VR Side-Effects: Memory & Proprioceptive Discrepancies After Leaving Virtual Reality

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Figure 1: While most tend to think that virtual reality (VR) hardware is still far from providing precise realism to replicate the real world, we argue that its current level of realism can already lead to side-effects as users leave to the real-world, i.e., cause an unwanted lingering effect leading to potential risks. Here, we demonstrate two such examples, inspired by cases we observed in our user studies: (a) This user is playing a VR game that uses hand-retargeting, in which the position of avatar hand differs from user's hand. (b) Suddenly, they hear their fire alarm and leave VR. However, they fail to locate their kitchen's fire-extinguisher, and instead, look at the position of an in—game extinguisher, despite not being in VR anymore––*a memory side-effect.* Then (c) they reach for an alarm button on the wall, but fail to accurately press it since their hands are still retargeted from the VR––*a proprioceptive side-effect.*

Abstract

Our brain's plasticity rapidly adapts our senses in VR, a phenomenon leveraged by techniques such a redirected walking, hand-redirection, etc. However, while most of HCI is interested in how users adapt to VR, we turn our attention to how users need to adapt their senses when *returning to the real-world.* We report cases where, even after leaving VR, users experience unintended, lingering side-effects: distortions in proprioception or memory that may pose safety or usability risks. To investigate, we conducted two studies examining (1) proprioceptive side-effects from altered hand movements (retargeting), and (2) memory distortions arising from spatial mismatches between the virtual and real-world locations of the same object. We found that, after leaving VR, (1) participants' hands remained redirected by up to 7cm, indicating residual proprioceptive distortion; and (2) participants incorrectly recalled the virtual location of objects rather than their actual real-world locations (e.g., remembering the location of a VR-extinguisher, even when trying to recall the real one). Finally, we discuss the implications of these findings for VR and propose a call-to action for a deeper study of these side-effects within HCI.

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CCS Concepts

• **Human-centered computing → Empirical studies in HCI**.

Keywords

Virtual Reality, Haptic retargeting, Memory Manipulations, Perceptual Manipulations

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1 Introduction

Our brain is known for its plasticity, allowing us, to rapidly and naturally integrate our senses in virtual reality (VR). This ability to adapt in VR has been leveraged countless times to create interactive techniques and novel virtual experiences. For example, *redirected walking* enables users to explore virtual space larger than the physical space, by redirecting their walking position without them noticing [44, 48]; *haptic retargeting* enables re-using a single prop as a source of haptics for multiple virtual objects, by altering the avatar-hand's location/trajectory [3, 12]. Along those lines, such a sensory integration can typically lead a user to perceive and react to their virtual surroundings as if they were real (e.g., when presented to a virtual cliff [61] or fire [62]).

However, while the human-computer interaction (HCI) community has been focusing on how users adapt to these VR manipulation techniques, little attention has been brought to *how they also need to re-adapt to the real world after immersion.* The understudied topic is our focus. According to our findings, it brings forward important implications for VR safety and HCI ethics. In so far, most of the attention regarding the adaptations that VR can induce post-immersion, has been focused on VR experiences as therapeutic/interventions (e.g., altruistic behaviors [28, 50] or skill acquisition (e.g., learning surgery [22] or table tennis [42]). While they demonstrate the positive impacts that users can experience after leaving VR, we argue that HCI researchers should also question the potential unintended adverse effects that VR manipulations can provoke.

These concerns are reinforced by existing evidence from neuroscience & psychology, demonstrating after-effects (e.g., motion [55, 74], color [40]) that persist after the user has stopped observing the stimulus (e.g., users still feel as if the environment is moving even after they stopped watching a moving scene [15]). As the realism of VR experiences is rapidly increasing, researchers have extrapolated on the potential long and short terms risks of such effects [8, 60, 69], including the risks of memory alteration, users being led to fall or hit their environment, or negative body perception. However, this issue still requires further work to establish a shared conceptualization and working definition. Moreover, as stated by Slater in a recent position paper [60], questions regarding ethical issues should not be addressed only from speculations but *empirical evidence* should also follow to better address and understand potential post-immersion risks provoked by VR manipulations. Indeed, in the absence of empirical evidence, the understanding of such risks remains superficial, preventing the elaboration of efficient countermeasures.

The lack of empirical HCI studies is especially concerning given some previous research, despite not directly posed to explore/study *VR risks*, has hinted at instances where VR habituations may linger after immersion. For example, habituation to a movement manipulation can disrupt vision-occluded reaching movements after leaving VR [24]. In another vein, some results show that users experience difficulties recalling if they observed an object inside the VR headset or in their surroundings [6, 44, 56]. Unfortunately, while important, these prior studies lack an HCI perspective, as usually, these are not attempting to *uncover risks for VR users* (e.g., the risk to collide with a dangerous/fragile object because of movement alteration, or to falsely remembering the position of safety-related objects due to memory alteration) but rather focus on therapy or understanding of cognition [16, 24, 70]. As a result, these often mention, or specifically tell participants to *focus* on the side-effect (e.g., by priming participants to focus on recalling VR objects [32, 56], and therefore do not account for the case where the participant is not cognizant about the side-effect. Moreover, these studies usually involve highly-constrained tasks (e.g., pointing under a desk for movement side-effect measurement [24, 71], or forcing participants to observe a set of objects for an arbitrary amount of time for memory side-effect measurement [6]). These restrict the insights that can be drawn regarding risks posed by common VR usage. The lack of attention from a HCI perspective also results in several critical aspects of such phenomenon remaining unaddressed (e.g., the impact of the VR surroundings on memory beyond object's presence, such as their position, or characteristics). Moreover, these are only examples for which early evidence———albeit insufficient———exists regarding potential post-immersion risks. Numerous other VR manipulations may entail various risks and require further attention from the community. For example, walking curvature [53, 63], body structure-perception [12], and speed [33] alterations, could lead users to collide with the real environment, and a reduction of the perceived body-vulnerability [13, 14] could lead to dangerous behaviors. Finally, while some recent preliminary work has started to address this question [6], different potential contributing factors such as exposure time, subjective embodiment, or presence would deserve more attention to better assess these risks. Taken together, many questions are still pending regarding actual risks, especially in contexts of use presenting lower constraints, closer to the common VR usages.

Hence, in the present paper, we focus on conceptualizing and unveiling negative effects that users might undergo after leaving a VR experience that altered different aspects of their perception (e.g., proprioception or memory). We do so by conceptualizing what we refer to as a *VR side-effect*, which we defined as an unintended lingering adaptation that leads to potential risks after leaving VR. Moreover, we propose to expand the understanding of the risks associated with two specific side-effects, using lower-constraint settings compared to those in the current literature. We did this by means of two studies in which **participants unknowingly (with IRB-approved deception)** experienced VR tasks [16] that either altered their movements (retargeting physical movements) or altered their virtual-surroundings (from replicas/scans of their physical surroundings). In these two studies, we found that immediately after leaving VR: (1) participants' hands were still redirected (e.g., by as much as 7cm); and (2) participants incorrectly recalled certain virtual-objects' positions instead of their real-counterparts' (e.g., remembering the location of a VR-extinguisher, even when trying to recall the real one). Then, we take a step away from our studies to discuss implications of our findings and call for a deeper and broader investigation of VR side-effects in HCI.

