and I was still very very motivated to do it very very precisely*”–P28. It even made one player physically move differently: “*I somehow always felt the need to kind of swing my foot along, as if I was really dangling myself*”–P34.

Participants often wished for a higher degree of realism, for example actually hanging from something rather than merely holding up their arms: “*well you hold your arms in the air and that’s not what you usually do while dangling*”–P17. Without this, the experience was lacking (“*some feedback was missing, you had—you’re gripping somehow but [...] when I hold on somewhere in the real world I get haptic feedback that I’m holding it, or that I’m slipping*”–P21) and made players aware of the unrealness: “*your muscle memory tells you, erm, you’re not climbing [...] there’s a bit of a dissonance*”–P29.

Nevertheless, some participants would have preferred additions that evoke less realism. Some of these additions consisted of enhanced feedback, such as more tolerance towards their grip slipping (“*if you at least don’t have to look but hear a humming or I don’t know, some feedback, like oh, you’re about to slip*”–P21 or “*if you move out of the area, that it starts to vibrate or something [...] maybe if the area got bigger to provide more tolerance*”–P30). One suggested a different movement metaphor: “*if you had moved yourself forward by moving, like shifting forward the room*”–P33, while another appreciated the existing usability consideration of calibration to their arm reach (“*I liked the distance with the arms [...] that’s always a problem when things are too far away*”–P19).

Audio Perception and Effect of Audio Condition. We omit the interview findings on players’ audio perception due to scope, and instead focus on the quantitative results.

	Dependent variables	*Mdn*	*IQR*
SAM	arousal	5	4–6
	valence	6	5–7
	dominance	5	4–6
IEQ	cognitive involvement	5.78	5.11–6.22
	dissociation	5	4.43–5.46
	emotional involvement	4.83	4.33–5.71
	challenge	4.87	4.25–5.5
	control	5	4.5–5.6
PEI	autonomy	3.8	3.35–4.25
	curiosity	4.4	4–4.6
E2I	presence	3.63	3.37–3.65
	enjoyment	3.9	3.55–4.4

Table 2: The overall player experience of whole-body movements was generally positive, but did not differ between conditions.

The PX measures yielded no significant difference in the quantitative scores, although they were overall rated favourably (see Table 2). A Kruskal-Wallis test showed a significant difference in the overall immersion score of the IEQ, $\chi(2)$=6.26, $p<0.05$. However, post-hoc Wilcoxon rank sum tests with Bonferroni correction applied found no significant differences in pairwise comparisons.

It should be noted that while participants were instructed to wear headphones fully (on both ears), the instructor also did not object if participants wanted to keep only one headphone on. One participant mentioned explicitly that the option to talk to the study investigator was comforting: “*[the sound] was somehow a little bit threatening*”–P23.

Discussion of Study 2

Overall, the incorporation of whole-body movements in VR game elements was perceived as novel and exciting, but also challenging and sometimes unfamiliar.

Even though the object manipulation in this study featured less IF than the *HF* condition in study 1, participants clearly enjoyed interacting with the items, as well as searching for them in the environment. We note that participants intuitively adopted sword-wielding movements even though this was not strictly necessary (which the large majority of participants realized during the tutorial). Participants’ enjoyment of searching for items in the environment supports existing VR guidelines that emphasize the importance of designing for exploration in VR [38, 46]. Only few participants wanted less realism in the form of additional abstractions (e.g., an inventory, and diegetic signals in the form of items disappearing after use); a single participant felt dubious towards full realism, speculating that they might find it aggravating having to perform high IF object manipulation tasks to overcome obstacles.

The interviews point towards a noticeably more diverse spectrum of opinions regarding fidelity and abstraction for the game elements with greater bodily involvement and no inclusion of object manipulation, i.e., crawling and dangling. Despite moderate IF, both were perceived as surprisingly real by a large portion of participants. The existing approximation of realism (i.e., teleporting for crouching, walking while reaching upwards for dangling) was enough to induce suspension of disbelief for many participants. Dangling in particular seems to have managed this via a substitute physical challenge (holding arms up and still while pressing a button), in combination with cognitive distraction (concentration required to move between bars). These game elements showed more varied responses in participants' appreciation of realism, pointing out safety issues, fatigue, social factors, and the importance of abstractions for increased usability (e.g., hyper-realistic haptic feedback as warnings). In comparison with the game elements that include object manipulation aspects, the contrast in desired realism appears noticeable.

With regards to social considerations, we note that the presence of onlookers—including study instructors—can induce self-consciousness in movement-based VR. This contrasts with their potential to also make participants feel more secure or comfortable (as was the case with unsettling audio).

Finally, regarding *RQ3*, the results of the measures concerning audio perception indicate that the presence of ambient noises had no effect on PX, thus corroborating existing findings in the literature that audio perception—pertaining to audio that does not constitute user feedback—is not a prominent factor in VR [38]. Given the game's focus on whole-body movements, this would conform to the hypothesis that bodily and sensory experiences can override effects of audio in VR (and matching findings from the sports domain [23]).

