MR Nudge: A Study on Behavior Changes Prompted by Virtual Objects in Mixed Reality

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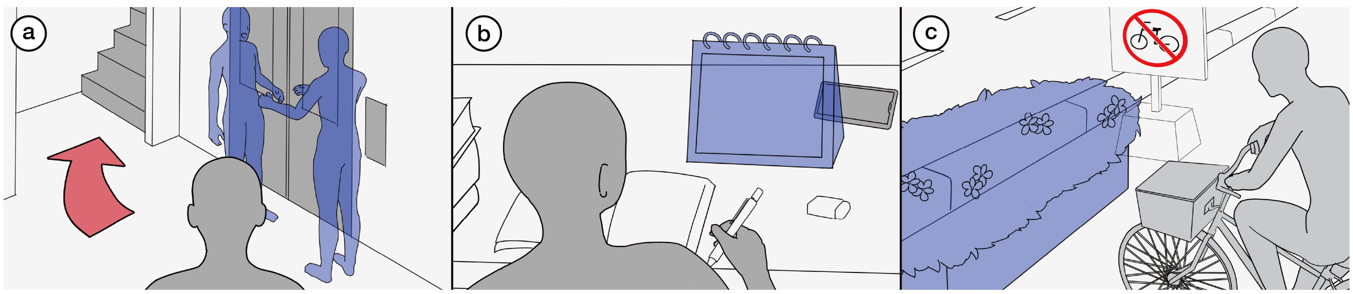

Figure 1: Example use cases of MR Nudge: The blue transparent objects represent MR objects. By leveraging users' collision avoidance behavior toward MR objects, MR Nudge can promote desirable actions, such as (a) encouraging the use of stairs instead of the elevator, (b) discouraging excessive smartphone use, and (c) preventing illegal bicycle parking.

Abstract

In a mixed reality (MR) environment, people tend to maintain a distance from MR objects and avoid contact with them, much as they would with real objects. In this study, we propose MR Nudge, a method that leverages users' collision avoidance behavior toward MR objects to guide them toward more desirable actions. For example, placing a humanoid MR object in front of an elevator could encourage users to avoid the elevator and take the stairs instead. Since MR objects are intangible and can be passed through, this form of guidance remains non-compulsory. In this study, we investigated the effectiveness of MR Nudge in guiding people and also determined whether its guiding force varies based on the appearance of the MR object. The results revealed that MR Nudge successfully guided 54% of the participants, with both its guiding force and the passing rate being influenced by the appearance of the MR object.

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CCS Concepts

• **Human-centered computing → Mixed / augmented reality**.

Keywords

Nudge, Mixed Realty, Behavioral Change

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1 Introduction

In behavioral economics and policymaking, Thaler and Sunstein introduced the concept of *nudging* [43]. This approach aims to influence people's behavior in predictable ways while preserving their freedom of choice, as it does not eliminate other options and remains entirely voluntary. Most nudging methods encourage behavioral change by providing visual information, such as text and images [1]. Furthermore, virtual reality (VR) and mixed reality (MR) technologies have been used to implement nudging methods [7, 12]. These technologies enable the placement of dynamic visual information in space, thereby enabling the designing of nudges that would be challenging or impossible to achieve in the physical world.

In this study, we propose a nudging method called *MR Nudge*, which leverages avoidance behavior toward collisions with MR objects. Due to the high sense of presence provided by virtual environments, people tend to interact with virtual objects as if they were real [13, 40]. Previous research has revealed that people often choose to take detours around virtual objects rather than actively passing through them [21, 38, 39]. Therefore, by strategically placing virtual objects, it is possible to guide users' physical movements along paths where virtual objects are not actually present. For example, placing MR objects in front of an elevator can visually block access and encourage users to take the stairs instead (Figure 1a). Since this guidance does not physically obstruct the elevator, users retain the option of taking the elevator while being subtly encouraged to choose the stairs.

In this study, we investigated whether it is possible to influence user behavior through avoidance actions toward virtual objects in an MR environment as well as how the appearance of virtual objects affects the extent of this influence. We employed a between-participants design study (N = 48) in which participants could take a shortcut by passing through an MR object with either their entire body or part of their body. The MR objects had four distinct appearances that were created by combining two factors: type (human or object) and opacity (100% or 70%). We observed that more than half of the participants chose not to pass through the MR object, thereby resulting in longer travel distances, with a maximum average distance of 92 m. Furthermore, human-type opaque MR objects most frequently triggered avoidance behavior and were significantly more likely to be avoided than human-type semi-transparent MR objects. These findings reveal that MR Nudge has a strong guiding force and that its guiding strength can be adjusted by modifying the appearance of MR objects.

The following are the main contributions of this study:

- The proposal of a nudging method that influences user behavior by encouraging actions to avoid collisions with MR objects.
- The demonstration that MR Nudge has a strong guiding force and can motivate many users to travel longer distances.
- The result that the appearance of the MR object and the user's personality significantly affect the guiding strength of MR Nudge.

2 Related Work and Our Proposed Method

2.1 The Concept of a Nudge

A nudge is defined as *"any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives. To count as a mere nudge, the intervention must be cheap and easy to avoid"* [43]. Since a nudge encourages voluntary choice without eliminating other options, careful consideration must be given to its design. Hansen et al. classified nudges based on whether users can perceive the underlying intentions and mechanisms [16]. Non-transparent nudges, which unconsciously guide people's choices, have been criticized for potentially infringing on individuals' autonomous thinking [17, 28]. Therefore, when designing a guiding principle such as a nudge, it is crucial to evaluate whether the intervention involves coercion and to thoroughly understand the type of behavioral change that the guidance will result in.

With advancements in digital technology, the concept of *digital nudging* has emerged as a derivative of traditional physical nudging. A digital nudge refers to an intervention that is digitally implemented or occurs within a digital environment [5, 44]. Most digital nudges are delivered through visual interfaces on mobile or desktop devices and are commonly applied in domains such as privacy and security [5, 47]. One key distinction between digital nudges and traditional physical nudges is their potential for personalization [8]. Because digital nudges are presented in digital formats, they can be tailored to each individual, thereby enabling the delivery of the most practical nudge for specific users.

2.2 Behavioral Change in VR/MR environments

VR constructs a visually immersive space composed entirely of virtual information, thus enabling users to experience a strong sense of presence within the VR environment. Users may perceive VR scenarios as real, often exhibiting physiological responses similar to those observed in real-world situations [13]. This capability enables the simulation of scenarios that would be impractical or unsafe to experience in real life [9, 14, 22, 34]. For example, exposure therapy methods using VR technology provide users with stimuli that would be difficult to replicate in real-world settings, such as those for treating arachnophobia [9], building resilience to street harassment [22], or aiding smoking cessation [14].

