Walking Through or Detour? Investigating Walking Paths with World-Anchored Mixed Reality Objects

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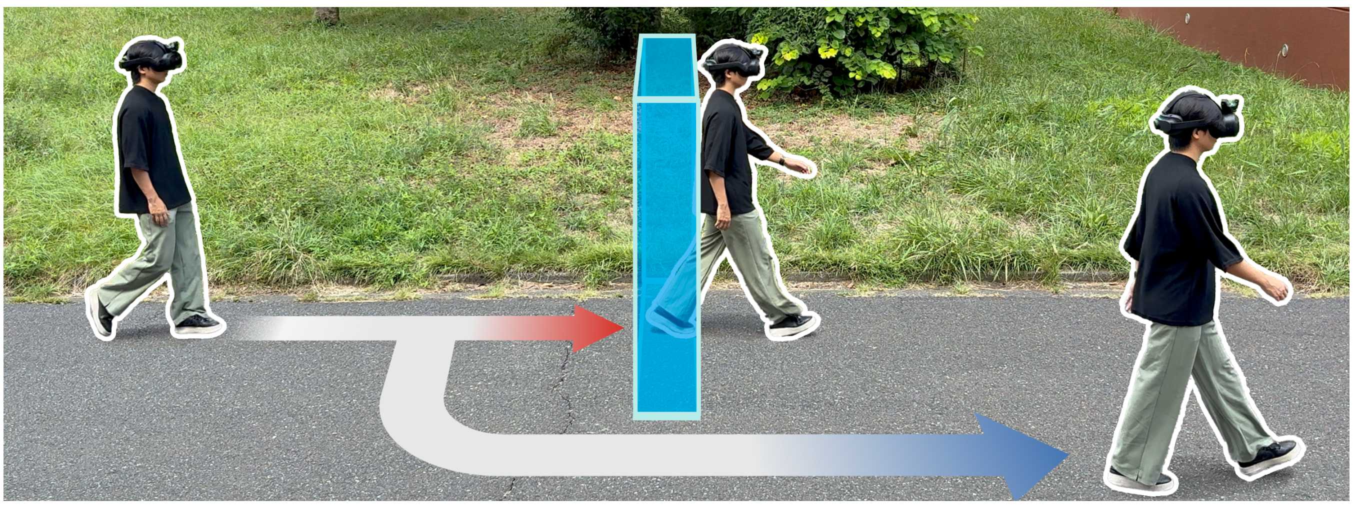

Figure 1: The user takes either a walking path that walks through the blue virtual object or a path that detours around it.

Abstract

In mixed reality environments, virtual objects can obscure real-world obstacles, creating a risk of collision when users walk through them. Although users may choose to detour around virtual objects, this behavior also carries risks, such as colliding with obstacles or pedestrians along the detour route. To reduce collision risks, it is essential to understand the factors that determine whether users walk through or detour, as well as the walking paths associated with each behavior. In this research, we investigated users' walking behavior toward both a static virtual obstacle and a virtual obstacle that disappeared as the user approached. Our findings suggest that individual characteristics and the width of the virtual obstacle influence the decision to walk through or detour. Furthermore, while most users initially chose paths that detoured around the virtual obstacle, once the obstacle began to disappear, they switched their walking paths toward the space where it had been.

Keywords

Mixed Reality, Augmented Reality, Extended Reality, Walk

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1 Introduction

Mixed reality (MR) technology, delivered via head-mounted displays (HMDs) or smart glasses, overlays virtual content onto the physical world and has significant potential to support users' daily activities. In a future where MR becomes widespread, it may be available to users at all times—whether at home, in urban spaces,

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or while walking. Virtual objects can be anchored in the world like real-world objects, and users may encounter a wide range of them, including virtual advertisements [55] or alerts [14, 30], virtual humanoid agents [24, 45, 68], elements of large-scale MR games [10, 61, 65, 66] or events [34, 47], and even virtual fences for pedestrian safety [73, 77]. Therefore, understanding how users interact with these virtual objects is essential for the successful adoption of MR technology in society.

MR experiences while walking often occur in everyday contexts, and walking in MR environments poses risks of collisions or falls because virtual objects can obscure obstacles [72, 79]. In addition, real-world objects are sometimes intentionally hidden behind virtual objects [14, 43]—a technique known as *diminished reality* [53, 54]—which increases collision risks [35]. In such cases, avoiding virtual objects may be desirable; however, there are also situations in which it is safer to walk through them. For example, when virtual objects narrow the road width, users attempting to avoid them may collide with obstacles or pedestrians at the detour destination [79]. This risk can be mitigated by walking through the virtual objects. Overall, whether users should detour around or walk through virtual objects depends on the surrounding environment in the direction of travel.

However, there is limited knowledge about walking paths when users detour around or walk through virtual objects in MR environments, making it difficult to design objects that minimize collision risk and anxiety. Previous research has reported that users consistently detour around virtual objects [25, 45, 68], whereas other studies suggest that individuals sometimes walk through virtual objects instead of detouring as a means of taking a shortcut [29, 32, 33]. Previous work on walking paths for virtual objects has primarily focused on detour routes [32, 45, 68], and leaving walk-through situations uninvestigated. Although research has confirmed that users sometimes walk through virtual objects [29, 32, 33], its primary aim was not to analyze walking paths. Furthermore, the parameters of the virtual objects influencing walk-through behavior in these studies [4, 13, 29, 58] are limited, and the effect of object shape on passage rates and walking paths remains unclear.

Our goal is to investigate walking paths toward virtual objects that may be encountered in MR environments and to identify the factors influencing whether users detour around or walk through those objects (Fig. 1). We consider it essential to examine users' walking paths for both static virtual objects that do not change in appearance and virtual objects with dynamic effects that disappear from the path when the user approaches. In virtual reality (VR) environments, methods have been proposed to reduce collision risks by displaying portions of the real space within the virtual scene [20, 78, 82]. Similarly, making virtual objects disappear as users approach could help reduce collision risks and anxiety in MR environments, and a technique that may be adopted in future MR systems.

Our research questions are as follows:

RQ1: Which factors influence walk-through rates for static virtual obstacles?

RQ2: How do walking paths differ between walk-through and detour behaviors for static virtual obstacles?

RQ3: When virtual obstacles disappear midway, how do walking paths change depending on the type of effect and the timing of disappearance?

RQ4: How do walk-through rates and walking paths change for static virtual obstacles after participants experience obstacles that disappear midway?

To address these questions, we conducted two studies: one investigating users' walking paths and walk-through rates for a static virtual obstacle (RQ1 and RQ2), and another examining a virtual obstacle that disappeared as the user approached (RQ3 and RQ4). Both studies focused on users' walking paths toward virtual obstacles on straight routes, replicating prior walking task paradigms [16, 17, 45, 57, 68]. We formulated hypotheses H1a–H1e in Study 1 (Section 4.3) and H2a–H2d in Study 2 (Section 6.4). H1a–H1e concern how obstacle geometry (width, depth, height, and opacity) and individual differences affect walk-through behavior for static obstacles. H2a–H2d address how dynamic effects and their start timing change walking paths and detour timing. Through these studies, we aim to gain a deeper understanding of human walking path selection between walk-through and detour-around behaviors toward virtual objects.

Our contributions are as follows:

- Investigating the factors that influence whether virtual objects are walked through or detoured
- Designing three dynamic effects in which virtual objects disappear as users approach
- Examining users' walking paths toward static virtual objects and virtual objects with dynamic effects
- Providing insights and future research directions for the design of world-anchored MR objects on walking paths

2 Related Work

In this section, we first summarize research on MR experiences during walking. Next, we summarize collision risks while walking in MR, review collision avoidance methods in VR and MR, and highlight the necessity of dynamic effects for reducing such risks in MR. Finally, we summarize the findings on collision avoidance behavior in VR and MR and identify gaps in understanding walking paths when detouring around or walking through virtual objects.

2.1 Walking in MR Environments

MR is a promising technology for supporting tasks performed while walking, such as operating browsers [42] and viewing text [39, 56] or videos [7, 8]. However, recent MR systems with commercial HMDs generally assume that users are stationary; for example, the user interface (UI) of Apple Vision Pro[1] does not follow the user's movements [71]. To address this limitation, body-anchored UIs [26, 42, 50, 52] are employed during walking. Studies have also investigated appropriate UI placement [7, 8, 56], proposed interaction methods [75], and examined usability and selection performance [26, 46, 48].

In addition to interacting with body-anchored UIs, scenarios involving interactions with world-anchored MR objects are increasingly envisioned. The concept film *Hyper-Reality*,[2] which portrays

[1]https://www.apple.com/apple-vision-pro/ (accessed 2026-01-25)
[2]http://hyper-reality.co/ (accessed 2026-01-25)

a future in which MR is ubiquitous, depicts people walking through city spaces filled with diverse world-anchored MR objects, such as virtual advertisements [55] and fences between the sidewalk and roadway [73, 77]. In practice, efforts to integrate MR into city-citizen interactions are growing [44], including tourism applications [3], pedestrian traffic safety support [21, 60, 74], and the development of large-scale MR games [10, 61, 65, 66]. Moreover, several studies have examined visual search performance during walking in environments containing various world-anchored MR objects [36, 37, 41].

Overall, prior studies have primarily focused on how to present and operate body-anchored UIs during walking. However, comparatively little is known about how world-anchored virtual objects influence people's walking behavior when they encounter them. In this work, we focus on walking in MR environments and investigate how users select their walking paths when facing world-anchored virtual obstacles.

2.2 Collision Risks and Collision Avoidance Methods in VR and MR

Walking carries the risk of colliding with real-world objects, and this risk is particularly heightened in MR environments [31]. Current video see-through HMDs have been shown to increase users' collision anxiety due to factors such as pass-through distortion, restricted peripheral vision, and low pixel density [71, 72]. As a result, walking speed decreases even when no virtual information is present [2], and attending to virtual information further degrades walking performance [39, 62]. Focusing on virtual objects has also been shown to reduce attention to real-world objects [80], thereby increasing the likelihood of collisions with obstacles.