Finally, it is worth reflecting on the nature of our investigation: we are not aiming to measure all factors contributing to VR side-effects (while these are important, they are also potentially limitless, e.g., duration of the exposure, participants' experience, type of VR setting—just to cite a few). Instead, our ambition is to verify empirically, and from an HCI perspective, that VR side-effects can be triggered in simple interactive VR situations. We believe that our findings will increase the focus on this subject, provide additional insights, and motivate future research not only on VR side-effects, but also instigate new VR designs that increase user safety, ethics, etc.

2 Related Work

Our work is inspired by prior research that discusses potential risks of VR, as well as by insights from neuroscience & psychology measuring perceptual after-effects that linger after a stimulus has ceased.

2.1 Risks while inside of VR

As with any interactive technology, VR carries risks that are important to account for in designs. Many of the potential risks that occur *while users wear* a headset have been studied by the HCI community. While the most well-known risk is cyber-sickness [37, 54, 73] (i.e., a type of motion sickness experienced during and/or after using VR), there are other VR issues that researchers started to uncover even beyond physical risks (e.g., privacy/security risks [2, 5, 18]).

Typically, the fact that VR headsets cover the real world can lead to drastic consequences. This was highlighted for examples by Dao et. al, who investigated different "breakdowns" occurring on existing YouTube videos [17], including users colliding with surroundings or spectators. Interestingly, they report that such breakdowns can be due to sensorimotor/proprioceptive mismatches (e.g., due to latency, or virtual head movements decoupled from the user). Moreover, Tseng et al. conducted a speculative design workshop with VR experts and designers in order to critique and reflect on potential misuses of VR [69]. In their workshop, they envisioned that many VR perceptual manipulations (e.g., redirected-walking or hand-retargeting) might be used maliciously and thus create potential risks [69]; these include scenarios such as "map apartment in VR and start to remove or add virtual objects to break the user's habituation of the environment" or "redirect the user's hand to reach an apple in VR to bite but grabs a solid object". While the authors did not conduct experiments to confirm if these risks would indeed occur in interactive VR, we take inspiration from their cautionary message and set out to validate if some of these aforementioned interactive techniques do indeed cause side-effects, not just *inside* of VR but also *after leaving* VR.

2.2 Speculations on risks that might persist after leaving VR

While the aforementioned risks inside of VR should be taken seriously, we turn our attention to risks that might appear *after* the user has removed the VR headset. In fact, the aforementioned cyber-sickness [37, 54, 73] is a well-known risk that can also persist after leaving VR. Many other fatigue risks exist, including ocular fatigue [30] or movement fatigue [29]. However, these are to some extent well-known and predictable effects that are not only unique to VR (e.g., fatigue, even ocular, can occur with many other interfaces).

Our attention is thus turned to risks that are idiosyncratic to when users leave VR. For instance, Knibbe et al reported participants' surprise and disorientation when upon leaving VR, due to alteration of controls or positions in the room can be different than those expected [36]. In another vein, in a workshop, Bonnail et al. envisioned & discussed potential threats related to malicious usages of VR to voluntarily alter users' memory, for example by manipulating the perception of a product, or leading to traumas [7, 8]. Additionally, researchers have also speculated about the risks of VR to lead to body-dissatisfaction due to a repeated embodiment of idealistic avatars [60] (similar to the tendency that can already be observed with current social media filters [52, 68], amplifying gender and racial stereotypical biases [25, 60], or spreading misinformation by presenting users to a distorted reconstruction of an event [9, 60].

However, despite efforts of the HCI community to speculate on potential VR risks stemming from techniques that manipulate perception in VR (e.g., retargeting, space perception), there is a dire need for *empirical* results, to understand if these effects linger sufficiently *after* users leave VR—to the extent that it would have an observable effect on how users act when they return to the real world. This would be important in situations that could pose danger, such as the fire-extinguisher example akin to Figure 1.

2.3 Empirical insights on risks that persist after leaving VR

Despite the lack of abundant HCI research on potential effects after leaving VR, some studies, mostly from neuroscience & psychology, provide valuable insights that VR experiences can lead to lingering effects. First, there is ample evidence from neuroscience that demonstrates many after-effects [34] that persist after the user has stopped observing the stimulus. For example, the adaption to an altered movement through a prism is known to linger even after the alteration [55, 74], the adaptation to an image color or contrast can later influence the perception of another image [40], and it is possible for users to still feel as if an environment is moving even after they stopped watching a moving scene [15]. Along those lines, "source-monitoring error" [34] is a phenomenon where someone incorrectly remembers the source of an event, which can typically lead them to remember a previous experience as being real, while it was actually presented to them through an image [27, 39, 70], a video [45, 46], or narration [23, 38]. Unsurprisingly, some of these effects have been measured while participants observed the stimulus in VR headsets; yet these efforts were not directly posed at exploring/studying VR risks. For example, the aforementioned prismatic adaptation has been replicated in VR, altering users' vision-occluded movement precision in the real world [24, 71, 72]. It was also shown that VR could lead preschool children to wrongly recall VR events as real memories, e.g., an experience of swimming with whales in VR [57]. Such source-monitoring errors could also affect adults, even though at a lower scale. Specifically, several studies reported that users presented to memory tasks may experience difficulties recalling if an object was presented inside the VR headset or in the real world [6, 32, 56], in a significantly stronger manner than when the objects are presented from a screen [32, 56]. It is also worth noting that this effect does not seem to be affected by the feeling of being present within the virtual world [6], or by the VR realism [44], and could therefore occur in a range of setups.

Limitations of prior work. However, these prior works having mostly been conducted without an initial focus on risk-measurement, they tend to exhibit limitations restraining the insights they offer us on actual risks of VR side-effects. First, **they tend to use highly constrained settings**. For example, the aforementioned post-immersion motion alteration provoked by a redirection of movement or viewpoint in VR, was only measured with eyes closed or hands pointing under a table [24, 71, 72], which is not a common interaction setup for most VR usages. Moreover, **these studies focus on non-interactive situations** [31, 55]. For example, in the previously mentioned studies related to memory alteration, users can usually not move around the scene [32, 56], and are forced to observe virtual objects during a prolonged time [6]. Additionally, **users are usually primed by being told about the purpose** of the experiment (e.g., by being aware that they have to remember objects they are presented to), which might impact their performance. Hence, these works are insufficient to assess if and when these manipulations pose a risk to participants in common interactive settings—e.g., after the user left an actual low-constraint, interactive VR experience that was not framed to the user as an experiment about their memory [32, 56] or movements [24, 71]. Furthermore, given the limited attention received by this phenomenon, several critical aspects remain unaddressed (e.g., the impact of the VR surroundings on memory beyond object's presence, such as their position, or characteristics). As such, we conducted two user studies, aiming at exploring questions unanswered from previous works, regarding side-effects that might impact one's experiences after leaving VR.

2.4 Framing risks after leaving VR as Side-effects

While the main contribution of our work consists in studies that confirm the impact of these effects after-VR, we found it important to also contribute a working definition of these effects, which we frame as a *side-effect*—an unintended lingering adaptation that leads to potential risks after leaving VR. With this terminology, we distance ourselves from the existing expression "*after-effect*", which has been used to describe a wide range of effects that "*side-effect*" does not focus on (especially cybersickness [43, 65]). It was chosen purposefully for its traditionally negative connotation, which stems from its mainstream use in medicine, i.e., the Center for Disease Control (CDC) and the Food and Drug Administration (FDA) both define a side effect as an "unintended adverse reaction"[1][2]. These aspects are key in our definition too. First, we focus on "unintended" VR effects since these represent hidden phenomena that end-users might not immediately expect after leaving VR (i.e., similar to how end-users of medical drugs need to be informed of the drug's side-effects as these are hardly predictable). In our definition, side-effects are "unintended" by the designer of the VR application, e.g., a designer's intention in using haptic-retargeting was to increase immersion, but it might carry the unintended effect of preventing a user from being able to pick up a phone call when leaving VR suddenly. Second, we focus on "adverse" VR effects since these represent a risk towards the user (other lingering effects of VR can be beneficial, e.g., VR therapy). Third, like medical side-effects, our VR side-effects are also meant to evoke "reaction" from the user, in that we denote a side-effect only if its reaction lingers sufficiently to have physical impact on the user after leaving VR.

