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Understanding Interaction and Breakouts of Safety Boundaries in Virtual Reality Through Mixed-Method Studies

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ABSTRACT

Virtual Reality (VR) technologies become ubiquitous, allowing people to employ immersive experiences in their homes. Since VR participants are visually disconnected from their real-world environment, commercial products propose safety boundaries to prevent colliding with their surroundings. However, there is a lack of empirical knowledge on how people perceive and interact with safety boundaries in everyday VR usage. This paper investigates this research gap with two mixed-method empirical studies. Study 1 reports an online survey (n=48) collecting data about attitudes towards safety boundaries, behavior while interacting with them, and reasons for breakout. Our analysis with open coding reveals that some VR participants ignored safety boundaries intentionally, even breaking out of them and continuing their actions. Study 2 investigates how and why VR participants intentionally break out when interacting close to safety boundaries and obstacles by replicating breakouts in a lab study (n=12). Our interview and breakout data discover three strategies, revealing VR participants sometimes break out of boundaries based on their real-world spatial information. Finally, we discuss improving future VR safety mechanisms by supporting participants' real-world spatial mental models using landmarks.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI

1 INTRODUCTION

Virtual Reality (VR) has become ubiquitous, and people can employ immersive experiences at homes with commercial Head-Mounted Displays (HMDs). Domestic environments around VR users are complex and may contain obstacles and bystanders in the same place. VR users are visually disconnected from their surroundings, imposing themselves in a vulnerable state. An example would be colliding with their real-world environment [10] like a piece of furniture located next to the edge of their play area, which is not shown in VR and could cause injuries [49, 9, 19]. To resolve these accidentals, VR products require users to set up a pre-defined play area and visualize the boundary of the available space, like Guardian [26] and Vive Chaperone [44].

Most research mitigating safety risks like collisions usually focuses on reducing the VR users' experience as little as possible. These safety mechanisms include preserving the sense of presence by notifying the user with multimodal feedback [14], procedurally generating a virtual environment based on the real-world geometry [37],

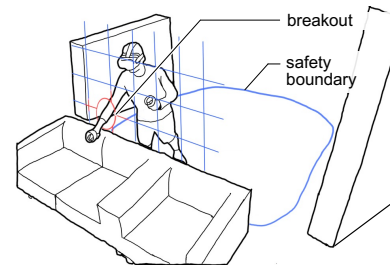


Figure 1: Despite having safety boundaries, VR users may still break out of them, shown as the red circle.

or notifying bystanders instead of VR users [51]. Although many safety mechanisms are presented, there is still a lack of understanding about how VR users perceive and interact with them in everyday usage. These cases are less available for the research community to observe because they usually happen in uncontrolled and domestic spaces. Understanding how users interact with them can shed new insights to shape future VR safety mechanisms.

Our paper systematically studies how people interact with safety boundaries in everyday VR usage based on two research questions (RQ). First, we investigated “**how do people perceive and interact with safety boundaries in VR (RQ1)**” by conducting an online survey (n=48) that gathered data about attitudes towards safety boundaries, behavior while interacting with boundaries, and reasons for breaking out of them. We studied breakouts since breaking out of safety boundaries in VR is one step before collisions and injuries. Through open coding [46], we formalized a behavior spectrum (*retreat, stop, adapt, ignore*) and a list of *accidental* and *intentional* breakout reasons. The most surprising finding was that some VR participants ignored safety boundaries intentionally, even breaking out of them and continuing their actions.

Next, we conducted a lab study (n=12) to investigate “**how and why VR participants intentionally break out when they interact close to boundaries and obstacles (RQ2)**”. The setup was designed with varying heights of obstacles to simulate a household including sofa, shelf, and wall in Fig. 1. We implemented a VR application (FruitSlicer) that nudges participants to the edge of the play area to increase the likelihood of breakouts. We recorded breakout positions and interviewed participants after the study with the goal of understanding the reasons why they left the play area, revealing three interaction strategies (*update, cage, and confine*). Through the most occurring theme, *update*, and the results from Study 1, our results indicated that VR participants update their real-world spatial mental model [42] when close to the obstacles, explaining why sometimes they were confident to break out of the safety boundaries.

The main contribution of our empirical findings in two studies is revealing VR participants sometimes break out of safety boundaries based on their real-world spatial information. To the best of our

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knowledge, we are the first to show this novel evidence. Finally, we discuss how to support VR users’ real-world spatial mental models and propose two design suggestions: 1) showing real-world landmarks to support VR participants’ spatial information; 2) controlling the safety level of how much real-world information to show as a tool for different usage contexts.

2 RELATED WORK

2.1 Safety risks in Virtual Reality

VR technologies immerse people with multi-sensory input to support 3D interaction in a virtual environment. Most VR experiences aim to achieve the sense of presence—how participants feel “being there” in the virtual environment [35, 29] and to what degree the virtual environment supports their actions successfully [12, 54]. VR applications and setups usually aim at minimizing distractions from the real-world environment to avoid break in presence [34]. VR participants are visually, sometimes also auditory, disconnected from the real-world environment for a higher presence and immersion.

However, this also exposes VR users in a vulnerable state, especially as standalone VR products like Meta Quest become more prevalent. Domestic VR setups are uncontrolled and full of uncertainty. People may experience falling over, colliding, and hitting in everyday usage, which might lead to injuries [49, 9, 19]. These cases were identified as breakdowns of VR experiences [10, 39]. More safety risks exist like the power imbalance between VR users and bystanders [25]. Social VR spaces, like VRChat, can involve harassment [56]. Malicious actors could exploit perceptual manipulations in VR [40, 3]. We focus on safety boundaries for the single VR user because this would become the most common safety risk when VR becomes available to the general public.

2.2 Safety mechanisms in VR

One reason for avoiding collisions originates from the mismatch between the size of virtual and physical space. VR setups have a limited physical tracking space and infinite virtual space that users can explore. Early works [7, 8] proposed interaction metaphors like magic barrier tape and virtual companion to avoid collision while allowing users to navigate the virtual environment. Participants might perceive these metaphors as a part of the narrative and consider them engaging. One challenge may be each metaphor has to be carefully designed or redesigned to fit different applications.

Therefore, a visual indicator for preventing collisions requires a generic form that applies to different VR applications. Commercial VR products propose the concept of the safety boundary that shows a 2D grid whenever a user is getting closer to the bounds of their predefined play area. Prominent examples are Guardian [26] and Vive Chaperone [44]. In addition, more recent devices come with the pass-through technique [27], which allows people to step outside their view in VR to see a real-time view of their surroundings.