In VR contexts, various collision avoidance methods have been proposed. One approach is to predefine a safety area free of obstacles [12, 84]. However, this method can be applied only in limited spaces and is not suitable for everyday walking scenarios. Another approach informs users of obstacle locations by placing virtual objects at their positions [9, 27, 70, 83]. By consistently avoiding these virtual objects, users can navigate larger areas; however, collisions still occur if users choose to walk through them [76]. A further approach involves indicating the positions of real-world objects by displaying portions of the real space within the virtual environment [20, 78, 82]. This approach may also be suitable for MR, as it enables users to recognize approaching obstacles and spontaneously avoid them.

Most collision avoidance research in MR has primarily focused on preventing collisions with real-world objects by highlighting them through MR [1, 18, 28, 51]. By contrast, methods that reduce collision risks caused by real-world objects being occluded by virtual content have scarcely been investigated. In this work, inspired by collision avoidance techniques in VR [20, 78], we design dynamic effects that make virtual obstacles on users' paths disappear as they approach, and we investigate the resulting changes in walking paths.

2.3 Collision Behavior for Virtual Objects

When virtual objects obstruct a user's walking path, individuals tend to detour around them in both VR [16, 17, 59, 69] and MR environments [25, 32, 45, 68]. Research on walking paths toward virtual objects typically employs simple tasks in which a virtual object is placed along a straight path [16, 17, 45, 57, 68] and analyzes metrics, such as path shape and clearance distance. Several studies have examined how walking paths change depending on the appearance [25, 57, 68] or movement [45, 59] of the virtual object. Comparisons between walking behavior for real and virtual objects have also been conducted, showing that virtual objects tend to elicit slower walking speeds and larger clearance distances [6, 17, 19, 68]. Despite these differences, collision avoidance behavior in virtual environments is largely comparable to that in the real world [6, 19], making VR and MR promising tools for investigating walking behavior.

However, unlike real-world objects, virtual objects can be walked through; several studies have confirmed that some participants chose to walk through virtual objects instead of detouring in both VR [4, 13, 58] and MR environments [29, 32, 33]. Kim et al. [32, 33] observed participants walking through a virtual humanoid agent in a wheelchair while moving around a room in MR environments to take shortcuts. Boldt et al. [4] reported that many participants walked through inner walls to take shortcuts in a virtual maze task. By replicating this task, researchers have investigated the factors contributing to the walk-through rate of virtual objects in both VR [13, 58] and MR [29] environments. These studies have consistently shown that the greater the benefit gained from such shortcuts, the higher the proportion of participants who walk through virtual objects [4, 29, 58]. In addition, prior work has suggested that factors such as the realism of virtual objects [13], the transparency of virtual humanoid agents [29], and user personality traits [29] may influence the walk-through rate.

Previous research on walking paths for virtual objects has generally assumed detour behavior and not examined walking paths when participants choose to walk through them [32, 45, 68]. Studies confirming walk-through behavior have also not investigated walking paths along straight routes [4, 29, 58]. In addition, research on the factors affecting walk-through rates is limited, and the influence of virtual object shape has yet to be examined. In this study, we conducted a walking task to investigate how the size, transparency, and placement of virtual objects affect both the walk-through rate and the resulting walking paths.

3 Overall Study Design

We conducted Study 1 to investigate walking paths for static virtual obstacles, and Study 2 to examine walking paths for virtual obstacles with dynamic effects applied. To satisfy the data requirements for statistical analysis while minimizing the physical burden associated with repeated walking, we performed separate investigations for RQ1 and RQ2 in Study 1 and for RQ3 and RQ4 in Study 2. Both studies were approved by the ethics review committee of our institute (number: 2025R018).

3.1 Participants

We recruited 28 participants for Study 1 (12 female, 16 male; mean age = 21.2 years, SD = 1.8; ID: P1–P28) and 30 participants for Study 2 (16 female, 14 male; mean age = 22.9 years, SD = 3.5; ID: P29–P58) from a local university. No participant took part in both studies. In Study 1, 13 participants had no prior experience with VR or MR, 14 had used VR or MR on several occasions, and one had more than three months of experience. In Study 2, 16 participants had no prior experience with VR or MR, 13 had used VR or MR on several occasions, and one had more than three months of experience. Each participant received US$13 as compensation, and each study session lasted approximately 60 minutes.

3.2 Apparatus

We used the HTC VIVE Focus Vision[3] and two HMD controllers. The HMD was operated as a video see-through MR device. According to the specifications, the HMD provides a visible field of view of 120°. The application used in this study was developed using Unity (Version 2022.3.9f1). Additionally, we used four HTC VIVE Tracker 3.0[4] to track the participants' body motion. Each tracker weighs 75 g and has an accuracy of 10–20 mm [40]. One tracker was attached to the HMD, one to the participant's chest, and the remaining two to both ankles.

3.3 Experimental Setup

The experimental setup is shown in Fig. 2a. It consisted of a road, a virtual obstacle, and cylinders indicating the start and goal positions. The road was enclosed by blue translucent virtual walls 0.4 m high. The width of the road was 1.6 m, which exceeds the minimum sidewalk/walkway widths adopted in the U.S.[5] and Germany[6]. We constrained walking to a road of fixed width to approximate real-world pedestrian walking on streets. The road length was 6.0 m in Study 1 and 7.0 m in Study 2. While the length in Study 1 followed Patotskaya et al. [59], Study 2 used a longer road to accommodate the various start timings of the dynamic effects. The start and goal positions were placed near the edges of the road, each 0.4 m from the respective sides. A red cylinder (0.8 m high, radius = 0.4 m) marked the start position, and a blue cylinder (2.0 m high, radius = 0.4 m) marked the goal position.

The virtual obstacle was a gray rectangular parallelepiped with an image displayed on one of its surfaces. The image depicted a coffee-themed advertisement and was generated using Gemini 2.5 Pro,[7] a large language model. The prompt was as follows: "Please generate an image. Image only. Make it look like a poster. Include an image of coffee." The display size of the image was scaled proportionally to match the size of the obstacle. The obstacle was placed at the center of the road, along the sideline shared by the start and goal positions, as in prior studies [57, 59, 68].

3.4 Task

The study task involved walking from the start position to the goal position on the road. In the initial state of each trial, the cylinders indicating the start and goal positions, the virtual walls, and a button were displayed. The button was positioned in front of the start cylinder. The participants moved to the start position and selected the button using a ray-casting selection method with a handheld controller. This selection was enabled only when the participant's head was within 0.2 m of the center of the start position. When the button was selected, it disappeared, and the virtual obstacle appeared. The participants then walked toward the goal position. When their heads reached within 0.2 m of the goal position, the obstacle disappeared, and the start cylinder, the goal cylinder, and the button for the next trial appeared. This sequence constituted one trial.

3.5 Procedure

Upon arrival at the designated university space, the participants read and signed an informed consent form and then completed a pre-task questionnaire collecting personal information. The participants then received detailed instructions, which included a prohibition on extending any body parts beyond the roadway and on asking questions during the study. Afterward, they donned the HMDs, held the controllers, and attached motion trackers to their chests and ankles.

The participants then completed a practice session designed to familiarize them with the task procedure. In this session, they walked from the start to the goal position twice. The presence of the virtual obstacle was neither disclosed nor visible during practice to prevent the participants from asking questions about it, as any explanation could bias their subsequent walking behavior. After the practice session, the participants proceeded to the main session. After each main session, they were free to take breaks as needed. Upon completing all the main sessions, they answered a post-task questionnaire regarding their impressions of the task. Finally, they participated in a semi-structured interview in which they were asked about the reasons behind their walking path choices.

3.6 Evaluation Metrics

An analysis was conducted on the following metrics:

(1) **Walk-through Rate**: This is the proportion of trials in which the participant's head or ankles intersected the virtual obstacle. Head positions were tracked using the HMD, and ankle positions were tracked using ankle trackers.
(2) **Lateral Deviation**: This is the deviation along the Y-axis between the participant's head position and the route connecting the start and goal positions, measured at the moment when the participant's and obstacle's X-axis positions coincided. The X-axis and Y-axis corresponded to the edge-to-edge (walking direction) and side-to-side (lateral direction) axes of the virtual road, respectively. The origin was defined as the point where the X-axis of the obstacle intersected with the Y-axis of the route. A negative value indicated that the participant approached the side of the road closer to the route. The coordinate system is shown in Fig. 2b.
(3) **Peak Position**: This is the X-axis coordinate at which the Y-axis reached its maximum value. It represents the point on the X-axis that is farthest laterally from the straight line connecting the start and the goal.
(4) **Regenbrecht's Presence Questionnaire (RPQ)** [63]: This questionnaire evaluates the sense of presence in MR, including realness, spatial presence, perceptual stress, and total

[3] https://www.vive.com/us/product/vive-focus-vision/overview/ (accessed 2026-01-25)
[4] https://www.vive.com/us/accessory/tracker3/ (accessed 2026-01-25)
[5] https://www.fhwa.dot.gov/publications/research/safety/pedbike/05085/chapt9.cfm (accessed 2026-01-25)
[6] https://www.leitfadenbarrierefreiesbauen.de/handlungsfelder/erschliessung/3-gehwege-und-aeussere-erschliessungsflaechen (accessed 2026-01-25)
[7] https://gemini.google.com/app (accessed 2026-01-25)

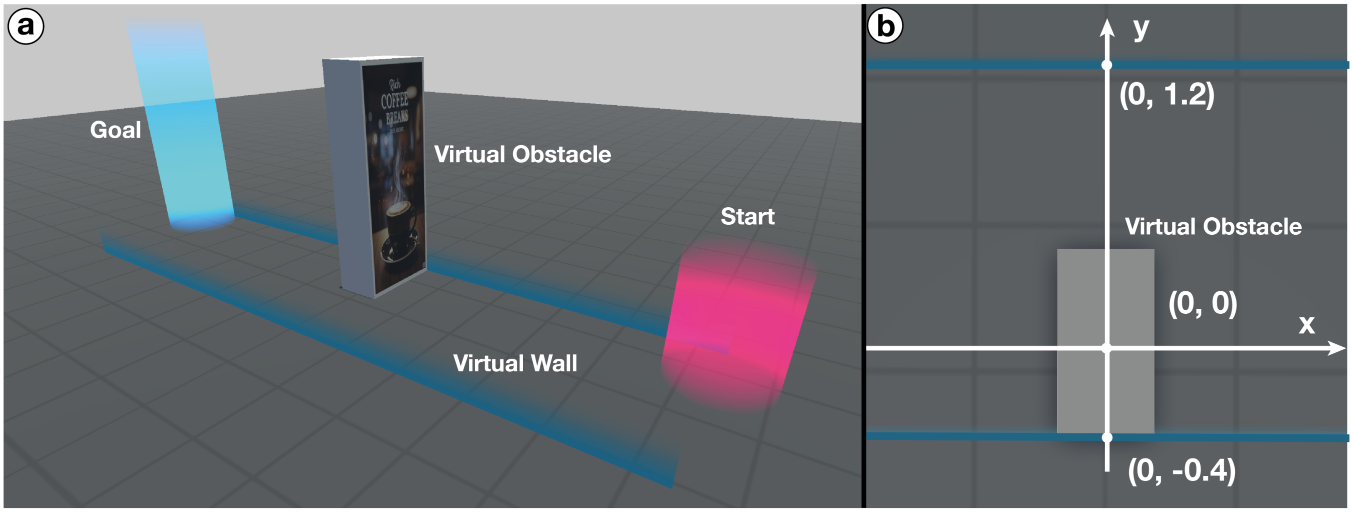

Figure 2: (a) Experimental setup and (b) coordinate system of the road.

presence. Several items from the original RPQ were modified to fit our study, following the approach of Kasahara et al. [29]. Responses were scored on a seven-point Likert scale.

