https://doi.org/10.2352/EI.2026.38.2.SDA-337

Basic Characteristics of Body-Visual Interaction in Mixed Reality Environments

Yusuke Ohira, Kazuki Deguchi, Yoshihiro Banchi, Takashi Kawai; Department of Intermedia Art and Science, School of Fundamental Science and Engineering, Waseda University; Tokyo, Japan.

Abstract

Mixed reality (MR) integrates virtual content with the physical world, enabling users to place virtual objects in real environments and interact with or observe them. As MR technologies advance, such experiences are becoming increasingly common. However, it remains unclear how the visual and interactive representation of virtual objects influences users, and few studies have examined users' behavioral responses to virtual objects. We investigated whether representation factors (interactivity, transparency, and size) affect users' sense of presence and their behaviors toward the object (e.g., avoidance or displacement). Here, interactivity refers to whether users can touch the virtual object. In two experiments (desk-scale and room-scale) conducted, participants performed a reaching task toward a real target located behind a virtual object whose representation factors were manipulated. Presence and behavior were assessed using subjective ratings and objective measures from tracking data and video observations. Perceived presence varied with interactivity, transparency, and size, whereas avoidance and displacement behaviors showed no reliable differences across conditions. Nonetheless, the results suggest that behavioral responses may emerge when interaction demands are stronger or the scale of interaction is larger. Overall, representation affected perceived presence but did not reliably change avoidance or displacement behavior in this task.

Introduction

Mixed Reality (MR) is a technology that integrates virtual content with the physical world [1]. In MR environments, head-mounted displays (HMDs) are widely used due to their high level of immersion. Recently, consumer MR HMDs such as the Meta Quest 3 (Meta) [2] have become available, making MR experiences more accessible. These devices are also equipped with hand-tracking functions that capture users' finger and hand movements [3]. Hand tracking enables users to manipulate virtual objects displayed on an HMD directly with their hands, rather than using handheld controllers, thereby supporting more seamless interaction in real-world settings.

With advances in MR and hand-tracking technologies, opportunities to work in environments where virtual objects are integrated into the real world (Figure 1) have been increasing. For example, virtual augmented displays that extend a PC or smartphone screen into an MR environment can effectively expand the limited physical workspace and may be particularly useful in constrained settings such as vehicle seats [4]. Such displays have also been studied as a means of transforming workplaces toward metaverse-like environments [5, 6]. Prior studies further suggest that MR can improve task performance [7, 8]. In addition, research on obstacle negotiation in MR has shown that virtual obstacles can elicit avoidance behaviors broadly comparable to those observed for real obstacles [9, 10]. Nevertheless, it remains unclear how user experience and behavior change in environments where virtual and real objects coexist. Moreover, few studies have examined how users' behavior depends on the specific representation of virtual objects.

In this paper, we investigate user behavior toward virtual objects by focusing on three representation factors (interactivity, transparency, and size). Here, interactivity refers to whether users can touch the virtual object. We examine whether variations in these factors influence users' sense of presence and their behavioral responses (e.g., avoidance or displacement of the virtual object). Specifically, we present virtual objects with different levels of interactivity, transparency, and size in an MR environment and ask participants to reach for or walk toward a real object located behind the virtual object. We assess presence and behavior using both subjective and objective measures. To further examine the role of interaction scale, we conduct two experiments with different interaction contexts: (1) a desk-scale condition in which participants interact with a virtual object using their hands, and (2) a room-scale condition in which participants interact with a virtual object using whole-body movements. The results indicate that perceived presence varies as a function of interactivity, transparency, and size, whereas avoidance and displacement behavior does not show reliable differences across these conditions. However, our findings suggest that behavioral responses may depend on the scale of interaction with the virtual object.

Figure 1-a. *Real-world environment*

Figure 1-b. *Mixed reality environment*

Experiment 1

Materials and Methods

In Experiment 1, the virtual object was presented on a desk. The stimulus was a white virtual cube (0.20 m per side), and the target real object was a paper cube (0.10 m per side) that participants were instructed to pick up. We employed a 2 × 2 within-subject design with two factors: interactivity (interactive vs. non-interactive) and transparency (opaque vs. transparent). In the interactive condition, the virtual cube had collision and could be displaced by direct hand contact; in the non-interactive condition, collision was disabled (i.e., the hand could pass through the cube) and the cube could not be displaced. For the transparency manipulation, the opaque condition used an alpha value of 255 (0–255), whereas the transparent condition used an alpha value of 2.