Similar to VR, MR can elicit physiological responses comparable to those experienced in real-life scenarios [20, 40]. MR is a technology that integrates virtual information into real-world environments, thus enabling virtual content to be presented in contexts more closely aligned with everyday life compared to VR. For example, Buljat proposed a nudge to improve environmental awareness by superimposing virtual information regarding marine debris onto the real world [7]. Similarly, Fuchs et al. proposed a nudge to promote healthier food choices by overlaying virtual calorie content information onto real food items [12]. However, these methods primarily focus on superimposing virtual information onto real-world spaces and do not explore nudges that involve user interaction with virtual information.

2.3 Collision Behavior When Encountering VR/MR Objects

When encountering VR or MR objects, people exhibit reactions similar to those they exhibit toward real objects. For example, when a virtual object obstructs their path, individuals tend to detour around it [21, 26, 27, 38, 39]. Additionally, people maintain personal space by maintaining a distance from virtual agents [20, 30]. These findings suggest that people's sense of distance from MR objects mirrors that of real objects, thereby leading to an aversion to actively colliding with MR objects. While many studies have documented evasive behavior toward virtual objects [21, 38, 39], few have investigated physical interference with them. This is likely because VR and MR research primarily aims to create environments that resemble reality, and phenomena such as virtual objects passing through the body are generally avoided. Although certain studies consider scenarios in which VR/MR objects pass through the body [20, 24, 32], these instances typically involve passive behavior rather than voluntary interaction.

To observe voluntary passage through virtual objects in VR environments, Boldt et al. designed a task in which participants could take a shortcut by passing through the inner walls of a VR room [6]. In this research, most participants who received no tactile or audio feedback when passing through the walls chose to pass through them to shorten their paths. Subsequent studies replicated Boldt et al.'s task [10, 31] and also observed participants passing through walls in VR environments. Ogawa et al. found that the realistic appearance of users' avatars reduced the likelihood of passing through walls [31], while Cmentowski et al. confirmed that a realistic wall appearance also reduced the likelihood of passing through the wall [10]. However, since these studies were conducted in VR environments, it remains unclear whether the same phenomenon occurs in MR environments. Furthermore, the objects that participants passed through were limited to wall-like structures, thus raising questions regarding whether this behavior generalizes to other types of objects.

2.4 MR Nudge: Proposed Method

We proposed MR Nudge, a nudging method that leverages human behavior in response to MR objects placed in these spaces. People tend to react to MR objects in 3D environments in a manner that is similar to how they would react to real objects, often taking actions to avoid collisions. By utilizing this behavior, MR Nudge enables guidance that would be challenging to implement using traditional nudging methods.

Examples of MR Nudge are depicted in Figure 1. Figure 1a illustrates a nudge where virtual persons are talking in front of an elevator, thereby prompting the user to take the stairs to avoid disturbing them. This nudge encourages users to choose an action with a higher exercise load. Figure 1b illustrates a nudge in which an MR object is placed in front of a smartphone and, thus, causing the user to hesitate before penetrating the MR object with their hand, thereby limiting excessive smartphone use. Figure 1c demonstrates a nudge that discourages people from parking their bicycles by placing a virtual flowerbed in a no-parking zone, thereby making users reluctant to crash their bicycles into the flowerbed. All these nudges leverage the aversion to passing through MR objects. Additionally, these nudges do not restrict users from selecting other options, as it is possible to pass through MR objects.

With nudges that use MR objects, it is possible to design scenario-specific nudges by modifying the object's appearance, as demonstrated in our examples. However, it remains unclear how the appearance of an MR object affects the guiding strength of an MR Nudge. Previous research in VR environments has revealed that factors such as feedback during object contact [6], the appearance of the user's avatar [31], and the realism of walls [10] influence the passing rate. However, these studies primarily focus on VR objects that have the appearance of walls, leaving the effects of other appearances underexplored. Therefore, we investigate whether the appearance of MR objects influences the pass rate in an MR environment. Additionally, we examine whether the MR Nudge satisfies the criteria of a nudge—that is, whether it exhibits a guiding force while preserving the availability of other options.

3 Study

We conducted a user study to evaluate the guiding force of MR Nudge. The study task required participants to press buttons in a specific order in virtual rooms, where the inner walls were composed of MR objects, as inspired by tasks in previous studies [6, 31]. Participants could take a shortcut by passing through the inner walls. Through this task, we investigated (1) the extent of the guiding force exhibited by MR Nudge, (2) whether the guiding force varies based on the appearance of the MR object, and (3) whether the guiding force of MR Nudge differs among individuals.

3.1 Apparatus

We used the HTC Vive XR Elite HMD and two HTC Vive XR Elite controllers. The HMD was operated as a video see-through MR HMD. According to the HMD's specifications, the visible field of view is 110°. The application used in the study was developed using Unity (Version 2022.3.9f1).

3.2 Participants

Forty-eight participants (10 female, 37 male, 1 other; mean age = 23.3 years, SD = 2.8 years; ID: P1–P48) from a local Japanese university were recruited for the study. Of the 48 participants, 42 had no prior experience with VR or MR, one (P44) had used VR or MR once, and five (P17, P19, P25, P27, and P28) had over three months of VR or MR experience. Participants wearing glasses removed them and adjusted the diopter dial on the HMD. Each participant received a US$13 compensation, and each study took approximately 30 minutes. The local ethics committee approved the study, and the study was conducted in a room at the local university.

3.3 Questionnaire

Before being assigned the study task, participants completed the Virtual Reality Sickness Questionnaire (VRSQ) [25] and the Big Five Inventory-2-Extra Short (BFI-2-XS) [42]. The VRSQ is designed to evaluate VR sickness and selects relevant questions from the Simulator Sickness Questionnaire (SSQ) [23], which assesses motion sickness. Each response was scored on a four-point Likert scale. This questionnaire has also been used in MR environments [2]. To assess whether participants experienced VR sickness, we compared VRSQ results collected before and after the study. The BFI-2-XS is an abbreviated version of the Big Five Inventory-2 (BFI-2) [41], which is designed to assess participants' personalities. Each response was scored on a five-point Likert scale. The BFI-2-XS was adopted to investigate the correlation between participants' personalities and the rate of their passing through MR objects. While the BFI-2 consists of 60 questions, the BFI-2-XS contains 15. In this study, the BFI-2-XS was used to reduce participant burden. Although the BFI-2-XS effectively evaluates the Big Five personality domains (extraversion, agreeableness, conscientiousness, negative emotionality, and open-mindedness), it is difficult to assess more specific facet traits [42]. Therefore, only the Big Five personality domains were evaluated.

After the study task, participants completed the VRSQ, Regenbrecht's presence questionnaire [35], and our original questionnaire. Regenbrecht's presence questionnaire assesses the sense of presence in MR objects (realness, spatial presence, perceptual stress, and total presence) and was adopted based on the assumption that MR object presence could influence the passing rate. Several questions from the original Regenbrecht's presence questionnaire were modified to fit our study (Table 1). Each response was scored on a seven-point Likert scale. The original questionnaire collected feedback on passing through MR objects and the perception of their guidance (Table 2). Each response was scored on a seven-point Likert scale (1: strongly disagree, 7: strongly agree). All questionnaire items were accompanied by a Japanese translation. The questions in the BFI-2-XS were adapted from the Japanese version of the BFI-2 [46].