(5) **Collision Anxiety Questionnaire (CAQ)** [64]: This questionnaire measures collision anxiety toward real-world objects in VR experiences. It has also been adapted to assess collision anxiety in MR environments [31]. Because our study task did not involve collisions with people or disorientation, we used only the items related to general collision anxiety. Responses were scored on a seven-point Likert scale.

In Study 1, we analyzed walk-through rate and lateral deviation only. In Study 2, we analyzed all five metrics. This difference arises because the additional metrics (peak position, RPQ, and CAQ) were incorporated to evaluate the influence of the dynamic effects. Peak position was included for examination when the participants transitioned from a detour path to a more direct path due to the dynamic effect. RPQ and CAQ were included to assess whether the participants' impressions of the virtual obstacle (i.e., presence and collision anxiety) differed depending on the type of dynamic effect.

3.7 Analysis

For the walk-through rate, we fitted a generalized linear mixed model (GLMM) [5] with independent variables as factors. The model was evaluated using type-III Wald χ^2 tests. Post-hoc analyses were performed using pairwise comparisons of estimated marginal means (EMMs) with Tukey correction.

The lateral deviation and peak position did not follow a normal distribution. Thus, we applied the aligned rank transform [22, 67, 81] to each dataset, followed by a repeated measures ANOVA with independent variables as factors. Effect sizes were reported using partial eta-squared (η_p^2). Post-hoc analyses were conducted using ART-C [15] with Holm correction [23].

To evaluate the RPQ and CAQ scores, we used the Friedman test across an independent variable. Pairwise comparisons were conducted using Wilcoxon signed-rank tests with Holm correction.

3.8 Data Preprocessing

The 3D coordinates of the HMDs and trackers (head, chest, and both ankles) recorded during the task were corrected. Because the coordinate systems of the HMD and trackers differed, we aligned them by matching the head tracker position to the HMD. All coordinate data were resampled to 50 Hz before alignment. In addition, all walking paths were transformed to have the same direction and identical start and end coordinates.

4 Study 1

We conducted a study with 28 participants (P1–P28) to collect walking-path data for static virtual obstacles and to investigate the factors that determine whether participants walk through or detour around these obstacles. The study was designed to address RQ1 (Which factors influence walk-through rates for static virtual obstacles?) and RQ2 (How do walking paths differ between walk-through and detour behaviors for static virtual obstacles?).

4.1 Design

We employed a within-participant design with four independent variables (Fig. 3):

- *Width*: 0.4 m, 0.8 m, 1.2 m
- *Depth*: 0.4 m, 0.001 m
- *Opacity*: 100%, 50%
- *Type*: grounded-1.0m (G1), grounded-2.0m (G2), floating-1.0m (F1)

Width and *Depth* define the virtual obstacle dimensions (Fig. 3a, b). Given a road width of 1.6 m, the three *Width* levels correspond to road occupancy rates of 25%, 50%, and 75%, respectively; larger *Width* values therefore require the participants to take wider detours around the obstacle. A *Depth* of 0.4 m represents a solid object, whereas a *Depth* of 0.001 m corresponds to a UI menu.

Opacity represents the transparency level of the virtual obstacle, where 100% indicates full opacity and 50% indicates semi-transparency (Fig. 3c). This factor was included as an independent

Figure 3: Independent variables in Study 1: (a) *Width*, (b) *Depth*, (c) *Opacity*, and (d) *Type*.

variable because semitransparent virtual objects are significantly walked through more frequently than fully opaque ones [13].

Type defines the position and height of the virtual obstacle (Fig. 3d). The G1 and G2 conditions refer to virtual obstacles with heights of 1.0 m and 2.0 m, respectively, that are in contact with the floor. Their dimensions and placement were chosen to roughly match world-anchored objects such as virtual human agents, fences, or walls. The F1 condition refers to virtual obstacles with a height of 1.0 m positioned 1.5 m above the floor, approximating virtual UI elements. Note that in all *Type* conditions, only height and position were varied; the obstacle itself was always rendered as the same simple rectangular parallelepipeds.

The participants completed 36 trials (3 *Width* levels $\times$ 2 *Depth* levels $\times$ 2 *Opacity* levels $\times$ 3 *Type* levels). The trial order was randomized. One set of 36 trials constituted a session, with each participant completing four sessions. These four sessions included two obstacle directions (left and right), each presented twice. When the direction was left, the obstacle, start position, and goal position were placed near the left edge of the road; when the direction was right, they were placed near the right edge. The session order was counterbalanced using a Latin square. In total, each participant completed 4 sessions $\times$ 36 trials = 144 valid trials, yielding 4,032 datasets across all 28 participants.

4.2 Analysis

In this study, we analyzed the walk-through rate and lateral deviation with *Width*, *Depth*, *Opacity*, and *Type* as factors. We also investigated whether lateral deviation differed significantly depending on whether the virtual obstacle was walked through. For this analysis, we fitted a linear mixed model (LMM) [49] with *Path* as a factor, consisting of detour-around (Detour) and walk-through (Pass). Trials in which no contact with the virtual obstacle was detected were classified as Detour, whereas trials in which the participant's head or ankles intersected the virtual obstacle were classified as Pass. The model was evaluated using EMMs, and effect sizes are reported using Cohen's *d*.

4.3 Hypotheses

Our hypotheses for RQ1 and RQ2 were as follows:

H1a: A greater obstacle width increases the walk-through rate.
H1b: A greater obstacle depth decreases the walk-through rate.
H1c: A lower obstacle opacity increases the walk-through rate.
H1d: A greater obstacle height decreases the walk-through rate.
H1e: The walk-through rate varies substantially across individuals.

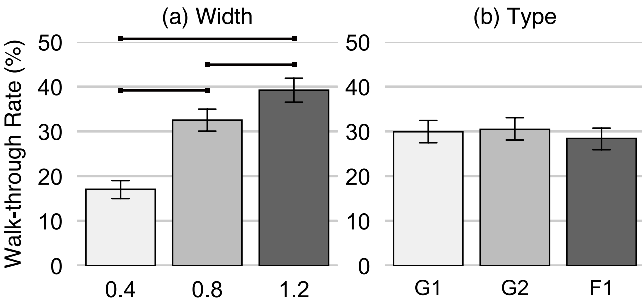

Figure 4: Walk-through rates by (a) *Width*, and (b) *Type*. The error bars denote the 95% confidence intervals. Significant differences ($p < .05$) between conditions are indicated by horizontal bars.

5 Results 1

In one trial, the ankle tracker detached after being accidentally kicked by the participant. Thus, the data from that trial were excluded from the analysis.

5.1 Walk-through Rate

The walk-through rates are shown in Fig. 4. The average walk-through rate across all trials was 29.6%. We found a significant main effect of *Width* ($\chi^2_{2,N=28} = 63.70$, $p < .01$) and *Type* ($\chi^2_{2,N=28} = 7.49$, $p < .05$). Post-hoc comparisons for *Width* revealed significant differences among all levels: The wider the obstacle, the higher the walk-through rate ($p < .01$).

The walk-through rate for each participant is shown in Table 1. The rates varied substantially across participants, with 15 participants walking through fewer than 3% of the virtual obstacles and six participants walking through more than 80%. In addition, 11 participants walked through the virtual obstacle on their first trial. The GLMM's random-intercept SD was very large (σ = 13.50 log-odds), indicating pronounced between-participant differences in walk-through rates. The intraclass correlation coefficient was 0.982, suggesting that about 98% of the variance in walk-through behavior was attributable to stable between-participant differences. Together, these results indicate that walk-through behavior is strongly influenced by individual differences.

As an exploratory analysis, we added obstacle direction (left vs. right relative to the direction of travel) to the GLMM and examined its effect on walk-through rate. The results showed a significant main effect of direction ($\chi^2_{1,N=28} = 45.09$, $p < .01$), with slightly higher walk-through rates on the right (31.5%) than on the left (27.6%). Prior research has shown that individuals tend to walk closer to obstacles on the side of their dominant hands, where personal space tends to be narrower [19]. Although we did not measure the participants' dominant hands in this study, the asymmetries in personal space on the dominant-hand side may have contributed to the elevated walk-through rate for right-side obstacles.

5.2 Lateral Deviation

The lateral deviations are shown in Fig. 5. We found significant main effects of *Width* ($F_{2,3968} = 928.67$, $p < .01$, $\eta^2_p = .319$), *Depth* ($F_{1,3968} = 11.19$, $p < .01$, $\eta^2_p = .003$), and *Type* ($F_{2,3968} = 52.52$, $p < .01$, $\eta^2_p = .026$). Additionally, significant interactions were observed for *Width* × *Type* ($F_{4,3968} = 18.22$, $p < .01$, $\eta^2_p = .018$). Post-hoc comparisons for *Width* × *Type* revealed significant differences among all *Width* levels within each *Type* condition: The wider the obstacle, the greater the lateral deviation ($p < .01$).