A Meta Quest 3 HMD was used to present the stimuli. Participants began the task in a seated position, but were not required to remain seated during the task. The initial HMD position was set 0.05 m outside the front edge of the desk and stabilized using a chin rest. The initial position of the participant's right hand was 0.05 m inside the front edge of the desk. The real object was placed 0.50 m in front of the initial hand position, and the virtual object was placed 0.30 m in front of the initial HMD position. As a subjective measure, participants rated the sense of presence of the virtual object on a 7-point scale after each trial. As an objective measure, we recorded the 3D coordinates of the participant's right hand throughout the reaching movement. An overview of the desk-scale setup is shown in Figure 2.

Twelve undergraduate students in their twenties participated in the experiment. All participants received an explanation of the study purpose and procedures in advance and provided informed consent. Each trial consisted of (1) reaching for and picking up the real object and (2) reporting the perceived presence of the virtual object. At the beginning of each trial, participants placed their right hand at the prescribed initial position. They then reached for the real object with their right hand, picked it up, and returned it to the initial position. This action could be performed standing and seating. Each experimental condition was repeated five times, resulting in 20 trials per participant, and the trial order was randomized.

Results

Figure 3 reports the mean presence score for the desk-scale virtual object. Error bars indicate standard errors. A two-way ANOVA with interactivity and transparency as factors revealed significant main effects of interactivity and transparency ($p < .05$).

Figure 4 illustrates example right-hand trajectories from the top and side views for the interactive and opaque condition. Across conditions, 10 of the 12 participants reached the real object without avoiding the virtual object, indicating no avoidance behavior in this desk-scale setup.

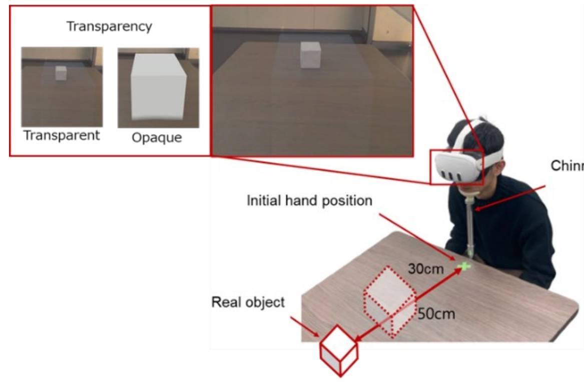

Figure 2. *An overview of the desk-scale setup*

Discussion

Subjective measures indicated higher perceived presence for the interactive and opaque virtual object. In post-experiment interviews, all participants reported that the interactive, opaque condition yielded the strongest sense of presence. Several participants also reported a sense of presence even in the non-interactive, opaque condition, noting a suction-like sensation when their hand overlapped the virtual object, as if it were pulling their hand in.

Objective measures suggested that neither interactivity nor transparency reliably affected behavioral responses toward the virtual object. Consistent with participants' introspective reports, many reported little hesitation or resistance when their hand intersected the virtual object; consequently, they did not adjust their reaching trajectories to avoid it.

Experiment 2

Materials and Methods

In Experiment 2, the virtual object was presented in a room-scale indoor environment. The stimulus was a white virtual cube, and the target real object was the same paper cube used in Experiment 1 (0.10 m per side). The design comprised 12 conditions, formed by crossing the four conditions from Experiment 1 (interactivity and transparency) with three levels of size (0.50 m,