3.4 Design

We used a between-participants design. There are two independent variables (Figure 2):

- *Type*: Human, Object
- *Opacity*: 100%, 70%

Type refers to the appearance of the MR object that forms the inner wall of the room. Based on findings that the user's proximity to an MR object varies depending on its appearance [20, 38], we adopted *Type* to investigate whether the appearance of the MR object influences the probability of an individual passing through it. The *Human* type is represented by a human avatar in the form of a realistic full-body 3D model. The avatar remains in an upright standing position and occasionally sways slightly from side to side. The *Object* type is a gray rectangular structure with a poster attached to it. The poster—generated using MidJourney [1], an image generation tool—is displayed on both the front and back of the object. The height of the *Human* was set to 166.65 cm, based on the global average human height [15], while its body width and depth were set to 45 cm and 20 cm, respectively. Similarly, the dimensions of the *Object* were set to 166.65 cm × 45 cm × 20 cm. *Opacity* refers to the transparency level of the MR object that composes the inner wall. Based on findings that users are more likely to pass through a semi-transparent wall-appearance object than an opaque wall-appearance object in VR environments [10], we adopted *Opacity* to examine its effect on the probability of passing through.

Further, we defined abbreviations for each *Type* × *Opacity* condition (Figure 2) in the following manner: *Human* × 100% is denoted as **H-100**, *Human* × 70% as **H-70**, *Object* × 100% as **O-100**, and *Object* × 70% as **O-70**. The participants were assigned conditions based on the remainder of their ID when divided by four: H-100 when the remainder was 1, H-70 when it was 2, O-100 when it was 3, and O-70 when it was 0.

3.5 Experimental Environment

The study task involved pressing buttons scattered around a virtual room in a specified order. After pressing all the buttons, participants were instructed to move toward the goal. This task was based on those utilized by Boldt et al. [6] and Ogawa et al. [31]. The virtual room was a 4 m × 4 m space with inner walls composed of MR objects. The outer wall was a 1 m-high blue wall with decreasing opacity toward the top. The inner walls were composed of MR objects arranged in a straight line, with a gap of 14.2 cm among them. This gap corresponds to the distance required to arrange seven MR objects at equal intervals such that they span the entire width of the virtual room. The button measured 10 cm × 10 cm × 3 cm and was positioned at the top of a rectangular box measuring 13 cm × 13 cm × 100 cm.

The participants were provided with four virtual rooms (Room 1, Room 2, Room 3, and Room 4), each offering different incentives to pass through the walls (Figure 3). Rooms 1–3 were designed in such a manner that higher room numbers corresponded to greater travel distances required to complete the task. By passing through the inner wall, participants could significantly reduce the travel distance to complete the task. To examine the trade-off between the incentive to pass through the inner wall and the discomfort it caused, we analyzed participants' movements in Rooms 1–3. Room 4 was designed to require participants to pass through the inner wall to complete the task. The aim of this setup was to compel participants who avoided passing through the inner wall in Rooms 1–3 to do so.

3.5.1 Room 1. This room was designed to encourage participants to put their hands through the inner wall. The positions of the buttons and the inner wall in this room were identical to those in Room 1 of Ogawa et al.'s study [31] (Figure 3a). Three pairs of consecutive buttons were positioned on opposite sides of the inner wall. By reaching through the inner wall, participants could easily press the paired buttons without needing to walk around. There were six buttons in Room 1.

3.5.2 Room 2. This room was designed to provide an incentive level that acted as an intermediary between Rooms 1 and 3 (Figure 3b). Four pairs of buttons were placed across three different locations, thus allowing participants to take a shortcut by passing through the inner wall. There were 12 buttons in Room 2.

3.5.3 Room 3. This room was designed to provide a greater incentive to pass through the inner wall than Rooms 1 and 2. The positions of the buttons and the inner wall in this room were identical to those in Room 2 of Ogawa et al.'s study [31] (Figure 3c). Ten buttons were arranged side-by-side along the inner wall, thus enabling participants to take a significant shortcut by passing through the inner wall. Completing the task within the time limit (180 s) without passing through the inner wall required participants to walk quickly. There were 20 buttons in Room 3.

3.5.4 Room 4. This room was designed to require participants to pass through the inner walls to complete the task. The inner walls completely divided the space in this room, thus making it impossible to complete the task without passing through them (Figure 3d). There were three buttons in Room 4, and participants needed to pass through the inner walls three times.

3.6 Procedure and Task

Upon arrival at the designated room in the local university, participants read and signed an informed consent form. Thereafter, they completed a pre-questionnaire that included personal information, such as name and gender, as well as the VRSQ. After completing the questionnaires, the participants proceeded to the experiment room. In the experiment room, the participants were provided an

[1] https://www.midjourney.com/home

Table 1: Items from Regenbrecht's presence questionnaire used in our study. Q1–Q3: Realness, Q4–Q5: Spatial Presence, Q6–Q7: Perceptual Stress.

#	Item	1	7
1	Was watching the virtual objects just as natural as watching the real world?	completely unnatural	completely natural
2	Did you have the impression that the virtual objects belonged to the floor, or did they seem separate from it?	belonged to the floor	completely separate from the floor
3	Did you have the impression that you could have touched the virtual objects?	strongly disagree	strongly agree
4	Did the virtual objects appear to be (visualized) on a screen, or did you have the impression that they were located in space?	appear to be on a screen	clearly located in space
5	Did you have the impression of seeing the virtual objects as merely flat images or as three-dimensional objects?	flat images	fully three-dimensional objects
6	Did you pay attention at all to the differences between real and virtual objects?	did not notice at all	fully aware of the difference
7	Did you have to make an effort to recognize the virtual objects as being three-dimensional?	strongly disagree	strongly agree

Table 2: Items from the original questionnaire. 1: strongly disagree, 7: strongly agree.

#	Item
1	I felt no resistance when passing through the virtual object.
2	I felt discomfort when passing through the virtual object.
3	Passing through the virtual object felt the same as passing through empty space.
4	I felt that the virtual object restricted my direction of movement.
5	I was able to freely decide my direction of movement.
6	I felt that the presence of the virtual object was obstructive.

(a) Human × 100% (H-100) (b) Human × 70% (H-70) (c) Object × 100% (O-100) (d) Object × 70% (O-70)

Figure 2: Images of MR objects that formed the inner walls for each combination of *Type* and *Opacity*.

overview of the study and a detailed explanation of the task. They were informed that they were not allowed to extend their hands or bodies outside the virtual room, that each task had to be completed within 180 s per virtual room, and that asking questions during the study was not permitted. After these instructions, the diopter and interpupillary distance of the HMD were adjusted, and the HMD was fitted. The participants held controllers in both hands and completed a practice task to familiarize themselves with the procedure. The practice task involved pressing a button and moving to the goal. During the practice task, the participants were unaware of the existence of the inner wall and could not see it. After completing the practice task, the experimenter exited the experiment room, and the participants proceeded to the main study task.