The lateral deviations for *Path* are shown in Fig. 5c. The median lateral deviation was 0.73 m in the Detour condition and 0.01 m in the Pass condition. LMM regression revealed a significant effect of *Path* (Detour vs. Pass) on lateral deviation ($\beta = -0.17$, $SE = 0.01$, $t = -15.27$, $p < .01$, $d = 0.96$).

5.3 Walking Path

The walking paths (head trajectories) for each trial are shown in Fig. 6. When the participants walked through the virtual obstacle, most followed relatively straight paths. By contrast, when the participants detoured around the obstacle, they generally took smooth, curved trajectories.

Unique detour paths were observed in which the head passed either above or below the virtual obstacle. Under the condition *Width* = 1.2 m × *Type* = F1, six participants crouched to avoid the obstacle in 64 trials. Consequently, the F1 condition yielded a lower lateral deviation than both the G1 condition ($t = -4.45$, $p < .01$) and the G2 condition ($t = -11.04$, $p < .01$) at *Width* = 1.2 m. In addition, under the condition *Width* = 1.2 m × *Type* = G1, 14 participants turned sideways and walked through the gap between the virtual obstacle and the edge of the road, with their heads passing over the obstacle in 49 trials. Accordingly, the G1 condition also produced a lower lateral deviation than the G2 condition ($t = -6.60$, $p < .01$) at *Width* = 1.2 m.

5.4 Participants' Feedback

Many participants who detoured around the virtual obstacle stated that they avoided it intuitively or out of habit, as if it were a real obstacle. P6 commented, "Even though I knew it wouldn't hurt me, I avoided it because I've developed the habit of dodging things directly in front of me." P6, P10, P13, and P16 detoured around the virtual obstacles even while understanding that they could walk through them. In addition, P12 and P25 stated that they consciously avoided virtual obstacles, keeping in mind that this was an experiment. By contrast, six participants who walked through the virtual obstacle stated that they did so because they understood it was possible, unlike with a real-world object. P15 commented, "At first, I avoided it, thinking it was a real-world object, but afterward, I recognized it as a virtual obstacle and decided to walk through."

Feedback on how the appearance of virtual obstacles affected walking behavior varied considerably among individuals. Fourteen participants commented on opacity, noting that translucent virtual obstacles allowed them to see through the objects and reduced collision anxiety, whereas opaque objects created resistance to walking through. By contrast, 10 participants stated that transparency did not affect their walking behavior. Nine participants reported that thicker objects felt more difficult to walk through, while three stated that the depth of the virtual obstacle did not influence their walking behavior. Although virtual obstacle types were rarely mentioned, the G1 condition was described as difficult to walk through because

Table 1: Walk-through rate for each participant (P1–P28).

P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
54.2%	94.4%	0.0%	0.0%	68.1%	0.0%	0.0%	40.3%	0.0%	3.5%	0.7%	0.0%	0.0%	83.3%
P15	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**	**P26**	**P27**	**P28**
71.5%	0.0%	95.1%	0.7%	0.0%	34.0%	85.4%	0.7%	95.1%	0.0%	7.6%	93.8%	0.0%	0.0%

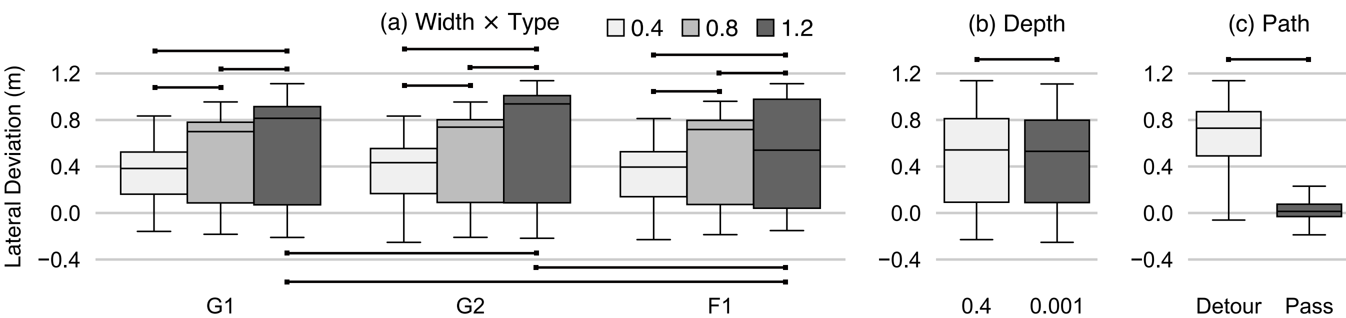

Figure 5: Lateral deviations by (a) *Width* × *Type*, (b) *Depth*, and (c) *Path*. Significant differences ($p < .05$) between conditions are indicated by horizontal bars.

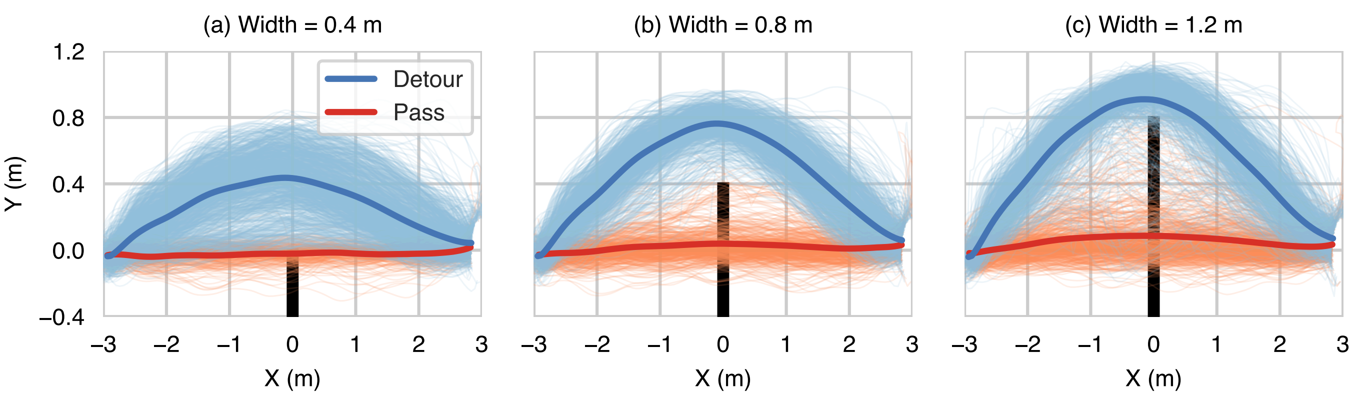

Figure 6: Walking paths for all trials by *Width*. Thin blue lines represent individual trials in which the participants detoured around the obstacle (Detour), while thin red lines represent trials in which they walked through it (Pass). Bold blue and red lines indicate the average walking paths for the Detour and Pass trials, respectively. The black rectangle represents the virtual obstacle. Trials in which the participants crouched to avoid the obstacle (64 trials) appear as detour paths whose head trajectories pass over the obstacle.

it made them feel as if they might bump their feet (P17, P26). In comparison, under the G2 and F1 conditions, when the virtual obstacle was opaque, it blocked the view of the scenery behind it, increasing collision anxiety (P10, P14, P20).

5.5 Summary 1

Width primarily affected the walk-through rate (0.4 m: 17.1%, 0.8 m: 32.5%, 1.2 m: 39.2%), supporting [H1a]. Although *Depth* increased lateral deviation (a greater depth led to larger detours), it did not significantly influence the walk-through rate; thus, [H1b] was not supported. *Opacity* also showed no significant effect on the walk-through rate, failing to support [H1c]; nevertheless, several participants reported that seeing the space behind the obstacle made walking through feel easier. Although *Type* (height/placement) had a significant main effect on the walk-through rate, post-hoc pairwise comparisons revealed no significant differences; thus, [H1d] was not supported. However, when *Width* was 1.2 m, the G2 condition yielded a larger lateral deviation than G1 and F1, suggesting that taller obstacles may induce greater detours. [H1e] was supported; walk-through propensity varied substantially across individuals. Six participants walked through in more than 80% of the trials, whereas 15 participants did so in fewer than 3%.

Walk-through paths were generally straight, whereas detour paths curved early to avoid the obstacle. For detour paths, lateral deviation increased with *Width*, resulting in more expansive trajectories.

6 Study 2

We conducted a study with 30 participants (P29–P58) to collect data on walking paths for virtual obstacles with dynamic effects, in which virtual objects disappeared as users approached. The study was designed to address RQ3 (When virtual obstacles disappear midway, how do walking paths change depending on the type of effect and the timing of disappearance?) and RQ4 (How do walk-through rates and walking paths change for static virtual obstacles after participants experience obstacles that disappear midway?).

6.1 Dynamic Effect

We designed three types of dynamic effects: *Fade*, which gradually changes the object's transparency; *Wipe*, which gradually reduces its width; and *Door*, which rotates the object by 90°. We hypothesized that walking paths would differ between an effect that keeps the object's width constant (Fade) and effects that gradually reduce its width (Wipe and Door), given that lateral deviation increases as obstacle width increases. For this reason, we adopted Fade, which keeps the object's width constant, and Wipe and Door, which reduce the width either visually or effectively through rotation.

Each effect began when the user entered a specified starting distance from the virtual obstacle and was completed when the user reached a defined ending distance, at which point the obstacle had completely disappeared from the walking path. The progression of the effect was modeled linearly as follows:

$$\alpha(d) = \frac{d - d_{end}}{d_{start} - d_{end}}, \quad \alpha \in [0, 1], \tag{1}$$

where d_{start} is the distance at which the effect begins, d_{end} is the distance at which the effect is completed, and d is the current distance between the user and the virtual object. In this study, d was calculated solely along the x-axis, corresponding to the user's walking direction. $\alpha(d)$ decreases linearly from 1 to 0 as the user approaches the object.