Although boundaries seem direct, simple, and easy to deploy, they are usually distance-dependent. To improve the responsiveness, previous research extended the boundary design by considering the user’s walking speed [55]. Boundaries focus on communicating the limit of a play area but not showing obstacles and bystanders inside. Recent works used cameras to detect potential obstacles [17, 20] or collisions [50, 6] inside a play area. To incorporate bystanders into a VR space, researchers proposed using augmented virtuality to include a part of the real-world environment in VR [23, 45], customizing the play area for people sharing the same space [53], or notifying bystanders for safety in a VR setup [51].

Visual indicators usually involve an alert to notify the potential danger. This may distract the user from a VR application, resulting in a high workload [48] and a decrease of their user experience like sense of presence. Most research aims to reduce the workload of VR users by notifying obstacles or boundaries with different sensory modalities, like auditory [1] and vibrotactile feedback [18, 43]. Allocating

the notification to other modalities can preserve the sense of presence and user experience in VR [14], further preventing users from passing through virtual boundaries and obstacles [2]. In addition, some safety mechanisms modify the interaction paradigm, like forcing the VR user’s arm motion to stop using electrical muscle stimulation when impending collisions are detected [11] or mapping the VR user’s physical arm movement to fingers to avoid colliding in confined spaces [41].

The challenge of VR safety mechanisms is to preserve the user experience in applications while communicating mismatches between the virtual and real-world environment. Another direction of research focuses on optimizing the user experience in VR. The idea originates from *substitutional reality*, where every physical object in the real-world environment is paired, with some degree of a discrepancy, to a virtual counterpart [32, 31]. Examples like Oasis [37], VRoamer [5], and DreamWalker [52] generated virtual contents based on the real-world obstacles. They mask the physical obstacles using virtual content to not distract VR users with notifications. A system may create virtual walls or traps, overlaying on real-world obstacles that users do not want to walk through. Specifically, it creates a virtual path to guide and nudge VR users to avoid collisions with the real-world environment. Recent research also integrated objects or stimuli from the physical environment into the virtual one to have a more congruent experience [36, 38, 16].

Prior research focuses on designing and implementing new mechanisms to prevent VR users from collisions. On the contrary, *how VR users perceive and interact with safety mechanisms in everyday VR are less explored*. Research in Human-Computer Interaction (HCI) and VR aims to understand new phenomena from VR experiences through empirical studies. Studying how users interact with safety boundaries helps us to understand this phenomenon and derive insights for future safety mechanisms. Among many safety mechanisms, we chose safety boundaries because they are more prevalent and available in everyday VR usage.

3 STUDY 1: ONLINE SURVEY

This study investigated RQ1, how do people perceive and interact with safety boundaries in VR. For this exploratory approach, we conducted an online survey and collected 48 responses, studying how participants felt toward the safety boundaries and how they reacted once the boundary indicated danger.

3.1 Design and structure

Fig. 2 shows the survey was structured into four parts. We developed our questionnaire in an iterative process. The first questionnaire was pilot-tested using small participant samples (n=16). Based on the feedback, we iterated on the question phrasing and created the

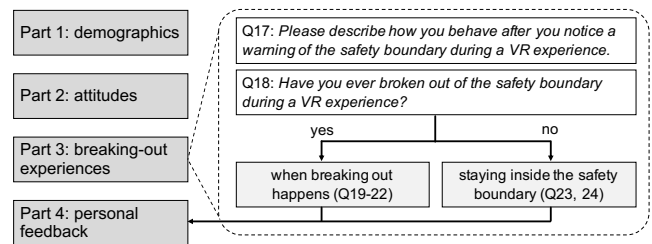


Figure 2: The survey has four parts, demographics, attitudes, breakout experiences, and subjective feedback. We separated participants by Q18 so that a part of them answered questions when breakouts happens, and the rest answered the experience staying inside the boundary. For the full survey, please see our supplementary material.

version we issued for our online survey. For the questions in our survey, please see our supplementary material.

Part 1 collected demographic data, including profession, the VR usage time per week, and their devices. Part 2 investigated the participants' attitudes toward safety boundaries using a five-point Likert scale. This part included two questions about the frequency of noticing and breakouts of safety boundaries in VR. There were two questions about feeling trust and usefulness on safety boundaries. We added two questions about feeling safe and annoyed by boundaries after our pilot test to assess if there were negative attitudes. To understand the attitudes toward the visual warning displayed by safety boundaries, we asked if participants felt safe, kept alert, and whether they continued their actions despite seeing warnings from safety boundaries, resulting in nine questions for Part 2.

Part 3 asked how and why participants interact with safety boundaries, while Part 4 was about their feedback on the current safety boundary design. These two parts were open-ended questions. The approach was inspired by collecting users' stories and descriptions of their experiences [25]. In Part 3, we were interested in breaking out of safety boundaries, called a breakout. A *breakout* means the user leaves the safety boundary with tracked body parts, like controllers and HMD. We were interested in inspecting breakouts because although most VR devices come with safety boundaries, accidents still happen. One can observe accidents where users run out of their boundary in VR fails [10]. We wanted to collect data on whether participants noticed safety boundaries, how and why they reacted. Breaking out of safety boundaries (Fig. 1) is one outcome that might lead to accidents. These data formed a body of breakout experiences for qualitative analysis of the participants' behaviors and reasons while interacting with safety boundaries in VR.

Part 3 started with two questions: 1) Please describe how you behave after you notice a warning of the safety boundary during a VR experience; 2) Have you ever broken out of the safety boundary during a VR experience. The first question collected actions that participants made when they saw the warnings of safety boundaries. Depending on the response to the second question, the participant answered questions either about *when breakout happens* or about *staying in the safety boundary*. The goal was to collect how and why participants broke out of a safety boundary and make them recall their breakout experiences in their VR usage. This part started with the question, "In this breakout experience, did you notice the warning of the safety boundary?" Next, we asked participants to elaborate on the reason for breakouts, indicate the type of applications when breakout happened, and describe the most memorable experience when they broke out of a safety boundary in VR. If participants kept themselves within their safety boundary and did not break out, we asked them to describe their reason, considering their overall VR experience. They also elaborated on the most memorable accident while staying inside a safety boundary.

Finally, Part 4 collected personal feedback on safety boundaries. We wanted to observe if the participants' feedback was related to the attitudes in Part 2. Participants responded to 1) Please list one to three positive adjectives (and negative) that come to your mind when you think of safety boundaries in VR, and 2) What would you change about the way that current safety mechanisms are working?

3.2 Data collection

We recruited participants via Amazon Mechanical Turk. They had to own a VR HMD and use VR applications at a weekly frequency. The online survey took about 15 minutes to complete, and participants were financially compensated with 2.5€ for their contributions. Prior to the analysis, we examined all the collected responses to ensure our data quality. We removed responses that were entirely blank or lacked sufficient detail. In addition, we manually inspected whether participants' responses were coherent to questions. Overall we received 48 valid responses.