At the beginning of the study task, the blue outer walls of the virtual room were displayed. A blue circle indicating the start position was also displayed on the floor, along with a box labeled "Start" positioned in front of the circle. The participants were required to move into the blue circle and select the box using ray-casting with their holding controller. The purpose of this procedure was to adjust the starting position of the participants for each virtual room, and it is always performed before each trial for each virtual room. After selecting the box, Room 1 was displayed. As feedforward, a green semi-transparent pillar was displayed to indicate the position of the button to be pressed. The pillar had a height of 2.4 m, thus allowing participants to see it through the inner walls. Additionally, a timer was displayed on the controller held in the participants' left hand, which enabled them to check the remaining time. The participants pressed the buttons by placing their hands on them.

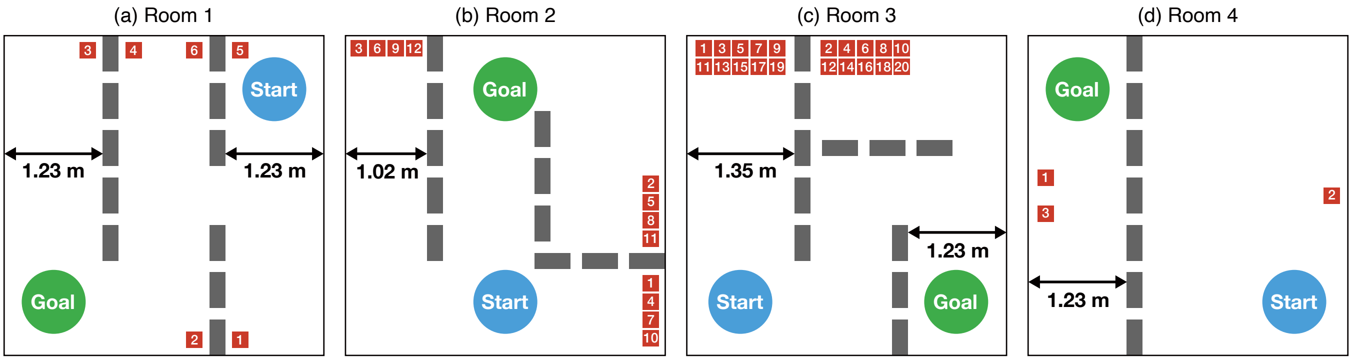

Figure 3: Layout of Rooms 1–4: The gray rectangles indicate MR objects forming the inner walls, while the red squares with white numbers represent buttons. The numbers on the buttons indicate the order in which they should be pressed.

When a button was pressed, the pillar feedforward for the button disappeared and a new pillar feedforward appeared above the next button to be pressed. Once all the buttons in the virtual room had been pressed, the pillar feedforward disappeared and a green cylinder was drawn on the floor to indicate the goal position. When participants reached the green cylinder, the objects in the virtual room (buttons and inner walls) disappeared, and a blue circle indicating the starting point and a box labeled "Next" appeared. The participants were required to move into the blue circle and select the box. Thereafter, Room 2 was displayed. This procedure was repeated until all trials across the virtual rooms were completed, with participants experiencing the rooms in the following order: Room 1, Room 2, Room 3, and Room 4. For Room 4, if the participant did not pass through the wall within the remaining 30 s (150 s had elapsed), the experimenter verbally instructed the participant to pass through the wall.

After completing the study task, participants returned to the room in which they had completed the pre-questionnaire, and then answered a post-questionnaire. The post-questionnaire included the VRSQ, Regenbrecht's presence questionnaire, the original questionnaire, and a survey regarding participants' impressions of the study.

4 Results

A Wilcoxon signed-rank test was conducted for each *Type* × *Opacity* condition to compare VRSQ questionnaire results before and after the study task. We found no significant differences (H-100: $Z = 0.18, p = 0.91$; H-70: $Z = -0.16, p = 0.89$; O-100: $Z = -0.53, p = 0.65$; O-70: $Z = -0.34, p = 0.81$), which indicated that the study task might not induce VR sickness.

4.1 Behavioral Data

For each virtual room (Rooms 1–3), we calculated the travel distance, travel time, and wall-passing rate. The travel distance refers to the total distance traveled from the beginning of the trial (the moment the virtual room was displayed to participants) to the goal for each room. The travel time refers to the total duration from the beginning of the trial to the goal for each room. The wall-passing rate represents the percentage of participants who passed through the inner wall with either their hands or bodies. Participants who did not pass through at all were classified as not having passed through (Not Passed), while those who passed through the inner wall at least once were classified as having passed through (Passed).

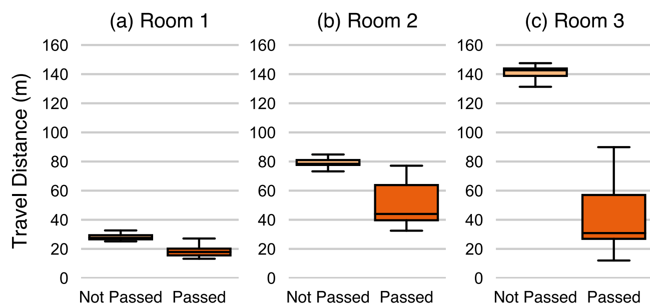

Figure 4: Travel distance in Rooms 1–3.

Further, we conducted a binary logistic regression with *Type* and *Opacity* as independent variables and the wall-passing rate as the dependent variable. Post-hoc analyses were performed using pairwise comparisons of estimated marginal means (EMM).

4.1.1 Room 1. The travel distance and time were 28.14 m and 43.69 s, respectively, for participants who did not pass through the inner wall and 18.67 m and 30.74 s, respectively, for those who did (Figure 4a and 5a, respectively). In other words, participants who did not pass through the inner wall walked an average of 9.47 m farther and took 12.95 s longer.

The wall-passing rates for each *Type* × *Opacity* condition (H-100, H-70, O-100, and O-70) were 16.7% (2/12), 41.7% (5/12), 16.7% (2/12), and 25.0% (3/12), respectively (Figure 6a). In the H-100 condition, one participant penetrated their hand into the inner wall but not their entire body. Overall, 36 participants did not pass through the MR objects (Figure 7a), while 12 participants did (Figure 7b).

A binary logistic regression revealed no significant differences (*Type*: $Z = -0.65, p = 0.52$; *Opacity*: $Z = -1.31, p = 0.19$; *Type* × *Opacity*: $Z = 0.54, p = 0.59$).