6.1.1 Fade. In this effect, the opacity of the virtual object decreases linearly from 100% (opaque) to 0% (fully transparent) as the user approaches, while the width of the object remains unchanged (Fig. 7a). The opacity of the virtual object decreases linearly with $\alpha(d)$ while the width remains constant:

$$Opacity(d) = 100 \cdot \alpha(d). \tag{2}$$

6.1.2 Wipe. In this effect, the portion of the virtual object farthest from the edge of the virtual road gradually disappears linearly as the user approaches, making the object appear narrower (Fig. 7b). The width of the virtual object decreases linearly with $\alpha(d)$:

$$Width(d) = W_0 \cdot \alpha(d), \tag{3}$$

where W_0 is the initial width of the virtual object.

6.1.3 Door. In this effect, the virtual object rotates 90° around its edge along the road (Fig. 7c). The axis of rotation is the Z-axis, which is perpendicular to the floor. As the object rotates, its center shifts toward the edge of the road. The resulting width is expressed as follows:

$$Width(d) = \left[\alpha(d) + \cos\big(\pi/2 \cdot (1 - \alpha(d))\big)\right] \cdot \frac{W_0}{2}. \tag{4}$$

6.2 Design

We employed a within-participant design with three independent variables:

- *Effect*: None, Fade, Wipe, Door
- *Width*: 0.8 m, 1.2 m
- *Timing*: 3-2, 3-1, 2-1

Effect includes the three dynamic effects introduced previously (Fade, Wipe, and Door) as well as a condition in which no effect occurs (None). The None condition was identical to the static virtual obstacle in Study 1 and was adopted as the baseline. *Width* defines the dimensions of the virtual obstacle. The height and depth of the virtual obstacle were set to 2.0 m and 0.001 m, respectively. In addition, the opacity was fixed at 100%, and the obstacle was placed on the floor. *Timing* specifies the distance between the starting point and the ending point of the dynamic effect. The 3-2, 3-1, and 2-1 conditions indicate that d_{start} was 3 m and d_{end} was 2 m, 3 m and 1 m, and 2 m and 1 m, respectively.

In the None condition, the participants completed 8 trials (2 × 2 *Width* levels × 2 obstacle directions). *Timing* was not combined with the None condition, as it has no effect in this case. In the Fade, Wipe, and Door conditions, the participants completed 32 trials for each effect. These consisted of 2 × (2 *Width* levels × 3 *Timing* levels × 2 obstacle directions) trials, plus 8 additional baseline trials in which the obstacle remained static. These baseline trials served two purposes: (1) to ensure that the disappearance of the virtual object was ambiguous until the user approached, thereby clarifying the optimal *Timing* value, and (2) to compare walking behavior when virtual objects never disappear with walking behavior when virtual objects occasionally do not disappear (RQ4).

The trial order was randomized. The order of *Effect* conditions always began with None, while the three other conditions were counterbalanced using a Latin square. After completing each *Effect* condition, the participants filled out the RPQ and CAQ. Upon completing all trials, they answered a post-task questionnaire that included their preferences for *Effect* and *Timing*. In total, each participant completed (8 trials + 3 × 32 trials) = 104 valid trials, yielding 3,120 datasets across all 30 participants.

6.3 Analysis

We repeatedly extracted specific subsets from the dataset for analysis. First, to investigate the impacts of the dynamic effects, we extracted a dataset excluding the baseline trials (hereafter, the *dataset for the impacts of dynamic effects*). Note that trials in the None condition were included as is, whereas only the baseline trials were excluded from the other *Effect* conditions. The independent variables were *Effect* (None, Fade, Wipe, and Door) and *Width*, and the dependent variables were lateral deviation and peak position.

Second, to investigate the impacts of *Timing* on the dynamic effects, we extracted a dataset excluding the None condition and the baseline trials (hereafter, the *dataset for the impacts of timings*). The independent variables were *Effect* (Fade, Wipe, and Door), *Width*, and *Timing*, and the dependent variables were lateral deviation and peak position. Third, to investigate walking behavior for static virtual obstacles, we extracted a dataset consisting of the None condition and the baseline trials from the Fade, Wipe, and Door conditions (hereafter, the *dataset for static virtual obstacles*). The

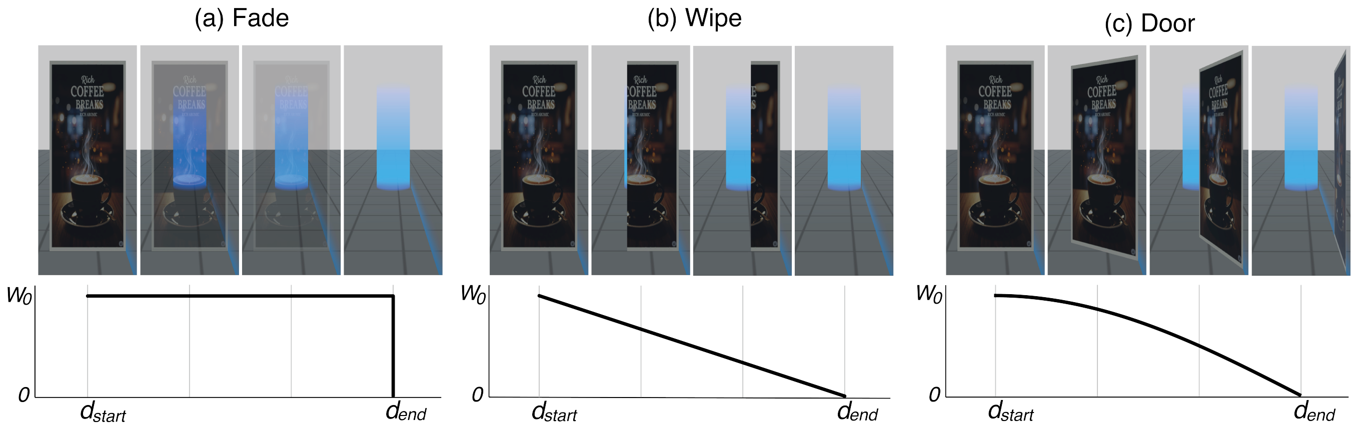

Figure 7: Transition of dynamic effects and virtual obstacle width: (a) Fade, (b) Wipe, and (c) Door.

independent variables were *Effect* (None, Fade, Wipe, and Door) and *Width*, and the dependent variables were walk-through rate, lateral deviation, and peak position. Finally, to evaluate RPQ and CAQ scores, we used the Friedman test across *Effect* conditions (None, Fade, Wipe, and Door).

6.4 Hypotheses

Our hypotheses for RQ3 and RQ4 were as follows:

H2a: Dynamic effects (Fade, Wipe, and Door) cause the participants' walking paths to diverge into two types: (1) a straight path based on the expectation that virtual obstacles will disappear, and (2) a path that initially detours around the obstacle but then switches to a more direct route toward the goal after confirming the dynamic effect.

H2b: Earlier initiation of dynamic effects enables a faster transition from the detour path to a more direct path toward the goal, resulting in reduced lateral deviation.

H2c: Dynamic effects in which the width of virtual obstacles gradually decreases as the participants approach (Wipe and Door) result in smaller lateral deviations during detours compared to effects in which the width remains constant (Fade).

H2d: When encountering static virtual obstacles after experiencing dynamic effects, the participants who follow a straight path tend to delay their detour timing or increase the proportion of obstacles they walk through.

7 Results 2

7.1 Behavioral Results: Impacts of Dynamic Effects

We conducted a two-way repeated-measures ANOVA on the dataset for the impacts of dynamic effects, with *Effect* and *Width* as factors.

7.1.1 *Lateral Deviation.*

The lateral deviations are shown in Fig. 8a. Significant main effects were found for *Effect* ($F_{3,2363} = 373.39$, $p < .01$, $\eta_p^2 = .322$) and *Width* ($F_{1,2363} = 68.61$, $p < .01$, $\eta_p^2 = .028$). In addition, a significant interaction was observed for *Effect* × *Width* ($F_{3,2363} = 17.45$, $p < .01$, $\eta_p^2 = .022$). Post-hoc comparisons revealed that Fade, Wipe, and Door all resulted in significantly smaller lateral deviations than None ($p < .01$) under both *Width* conditions. Furthermore, Wipe and Door produced significantly smaller lateral deviations than Fade ($p < .05$) under both *Width* conditions.

7.1.2 *Peak Position.*

The peak positions are shown in Fig. 8b. Significant main effects were found for *Effect* ($F_{3,2363} = 42.35$, $p < .01$, $\eta_p^2 = .051$) and *Width* ($F_{1,2363} = 12.99$, $p < .01$, $\eta_p^2 = .005$). Post-hoc comparisons revealed that Fade, Wipe, and Door all resulted in significantly earlier peak positions than None ($p < .01$). Furthermore, Door exhibited a significantly earlier peak position than Fade ($t = -4.32$, $p < .01$).

7.1.3 *Walking Path.*

The walking paths (head trajectories) for each *Effect* condition are shown in Fig. 9. In Fade, Wipe, and Door, 29.2% of the trials (631/2160) involved participants avoiding the location where the virtual obstacle had been present. By contrast, 19.7% of the trials (425/2160) involved walking straight from the start—defined as trials with lateral deviations smaller than 0.23 m, which was the maximum lateral deviation after removing outliers from the detour dataset in Study 1. The remaining 51.1% of the trials (1104/2160) transitioned from a detour path to a more direct path toward the goal as a result of the dynamic effects.

7.2 Behavioral Results: Impacts of Timing

We conducted a three-way repeated-measures ANOVA on the dataset for the impacts of timings, with *Effect*, *Width*, and *Timing* as factors.