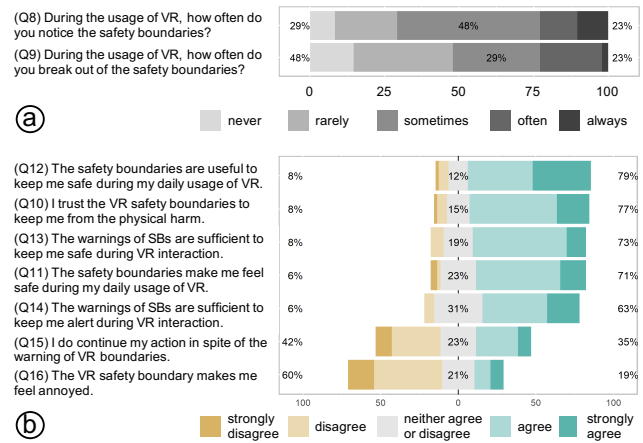


Figure 3: Participants (n=48) rated on a 5-point Likert scale: (a) the frequency of noticing safety boundaries and breakouts (Q8-9), and (b) the attitudes toward safety boundaries in VR. Although results were overall positive, some participants reported they continued their action despite seeing safety boundaries in Q15.

3.3 Analysis

We reported descriptive statistics of demographics (Part 1) and percentage of the Likert scale responses about attitudes toward safety boundaries (Part 2). Open-ended questions in Parts 3 and 4 collected a body of qualitative data. We applied open coding [46] to summarize responses and group them into two higher-level themes: behavior spectrum and reasons. Three authors performed the analysis in one joint open coding session. They read the transcript and did an initial round of codes. In the joint coding session, they merged their codes and resolved conflicts.

3.4 Results

3.4.1 Demographics

Our participants included 19 women, 28 men, and one prefer not to say. They aged between 20 to 63 ($M = 32.4, SD = 9.1$). There were 35 participants identified themselves as gamer, eight as developer, and five as designer. The average of "how many hours per week do you use VR headset" was 10.6 ($SD = 7.1$) hours per week. For the device they used the most, 23 participants reported Oculus Quest, 13 for Oculus Rift, six for Windows Mixed Reality headset, four for HTC Vive Focus, and two for HTC Vive Pro. 14 participants responded that they did not remove the obstacles inside the play area during the setup (Q7).

3.4.2 Attitudes toward safety boundaries

We investigated the frequency of noticing safety boundaries (Q8) and breakout (Q9) during VR usage. Participants answered with a 5-point Likert scale where 1-5 represented *never*, *rarely*, *sometimes*, *often*, and *always*. Fig. 3a shows the responses of Q8 and Q9. Although most participants noticed their safety boundary (71%, including *sometimes*, *often*, and *always*), half of them (52%) still broke out while using VR. This result was the first indicator that safety boundaries could not prevent all participants from breakouts.

We collected the 5-point Likert scale responses for participants' attitudes toward safety boundaries. The scale was *strongly disagree*, *disagree*, *neither agree or disagree*, *agree*, and *strongly agree*. Fig. 3b shows the questions and results from Q10 to Q16. Attitudes toward safety boundaries were overall positive. Participants showed they trusted the safety boundary (Q10), and safety boundaries make them feel safe (Q11). They considered safety boundaries to be useful to keep them safe (Q12, 79%), and the visual warnings of safety

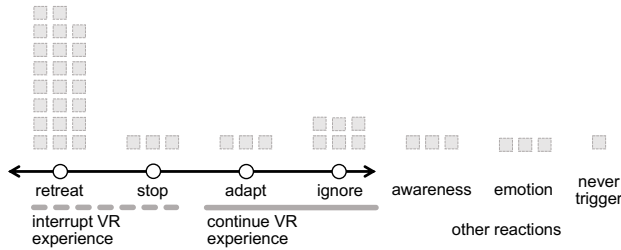


Figure 4: Codes identified from Q17, “please describe how you behave after you notice a warning of the safety boundary during a VR experience.” Circles represent the physical behavior, and squares represent the number of codes. Although 26 out of 48 codes indicate interrupting the VR experience (*retreat* and *stop*), nine responses report continuing their VR experience despite seeing safety boundaries (*adapt* and *ignore*).

boundaries are sufficient to keep them alert (Q13) and safe (Q14). In addition, Q16, “safety boundaries make me feel annoyed,” supported our findings because only 20% of participants felt annoyed. Although participants perceived safety boundaries as positive and helpful during everyday VR usage, 35% of responses showed the participants continued their action despite seeing the warnings of safety boundaries (Q15). In Q25 and 26, we asked the participants to describe safety boundaries with at most three positive and negative adjectives. We reported the frequency for positive adjectives: 16 safe, six helpful, four secure, four reliable, and four protective. Negative adjectives included 15 annoying, three distracting, three fear, and three limited.

3.4.3 Behavior spectrum when seeing safety boundaries

To understand how VR users react when they see a safety boundary, we analyzed Q17, “please describe how you behave after you notice a warning of the safety boundary during a VR experience.” Participants responded with short stories. Three of the authors coded responses in the process described in Sect. 3.3. Fig. 4 showed the code identified, including 23 *retreat*, six *ignore*, three *stop*, three *adapt*, three *awareness*, three *emotion*, and one *never trigger*. The first four codes formed a higher-level concept — *physical behavior* that participants performed after noticing safety boundaries. *Awareness* and *emotion* were implicit behaviors reported by participants.

Fig. 4 showed a spectrum with four codes varying from interrupting to continuing their VR experience. Most participants reported they re-positioned themselves back inside the center of their safety boundary. We coded these responses as *retreat*, for instance, “I will take a step back and [reorient] myself back to the center” (P12). In addition, *stop* showed participants experienced a brief breakdown of experience or their current action. Examples would be, “[I] will stop the action” (P30), or “I stop briefly to see what is going on” (P46). *Retreat* and *stop* occurred 26 out of 48 codes.

We coded three responses as *adapt* when participants reported slowing down and being more cautious. Here, participants continued their VR experiences, like “I go a bit slower with the hands to make sure I don’t break anything” (P4). Although *retreat*, *stop*, and *adapt* show safety boundaries are functioning and supporting participants to stay alert, some of them still *ignore* their boundary and continue their action. We coded them as *ignore*. *Ignore* indicated participants continued their action because they relied on their understanding of their physical environment rather the safety boundary. For instance, “I sometimes just ignore it if I know I am safe” (P21), and “most of the time I ignore it and continue what I am doing” (P9). Finally, participants reported that they felt alerted after seeing safety boundaries, which we coded these cases as *awareness*. This reaction was the purpose of using safety boundaries but came with some

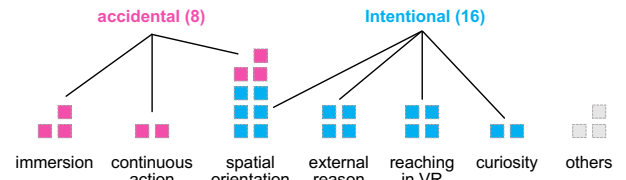


Figure 5: We identified reasons for breakout from Q19, “please elaborate why you broke out of the safety boundaries in VR.” Pink squares represent the number of codes with the *accidental* reason (e.g., *immersion* and *continuous action*). Blue squares represent the *intentional* reason, including *external reason*, *reaching in VR*, *curiosity*. *Spatial orientation* contains both reasons.

negative *emotion*, like fear, irritation, stress. The overall results of behavior made us curious about exploring the reason for continuing their VR experience instead of *retreat* or *stop*.