4.1.2 Room 2. The travel distance and time were 79.69 m and 96.65 s, respectively, for participants who did not pass through the inner wall and 50.60 m and 63.44 s, respectively, for those who did (Figure 4b and 5b, respectively). In other words, participants who did not

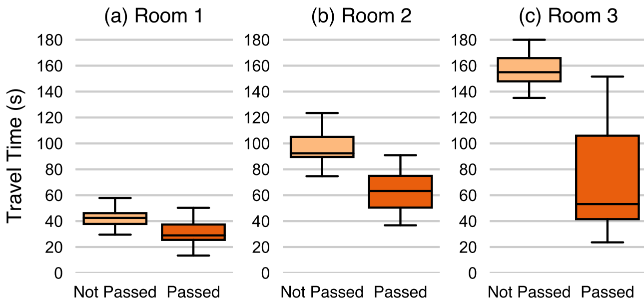

Figure 5: Travel time in Rooms 1–3.

pass through the inner wall walked an average of 29.09 m farther and took 33.21 s longer.

The wall-passing rates for each *Type* × *Opacity* condition (H-100, H-70, O-100, and O-70) were 16.7% (2/12), 58.3% (7/12), 41.7% (5/12), and 25.0% (3/12), respectively (Figure 6b). In both the H-100 and O-100 conditions, one participant penetrated their hand into the inner wall but not their entire body. The routes taken by participants who passed through the inner wall can be classified into two categories: 11 participants passed through the inner walls at only two locations where the incentive for taking the shortcut was high (Figure 7d), while six participants completely ignored the inner wall and took the shortest route (Figure 7e). Overall, 31 participants did not pass through the MR objects (Figure 7c), while 17 participants did (Figure 7d, e).

A binary logistic regression revealed that *Type* ($Z = -2.08, p < 0.05$), *Opacity* ($Z = -2.00, p < 0.05$), and *Type* × *Opacity* ($Z = 2.06, p < 0.05$) had significant differences. Post-hoc tests revealed significant differences between H-100 and H-70 ($Z = -2.00, p < 0.05$).

4.1.3 Room 3. The travel distance and time were 142.90 m and 156.91 s, respectively, for participants who did not pass through the inner wall and 50.66 m and 71.95 s, respectively, for those who did (Figure 4c and 5c, respectively). In other words, participants who did not pass through the inner wall walked an average of 92.24 m farther and took 84.96 s longer.

The wall-passing rates for each *Type* × *Opacity* condition (H-100, H-70, O-100, and O-70) were 25.0% (3/12), 58.3% (7/12), 50.0% (6/12), and 41.7% (5/12), respectively (Figure 6c). In both the H-70 and O-70 conditions, one participant penetrated their hand into the inner wall but not their entire body. Overall, 27 participants did not pass through the MR objects (Figure 7f), while 21 participants did (Figure 7g).

A binary logistic regression revealed no significant differences (*Type*: $Z = -1.40, p = 0.14$; *Opacity*: $Z = -1.62, p = 0.11$; *Type* × *Opacity*: $Z = 1.46, p = 0.14$).

4.1.4 Room 4. Room 4 was designed to require participants to pass through the inner wall to complete the task, thereby ensuring that all participants experienced passing through it (Figure 7h). Only one participant (P8, in the O-70 condition) did not pass through the inner wall in Room 4 until the final 30 s (Figure 7i). This participant was verbally encouraged to pass through the wall.

Figure 8 visualizes the velocity at which participants first passed through the inner wall of Room 4. The velocity was calculated for each frame and averaged over 0.1-s intervals for each participant. The moment of wall collision was set to 0 s. In all conditions except for the H-100 condition, velocity increased upon collision with the inner wall. This result is consistent with the findings of Ogawa et al. [31]. Conversely, in the H-100 condition, velocity decreased upon collision with the inner wall. This suggests that participants experienced a different sensation under the H-100 condition than the others. P13 (H-100) commented, *"I felt slightly guilty, as if I were actually passing through real people."* Similarly, P17 (H-100) remarked, *"It was interesting to become aware of the virtual objects' faces as I walked through them and tried to act in a manner that would avoid getting in their way."* This comment suggests that participants perceived the human-like MR objects as real people, thus potentially influencing the velocity at which they passed through them.

4.2 Subjective Data

For each questionnaire (BFI-2-XS, Regenbrecht's Presence Questionnaire, and the original questionnaire), we applied a non-parametric aligned rank transformation method [18, 37, 45], as Likert scales are considered ordinal. Thereafter, a two-way factorial ANOVA was conducted with *Type* and *Opacity* as factors. Post-hoc analyses among factors were performed using ART-C [11] with Holm correction [19]. Additionally, to investigate the correlation between questionnaire results and participants' wall-passing behavior, we conducted binary logistic regression with the wall-passing rate as the dependent variable for each virtual room (Rooms 1–3).

4.2.1 Big Five Inventory-2-Extra Short (BFI-2-XS). A two-way ANOVA revealed a trend toward a main effect of *Type* on negative emotionality ($F_{1,44} = 3.09, p < 0.1, \eta_p^2 = 0.07$), with mean scores of 2.81 for the *Human* condition and 3.34 for the *Object* condition. This indicates a bias toward participants exhibiting more negative emotionality in the *Human* condition. Binary logistic regression indicated a significant effect of conscientiousness in Room 3 ($Z = 1.95, p < .05$), and open-mindedness revealed a significant trend in Room 2 ($Z = -1.97, p < 0.1$). Figure 9 presents the results of BFI-2-XS.

4.2.2 Regenbrecht's Presence Questionnaire. A two-way ANOVA indicated a trend toward an interaction effect of *Type* × *Opacity* on spatial presence measures ($F_{1,44} = 3.29, p < 0.1, \eta_p^2 = 0.07$). However, post-hoc analyses revealed no significant differences; binary logistic regression also revealed no significant differences. Figure 10 presents the result of Regenbrecht's presence questionnaire.

4.2.3 Original Questionnaire. A two-way ANOVA revealed significant effects of *Type* on Q2 ($F_{1,44} = 7.78, p < 0.01, \eta_p^2 = 0.15$) and Q5 ($F_{1,44} = 6.90, p < 0.05, \eta_p^2 = 0.14$). Binary logistic regression revealed significant effects in each virtual room. In Room 1, a significant trend was observed for Q2 ($Z = -1.79, p < 0.1$), while significant effects were observed for Q3 ($Z = 1.98, p < 0.05$), Q4 ($Z = -2.63, p < 0.01$), and Q5 ($Z = 2.40, p < 0.01$). In Room 2, significant effects were observed for Q4 ($Z = -2.32, p < 0.05$) and Q5 ($Z = 2.56, p < 0.05$). In Room 3, a significant trend was observed for Q4 ($Z = -1.88, p < 0.1$), while significant effects were observed

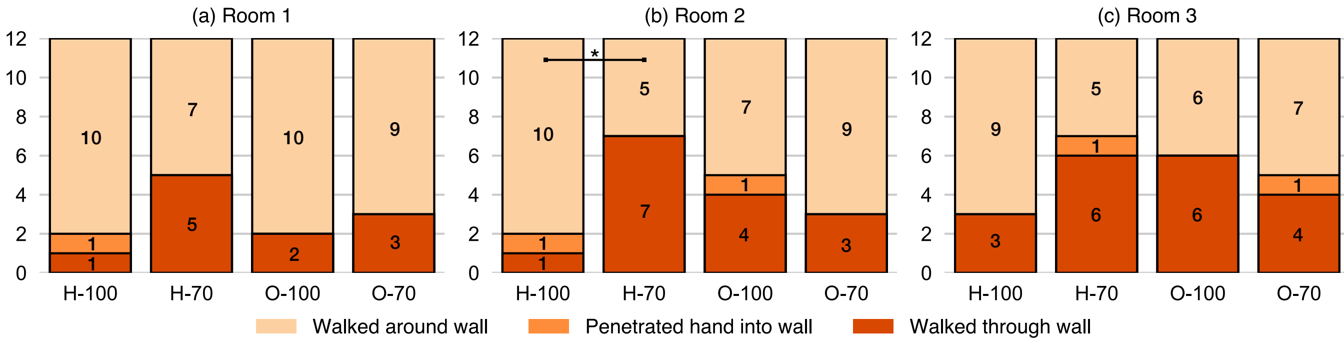

Figure 6: Wall-passing rate for Rooms 1–3. Statistical significance: $^{*}p < 0.05$.