7.2.1 *Lateral Deviation.*

The lateral deviations are shown in Fig. 10a. Significant main effects were found for *Effect* ($F_{2,2113} = 50.52$, $p < .01$, $\eta_p^2 = .046$), *Width* ($F_{1,2113} = 45.28$, $p < .01$, $\eta_p^2 = .020$), and *Timing* ($F_{2,2113} = 238.27$, $p < .01$, $\eta_p^2 = .184$). In addition, significant interactions were observed for *Effect* × *Timing* ($F_{4,2113} = 3.47$, $p < .01$, $\eta_p^2 = .007$) and *Width* × *Timing* ($F_{2,2113} = 3.67$, $p < .05$, $\eta_p^2 = .003$). Post-hoc comparisons revealed that, across all *Effect* conditions, 2-1 produced significantly greater lateral deviation than 3-2 and 3-1 ($p < .01$). In addition, under

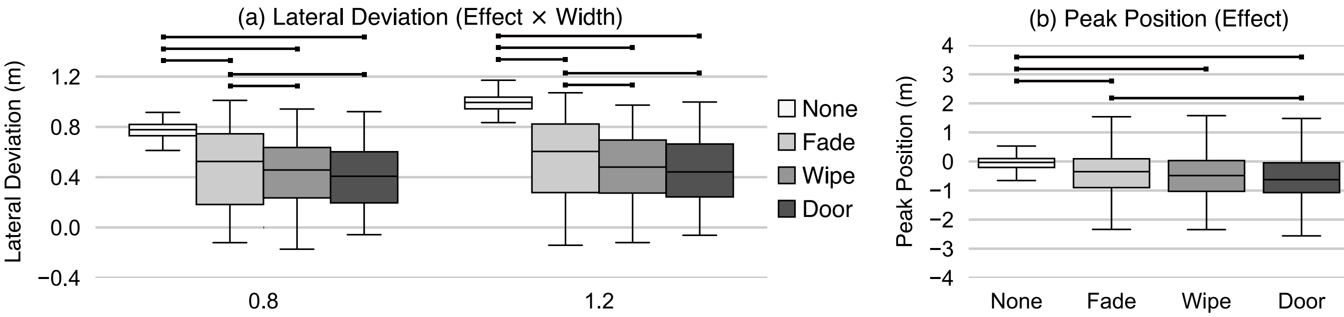

Figure 8: In the dataset for the impacts of dynamic effects: (a) lateral deviations by *Effect* × *Width*, and (b) peak positions by *Effect*. Significant differences (p < .05) between conditions are indicated by horizontal bars.

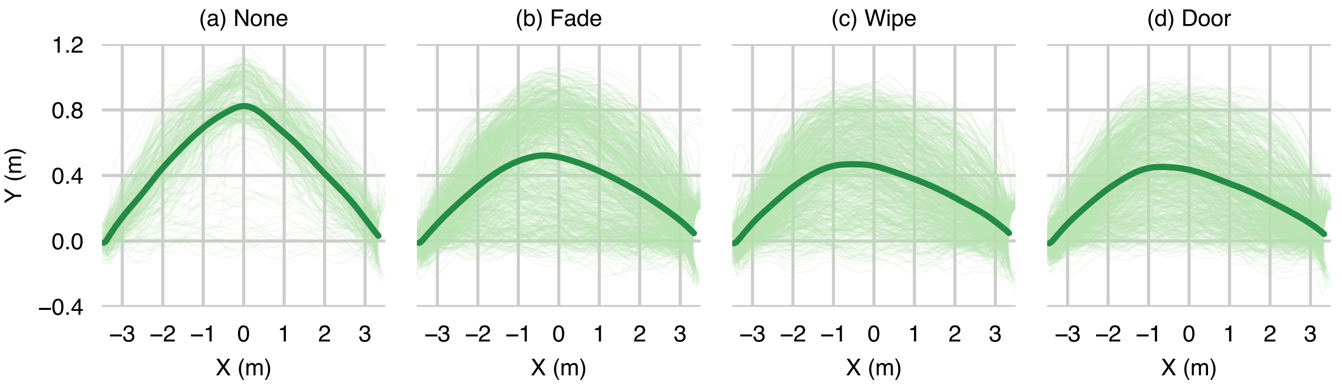

Figure 9: Walking paths by *Effect* in the dataset for the impacts of dynamic effects. Thin green lines represent individual trials, and the bold green line indicates the average walking path.

Timing 3-1 and 2-1, Fade resulted in a significantly greater lateral deviation than Wipe and Door (p < .01).

7.2.2 Peak Position. The peak positions are shown in Fig. 10b. Significant main effects were found for *Effect* ($F_{2,2113}$ = 7.92, p < .01, η_p^2 = .008), *Width* ($F_{1,2113}$ = 13.56, p < .01, η_p^2 = .006), and *Timing* ($F_{2,2113}$ = 20.92, p < .01, η_p^2 = .019). In addition, significant interactions were observed for *Effect* × *Timing* ($F_{4,2113}$ = 5.36, p < .01, η_p^2 = .010). Post-hoc comparisons revealed that, in the Fade condition, 3-2 resulted in significantly earlier peak positions than 3-1 ($t = -5.93, p < .01$) and 2-1 ($t = -6.41, p < .01$). In addition, under the 3-1 and 2-1 conditions, Fade produced significantly later peak positions than Door (p < .01).

7.2.3 Walking Path. The walking paths (head trajectories) for each *Effect* × *Timing* condition are shown in Fig. 11. The walking path for *Timing* 2-1 exhibited a greater lateral deviation than those for the other timings, indicating that a delayed start of the dynamic effect caused a delay in switching from the detour route to a more direct route toward the goal. In Wipe and Door, the average walking paths for *Timing* 3-2 and 3-1 were nearly identical in shape. By contrast, in Fade, the walking path for *Timing* 3-1 exhibited a greater lateral deviation than that for *Timing* 3-2, and its peak position occurred later.

7.3 Behavioral Results: Static Virtual Obstacles

We conducted a GLMM and a two-way repeated-measures ANOVA on the dataset for static virtual obstacles, with *Effect* and *Width* as factors.

7.3.1 Walk-through Rate. The average walk-through rates for *Effect* were 8.75% for None, 13.75% for Fade, 12.50% for Wipe, and 11.67% for Door. No significant main effects were observed for *Effect* ($\chi^2_{3,N=30}$ = 6.82, p = .08) or *Width* ($\chi^2_{1,N=30}$ = 2.86, p = .09). Eight participants walked through the virtual obstacle, four of whom walked through in all *Effect* conditions (walk-through rates: P33 = 28%, P35 = 100%, P43 = 100%, P57 = 78%). P49 and P53 walked through only once (3%), P36 only in the Fade condition (13%), and P51 in all *Effect* conditions except None (25%).

7.3.2 Lateral Deviation and Peak Position. For lateral deviation, a significant main effect was found for *Width* ($F_{1,923}$ = 1777.02, p < .01, η_p^2 = .658). However, no significant main effect of *Effect* was observed ($F_{3,923}$ = 2.55, p = .05, η_p^2 = .008).

The peak positions are shown in Fig. 12. For peak position, significant main effects were found for *Effect* ($F_{3,923}$ = 6.30, p < .01, η_p^2 = .020) and *Width* ($F_{1,923}$ = 18.80, p < .01, η_p^2 = .020). In addition, significant interactions were observed for *Effect* × *Width* ($F_{3,923}$ = 4.60, p < .01, η_p^2 = .014). Post-hoc comparisons revealed

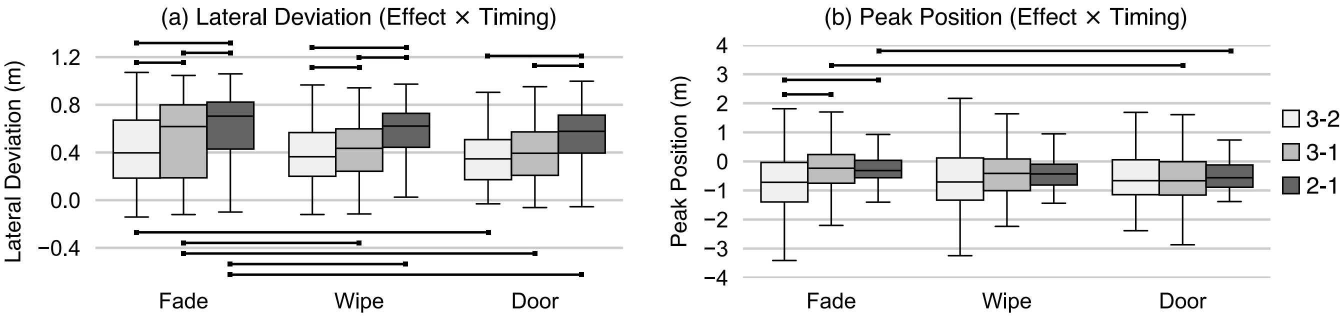

Figure 10: In the dataset for the impacts of timings: (a) lateral deviations by *Effect* × *Timing*, and (b) peak positions by *Effect* × *Timing*. Significant differences ($p < .05$) between conditions are indicated by horizontal bars.

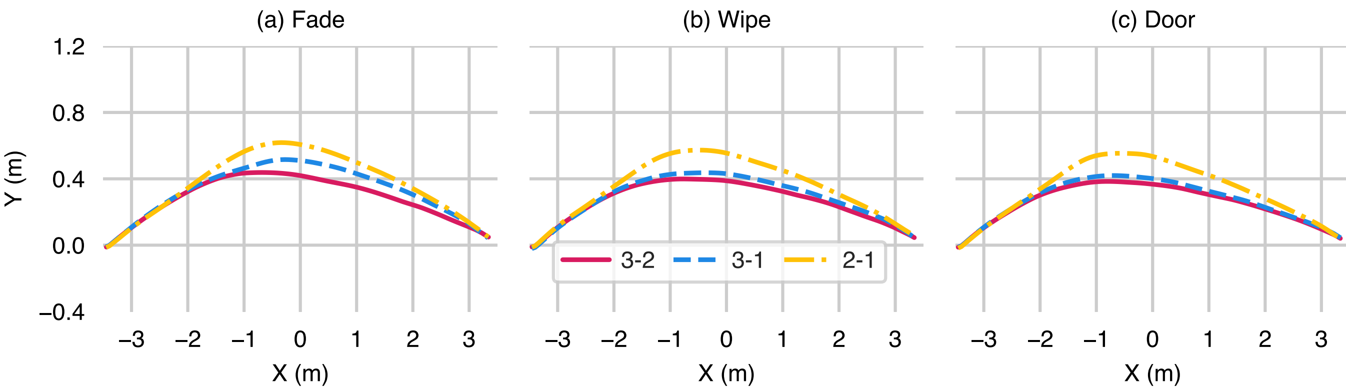

Figure 11: Walking paths by *Effect* × *Timing* in the dataset for the impacts of timings. Lines indicate the average walking paths.