3.4.4 Reasons for breakouts

Since Q18 splits the survey into two parts, we collected 27 responses about when the breakout happens. The result of Q18 echoed Q15 in Part 2, where 27 out of 48 participants in the survey reported they had at least once broken out of the boundary. We further investigated why participants continued their actions in VR and breakout by analyzing Q19, “please elaborate why you broke out of the safety boundary in VR.” The coding process was the same as in Sect. 3.4.3. As shown in Fig. 5, we identified *immersion*, *continuous action*, *spatial orientation*, *external reason*, *reaching in VR*, and *curiosity*. The codes formed two higher-level concepts of reasons for breakouts — eight *accidental* and 16 *intentional*. *Spatial orientation* was categorized into both higher-level concepts. Three codes were identified as *others* because they did not fit into any theme.

Accidental indicated participants broke out of the safety boundary without intention. One reason was *immersion*, which represents participant got lost in a VR experience but not as the constructed measured by questionnaires. For example, “I noticed the warning but was immersed in the VR [application] and broke the boundaries without noticing” (P36). One explanation of breakouts could be the sense of presence and a high enjoyment. Participants were focusing on the VR experience without noticing their safety boundary. Another reason of accidental breakouts was *continuous action*. Participants reported they realized they were about to break out, but could not stop their action like stumbling. Lastly, we identified *spatial orientation*, where participants reported they lost their spatial orientation in the physical environment. One example was “the game was pretty intense, and I was all over the room and just lost out of where exactly in the room I was at that moment” (P21).

The other group of codes was the *intentional* breakout. Although breakouts may happen accidentally because of losing *spatial orientation*, this sense of the physical environment was also the most stated reason for intentional breakouts. When having an intentional breakout, some participants broke out and even felt safe doing so. “Because I know there were no objects in the area that I could collide with” (P2), and “I know that I have a bit of margin [of space] still” (P4). The reason was that they assumed they could break out in this specific location without colliding with anything. *External reason* was associated with an event in the physical environment while using VR. When there was a reason outside the VR experience like reaching their phone because someone called, participants broke out the safety boundary. In addition to the physical environment, *reaching in VR* described a situation when participants tried to reach out to a virtual object outside their safety boundary and broke out to get it. For instance, “I could not reach something in the game that I

needed to” (P40). Lastly, *curiosity* described that participants wanted to see what happened when breakouts occur or what was behind the safety boundary. These results indicated that breakouts were not only exclusively accidental but also intentional.

3.5 Summary of online survey

In Study 1, we identified participants’ attitudes toward safety boundaries, a behavior spectrum when seeing safety boundaries, and a list breakout reason. Participants perceived safety boundaries as positive and helpful, keeping them safe and alerted during their VR experience. This trend was in line with behaviors, in which most participants interrupted their actions and *retreat* when seeing safety boundaries. However, 27 out of 48 participants continued their action despite their safety boundary’s warning. Our results revealed that participants adapted their movements or even ignored safety boundaries. Through reasons for breaking out, we identified two classes, *accidental* and *intentional*. In accidental breakouts, participants broke out because they were focusing on VR or could not stop their movements, like *immersion* and *continuous action*. For intentional breakouts, participants felt safe to break out because they were aware of their physical environment.

Although we summarized each response with the most representative code, we wanted to emphasize that interacting with safety boundaries was a continuous process. Multiple *physical behaviors* might form into a strategy when interacting close to the bound of a play area. One participant reported, “if I expected [safety boundary] to occur, I just continued with the activity. If I did not expect it [to show], I move [back] so that I will not break the boundaries anymore” (P2). The reason for P2 to broke out safety boundaries was knowing there were no objects in that space. Our findings indicated that people interact with safety boundaries not only based on their visual information. They might rely on their understanding of physical environments during the VR experience. To observe these phenomena in detail, we decided to replicate a VR experience where participants have to walk closer to their boundary and interact next to it while there are obstacles outside of the play area.

4 STUDY 2: REPLICATING INTENTIONAL BREAKOUTS

To understand how and why VR participants intentionally break out when interacting close to boundaries and obstacles (RQ2), we implemented a VR application (FruitSlicer) in our lab to support this need. FruitSlicer was a VR game that can nudge participants closer to safety boundaries and even break out of them. We conducted a lab study (n=12) and exposed participants to play FruitSlicer, provoke intentional breakouts, and interview them afterward. Since we replicated the whole process of breakouts, this setup allowed us to observe the participant’s strategy and behavior in detail. The goal was to include qualitative and quantitative data to investigate VR users’ behavior and thought processes for intentional breakouts.

4.1 FruitSlicer

FruitSlicer was a multi-player VR game with one client running on an Meta Quest 2 (participant) and the other client running on a desktop PC (experimenter). We were inspired by Fruit Ninja¹. The participant used the saber attached to both controllers to cut fruits and accumulate scores by performing consecutive slices (Fig. 6a). A virtual avatar threw fruits, and the participant had to walk in VR towards targets to cut them. FruitSlicer had a console for the experimenter to see the participant’s position and the safety boundary from a third-person view (Fig. 6b). Here, the experimenter can assign the location at which the virtual fruit was thrown with a mouse cursor through this console. The application was developed with Unity 2019.3.15 and Photon Unity Networking 2.22.

This asymmetric setup allowed us to run a Wizard-of-Oz study. The experimenter could direct participants toward specific locations

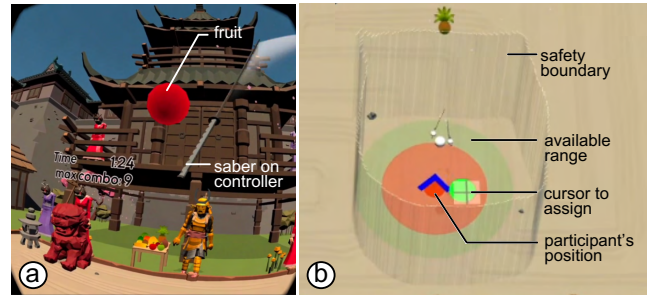


Figure 6: (a) The player cuts virtual fruits to maximize combos in FruitSlicer. The combos and the remaining time overlay in the scene. (b) The experimenter’s view shows the safety boundary and the VR player’s position. By assigning the location of thrown virtual fruits using the cursor, the experimenter nudges the player toward the boundary and provokes breakouts by sending fruits outside.

in the play area, provoking and replicating breakouts, and interview participants after their VR exposure. A concentric circle followed the participant’s HMD position (Fig. 6b). The green circle had a 150-cm radius, and the red one had a 120-cm radius. These two areas were the maximum area that the experimenter assigned a new target to ensure the target was within a reachable distance of participants. Thus, the experimenter knows where to assign the next fruit and directs each participant toward the safety boundary.