Limitations. In terms of general usability, we point out that some participants had trouble with orientation using the sonar wave mechanic. These issues could have distracted them from the intended focus on movement-based game elements. However, participants very rarely used the wave mechanic during the obstacle interactions; the waves were mostly used between obstacles, or to find the virtual items. Further, the large majority of participants indicated that they found the overall experience immersive, as such any effects were likely small.

Like most VR studies, we must mention potential effects of novelty bias. Whole-body movements as a VR game element in general, and moderate to high IF in their implementation in particular could have influenced results through novelty bias, although the variance for participants' prior VR experience was larger than in the first study. We attempted to tease out participants' perspectives on the interactions through the interviews, to separate enjoyment of task from enjoyment of fidelity, but we cannot completely disavow any effects. We further note that the prototype offered no visible avatar. Well-designed VR avatars can increase task performance and decrease cognitive load [45], whereas mismatches with self perception (even hand-only representation) can negatively impact user experience [27, 42, 43]. Adding hand representation to our study design could thus distract from the bodily experience, or potentially amplify results.

Finally, while the number of participants was fully sufficient for qualitative analysis, the PX measures are based on a between-subjects design. The moderate number in each group must be considered in reviewing the (quantitative) effects of ambient noises in VR. The results for this secondary RQ will thus need to be corroborated in future work with a larger overall sample size.

6 OVERALL IMPLICATIONS

Based on the results of both studies, we formulate guidelines and discuss implications for the design of IF in VR games.

High IF for Object Manipulation Tasks in VR. The first study showed a clear preference on part of players for high IF for object manipulation tasks, and a significant improvement of PX compared to low IF. In the second study, object manipulation tasks were integrated in game elements that also required navigation, orientation, and (moderate) whole-body movement; here participants still reported a higher appreciation of realism compared to the game elements based more strongly on whole-body movements. We thus recommend high IF implementations for such VR tasks.

Moderate IF for Whole-Body Movements in VR. Participants were of two minds regarding IF for whole-body movement in VR, suggesting that for this kind of task, VR games should not strive for full realism and instead offer more abstractions for increased usability and ease. Not all players enjoy extensive physical challenge, and some players may even find intricate movement challenges unnecessary or aggravating. VR game developers should consider customization options and careful playtesting, to allow players a degree of control over IF for whole-body movements in VR. Further, this can also facilitate more accessible, inclusive interaction design, which has not yet been discussed in much detail in the context of VR [1, 34].

Substitutions and Approximations of Challenge. Participants' reported experiences of dangling and crawling in VR indicate that substitutions of physical challenge (e.g., holding a button to simulate holding on to a bar) and approximations thereof (e.g., holding your arms up in a fixed position instead of hanging from something) can help to induce suspension of disbelief for moderate IF. Cognitive challenge also appears to play a role in this process. VR designers and researchers should consider and explore the use of substitutions and approximations of physical and cognitive challenges when designing moderate IF for whole-body movements.

Enjoyment of Exploration in VR. Our findings provide further support for a factor suggested by prior research as well [38, 46]: players find significant enjoyment in exploration in VR. In this paper, the sonar wave mechanic was perceived as very immersive, even though the prototype was not visually complex, indicating a potential addendum to these guidelines in that design for exploration need not always focus on visual exploration only: designing for exploration in VR can also apply to novel forms of navigation and orientation, and the use of search-based game mechanics.

Consider Dichotomy of Onlooker Effects. The presence of onlookers to the VR experience can engender feelings of self-consciousness, which should be considered in the design process of movement-based VR game elements. Guidelines for movement-based games in general have emphasized the potential in supporting social fun [32]. In VR, this should be weighed carefully against the above drawbacks; VR developers need to consider how social power imbalances can occur between the HMD-wearing player and onlookers who can move and look about the real world freely (cf. [18]). Further, we suggest that researchers should examine how positive effects of onlookers (e.g., decreased feelings of isolation) can be facilitated through or even integrated in the design process.

7 CONCLUSION

In two user studies, we provide an investigation of IF in modern HMD-based VR. The first study showed that PX is improved through high IF for object manipulation tasks. The second study explored tradeoffs between realism and abstraction in moderate IF for whole-body movements, and also replicated findings of prior research on (auditory) display fidelity. Our results constitute a first exploration of effects of IF in modern VR games, and show that the impact of IF on PX varies depending on the interaction task. Specifically, VR players prefer high IF implementations of object manipulation, as opposed to moderate IF in favour of abstractions for whole-body movements.

Based on our findings, we offer five guidelines to inform the design of future VR games with regards to degrees of IF for object manipulation tasks and whole-body movements. We suggest the use of substitutions and approximations of realistic physical challenge in combination with cognitive challenge as a way to induce suspension of disbelief for moderate IF in whole-body movements. Our results extend existing guidelines on exploration enjoyment and dichotomous effects of social factors in VR. As such, our work offers insights for further development of higher quality VR game experiences, as well as research on playful bodily experiences with regards to their effects on PX in VR games.

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