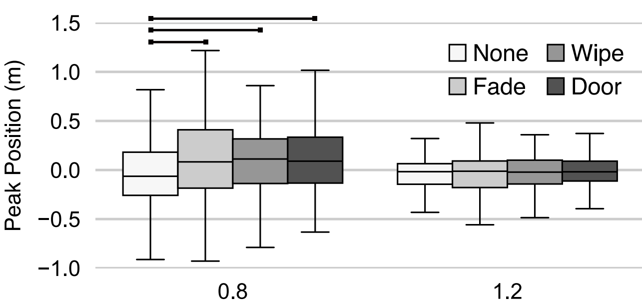

Figure 12: Peak positions for *Effect* × *Width* in the dataset for static virtual obstacles. Significant differences ($p < .05$) between conditions are indicated by horizontal bars.

that, in *Width* 0.8, None resulted in a significantly earlier peak position than Fade ($t = -3.56$, $p < .05$), Wipe ($t = -3.76$, $p < .01$), and Door ($t = -3.54$, $p < .05$).

7.3.3 Walking Path. The walking paths for each *Effect* condition are shown in Fig. 13. The shapes of the walking paths were nearly identical across all *Effect* conditions. However, for *Effect* conditions other than None, some walking paths showed a delayed transition from a straight path to a detour path.

7.4 Subjective Results

7.4.1 Regenbrecht's Presence Questionnaire (RPQ). The RPQ scores are shown in Fig. 14a. The average total presence scores (higher is better) for *Effect* were 4.60 for None, 4.81 for Fade, 4.54 for Wipe, and 4.97 for Door. A Friedman test revealed significant effects for Realness ($\chi^2_{3,N=30} = 8.34$, $p < .05$) and Perceptual Stress ($\chi^2_{3,N=30} = 11.29$, $p < .05$). Post-hoc comparisons indicated that Door had significantly higher Realness scores than Wipe ($Z = -2.67$, $p < .05$).

7.4.2 Collision Anxiety Questionnaire (CAQ). The CAQ scores are shown in Fig. 14b. The average CAQ scores (lower is better) for *Effect* were 1.81 for None, 1.70 for Fade, 1.42 for Wipe, and 1.35 for Door. *Effect* had a significant main effect ($\chi^2_{3,N=30} = 21.37$, $p < .01$). Post-hoc comparisons revealed that Wipe and Door had significantly lower collision anxiety for real-world objects than None ($p < .05$).

7.4.3 Effect Preference. The average preference ranks (lower is better) for *Effect* were 3.00 for None (first: 4, second: 5, third: 8, fourth: 13), 2.53 for Fade (first: 6, second: 9, third: 8, fourth: 7), 2.47 for Wipe (first: 7, second: 9, third: 7, fourth: 7), and 2.00 for Door (first: 13, second: 7, third: 7, fourth: 3).

None was the least preferred condition; most participants favored virtual obstacles with dynamic effects and showed a relatively low preference for static obstacles. By contrast, P58 selected None as their most preferred effect because they disliked the other dynamic

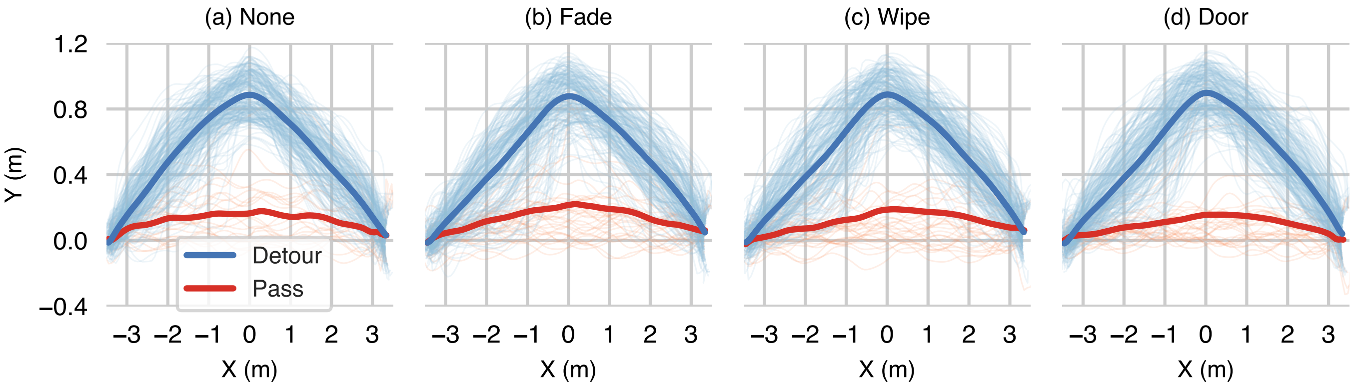

Figure 13: Walking paths by *Effect* in the dataset for static virtual obstacles. Thin blue lines represent individual trials in which the participants detoured around it (Detour), while thin red lines represent trials in which they walked through it (Pass). Bold blue and red lines indicate the average walking paths for the Detour and Pass trials, respectively.

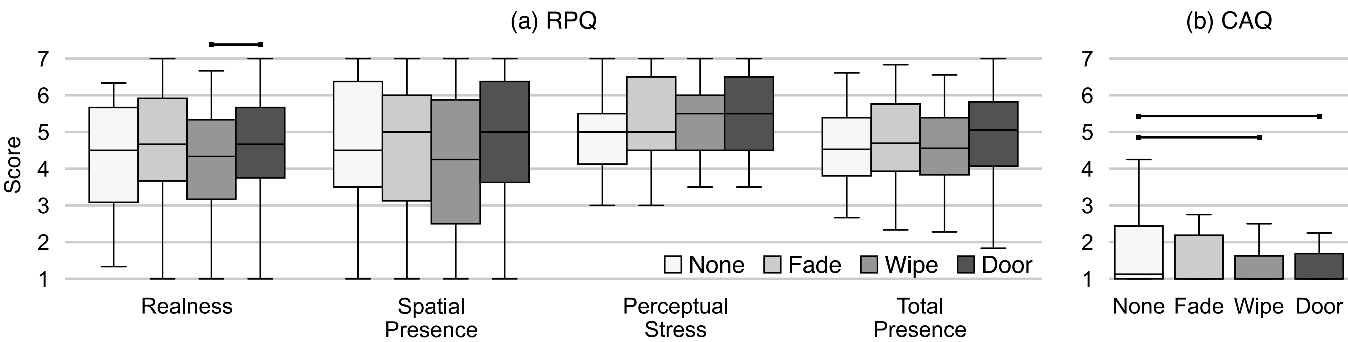

Figure 14: Scores for (a) RPQ and (b) CAQ. Significant differences ($p < .05$) between conditions are indicated by horizontal bars.

effects ("Concerns arose that virtual objects with fading or moving effects might move again or come toward me.").

Fade was the third most preferred effect, with an average ranking comparable to Wipe. Four participants rated Fade as most preferred, noting that making virtual objects transparent was interesting precisely because it is unrealistic. P36 commented, "It was interesting how transparency seemed to phase through walls, something impossible in reality." Conversely, nine participants found semitransparent virtual objects undesirable because they could not sufficiently reduce collision anxiety. P46 stated, "I couldn't shake off the lingering sense of danger—that the virtual object might collide with me—until it disappeared completely."

Wipe was the second most preferred effect, with an average ranking comparable to Fade. Eight participants rated it highly for ease of walking, noting that parts of the virtual obstacle disappeared completely, allowing them to walk into the vacated space. P54 noted, "The effect made it easier to walk because the center of the path opened up early on." P37, P38, and P50 found Wipe interesting because it was unrealistic, while P54 disliked Wipe for the same reason, stating, "Wipe was the least preferred effect because it was one I had rarely seen in the real world."

Door was the most preferred effect. Six participants gave it favorable reviews because, like Wipe, it allowed them to walk toward spaces where virtual obstacles had been removed. Additionally, P41, P52, and P57 preferred Door because the virtual object remained visible without completely disappearing, unlike in Fade or Wipe. P52 commented, "Virtual objects with the Door effect have a long display time, so it's great that I can read them whenever I want to see the content." However, six participants expressed dissatisfaction with Door, noting that, unlike the other dynamic effects, it involved moving virtual obstacles. P33 stated, "I made sure to dodge the virtual object moving like a door at the last possible moment because it was a bit scary."

7.4.4 Timing Preference. The average preference ranks (lower is better) for *Timing* were 1.40 for 3-2 (first: 20, second: 8, third: 2), 1.87 for 3-1 (first: 9, second: 16, third: 5), and 2.73 for 2-1 (first: 1, second: 6, third: 23).

Except for P43, the preferred start timing for the effect was 3 m. Most participants stated that starting the dynamic effect from 2 m was too late to alter their walking path, and that a distance of 3 m or more was required. The preferred completion timing was 2 m rather than 1 m because the participants felt that the effect in 3-1 ended too late. However, because the virtual objects in 3-2 disappeared quickly, six participants preferred 3-1, where the virtual objects remained visible for a longer time. P33 commented, "Since fading out too quickly makes it feel as if it never existed in the first place, we prioritized evaluating the timing for a gradual fade-out."

7.5 Summary 2

[H2a] was partially supported; in addition to the two anticipated walking paths (straight walk-through and detour-then-switch), a third path was observed, in which the participants detoured around virtual obstacles regardless of the dynamic effects. Overall, most walking paths initially followed detour routes. [H2b] was supported; when the start timing of dynamic effects was earlier, the transition from the detour path to the straight path occurred more quickly, and lateral deviation was significantly reduced. [H2c] was supported; at *Timing* 3-1 and 2-1, Fade resulted in a significantly greater lateral deviation than Wipe and Door. [H2d] was partially supported; after the participants experienced dynamic effects, the peak position of the detour path for static virtual obstacles shifted significantly later, suggesting delayed initiation of detour behavior. However, no significant difference was observed in the walk-through rate before versus after exposure to dynamic effects.