The mechanism of FruitSlicer was inspired by nudging the VR user’s movement through games. Previous work directed the position of a VR user in a physical space by asking them to dodge virtual projectiles [28]. We designed game mechanics to increase the likelihood of the breakout in VR, like slicing threshold and combo. Cutting fruits were detected if participants reached a high acceleration threshold on controllers. Thus, slow slices were impossible to trigger cuts. This encouraged large and continuous gestures based on insights from Sect. 3. The combo mechanic made participants avoid losing their score and pursue the next fruit. When the experimenter assigned a fruit outside of the boundary, we expect participants to reach the target and provoke breakouts.

4.2 Setup and apparatus

The play area was $3 \times 3 m^2$ (Fig. 7a). The study simulated an environment similar to a user’s home by choosing an open and illuminated space in our institution with multiple props (Fig. 7b). Three obstacles surrounded the play area and varied in height (sofa: 70 cm, shelf: 120 cm, wall: 200 cm). These heights resembled different conditions of an environment that VR users may likely have in their homes. We expected to see different breakout behaviors on three sides. The sofa allowed participants to continue their interactions above, and the shelf represented furniture that the participant’s body cannot lean over but can still interact above it by raising their arm. Participants could not pass through the wall. The shelf and the wall were hollowed cardboard. In addition, the environment that could be reached by the participant’s hands was cushioned using styrofoam to prevent the impact of the collision. We ensured participants would not be harmed even when they broke out or collided with the environment. They used Meta Quest 2 with controllers. The experimenter assigned targets using another PC. The PC and Quest 2 communicated through a wireless local area network. Each participant had to wear noise-canceling headphones to avoid interruptions.

4.3 Procedure

Study 2 had three parts, pre-VR, in-VR, and post-VR (Fig. 8). In the pre-VR part, we described the study as exploring enjoyment

¹<https://www.halfbrick.com/games/fruit-ninja-vr>

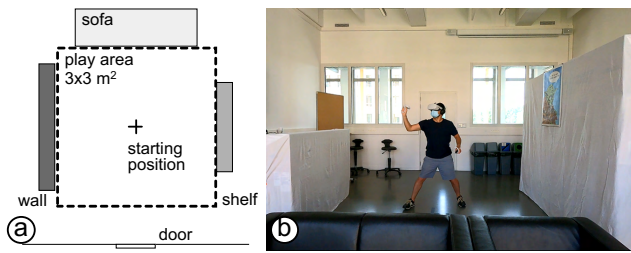


Figure 7: (a) The floor plan and (b) mock-up living room of Study 2.

and presence while playing FruitSlicer in VR. The motivation of understanding breakout of safety boundaries was concealed from participants to observe their natural behavior of breakouts when using FruitSlicer. Next, we instructed participants on how to play FruitSlicer, including accumulating combos by cutting fruits consecutively without missing for a higher score and triggering cut requires a certain speed. We aimed for the worst-case scenario where users have to walk around and interact in the play area, like Half-life Alyx, and there are obstacles surrounding the play area. We instructed participants that they are free to use whole-body motion to interact with FruitSlicer. To ensure the validity of our approach, each participant had to set up their safety boundary before playing FruitSlicer. We explained the meaning and necessity of boundaries to participants by showing them *the tutorial of Oculus Guardian*². We removed the previous boundary to avoid participants being biased by the last setup. Lastly, we helped participants put on the HMD, controllers, and noise-canceling headphones, and they proceeded in VR.

The in-VR part asked participants to create safety boundaries and exposed them to FruitSlicer. They stood at the center of the play area, oriented their front view in VR by facing the sofa, and launched FruitSlicer. The FruitSlicer exposure included a two-minute training and a five-minute study. The two-minute training step aimed to make participants get familiar with FruitSlicer. Here, the experimenter only assigned virtual fruits inside the safety boundary. In the five-minute study, the experimenter directed participants to the boundary and assigned fruits to each obstacle area. Each obstacle area required ten assigned fruits before moving to the next one. If any collisions happened, the experimenter ensured participants that there was no problem and that they did nothing wrong. When participants asked what to do while stopping at the boundaries, the experimenter told them to behave as if they were playing this game at home. The location of fruits did not direct the participant to other objects in the environment. After finishing FruitSlicer, the experimenter asked participants to indicate where they felt comfortable and safe interacting by marking 3D points in space using controllers. The idea was to collect a point cloud in space so we could compare it with the safety boundary they set up. Participants could walk in the application freely and use controllers to mark 3-D points using the trigger on controllers. Meanwhile, they were still able to see their safety boundary. We video-recorded the whole process while participants were in FruitSlicer.

Finally, we asked participants to fill out a questionnaire and conducted a semi-structured interview in the post-VR part. All the interviews were audio-recorded. Next, we debriefed the study and explained to participants how the experimenter directed them using FruitSlicer. We thanked participants for attending, and the study ended. Each participant took about one hour to complete.

²How to set up and use the Guardian system: <https://www.youtube.com/watch?v=zh51dprM5Mg>

Pre-VR	In VR	Post-VR
Instruction The study was framed as exploring enjoyment and presence while using FruitSlicer.	1) Set up safety boundary 2) FruitSlicer <ol style="list-style-type: none"> Training (2 mins) Study (5 mins) Draw the space that the user feels comfortable to interact with. 	1) Questionnaire <ol style="list-style-type: none"> SAM IPQ Q8-16 from Study 1 2) Interview 3) Debrief

Figure 8: Study 2 has pre-VR, in-VR, and post-VR steps. Participants set up their safety boundaries and experienced FruitSlicer. Next, they went through questionnaire, interview, and debriefing.

4.4 Study design

The study was a within-subject design with one independent variable, OBSTACLE HEIGHT, containing three levels (*low*, *medium*, and *high*). The order of conditions followed a 3×3 Latin square. Each condition was marked as complete when ten targets were assigned to the predefined area of an obstacle. The experimenter could only assign virtual fruit in the concentric circle centered at the participant's position. Because participants started at the center of the play area, they were distanced from the obstacles. The experimenter had to nudge them to get closer to the obstacle. Thus, participants might cut more than ten fruits in each condition. In addition, safety boundaries created by participants might not align to furniture so that there were margins between the boundary and obstacle areas. The number of targets assigned outside of safety boundaries and breakouts could be more than ten. One of the authors was the experimenter for all the data collection to control the interpersonal bias of directing participants.