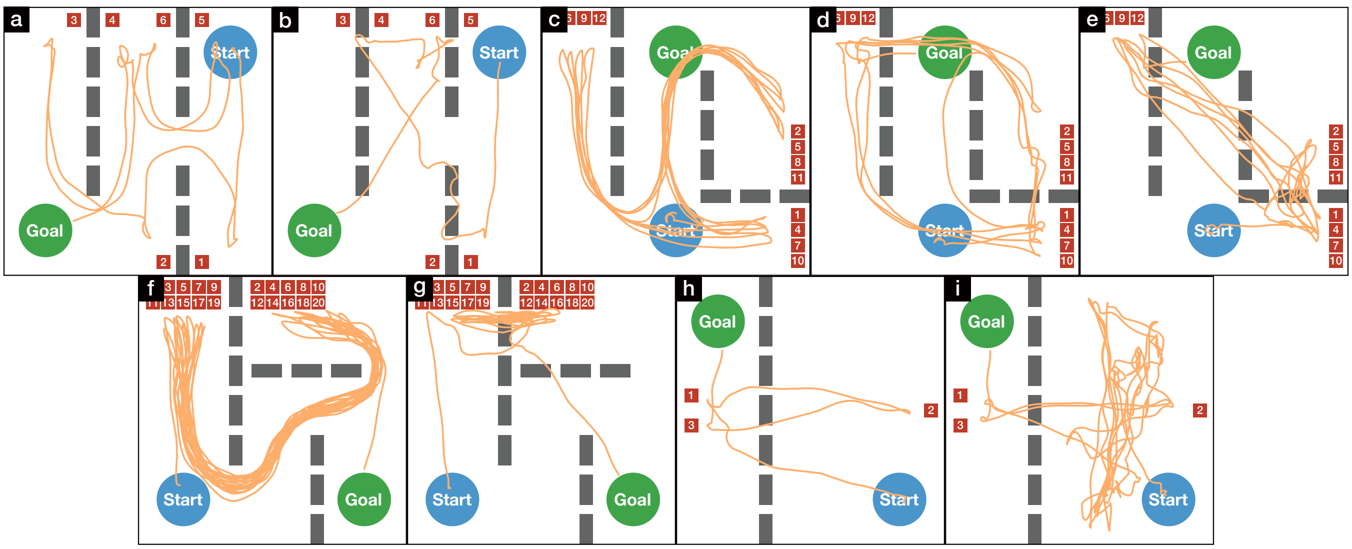

Figure 7: Trajectories of participants' head movements in each virtual room. Each trajectory represents the movement path of a typical participant. (a, b) Room 1, (c, d, e) Room 2, (f, g) Room 3, and (h, i) Room 4.

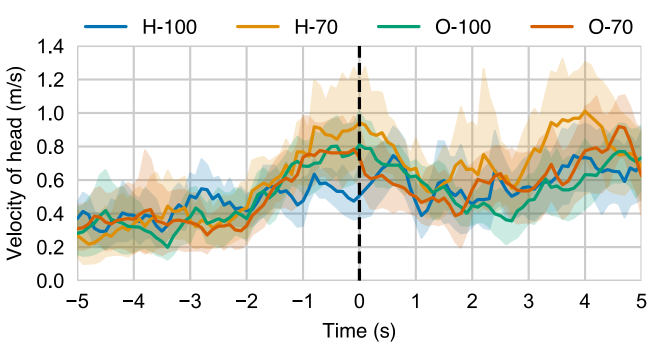

Figure 8: The velocity that passed through the inner wall per *Type* × *Opacity*. Translucent bands indicate a 95% confidence interval.

for Q5 ($Z = 2.39, p < 0.05$) and Q6 ($Z = 2.40, p < 0.05$). Figure 11 presents the result of the original questionnaire.

4.2.4 Comment on Passing Through the Inner Wall. The participants reported hesitation when passing through the inner wall. P4 (O-70) commented, *"If I have to go through the inner wall, I will, but I still couldn't help but hesitate."* Participants who experienced the *Human* condition commented that they avoided passing through the inner wall because it was composed of Human-type MR objects. P30 (H-70) remarked, *"Because the virtual object was human-shaped, I felt a stronger sense of wanting to avoid bumping into it."* In contrast, participants who experienced the *Object* condition did not comment on the properties of the MR objects but only mentioned avoiding collisions with them. Additionally, participants described unique sensations when passing through the wall. P5 (H-100) remarked, *"It felt like a real mannequin was passing through my body,"* while P36 (O-70) stated, *"I felt like I had just stepped into a swimming pool."*

A few participants also reported actively attempting to pass through gaps in the inner wall. P25 (H-100) noted, *"The discomfort decreased by moving in a way that passed between virtual objects."* Similarly, P34 (H-70) shared, *"Even though I knew they weren't actually there, I tried to walk between the humanoid virtual objects*

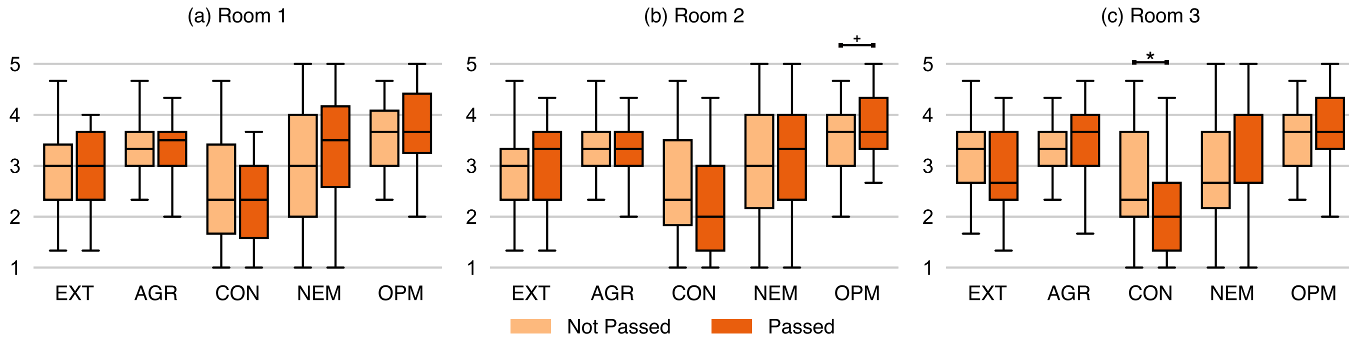

Figure 9: Results of BFI-2-XS for Rooms 1–3. EXT, AGR, CON, NEM, and OPM represent extraversion, agreeableness, conscientiousness, negative emotionality, and open-mindedness. Statistical significance: $^{+}p < 0.1$, $^{*}p < 0.05$.