Finally, to frame our VR side-effects it is worth exploring what is not encompassed by our framing. First, non-physical effects (i.e., risks that do not entail physical consequences) were not part of our scope, including VR privacy, security, misinformation, altered feelings of self (e.g., Proteus effect [75]), or biases to others. Secondly, intended effects that linger after leaving VR are not encompassed in our framing (e.g., VR therapies or VR artworks meant to disorient/overwhelm—assuming participants were seeking these experiences voluntarily). All together proposing the term "VR side-effect" allows us to denote a class of potential unintended consequences of VR interactive techniques, such as retargeting, embodiment, etc.

3 Overview of our User Studies

We conducted two studies to measure the risks of VR side-effects in interactive contexts. We focused on memory and movement alterations, considering the numerous existing insights indicating their potential risks of side-effects. Moreover, our studies address the lack of an HCI perspective observed in prior art (e.g., often focused on non-interactive, highly constrained contexts, with participants already primed/aware of the alterations ahead of time, etc.), which hampers the insights they provide. As aforementioned, our goal with these studies is not to study the exhaustive list of all possible factors that can lead or modulate a side-effect, since these factors would be limitless and very few research efforts have rigorously focused on VR side effects; instead, our goal was to demonstrate that VR side-effects can *already* occur in interactive settings presenting lower-constraint settings compared to those in the current literature, closer to what can usually be observed in existing VR setups.

Design. Our studies were partly inspired by the work of Tseng et al [69], which envisioned in their speculative workshop, among other ideas, the following two hypothetical risks: (1) "map apartment in VR and start to remove or add virtual objects to break the user's habituation of the environment"—which inspired the basis for our Study 2 on memory side-effects that might persist after leaving VR, and (2) "redirect the user's hand to reach an apple in VR to bite but grabs a solid object"—which inspired the basis for our Study 1 on proprioceptive side-effects. Note that Tseng et al [69], did not postulate neither study these risks after leaving VR. To verify that these two techniques had an impact after leaving VR, we conducted both studies using controlled-experimental designs, including baseline conditions in which participants also experienced VR but without the manipulation. We found that: **(Study 1)** participants' hands were still redirected (e.g., on average by 3.39 cm, up to 7cm), which suggested that techniques such as hand-retargeting

[1]https://www.cdc.gov/vaccines/vac-gen/side-effects.htm
[2]https://www.fda.gov/drugs/information-consumers-and-patientsdrugs/finding-and-learning-about-side-effects-adverse-reactions

have a lingering effect after leaving VR; moreover (participants required several repetitions of a pointing task to re-adapt back to normal accuracy); and **(Study 2)** participants' memory could be manipulated to recall VR-objects over real-objects (e.g., trying to locate a real fire-extinguisher in the room, but, instead incorrectly recalling the location of a VR-extinguisher).

Deception. In all our studies, unlike many prior works (e.g., [32, 56]), we did *not inform* our participants about the true purpose of the study—our studies featured deception, which was revealed at the end, as per ethical approval. This allowed us to understand the impact of these effects in the worst-case scenario, in which the participant is not aware that a technique is being employed (e.g., hand-retargeting).

Ethics. All our studies were approved by our Institutional Review Board (IRB23-1056).

Apparatus. Our study apparatus will be provided as open-source to incite future research in this area[3]. It is worth noting that in the case of existing VR games that already make use of similar techniques (e.g., VR games that employ simple forms of hand retargeting), their source-code, and more importantly, technical specifications are not available (e.g., how much retargeting they use, when it starts/stops, etc.) and thus could not have been used for a rigorous/replicable study.

4 User Study#1: Proprioceptive Side-effect

Our first user study aimed at uncovering a movement side-effect that could potentially occur after one is immersed in a VR experience that makes use of movement-manipulation techniques, in particular, hand-retargeting [4, 10]. This was inspired by the popularity of retargeting techniques (e.g. [1, 3, 20, 41, 64]) and by the speculative work of Tseng et al [69], which speculated a possible risk: "redirect the user's hand to reach an apple in VR to bite but grabs a solid object". While previous works established the possibility to transfer a movement adaptation to real movements post-immersion [24, 71, 72], they tested the real-world effects on constrained, un-ecological movements (with eye-closed, or under the table), contrary to our study. More specifically, we designed a study where users performed a pointing task in VR and then were asked to take off the VR headset and point to a real target. Except, participants also performed this task after the VR pointing task featured hand-redirection—in other words, without their knowledge, the position of their VR hand was altered compared to the movement of their own hand (also known as hand retargeting [4, 10]).

4.1 Study design

Pointing task (~2minutes). Regardless of condition or phase, participants performed the same pointing task by touching targets with their dominant finger (illustrated in Figure 2). **(1) In VR**: they waited for a sound cue and then pointed at targets that appeared in a sequence as fast and accurately as possible. These targets alternated between a target ahead of the user and one closer to the user's body—both positions were fixed for all users. Participants repeated this VR pointing 24 times with the cue speed increased linearly during the trial, between 2 seconds (first target) to 0.4 seconds (last target). **(2) After leaving VR**: in the last VR target, a different pitch was played, which indicated they should reach the target closest to their body, and immediately remove the VR headset with their non-dominant hand and, finally, touch the target that was further away with their dominant hand in one movement (as they had done in VR). After leaving VR, participants performed 10 reaching movements, repeating at three-second intervals. For each of them, we calculated the error between participants final finger-tip's pointing position (where their velocity was close to zero) and the target's position.

[3]Source code is accessible at: https://lab.popes.org/#VR-side-effects

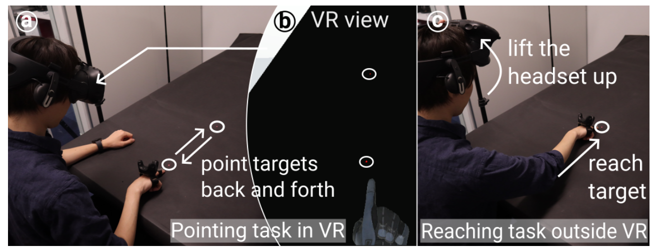

Figure 2: Apparatus for retargeting study: (a) Pointing task in VR; (b) Leave VR and perform pointing task in real-world.

Study phases. This within-subjects study was comprised of three phases (illustrated in Figure 3): **(1) baseline**; **(2) determination of the redirection gains**; and **(3) redirections**. Conditions were counterbalanced by applying two separate Latin squares for baseline and experimental conditions respectively. These were then paired and balanced to ensure counterbalancing across the full sequence.

Gain conditions. In the baseline phase, participants performed the pointing task in the baseline condition (no-redirection). This established their own accuracy at pointing immediately after leaving a VR experience. Then, in the redirections phase, participants were exposed to our two study conditions: high-gain redirection (i.e., the VR pointing task used hand redirection, just below a participant's own threshold of noticing the redirection – AVG: 15.2°); and low-gain redirection (i.e., redirection with twice a participant's own low-gain threshold – AVG: 7.6°). Individual redirection thresholds were determined in the redirection-gain determination phase. Specifically, redirections consisted in a leftward linear remapping of the hand position by a fixed angle on the horizontal axis (akin to [48]), based on the fingertip position, and with the origin placed at the movement starting position.