We collected the position of HMD, controllers, and safety boundaries to observe breakouts. We considered breakouts of the safety boundary is an action before collisions happen, and each collision implies at least one breakout. By collecting the spatial data that participants felt comfortable interacting with, we visualized and compared the area between each participant's interaction space and the safety boundary they set up before playing FruitSlicer. For the data collection in the post-VR part, participants answered the Self-Assessment-Manikin (SAM) scale [4] for enjoyment, Igroup Presence Questionnaire (IPQ) [30] for the sense of presence, and the questions (Q8-16) of attitudes toward safety boundaries used in Study 1 (Sect. 3.4.2). We collected qualitative feedback in the interview by asking the following three questions:

1. What is your overall VR experience with FruitSlicer?
2. How did you react after you saw the safety boundary?
3. Why did you break out of the safety boundary?

The goal of the first question was to obtain the overall VR experience while playing FruitSlicer. We included the second and third because we wanted to understand whether behavior when seeing safety boundaries and reasons for breaking out of them have overlapped with Study 1. Thus, they used the same phrasing as Q17 and Q19 in our online survey.

4.5 Participants

The study was reviewed and approved by the research ethics committee of the Paris-Saclay University. We recruited 12 participants (five women and seven men) aged 23-37 years ($M = 27.3, SD = 4.3$) by convenience sampling in our institution. One participant used VR frequently for developing (15 hours per week). Eight of them used VR occasionally, and three had never used VR before. Each participant received a 10€ Amazon gift card after the study.

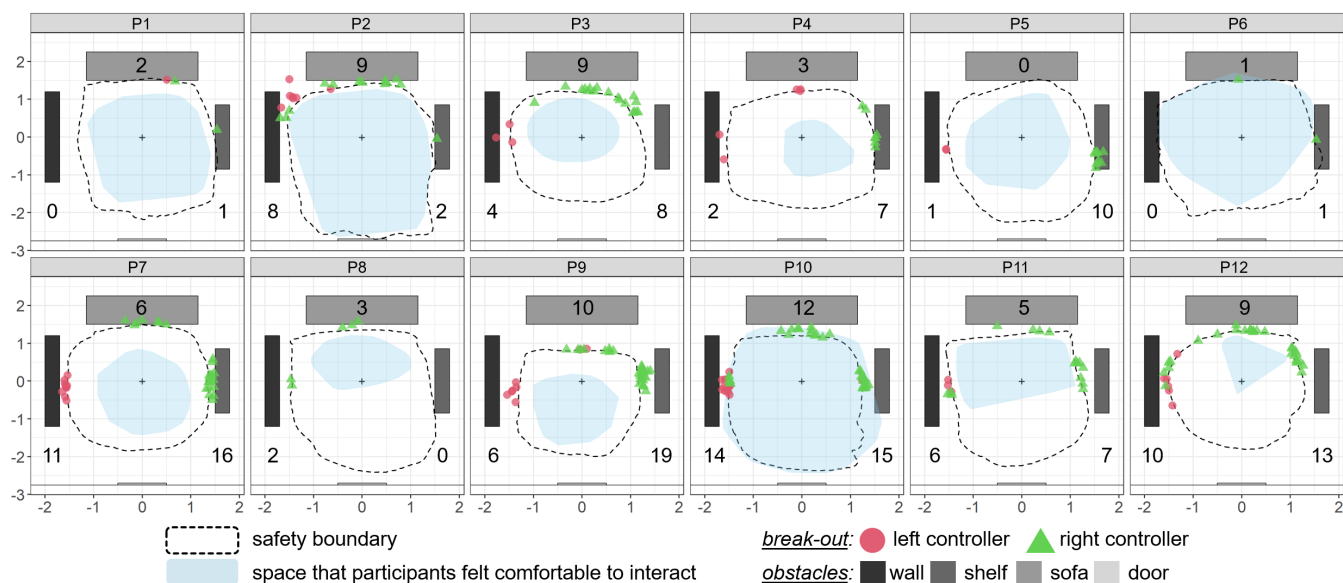


Figure 9: The dashed line represents the safety boundary, and the light blue polygon shows the space that each participant feels comfortable interacting with. Red circles represent the position of breakouts with the left controller, while green triangles are for the right controller. The counts of breakouts on each side are annotated close to each obstacle. For the trajectory plot, please see our supplementary material.

4.6 Results

4.6.1 Counts of breakouts

All the participants experienced breakout during their session. Breakouts counted as one of the controllers passing through the safety boundary. All breakouts were marked in Fig. 9 with the safety boundary drew by each participant and their comfortable interaction space. Their overall breakouts ranged from two to 41 times ($M = 19.3, SD = 13.4$ times). We observed counts by types of body (Fig. 10a) and OBSTACLES (Fig. 10b). This study design aimed to understand the phenomenon of breakout. We prioritized exploratory analysis instead of confirmatory. We reported 95% confidence intervals for means using Morey’s correction in repeated-measures designs [24] to estimate the number of breakouts. No participants broke out with the HMD. The estimation of breakout counts was $M = 4.4, 95\% CI [2.7, 6.1]$ for the left controller and $M = 14.9, 95\% CI [10.2, 19.6]$ for the right controller. The difference between the left and right controller indicated a bias toward right-handedness in our population. When splitting by OBSTACLES, estimations of each condition were: *low* $M = 5.9, 95\% CI [4.2, 7.6]$, *medium* $M = 8.1, 95\% CI [5.6, 10.6]$, and *high* $M = 5.3, 95\% CI [3.8, 6.8]$. Although we expected *low obstacle* having the most amount of breakouts, it turned out to be *medium obstacle*. This observation could be a bias in the right-handedness since *medium obstacle* was always positioned at the right of the participant (Fig. 9). Some collisions were observed during the study (Low: 0, Medium: 5, High: 9), but our main focus was breakouts so we did not further analyse these collisions.