8 Discussion

The following are the main findings and answers to the research questions (RQ1–RQ4) of this study:

(1) *The walk-through rate for static virtual obstacles increased as object width grew larger*, while the effects of depth, height, and opacity were not significant. Furthermore, *the walk-through rate varied substantially across individuals.*
(2) Participants who detoured around the static virtual obstacle followed a curved walking path to avoid it, and several participants crouched to avoid the floating virtual obstacles. By contrast, *participants who walked through the static virtual obstacle generally chose a straight path toward the goal.*
(3) When the participants approached virtual obstacles with dynamic effects, *they initially detoured while confirming the obstacles' disappearance and then transitioned to a direct path toward the goal.* The effect in which obstacles gradually became transparent (Fade) delayed this transition more than the effects in which the width of the virtual obstacles gradually decreased (Wipe and Door).
(4) The walk-through rate for static virtual obstacles during the dynamic effect remained largely unchanged compared to before experiencing the dynamic effect. However, the number of walking paths that delayed switching from a straight path to a detour path increased.

8.1 Walk-through and Detour Behaviors for Static Virtual Obstacles

The results from Studies 1 and 2 confirmed that several participants frequently walked through virtual objects even during simple walking tasks. Specifically, 25.9% of participants (15/58) frequently walked through virtual objects, defined as a walk-through rate of 30% or higher. Moreover, 13.8% of participants (8/58) walked through virtual objects in more than 80% of trials across both studies. This indicates that *the presence of users walking through virtual objects must always be assumed.*

Our results showed that the larger the width of the virtual object, the greater the walk-through rate. This is consistent with previous findings [4, 29, 58]. However, our results also indicate that some people may choose to walk through even when the gains are minimal. In Study 1, the participants who walked through virtual obstacles (mean task time = 5.73 s, mean walking distance = 5.83 m) reached the goal 1.04 s faster and with a 0.26 m shorter walking distance than the participants who did not (mean task time = 6.77 s, mean walking distance = 6.09 m). This gain was considerably smaller than those reported in previous studies [29].

Additionally, *the walk-through rate varied considerably across participants, highlighting the importance of personalizing the placement of virtual objects during walking.* Because the walking path tendencies of these users are relatively predictable, presenting each user with a personalized arrangement of virtual objects could help reduce collision risks. For example, virtual objects could be avoided in front of real-world obstacles for users who tend to walk through virtual objects.

By contrast, the walk-through rate differed between Study 1 (29.6%) and Study 2 (11.7%), with the rate in Study 2 being lower. One possible explanation is that it may have been more difficult for participants in Study 2 to walk through the virtual object for the first time. The virtual obstacle in Study 2 was an opaque object 2 m high, which the participants in Study 1 reported as more resistant to passage. Since walking through a virtual object even once can reduce psychological resistance to subsequent passage [29], the semitransparent virtual obstacles used in Study 1 may have facilitated higher walk-through rates.

8.2 Changing Walking Path by Dynamic Effect

In Study 2, dynamic effects increased the number of walking paths that entered the space where the virtual obstacle had been in 70.8% of the trials, showing that they can reduce excessive detours. However, only 19.7% of trials followed a straight path from the start. Most participants initially detoured, confirmed the obstacle's disappearance, and then transitioned to a more direct path toward the goal. This indicates that, *as long as there is uncertainty about whether an obstacle will disappear, users tend to maintain detours until disappearance is confirmed.*

The start timing of dynamic effects influences the walking path. Initiating the dynamic effect at 2 m was too late for the participants to determine whether a virtual obstacle was static or dynamic, resulting in unnecessarily large lateral deviations. Thus, *a 2 m start timing is unsuitable for dynamic effects; 3 m or greater is more appropriate.* However, some studies have reported that detour behavior tends to begin at distances of approximately 4 m [11, 16, 38]. Thus, if the goal is to prevent users from initiating detours around virtual obstacles, a start timing greater than 4 m may be appropriate.

The end timing of dynamic effects also influenced the walking path. At *Timing* 3-1, only Fade produced a wider walking path and greater lateral deviation compared to 3-2. Several participants commented that in Fade, they continued detouring until the virtual obstacle became completely transparent. By contrast, in Wipe and Door, in which the width of the virtual obstacle gradually decreased, the participants walked toward the positions where the obstacle had already disappeared, resulting in smaller lateral deviations compared to Fade. *These results suggest that for dynamic effects such as Fade, in which the object width remains constant, it is advisable to terminate the effect earlier to prevent unnecessary detours.*

In situations in which virtual obstacles with and without dynamic effects coexist, the detour timing for virtual static obstacles may become slightly delayed. In our results, under the Fade, Wipe, and Door conditions, the peak position of the walking path for a static virtual obstacle 0.8 m wide was larger than that in the None condition, indicating delayed avoidance behavior. This effect appears to stem from users' expectations that the obstacle might disappear. That is, *repeated exposure to disappearing obstacles may temporarily recalibrate the distance users consider safe around virtual obstacles*, reflecting a form of perceptual-motor adaptation that shifts detour timing even when no dynamic effect is actually present.

8.3 Use Case for Dynamic Effect

Our CAQ results suggest that dynamic effects can mitigate collision anxiety: Wipe and Door significantly reduced CAQ scores compared to the None condition. Because our tasks were conducted in environments without potential collisions with physical objects, the overall CAQ scores were very low. While these findings are limited, they suggest that dynamic effects may mitigate collision risks.

However, the constant use of dynamic effects is not always appropriate. First, unnatural dynamic effects may negatively impact the perceived realism and immersion. For example, applying Wipe to virtual objects, such as virtual agents, may further degrade user impressions due to mismatches with real-world expectations. Thus, dynamic effects should be chosen to match the object's characteristics and role. Second, some effects may not fully clear the user's path. Although Door was a highly favored effect, rotating a thick virtual object by 90° does not reduce its width to zero. This suggests the need to select effects depending on object geometry. Finally, constantly applying dynamic effects can substantially reduce the functionality of MR applications. Once the user approaches within the activation distance, the virtual object is effectively removed, preventing close interaction with it. This underscores the need for alternative collision avoidance techniques suited to such situations.

8.4 Collision Behavior in Various Contexts

Although most participants detoured around the virtual object in our studies, walk-through behavior may become more prevalent in certain contexts. First, prior experience with walking through virtual objects may increase the likelihood of walk-throughs [29]. The participants who consistently walked through virtual objects reported that they did so because they understood that virtual objects have no physical substance and can be walked through safely. As HMDs become more widespread and people become accustomed to living with virtual information, this perception may become more common, potentially leading to higher walk-through rates.

Second, walk-through rates may also increase in public spaces. In such settings, users are surrounded by bystanders who may not be wearing MR devices or who may be experiencing different MR content. Detouring around seemingly empty space could seem socially odd to others, making detours less socially acceptable. Consequently, users might prefer more direct paths, including walking through virtual objects. Overall, our study examined walking behavior toward virtual objects under controlled conditions in a period when MR is not yet widespread. Future work should investigate collision behavior in more diverse and realistic environments.

8.5 Real-world Applicability

Based on the findings of this study, we outline the implications for the placement of world-anchored virtual objects in MR environments. First, for nonessential virtual objects such as advertisements or UI elements that users do not intend to interact with, applying dynamic effects is advisable. Hiding these objects as the user approaches can reduce both collision risks and anxiety. Furthermore, opaque virtual objects located outside the user's direction of travel (e.g., roadside advertisements) can still pose collision risks by obscuring pedestrians approaching from behind them. Thus, such virtual objects should become semitransparent or disappear when the user approaches.

Second, virtual objects that are intended to interact with users upon approach (e.g., virtual agents) should be positioned carefully to minimize collision risk. Because dynamic effects are often difficult to apply to such objects, it is advisable to avoid placing them in locations with high collision risk, such as crowded environments. When unavoidable, their visual appearance should be adjusted to help mitigate collisions—for example, by increasing their transparency near the user's path, even if they cannot be fully removed. In addition, because users may choose to walk through these objects, it is also preferable not to overlay them directly onto real-world objects.

Finally, virtual objects that must not be passed, such as virtual fences for traffic safety, require designs that strongly discourage users from walking through them. Possible approaches include displaying warning text on the virtual object or presenting warning notifications when the user approaches too closely. However, as long as some users consistently choose to walk through virtual objects, design-based solutions alone have inherent limitations. Therefore, *it may be necessary to establish broader regulatory guidelines that define when virtual objects may or may not be walked through, similar to traffic rules.*

8.6 Limitations

This study has several limitations. First, there are limitations regarding participant demographics and the apparatus used. The participants in our study were primarily undergraduate and graduate students, resulting in a narrow age range. In addition, the results may differ with optical see-through HMDs or higher-performance devices. Second, there was a potential order effect in Study 2. The None condition was always performed first to collect walking paths for static virtual obstacles before the participants experienced dynamic effects. Thus, the statistical results based on the None condition were not confounded by order effects. However, to address RQ4, we deliberately accepted this order effect and conducted the None condition first.

Third, the appearance of the virtual obstacle was restricted. Because we used only one obstacle appearance, the walk-through rate and walking paths may differ from other appearances, such as a virtual humanoid agent. We intentionally limited the appearance to avoid confounding the effects on collision avoidance behavior. It would be valuable to investigate walk-through rates for virtual objects with a variety of appearances and movements. Finally, our study task focused solely on walking under limited conditions. We examined walking paths only for a single virtual obstacle placed along a straight route in an environment without real-world obstacles, and participants were instructed to remain on the roadway. Thus, walk-through paths and walk-through rates remain unknown in scenarios with multiple virtual objects, varying parameters (e.g., road width, length, obstacle placement, or start-goal distance), more complex paths, the freedom to leave the roadway, or the presence of real-world obstacles and pedestrians.

9 Conclusion

This study identified the factors affecting walk-through behavior for static virtual obstacles and compared walking paths for both static virtual obstacles and virtual obstacles with dynamic effects. We found that walk-through rates increased with obstacle width and varied substantially across individuals. Walking paths comprised two types for static obstacles—detours (curved paths) and walk-throughs (straight paths)—and a third type for dynamic obstacles, in which users initially detoured but switched to a direct path once the obstacle began to disappear. Together, these findings clarify how world-anchored MR objects affect walking behavior and offer a foundation for designing safer MR walking experiences in everyday environments.

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