Eye-openness. Additionally, we asked participants to perform each gain condition in two eye-openness conditions (eyes-open vs. eyes-closed; order counterbalanced across all participants). During eyes-open movement, after removing the VR headset, participants touched the target while their eyes remained open during reaching. Conversely, during eyes-closed movement, after removing the VR headset, participants looked at the target but then closed their eyes and performed the reaching movement eyes-free. We did this to explore secondary side-effects in which users might leave VR and reach for an object out of sight (eyes-free).

Apparatus. Participants were seated at a table covered with antireflective material. Targets we created via perpendicular laser-pointers, 30cm apart. Participants wore a VIVE VR headset and

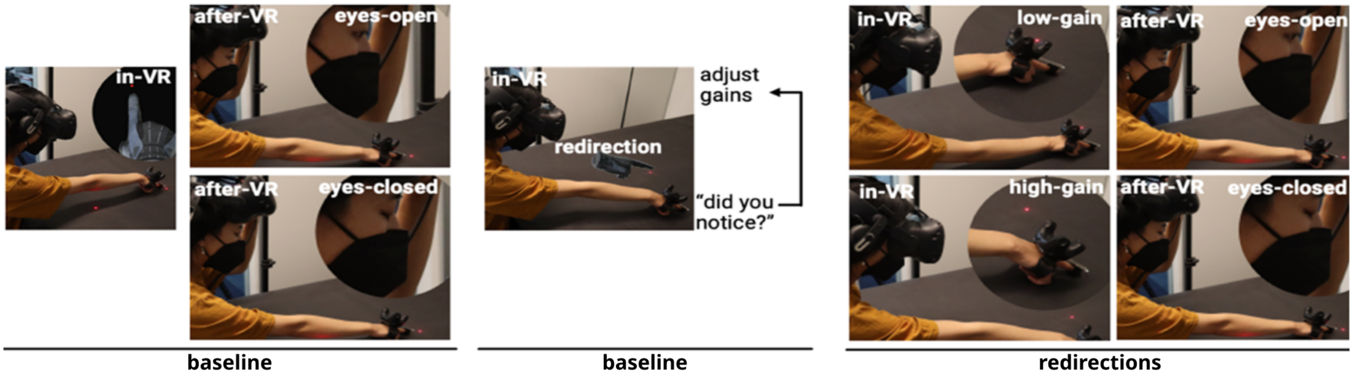

Figure 3: Apparatus for retargeting study: (a) Pointing task in VR; (b) Leave VR and perform pointing task in the real world.

tracker attached to their dominant hand. A plastic panel secured their index finger to the tracker to lock their pointing pose. The VR scene replicated the same study room, also showing the table and the two laser points.

Redirection-gain determination (~12 minutes). Prior to the redirection conditions, we determined the maximum redirection gain that each participant accepted without noticing it. Participants were not informed of the purpose of this redirection-gain measurement to not bias movements. To determine the gain, we used the standardized double-staircase procedure used in prior studies (e.g., [26]). On a trial, participants were asked to perform five forward movements between targets, to which a specific redirection angle was applied, with a similar implementation to that described in the Gain Condition section. Two independent staircases, defining the applied angle alternated at every trial. At first, each staircase value was set to 9° and the descending at a redirection angle of 17° respectively (these values were set to be respectively way lower and higher to participants' noticeability threshold, according to a pilot study). At every trial, participants were asked if they felt that the virtual hand movement and position were aligned with their own (yes/no answer). Depending on their answer, the next trial's gain for this staircase was decremented by 1° or incremented by 1°, respectively for "yes" and "no". Each staircase consisted of 10 trials, in which participants experienced two different redirection gains (e.g., one fixed as baseline). Finally, this participant's low-gain threshold (the angle of redirection of which they did not reliably detect the redirection) was calculated by averaging each of the last five trials of each staircase.

Participants. We recruited 12 right-handed participants (4 identified as women, 8 as men), with an average age of 28.9 years old (SD = 8.3). Participants received $20.

4.2 Results

Figure 4 depicts movement error in attempting to hit the targets after leaving VR (all conditions). More specifically, the error was calculated by measuring the offset between the fingertip and the target, in the direction opposite to the applied redirection in VR. A three-way repeated measures ANOVA was conducted to evaluate the effects of redirection, eye-openness, and trial on error measurements. The test did not show a statistically significant three-way interaction but showed significant two-way interactions between *eye-openness* and *redirection* ($p<0.05$, $F(1.25, 13.74) = 7.45$) and between *redirection* and *trial* ($p<0.00001$, $F(18, 198) = 8.09$).

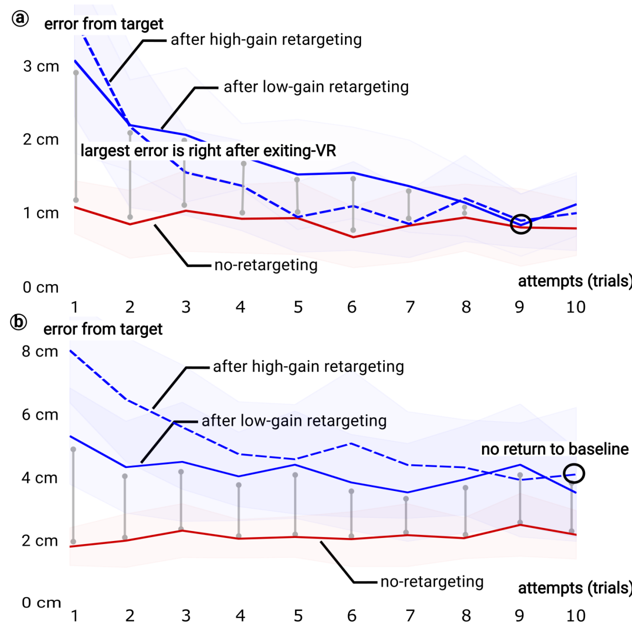

Figure 4: Error during pointing task immediately after leaving VR, i.e., trial 1 is already outside of VR. (a) Pointing task with eyes open; (b) Pointing task with eyes closed during movement (i.e., find target visually, close, and move eyes-free).

Moreover, as depicted in Table 1, we also detail the descriptive statistics (average and standard deviation) associated with the error measured in each condition, across all ten movement trials after leaving VR.