4.6.2 Comfortable interaction space vs. safety boundary

We projected the point cloud of comfortable interaction space and safety boundary positions onto the floor. The estimated size of safety boundaries was $M = 8.5 m^2, 95\% CI [7.8, 9.2]$, while the comfortable interaction space had an average size of $M = 4.6 m^2, 95\% CI [2.8, 6.3]$. Participants indicated a comfortable interaction space is 2.67 times smaller than the safety boundary on average. In addition, when comparing the shape of the comfortable space with its corresponded safety boundary, two participants had their comfort space outside, exceeding the boundary (P6 and P10 in Fig. 9). These observations

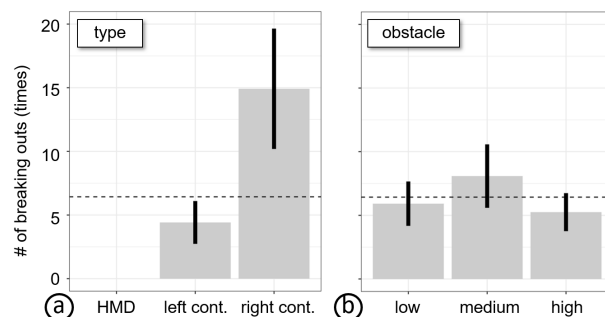


Figure 10: The breakout counts by (a) type and (b) obstacles. The error bar represents 95% CIs.

were another indicator that there is a specific group of VR users who broke out of the safety boundary since their comfort space of interaction was larger than the constraint boundary, showing that we replicated intentional breakouts.

4.6.3 Questionnaire

Participants answered the IPQ questionnaire for presence and SAM scales for enjoyment. Results show the average valence value of 6.42 ($SD = 1.8$, on a 9-point scale) and an average presence score of 4.27 ($SD = 0.88$, on a 7-point scale), indicating participants enjoyed and were immersed in their experience of FruitSlicer. We also collected attitudes toward safety boundaries using the same questions (Q8-16) from the online survey (Fig. 11). Participants were overall positive toward safety boundaries. However, we found differences in Q13 (“Warnings of safety boundaries are sufficient to keep me safe during VR interaction”) and Q15 (“I do continue my action despite warnings of VR boundaries”). Participants disagreed with the statement in Q13 more than Study 1 (33% vs. 8% in Study 1). This result may be caused by some participants having collisions with obstacles while playing FruitSlicer. In Q15, 58% (7/12) of participants reported

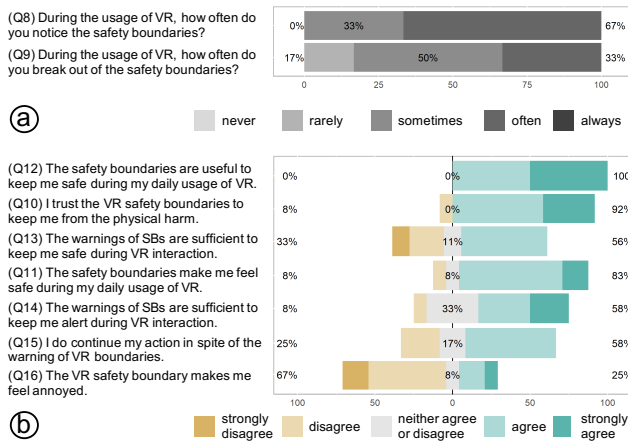


Figure 11: Participants (n=12) rated on the Study 1 questionnaire (Q8-16) using a 5-point Likert scale. They considered safety boundaries were less sufficient to keep them safe (Q13) and continued their actions more when seeing safety boundaries (Q15).

they did continue their actions when they got a warning from the safety boundary, which is higher than the result of Study 1 (35%). This observation can be biased since the participants filled out the questionnaire after they experienced a high amount of breakouts.

4.6.4 Qualitative results from interview data

The interview aimed to understand the intentional breakout provoked by FruitSlicer. Participants enjoyed the experience and reported having fun, and the application was interesting. This feedback echoed the above-average score of IPQ and SAM. When setting up the safety boundaries, most participants went for maximizing their play area. P1 and P9 mentioned they reserved a buffer space between obstacles and their safety boundary. In Fig. 9, P1 had a blank between the safety boundary and the wall; P9 had a smaller boundary, keeping a safe distance from obstacles.

To compare to the results of Study 1, we applied open coding as in Sect. 3.3 to analyze interview questions. All the audio recordings were transcribed and anonymized. Three authors, same as in Sect. 3.3, performed one joint coding session. The coding was on the sentence level. Before the session, they reviewed the findings in Study 1. Although we applied the same codes and themes in *behaviors* and *reasons* from Study 1 to label the data, we were still open to new ones. We identified 15 new codes, including six *update*, five *cage*, and four *confine*. These three codes were strategies when participants interacted close to safety boundaries and obstacles. New insights from these three categories of codes that extended or deepened our understanding of Study 1 are presenting as the following.

The code *update* describes that participants involved in a trial and error process to increase their understanding of the environment, helping them to decide whether to break out of the safety boundary to cut fruits. “I knew sofa was low, and for the shelf, I touched it once. Then I knew it was quite high. So, I did not try on the right” (P2). This knowledge also came from their memory of the physical environment, “at the sofa, I think it was quite safe to cut the fruits because it was low, [...] and on the shelf side and the wall side I didn’t dare to repeat” (P7), and “I have an impression [of the obstacle location] when I set up the safety boundary” (P1). These responses explained participants had the layout and obstacles of the play area in their mind and broke out while considering the physical environment. These results also explained why P6 and P10 had a larger comfortable interaction space over their safety boundary because they assumed some areas were safe, so they dared to break out while playing FruitSlicer.

Cage and *confine* coded how participants perceived safety boundaries were functioning in VR. *Cage*, which mentioned five times, indicated that participants positioned themselves close to their safety boundary and extended their arms outside. Examples were, “I feel the VSB is like a cage. In this cage, my body cannot get out, but my hands can. So I avoid my body breaking out but sometimes extend my hands outside the cage to reach fruits” (P9), and “[...] did not go further with my legs, but my hands were okay” (P6). This code implied that safety boundaries only represent an area for walking. Current boundary designs did provide detailed interaction space. Therefore, some participants broke out of the boundary and interacted above obstacles, which explained why we only observed breakouts with controllers but none with HMD. This observation also incorporated well with *reaching in VR* - one intentional reason of breakouts in Study 1. Four participants reported they had the impression that safety boundaries *confined* them in the play area. These responses were in line with the code *retreat* and *stop* in Study 1, showing participants still followed safety boundaries in FruitSlicer.

5 DISCUSSION

We have presented two mixed-method design studies to investigate two RQs. While Study 1 focused on exploring how VR users perceive and interact with safety boundaries in everyday usage, Study 2 replicated intentional breakouts in our lab with FruitSlicer and examines participants’ interaction with safety boundaries in detail with semi-structured interviews afterward. Our results reveal participants’ attitudes toward safety boundaries, a behavior spectrum while seeing boundaries, a list of breakout reasons, and three interaction strategies when participants are close to the boundary and obstacles.

Codes from our results, including *ignore*, *spatial orientation*, *reaching in VR*, *cage*, and *update*, show that participants considered different real-world spatial information while interacting close to the safety boundaries in VR. We interpret this new insight through spatial mental models (SMM) [42, 13], which capture the categorical spatial relations among elements in small or well-learned environments coherently, allowing perspective-taking, reorientation, and spatial inferences. Our view is distinct from prior research, either using abstract notifications without directly displaying sufficient spatial information [14] or leveraging high presence and immersion to direct the user to keep safe [5, 37]. We argue that future safety mechanisms should support people in incorporating their real-world spatial information while using VR and provide two design suggestions.