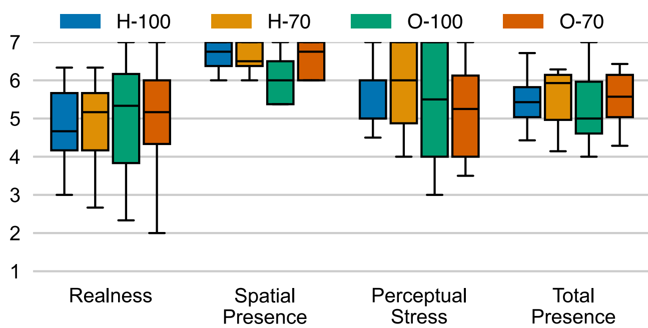

Figure 10: Results of Regenbrecht's presence questionnaire for *Type* × *Opacity*.

as much as possible." Additionally, P13 and P46 reported feeling less resistance when passing behind the human-type MR objects compared to passing in front of them. P13 (H-100) commented, *"I think I felt less guilty when passing through the virtual object from behind. Maybe it was because I couldn't see its face."* In contrast, five participants (P18, P31, P35, P44, and P46) reported that the resistance felt when passing through the inner wall decreased with repeated exposure. P31 (O-100) commented, *"When I first passed through the virtual object, I felt some resistance, but after I got used to it, it didn't bother me anymore."*

5 Discussion

5.1 Summary of Results

The following are the main findings of this study:

1) The higher the incentive to pass through the MR object—resulting in reduced travel distance and time—the more participants opted to do so (Room 1: 12/48, Room 2: 17/48, Room 3: 21/48). In Room 3, the 27 participants who did not pass through the MR object traveled an average of 92 m further and took 85 s longer than the 21 participants who did.

2) In Room 2, participants passed through the opaque human-type MR object (H-100) significantly less frequently than the translucent human-type MR object (H-70). The results from the original questionnaire indicated that participants experienced more discomfort when passing through the human-type MR object than the object-type MR object. Additionally, participants reported that it was easier to determine the direction of movement in a space with human-type MR objects than in a space with object-type MR objects.

3) The results from the BFI-2-XS revealed that participants with high open-mindedness in Room 2 and low conscientiousness in Room 3 were significantly more likely to pass through the MR objects. The results from Regenbrecht's presence questionnaire indicated that none of the MR objects showed significant differences in this regard. Moreover, the measures of presence for the MR object did not significantly influence participants' decisions to pass through the MR object. Further, the findings from the original questionnaire suggested that participants who passed through the MR object felt they could freely choose their direction of movement, even though the MR object restricted the direction of movement in Rooms 1–3.

5.2 The Nudging Force of the MR Object

This study's results indicated that, consistent with previous studies conducted in VR environments [6, 10, 31], virtual objects in an MR environment significantly influence participants' movement paths and encourage them to take detours. In this study, 54% (26 out of 48) of participants opted not to pass through the MR objects in Rooms 1–3. Additionally, in Room 3, 58% (28 out of 48) of participants traveled an additional 92 m on average and took 85 s longer to complete the task, thereby demonstrating the influence of the MR Nudge on their behavior. These findings suggest that MR Nudge could serve as an effective method for guiding movement and altering user behavior.

In contrast, the MR Nudge did not guide all participants equally—a few were strongly influenced, while others showed no response to the guidance. In Room 1, which featured the shortest travel distance, six participants passed through the MR object within 10 s of the start of the trial, thus revealing that they were not influenced by the MR Nudge at all. This demonstrates that MR Nudge is not an entirely coercive method. Conversely, in Room 4, one participant hesitated for 150 s before eventually passing through the MR objects; this suggested that, for this individual, the MR Nudge functioned as forced guidance. These findings indicate that MR Nudge