We found a statistically significant interaction effect between redirection and trial (for both eyes-open and eyes-closed, (respectively at $p<0.00001$, $F(18, 198) = 4.94$ and $p<0.00001$, $F(18, 198) = 4.40$). Thus, we analyze each eye-openness condition separately.

eyes	open			closed		
gain	none	low	high	none	low	high
trial: 1	1.1 (0.6)	3.1 (2.0)	3.7 (2.1)	1.6 (1.0)	5.2 (2.4)	7.9 (2.7)
2	0.9 (0.7)	2.2 (1.0)	2.2 (1.7)	1.8 (1.4)	4.2 (2.3)	6.4 (3.2)
3	1.1 (0.9)	2.1 (1.4)	1.6 (0.9)	2.1 (1.4)	4.4 (3.0)	5.5 (3.2)
4	0.9 (0.7)	1.8 (0.7)	1.4 (1.0)	1.9 (1.0)	3.9 (2.2)	4.6 (2.7)
5	1.0 (0.8)	1.5 (1.2)	1.0 (0.7)	1.9 (1.0)	4.3 (2.7)	4.4 (2.8)
6	0.7 (0.7)	1.6 (1.0)	1.1 (0.9)	1.9 (1.4)	3.7 (2.4)	4.9 (3.7)
7	0.9 (0.8)	1.4 (1.0)	0.9 (0.7)	2.0 (1.6)	3.4 (2.5)	4.3 (2.7)
8	1.0 (0.7)	1.2 (0.7)	1.2 (0.9)	1.9 (1.0)	3.8 (2.7)	4.2 (2.4)
9	1.0 (0.7)	1.2 (0.7)	1.2 (0.9)	1.9 (1.0)	3.8 (2.7)	4.2 (2.4)
10	0.8 (0.6)	1.1 (0.7)	1.0 (0.8)	2.0 (1.2)	3.3 (2.2)	3.9 (3.4)

Table 1: Descriptive statistics for each condition's error in cm (eye-openness: open vs. closed; redirection-gain: none vs. low vs. high) across all ten trials. Each data point depicts the average, and in parenthesis, the standard deviation.

eyes	open			closed		
Gains pair	none vs. low	none vs. high	low vs. high	none vs. low	none vs. high	low vs. high
trial: 1	**	***	-	***	*****	***
2	**	**	-	**	***	**
3	-	-	-	-	**	-
4	-	-	-	-	-	-
5	-	-	-	*	**	-
6	-	-	-	-	*	-
7-10	-	-	-	-	-	-

Table 2: Results of pairwise comparisons between redirection pairs, for each eye-openness condition (open vs. closed) across all ten trials. Non-significant p-values are depicted via a hyphen (-). Asterisk (*) depicts significance levels with additional asterisks indicating a higher significance value, respectively p<0.0167, p<0.01, p<0.001, p<0.0001, p<0.0000. Each trial 7 to 10 was not significant.

To measure the main effect of redirection across trials for each eye-openness condition, we performed a one-way repeated measure ANOVA with Bonferroni correction ($\alpha_{\text{adj}} = 0.025$). For the eyes-open condition, we found a statistically significant difference between redirection conditions for trials 1 (p<0.001, F(2, 22) = 9.42), and trial 2 (p<0.05, F(2, 22) = 8.28). For the eyes-closed condition, we found a statistically significant difference between redirection conditions for trials 1 (p<0.00001, F(2, 22) = 40.00), trials 2 (p<0.001, F(2, 22) = 16.70), trials 3 (p<0.001, F(2, 22) = 7.77), trials 5 (p<0.005, F(2, 22) = 8.29), and trial 6 (p<0.005, F(2, 22) = 6.87). Finally, to identify significantly different redirection pairs within each trial, we performed pairwise comparisons with Bonferroni correction ($\alpha_{\text{adj}} = 0.0167$), depicted in Table 2.

4.3 Summary of findings & Discussion

Summary of findings. We observed statistically significant differences in the pointing error in the first reaching movements, whether they were presented to noticeable movement alteration or not. This confirmed that participants' hands were found to be still retargeted immediately after leaving VR. Even more dramatically, participants who visually locked on the target but then were asked to move with their eyes-closed (eyes-free movement) continued to deviate from their baseline pointing accuracy for longer. The reported errors' amplitudes (3.1cm and 3.7cm, respectively in low and high gain conditions), which may occasionally be substantially higher as they only represent average values, may be sufficient to miss a targeted object and put the user at risk of hurting themselves (e.g., with a cup of boiling coffee) or breaking a fragile object, especially if used in high-risks environments (e.g., in a factory in a training). Furthermore, our results indicate that the movement-side effect did not only occur at the first movement after leaving VR, even though their intensity significantly decreased at each repetition.

Study limitations. As previously mentioned, numerous factors might have proprioceptive side-effects, which cannot be exhaustively explored within the scope of a single study. To begin with, our results do not inform the potential impacts of the VR stimuli duration, which was found to have an impact on the movement disruption magnitude and duration, in previous studies involving higher-constrained settings (i.e., reaching-hand hidden [71])—this might be the focus in future studies. Similarly, one could investigate other types of movements (e.g., varying amplitude, non-linear, those where the direction of VR-to-real movement is not aligned, or even different body parts, e.g., redirected walking).

5 User Study#2: Memory Side-Effect

Our second user study aimed at observing if a *memory* side-effect could potentially occur after one is immersed in a VR experience that contains objects similar to those in one's surroundings, but that have been altered in VR. Such alteration can be typically implemented in applications aiming to remove distracting objects from a room [11], or to use the real-place replica with objects gradually disappearing, to facilitate the transition between VR places [51]. More simply, it can also result from a wrong reconstruction of a VR place, or from a modification of the real environment after the virtual scene creation. This can specifically occur in the context of training applications aiming at habituating users to a real-world condition without them taking the risk of facing actual hazards. The study was inspired by the speculative work of Tseng et al [69], which envisioned a possible risk of confusing users by "map apartment in VR and start to remove or add virtual objects to break the user's habituation of the environment". While previous works established the possibility of mixing objects seen in VR with objects seen in the real-world (and vice versa), these studies were conducted with objects seen in constrained, non-interactive setups [6, 32, 56] (i.e., participants were simply asked to observe the objects without any other task, which is highly unlikely in real VR applications), which is not the case in this study. Moreover, unlike previous studies that focused on recalling the presence of objects in a real room, we broaden our scope by examining the impact of these settings on the recall of object's positions and attributes as well. More specifically, we designed a study where users interact with a replica of the virtual room that has been modified to alter the location and attributes of objects that also exist in the real room where the study takes place.

5.1 Study design

Since this was a memory study with deception (participants were not aware of the study's true purpose), a single participant could not perform the study twice, in different conditions. As such, we followed a between-subjects design.

Study overview. The process had the four phases depicted in Figure 5: (1) real-room task for 4 minutes (find objects in the real room); (2) VR task for 4 minutes (control group played a VR puzzle game; experimental group was asked to find objects in a modified VR-replica of the study room); (3) recall task (after leaving VR and the study room, participants were asked to recall objects in the real room); and, (4) debrief, in which the study purpose was revealed.

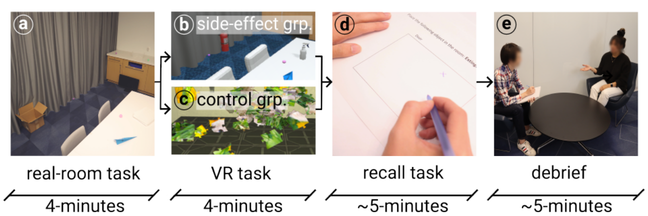

Figure 5: Our study was comprised of three phases: (a) real-room task; (b) VR task; (c) recall task; and (d) debrief.

Groups. The study was identical for both groups with the exception of the VR content. The side-effect group (experimental group) experienced a modified VR replica of the physical room where the study took place, but with objects displaced and visually altered. Instead, the control group (baseline), experienced a generic VR game (Jigsaw Puzzle VR[4]). Participants were allocated to each of these groups at random during recruitment.

Apparatus. We used the room depicted in Figure 6 (5.9m x 4.16m) furnished with a desk, shelf, and 37 objects placed in predefined positions (14 balls and 23 everyday objects). The objects were selected based on the plausibility of being found in such a study room (e.g., we did not include objects that were obviously implausible), with an effort made to include diverse size and color saliences. Participants experienced the VR portion of the task using a Meta Quest 2 with hand-held controllers for input and were free to move around the room.