5.1 Interpreting intentional breakouts with SMM

In Study 1, we discover participants might *retreat* or *stop* their VR experiences when they saw safety boundaries. These visual indicators from safety boundaries draw their attention, making them more cautious (*awareness*) but sometimes with negative *emotions* like feeling annoyed and distracted. The *confine* strategy identified in Study 2 is in line with this observation. These results indicate that boundaries as a safety mechanism can prevent VR users from colliding with their environment. Previous research on VR safety mechanisms examine indicators with different modalities to reduce cognitive load when notifying users [14, 43, 2].

Surprisingly, our results show that participants thought of and acted with spatial information of the real-world environment when they were close to safety boundaries. An example would be the reason *spatial orientation* for intentional breakouts. Some participants broke out of safety boundaries because they knew there was nothing in front of them at home. Thus, they *ignored* the notification of safety boundaries. Participants in Study 2 mentioned that they knew the sofa was lower. Therefore, they could interact above it by extending arms outside the boundary (*cage*). This finding also explained the code, *reaching in VR*, when participants broke out of safety boundaries to interact with virtual contents. While not seeing their real-world environment, participants could still gather spatial information through slight collisions

with obstacles (*update*). The evidence above all points toward VR users looking for spatial information of the real-world environment while interacting close to the safety boundaries. Nevertheless, VR safety boundaries provide limited spatial information for the walking area only. They fail to provide sufficient spatial information of the real-world environment like obstacles and available interaction space.

We interpret our results using the concept of spatial mental model from Psychology. A spatial mental model is a mental model that contains spatial representations of an well-learned or small environment [42]. These representations are categorical spatial relations, allowing perspective-taking, reorientation, and spatial inferences. Prior research shows people can form spatial mental models through text comprehension [13] or direct experience. They can also learn a spatial mental model of virtual environments [15, 47].

We hypothesize VR users form spatial mental models of their real-world environment because they are either familiar with the place, like their homes or the space is simple (Study 2). While VR users are close to safety boundaries and obstacles, requiring additional information from the real-world environment, they retrieve this information from their spatial mental models to support their interaction. This explains well why participants had intentional breakouts (*spatial orientation* and *ignore*) with strategies like *cage*. They can also *update* their spatial mental models when receiving new information as they touch the obstacles.

5.2 Integrating real-world spatial information in VR

Our studies show early evidence that VR users leverage their spatial mental models to inform what is out there when they are close to boundaries or obstacles. We argue future safety mechanisms should provide sufficient spatial information about the real-world environment for VR users to support their spatial mental models. The idea is to give them enough information to decide how they want to interact. Safety boundaries and indicator-style mechanisms usually show VR users that they are close to an obstacle or the limit of a play area [14, 43, 2], without presenting exact spatial information in the real-world environment, like what type of obstacles. Recent techniques [5, 37, 38, 52] aim at masking the physical obstacles and surroundings by using virtual contents to avoid collision while preserving user experiences like presence and immersion. However, this approach exposes VR users to a vulnerable state because there is no information to support their spatial mental model of the real-world environment if needed. This might become more problematic once VR is more frequently used outside the user's home. We provide two suggestions to support the real-world spatial mental model of VR participants to improve future safety mechanisms.

5.2.1 Using landmarks to enhance spatial mental models

We propose that future safety mechanisms should provide landmarks in a real-world environment directly to VR users. The idea is to reduce disorientation [21] and support their spatial mental models of real-world environments [22]. A potential implementation would be capturing depth data from the environment, reconstructing meshes of salient landmarks in the real-world environment, and showing them in VR. Landmarks can provide sufficient spatial information for people to decide how they interact in VR without colliding. The concept is to provide sufficient spatial information to keep safe instead of constraining the user in a pre-defined area. VR participants would also have more interaction space in the play area, resolving the breakouts like *reaching out in VR* and situations like *cage*.

5.2.2 A slider for controlling the safety level

We propose a construct that allows VR users to choose the safety level according to their current situation requirements. An example would be a slider to control how much spatial information, like landmarks, to be presented in a VR experience. When in an empty room with plenty of margins to the wall, users can select the lowest safety level

where the system opts out all spatial information from real-world environments. Thus, they can fully engage in VR, pursuing a high presence and immersion. As the complexity of real-world environments increases, VR users can display more landmarks in the real world to support their spatial mental models for interacting safely. We are inspired by Slater et al. [33], where they proposed selecting levels of realism to give the agency back to the user on how much they want to be influenced by a VR application. VR users can choose their preferred safety level and user experience that are suitable to environment requirements, resolving situations like our code *immersion* where participants were lost in their VR experience.

5.3 Limitations and future work

Our goal is to provide an initial empirical knowledge about how people perceive and interact with safety boundaries in everyday VR usage (RQ1 and RQ2) by focusing on the reasons and strategies for (intentional) breakouts. Our insight leads to new variables that might be relevant to breakouts in VR. Based on our code, future research can study new variables, like non/dominant hand, different age groups, stationary boundaries, and spatial ability.

Although using FruitSlicer to provoke breakouts might potentially bias the results in Study 2, our setup still provides unbiased explanations of the participants' behavior and strategies when interacting close to the safety boundary and obstacles. We did not conduct inferential statistical analysis in the quantitative part of Study 2 because we prioritized exploratory analysis instead of confirmatory. In addition, the lab study setup is not fully balanced in obstacles and misses the back side. The breakout data observed in our study depend on the previous position assigned by the experimenter, which was a limitation of the Wizard of Oz study design. Future studies can model breakouts, like the Markov chain model [34].

Finally, we argue future research and practitioners should investigate how the landmark and slider designs can support VR user's spatial mental models of the real-world environment. This direction would require more empirical studies on how users construct their spatial mental models in VR and real-world environments. In addition, we need to understand the cognitive process between spatial mental models and other VR metrics like the sense of presence.

6 CONCLUSION

This paper has presented the first analysis of how people perceive and interact with safety boundaries in VR (RQ1) and how VR participants intentionally break out when interacting close to safety boundaries and obstacles (RQ2). We contribute two mixed-method design studies, including an online survey (Study 1) and a lab study (Study 2). Our main contribution is revealing VR participants sometimes break out of safety boundaries based on their real-world spatial information. We end this paper by explaining intentional breakouts with spatial mental models and proposing two design suggestions to support real-world spatial information when using VR. Examples include showing real-world landmarks to support VR participants' spatial information and controlling how much real-world spatial information to show as a tool for different usage contexts. We argue that when VR becomes more available in homes and even open spaces, people should have sufficient real-world spatial information to stay safe before engaging in immersive experiences.

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