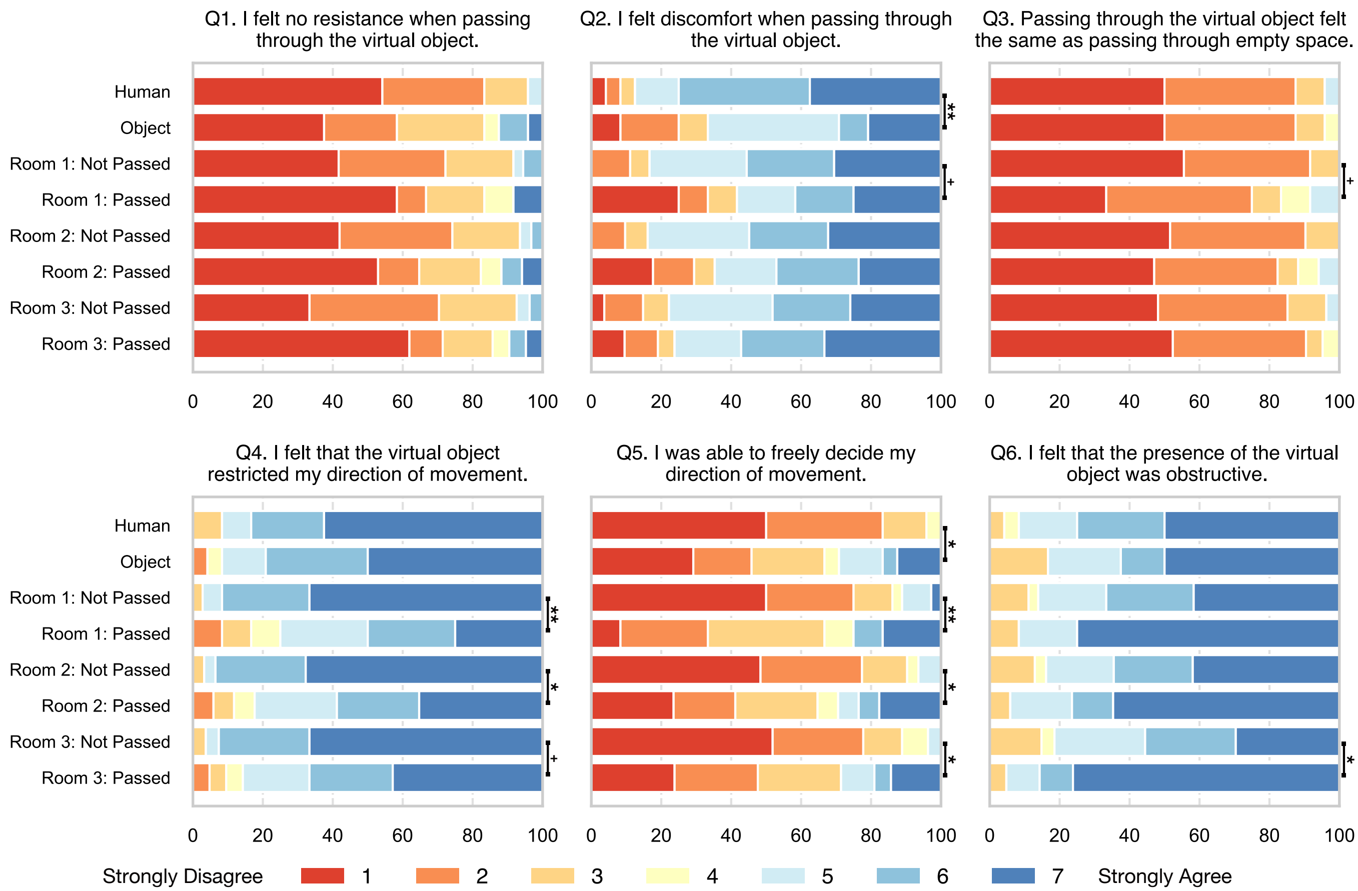

Figure 11: Results of the original questionnaire. The X-axis is a percentage. Statistical significance: $^{+}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$.

may not be suitable for everyone and that its guiding strength may need to be adjusted to accommodate individual differences.

Furthermore, the results of the BFI-2-XS revealed that the rate of passing through MR objects varied depending on the user's personality. In Room 2, participants who passed through the virtual object tended to have significantly higher open-mindedness than those who did not, while in Room 3, they exhibited significantly lower conscientiousness. These results suggest that high curiosity and low orderliness may lead to an individual's willingness to pass through an MR object. Thus, a user's personality may be an important factor in estimating their likelihood of passing through an MR object.

5.3 Effect of MR Object Appearance

The results of this study revealed that the appearance of MR objects influenced both the wall-passing rate and participants' perceptions of the passage. In this study, the H-100 condition exhibited the lowest wall-passing rate, with participants reporting significantly greater discomfort when passing through human-type MR objects compared to object-type MR objects. This can be attributed to participants perceiving human-type MR objects as resembling real people, thus making the awkwardness of walking through them a deterrent to passage. In contrast, the presence of the MR objects did not significantly affect the wall-passing rate. Previous studies have revealed that increasing the transparency of objects reduces users' sense of presence and increases the passing rate [10]. However, in this study, increasing the transparency of MR objects did not significantly alter their sense of presence. Therefore, further investigation is needed to explore the relationship between presence and passage rate, such as by using MR objects with a lower sense of presence.

Further, in Room 2, the H-100 condition exhibited a significantly lower passing rate than the H-70 condition, thereby suggesting that the passing rate of human-type MR objects may decrease as their transparency increases. In contrast, no significant differences were observed in the *Object* condition, which indicated that rectangular cuboid-shaped MR objects may be unaffected by opacity. The increased passing rate for human-type MR objects may be attributed to a reduction in their social presence as transparency increases. For example, Benjamin et al. confirmed that increasing the transparency of humanoid agents displayed on AR screens diminishes their social presence [4]. Consequently, translucent human-type MR objects are perceived more as inanimate objects than as humans, thus reducing the sense of resistance to passing through them.

Overall, these results demonstrate that MR Nudge can adjust the extent of the guiding force by designing the appearance of the MR object to fit a specific scenario. For example, the guiding force of MR Nudge can be reduced by increasing the transparency of the human-type MR object as users approach it. Conversely, the guiding force may be heightened if the MR object responds to the user's actions in some manner, such as humanoid MR objects looking at the user or performing active motions. Previous research has revealed that users tend to take a substantial detour to avoid virtual characters that stare at them [29] or display neurotic movements [33]. Therefore, since the behavior of the MR object may influence users' passing behavior, further research is needed to investigate how this behavior impacts the effectiveness of MR Nudge.

5.4 Limitations

This study has several limitations. First, this study has limitations in terms of the participants and apparatus. Most participants were young Japanese university students, which resulted in a narrow range of ages and cultural backgrounds. Additionally, the MR environment in this study was presented using a video see-through method with the selected HMD, thereby creating a lack of clarity regarding whether MR Nudge would be effective with an optical see-through MR. A few participants noted that the images displayed on the HMD created a different sense of distance compared to reality, as objects appeared closer than they actually were. Thus, the influence of MR Nudge may vary depending on the resolution and fidelity of MR experiences. Overall, these limitations suggest that the effects of MR Nudge cannot be fully generalized from our study results alone.

Second, the types and behaviors of the MR objects used in this study were limited. This study only examined the appearances of two types of MR objects—humans and rectangular cuboids—and did not explore other possible appearances of MR objects. To apply MR Nudge in more realistic scenarios, it is necessary to investigate user reactions to a broader range of MR objects, such as trees, bushes, furniture, and animals. Additionally, the MR objects in this study were largely stationary, thus making it unclear whether object motion would influence the guiding force. Overall, further research is needed to evaluate and broaden the applicability of MR Nudge.

Third, the long-term effects of MR Nudge remain unknown. Among the 12 participants who passed through the MR object in Room 1, 11 also passed through it in Room 2. Similarly, of the 17 participants who passed through the MR object in Room 2, 16 also passed through it in Room 3. This pattern suggests that participants became increasingly accustomed to passing through the MR object over time. Consequently, it can be surmised that the guiding effectiveness of MR Nudge probably diminishes with repeated exposure. Therefore, long-term research on the effects of MR Nudge is necessary to understand its durability and effectiveness.

Finally, our study did not directly examine whether MR Nudge can effectively improve users' behavior. While we indirectly demonstrated its potential usefulness by showing that MR Nudge significantly increases the distance traveled by users, it remains unclear whether it can reliably influence user behavior in realistic scenarios. Most studies proposing behavior change methods measure the reactions of passers-by in real-world settings [3, 36]. However, since MR technology has not yet been widely adopted in society, it is not possible to evaluate the efficacy of MR Nudge through such studies. In the future, as MR becomes integrated into everyday life, it will be crucial to investigate how users interact with MR objects. Therefore, studies that assess the effectiveness of MR Nudge in real-world environments will be necessary.

6 Conclusion

In this study, we proposed MR Nudge, a nudging method that leverages collision-avoidance behavior toward MR objects to influence user behavior. To evaluate the effectiveness of MR Nudge, we designed a task that included an incentive to pass through the MR object. The results revealed that 54% of participants avoided passing through the MR object. Additionally, we found that the passing rate varied based on the appearance and transparency of the MR object. These findings suggest that the guiding effectiveness of MR Nudge is adjustable, thus emphasizing the importance of further research into MR object designs that seamlessly integrate with realistic scenarios.

Acknowledgments

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