Task in the modified VR room. While the participants in the control group played the VR game, the side-effect group was asked to find the plastic balls in VR in a replica of the study room, i.e., they were asked to perform the same task as they had done in the real-world, prior to entering VR. However, this replica room was modified as depicted in Figure 6, in which 20 objects were altered. This included three modifications: (1) *position*: six objects were moved (fire extinguisher, paper box, cup, stack of paper, keyboard, and fire-alarm); (2) *addition*: six virtual objects were added, which were not in the real room (backpack, thermos-bottle, spray can, tissue-box, coat-rack, and trashcan); and (3) *alteration*: eight objects were altered, either by switching their color to a complimentary color, or inverting their state (e.g., if a box was open in real world, it was closed in VR); the altered objects were: book, t-shirt, shape drawn on whiteboard, paper origami, two boxes, and two lights.

Figure 6: Real room (a meeting room) equipped with study objects; and, (b) replica VR room with modified objects.

Detailed procedure. Consent, recall, and debrief phase were conducted outside the study room, in order to control exposure time to the room. Then, the participant and experimenter entered the room, which was already prepared with plastic balls at predetermined locations used in the first phase. (1) Real task: participants were asked to find plastic balls in the room. This task was designed to provide all participants with an opportunity to experience the room in a repeatable manner (i.e., parameters such as the order of these balls, their location, or the duration of this exploration were fixed), yet, without revealing the memory aspect of this study. At the start of this task, the experimenter read the "target ball" by its color and rough position (i.e., whether they were placed near the desk, shelf, or floor). After finding a plastic ball, participants had to walk toward it before the experimenter would indicate another one. Without participants' knowledge this was a timed task, i.e., we were not interested in their performance (i.e., how many balls they found) but, instead, in exposing them to the diverse objects in the room, which were always next to the first 14 balls, for exactly 4 minutes. (2) VR task: participants were asked to play a VR experience. The control group played the aforementioned VR puzzle, while the side-effect group played a replica of the previous task, but in the modified VR room. Similarly, without their knowledge, we stopped the task at exactly 4 minutes. At the end of the VR task, participants were asked to leave the room without removing the headset (assisted by the experimenter if needed). (3) Recall: participants were asked to recall characteristics of "real objects in the study room" (emphasis was given by experimenter and written on questionnaire). This included: (i) object's position by placing a cross in a rectangle with the room layout; (ii) object's presence by answering yes/no to the question "Was the [name] object in the real room?"; (iii) object's color was given by drawing a cross on a color wheel; (iv) object's shape by drawing (only for the shape on whiteboard); and (v) object's state by answering on/off or open/closed. (vi) Debrief: participants were made aware of the true purpose of the study, i.e., study their recall of the VR objects—deception approved by IRB.

[4]https://www.meta.com/experiences/quest/5080756015327836/

Participants. We recruited 24 participants (3 identified as non-binary, 6 as women, 15 as men), with an average age of 26.88 years old (SD = 7.67). Participants received $20.

5.2 Results

We analyzed each type of modification: (1) *position* (six objects that were moved to a new location in VR); (2) *addition* (six virtual objects were added to VR); and (3) *alteration* (the eight objects' attributes were modified in VR). Since we have a control group, that did not experience the modified-VR-room, we can account for the normal effects of memory loss—it is normal that across all participants, even the control group will occasionally not remember the correct location of an object, and so forth.

Recalling an object's position. Figure 7 shows the raw results for both groups recalling the position of each object in the real room. To assist readers in understanding this spatial data, we provide one enlarged example in 7 (a). The black and cyan circles respectively represent the position of the real object in the room, and virtual object in VR. Red and blue dots represent each participant's position-recalls, respectively for the control and side-effect groups, the average position of each group is displayed respectively by a blue and red circle. Hence, a side-effect is typically observed when the blue circle is closer to the cyan circle than the black circle while the red circle shows an opposite trend. With this spatial data we can assess whether the side-effect group's memory was modified by measuring the average position & spread of the guesses of each group.

Real-to-virtual recall distance. Participants' memory of two real objects was manipulated as a side-effect of experiencing VR. First, the fire-extinguisher's position-recalls from the side-effect group are considerably closer to the virtual location than to the real location (M=2.38m, SD=1.50). Conversely, this is not the case for the control group, with most guesses either close to the real position or on that side of the room (M=2.9m, SD=2.06). Secondly, we observed a similar effect for the cup where the position-recalls from the side-effect group are considerably closer to the virtual location than to the real location (M=2.38m, SD=1.50). Conversely, this is not the case for the control group, with most guesses either close to the real position or on that side of the room (M=2.9m, SD=2.06). Moreover, 8 depicts a secondary analysis, which compares the number of times that a recalled object's position was closer to either the virtual or real object's position, for both side-effect and control groups (i.e., when distance was lower than 40% of the distance between the same virtual & real object). Again, this analysis shows that for two objects (fire extinguisher and cup) more recalled positions from the side-effect group were closer to the virtual object than for the control-group. Additionally, in Appendix, Table 3, we provide the raw distance-to-object data for all participants, so that readers can analyze these results with different thresholds in mind.

Recalling an object's existence. We compared the number of participants who reported recalling objects not present in the real room. Unlike the errors we observed in positions, we did not observe the same trend with regards to recalling whether an object was not in the room (but instead was in VR). Overall, most participants correctly indicated that these objects were not in the room (control: M=4.4, SD=2.33; side-effect: M=3.8; SD=2.1). Given the

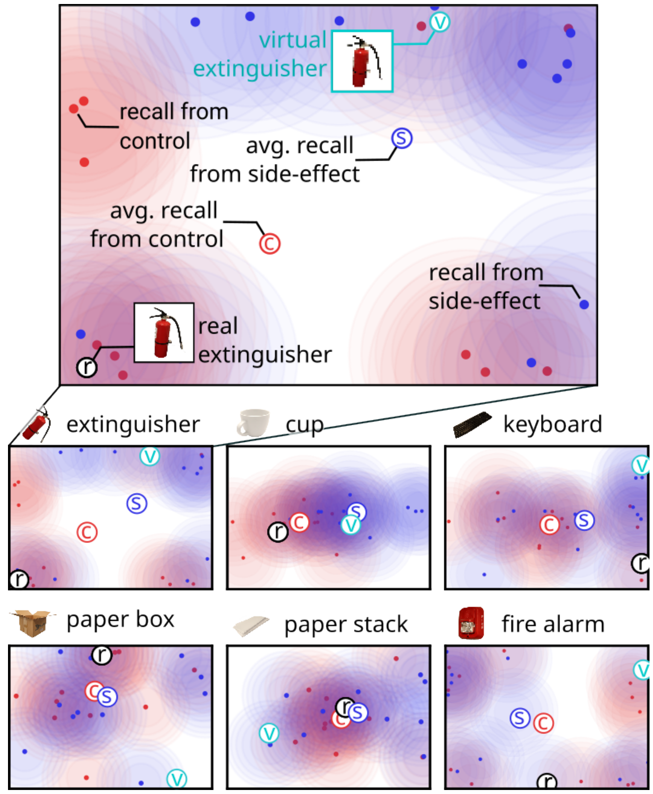

Figure 7: Heat-maps for recalling an object's position after leaving the study. colored dots (blue or red) depict participants guesses, enhanced with a halo for the sake visual clarity.

small sample size, we conducted a Monte Carlo simulation (10,000 trials) to evaluate potential group differences. The results did not reveal any significant differences (p>0.05). In fact, only one object presented a much larger amount of error in the side-effect group than in the control group, the backpack (control=1; side-effect=5). Most other objects had similar errors for both groups (e.g., thermos-bottle at 4:3, spray can at 5:7, tissue-box at 7:6). Conversely, only the coat rack generated a larger amount of error for the control-group (3) than side-effect group (0).

Recalling an object's attributes. Next, we analyze three types of modifications we did to the objects: (1) *Color*: Color distance was deducted from the angular distance on the color wheel between users' answer and object's real color, divided by 180 degrees so that 1.0 stands as the complementary color We did not find a statistical significance on the colors recalled by the two groups by means of a t-test (p=0.77). The distance between the colors recalled by both groups was fairly consistent: book (control: M=0.39, SD=0.18; side-effect: M=0.33, SD=0.16) and shirt (control: M=0.33, SD=0.24; side-effect: M=0.41, SD=0.19). (2) *Shape*: We found similar results across the two groups, with roughly half of the participants on each group being able to recall the correct shape of both the whiteboard's sketch (control: 6; side-effect: 5) and the origami folds (control: 7; side-effect: 5); while the results suggest some additional error on

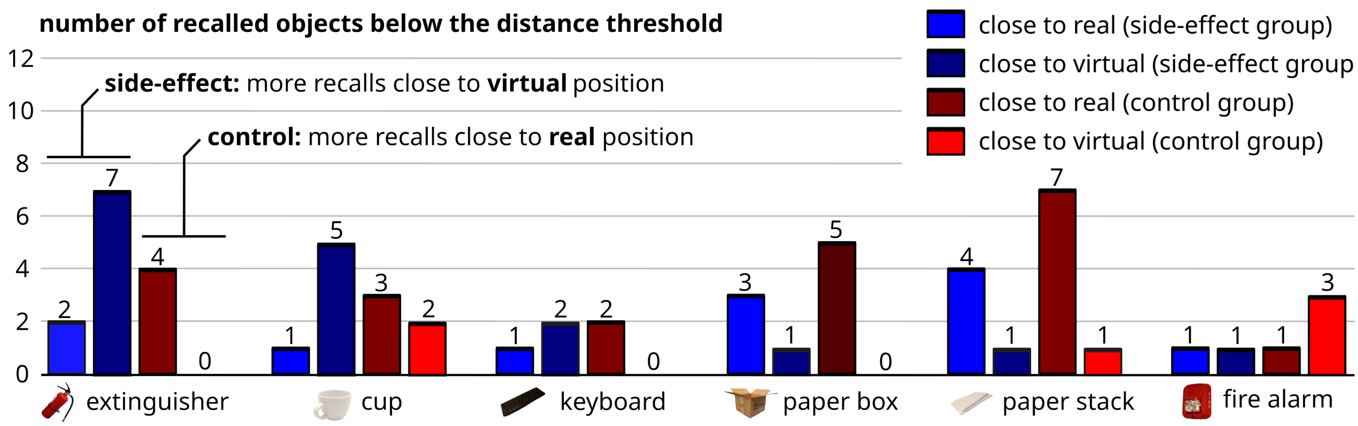

Figure 8: Number of recalls that were closer to either virtual or real object's position (i.e., distance lower than a threshold of 40% of the distance between the same virtual & real object), for control vs. side-effect groups and for all tested objects.

side-effect group it is likely negligible, when contrasted with the position recalls. (3) *State*: we observed a similar trend, with roughly half of the participants on each group being able to recall the correct state of the two plastic-box lids (control: 11; side-effect: 11) and the two LED lights (control: 11; side-effect: 11).

5.3 Summary of findings & Discussion

Summary of findings. Our main finding in this study was that the recalled positions of two (out of six) objects in the side-effect group (fire extinguisher and cup) were shifted towards the virtual objects, more than in the control group—this provides some evidence for misremembering side-effects after leaving VR. However, note that the side-effect was not observed on all six objects, which might further relate to the salience of the object or other unstudied parameters. Additionally, unlike in the case of the recalled position of an object, we did not observe any side-effect of other attributes of objects, such as their state, color, or shape. Especially, the absence of memory side-effects regarding the objects' presence comes in contradiction with previous findings in VR [6, 32, 56]. While the result might be explained by the difference of objects used between these studies, it is most likely due to the un-constrained nature of our setups, which might have reduced the memory confusion by not forcing participants to directly observe objects for a given amount of time. Taken together, **the existence of even a few cases** of this memory manipulation highlights the risk of VR experiences to induce side-effects on the user's memory. This could lead users to confusion in their daily life, but also more dramatically, to take additional time to find a safety-related object in an emergency situation (as depicted in our 1). Thus, we also denote these memory alterations as a side-effect of VR and argue that this urges more HCI researchers to investigate this critical topic.

Study limitations & perspectives. As for study 1, numerous factors could influence the elicitation of memory side-effects, which cannot be exhaustively explored within the scope of a single study. Still, they seem important to mention, in order to motivate future research. First, while we focused in this study on the effect of altered room replica, which can be employed in numerous applications [11, 51], future studies should also investigate whether the observed memory side-effects would occur in a VR room differing from the real users' surroundings, which would therefore encompass a significantly larger amount of VR applications. Investing the effect of modified replicas with different orientations, or without it being colocalized to the real room, seems also important for better understanding risks of memory side-effects. Along those lines, it seems interesting to also investigate whether, and to what extent, a side-effect would still occur if the users already encountered the virtual replica before visiting the real room. Moreover, as the effects of positional side effects were not consistent across objects, it suggests that some factors might influence the emergence of memory side-effects (e.g., position, color, or size). Further investigation into these potential factors may help mitigate the risks associated with memory side-effects. Finally, as mentioned earlier, our results are not consistent with previous results regarding the effect of VR on objects' presence recalling, which calls for further investigations regarding potential factors explaining this difference, such as the level of interaction constraint, and duration of exposition. The number of objects modifications that we tested (i.e., position, addition and alteration), could also have impacted on the results.

6 Design Suggestions and Call-To-Action for VR Side-effects

We propose a preliminary set of design suggestions and a call-to-action for future VR creators & researchers.

1. A call-to-action for research on VR side-effects. While our work suggests that VR can induce side-effects in relatively unconstrained scenarios, more research should follow to broaden our understanding and better assess their risks. First, in this study, we only focused on a limited subset of the large variety of perceptual manipulations that can be presented to a VR user. Therefore, future work should investigate the potential of VR side-effects of other perceptual manipulations, such as walking curvature [53, 63], speed alteration [33], or alteration of one's virtual body structure [12], are likely to reveal similar to the side-effects induced by hand-retargeting that we observed in our studies. Altering the perception of an object's physical properties (e.g., its weight, its tangibility, etc.) could also lead users to adopt mis-adapted, potentially dangerous, behaviors (especially if they incorrectly learn to interact with a fragile or harmful object). Moreover, as previously mentioned, more factors might be hiding at play. For example, the duration of exposure in VR, should be investigated, as it might impact a side-effect's magnitude and lingering duration. Moreover, the intensity of perceptual qualia, such as presence [58, 59] or embodiment [35] might be interesting predictors to the emergence of VR side-effects, . We can also imagine that individual differences, such as personality traits or gender might impact the occurrence of side effects, which would align with previous works reporting their influence on the occurrence of illusions within VR [19, 47]. Finally, additional research should continue exploring the different factors influencing movements and memory side-effects, for instance by addressing their aforementioned limitations.

2. Warn users ahead of time about the potential side-effects. While this might sound simplistic, we suggest to warn users ahead of time that they might experience side-effects. This could take the form of messages on the start-screen of the VR experience. For instance, a VR application using hand-retargeting could state: "this makes use of VR-effects that modify your movements, as such, you might experience some inaccuracy with your movements even after leaving VR" or "this experience contains virtual objects modelled after emergency items you might have around you. To prevent confusion, take a moment to memorize the location of these items now". Naturally, more research is needed to understand the effectiveness of such approaches in preventing side-effects, as well as the potential drawbacks (e.g., confusion) that it could cause to the user experience.

3. Label by effect size. The previous suggestion can be enhanced by informing users about the *likelihood* of a side-effect. As more studies will follow ours and uncover the effect-size of these effects, these warnings can denote the effect-size, from *very common* to *very rare* side-effect—this is a scale used in medications, for instance, "*very common (1/10)*", if a side-effect of this drug is experienced by 1 out of 10 participants in the established studies. This scale [21] ranges from: very common (1/10), common (1/10 to 1/100), uncommon (1/100 to 1/1000), rare (1/1000 to 1/10000), and very rare (< 1/10000), and could be adapted for VR side-effects.

4. Warn on exit. Another option is to add interactive warnings when users leave VR experience that has a potential side effect. For instance, VR application implementing hand-retargeting could beep on exit, and play a sound stating: "your body movements might be inaccurate for some minutes, due to a side-effect of VR." (Note that modern VR headsets already contain a sensor that detects if users are wearing them).

5. Fading out the side-effect. If the target VR application allows, it is possible that some side-effects can be faded out slowly, by gradually reducing the *VR vs. Real* incongruency, rather than stopping it abruptly. For instance, implementations of hand-retargeting could slowly decrease the retargeting-gain over the last minutes of the experience, ensuring that users are back to baseline at this point. Ideally, the fading might be integrated to the VR design to not negatively impact the realism [66]. This suggestion does not work in the case where users abruptly leave VR (e.g., emergencies, VR headset crash, and so forth).

6. Avoid certain objects/contexts/setup. While this depends heavily on the designer's goal, we recommend that certain VR objects or spaces are avoided if they are not critical for the VR experience. For instance, unless necessary for realizing the goal of the experience, we recommend not altering attributes of the room that relate to its safety (e.g., alarms, fire extinguishers, emergency exit signage, escape routes, and so forth).

7. Consider environmental risks. Obviously, the severity of a side-effect depends on the environment it occurs in. As VR headsets become more mobile, users wear them everywhere. As such, designers should consider in which scenarios these VR experiences will occur and take appropriate precautions regarding side-effects. For instance, a VR experience at a theme park (a controlled environment where users expect drastic experiences) is likely to be safer than one experienced at home, or while walking [67] or in a moving car [31, 49]. As such, designers can also include these warnings/suggestions at the start of their VR experiences depending on the usage context.

7 Conclusion

While a large amount of the HCI community has been interested in how users adapt to VR, in this paper, we turned our attention to how they might need to adapt when returning to the real-world. In that context, we report cases where even after leaving VR, users might experience a side-effect—an unwanted lingering adaptation leading to potential risks. Specifically, we demonstrated two specific side-effects, with setting significantly less-constraints than existing results: *movement side-effects* (a side effect of techniques such as hand retargeting) and *memory-side effects* (a side-effect of creating replicas of the user's real environment). We argue that even a few instances of these side-effects occurring could be enough to pose dangers for future users of VR. For instance, a movement side-effect could cause a user to press the wrong button on an alarm, or a memory side-effect could cause disorientation in finding the emergency escape door. These examples are meant to depict the urgency that our work is attempting to impress on our research community. As such, to emphasize this, we discuss also a set of initial suggestions to start designing around these types of side-effects in VR. We hope that future research expands on these and follows with more investigations of other factors that might contribute to side effects (e.g., the length of the exposure, the background of participants, and much more).

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A Appendix

group and participant	**extinguisher** (5.37)		**cup** (2.12)		**keyboard** 2.90		**paper box** (4.33)		**paper stack** (2.31)		**fire alarm** (4.51)	
	dist. to real	dist. to virtual	dist. to real	dist. to virtual	dist. to real	dist. to virtual	dist. to real	dist. to virtual	dist.to real real	dist.to virtual	dist.to real	dist.to virtual
side-effect #1	6.06	1.46	1.78	0.35	2.43	2.39	1.81	2.91	1.83	1.18	0.28	4.34
side-effect #2	5.52	0.21	2.32	0.87	1.34	1.55	1.90	3.51	1.45	0.96	2.98	2.74
side -effect #3	3.99	2.63	1.28	1.04	1.48	1.43	1.23	5.07	0.71	1.64	2.42	4.09
side -effect #4	6.24	1.51	4.19	2.08	2.55	0.35	2.95	3.11	1.18	3.4	3.96	4.07
side -effect #4	0.39	5.17	1.96	0.46	4.58	5.56	3.20	2.68	0.64	2.81	2.08	3.33
side -effect #6	5.83	1.05	2.65	0.65	1.90	3.06	0.39	4.37	2.45	0.34	4.40	0.21
side -effect #7	4.88	3.86	3.80	1.10	3.22	3.10	2.06	3.56	0.21	2.50	2.70	6.29
side -effect #8	4.72	1.05	2.21	0.29	0.17	3.04	3.97	1.05	2.17	4.38	4.17	5.72
side -effect #9	4.26	2.03	2.40	0.44	4.04	3.94	0.14	4.46	2.41	4.72	4.95	5.85
side -effect #10	5.50	3.48	0.47	1.80	2.55	0.39	3.67	4.51	2.59	4.49	2.16	5.53
side-effect #11	6.46	1.48	4.01	1.90	1.71	1.23	1.99	4.08	0.20	2.51	4.33	5.69
side-effect #12	1.03	4.61	1.34	0.97	4.37	4.45	2.29	3.66	2.37	4.67	3.99	5.85
control #1	2.94	3.95	2.28	0.32	1.75	1.23	1.87	3.17	0.45	1.87	4.16	5.47
control #2	2.27	4.14	1.62	0.65	0.44	3.33	1.96	4.20	1.27	1.67	3.45	1.28
control #3	4.16	3.64	1.26	1.03	3.03	2.91	0.35	4.16	0.56	1.78	4.54	5.76
control #4	0.83	4.57	1.15	0.99	5.74	5.83	2.71	3.28	0.13	2.39	3.58	0.95
control #4	0.28	5.12	1.30	3.30	2.68	2.78	3.68	2.64	0.67	2.88	3.86	0.66
control #6	6.47	1.46	0.24	2.02	4.37	4.47	0.22	4.13	0.70	1.90	2.46	3.38
control #7	4.37	3.86	0.26	1.97	4.22	4.28	2.02	2.35	2.57	4.47	4.08	5.82
control #8	0.40	5.16	0.53	2.29	4.68	4.25	1.67	4.23	2.08	4.24	4.20	4.20
control #9	2.86	4.07	1.38	3.47	3.01	3.82	2.82	5.29	0.75	1.59	2.90	6.43
control #10	0.33	5.06	1.06	1.08	2.41	2.80	0.47	4.13	0.84	1.56	0.96	3.81
control #11	5.26	0.15	1.17	1.57	3.02	3.77	0.19	4.16	1.76	0.75	2.31	3.43
control #12	5.05	4.00	1.80	0.97	1.11	1.79	1.87	4.01	1.30	1.99	2.25	6.12

Table 3: Distance between each participant's position-recall and both virtual a real object position, for each object. Distance between virtual and real object's positions are also provided for each object, under their name. Values are written in meter.