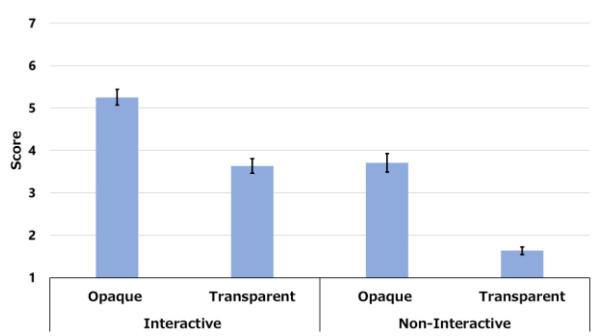

Figure 3. *The mean presence score for the desk-scale virtual object*

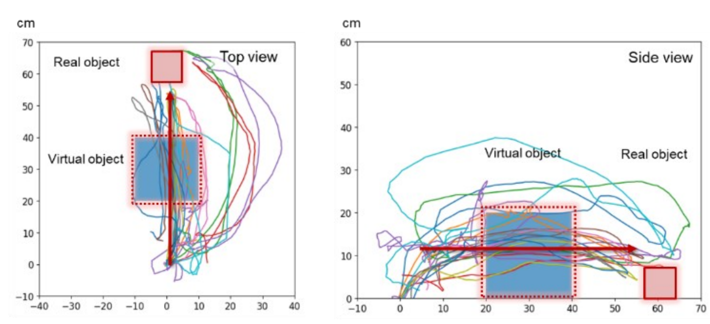

Figure 4. *The trajectories of the right hand seen from the top and side view*

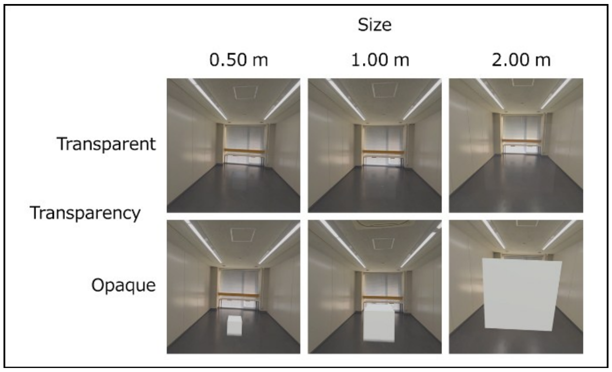

Figure 5. The appearance of the virtual objects for each condition

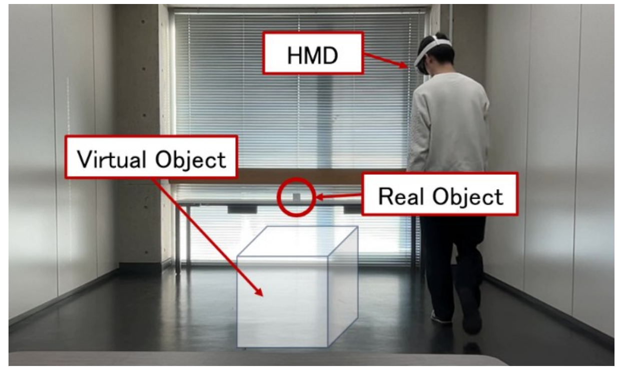

Figure 6. An overview of the room-scale setup

1.00 m, and 2.00 m per side). Figure 5 illustrates the appearance of the virtual objects across conditions.

Participants performed the task while standing. A desk was placed against the front wall, and the real object was positioned on the desk. The initial HMD position was set such that participants started 5.0 m away from the real object. The virtual object was positioned so that its center was located 3.0 m in front of the initial HMD position. As a subjective measure, participants rated the perceived presence of the virtual object. As objective measures, we recorded the 3D coordinates of the participant's head and both hands throughout the task. An overview of the room-scale setup is shown in Figure 6.

Ten undergraduate students in their twenties participated in the experiment. All participants received an explanation of the study purpose and procedures in advance and provided informed consent. Each trial consisted of (1) walking toward the real object and retrieving it and (2) rating the perceived presence of the virtual object. At the start of each trial, participants stood at the designated initial position. They then walked through the room to approach and pick up the real object and carried it to a desk located near the initial position. No specific walking route was prescribed. Each experimental condition was repeated three times, resulting in 36 trials per participant, and the trial order was randomized.

Results

Figure 7 reports the mean presence score for the room-scale virtual object. Error bars indicate standard errors. A three-way ANOVA with interactivity, transparency, and size as factors revealed significant main effects for all three factors ($p < .05$).

Figure 8 illustrates example head trajectories from a top-down view for each size level in the interactive and opaque condition. Analysis of the head-position data showed that 7 of the 10 participants exhibited avoidance of the virtual object, and this tendency was observed across conditions.

Discussion

Subjective measures indicated that perceived presence was higher for virtual objects that were larger, interactive, and opaque. For interactivity and transparency, we observed patterns consistent with Experiment 1, suggesting that enabling interaction and reducing transparency can strengthen presence. With respect to size, interview responses suggested that larger virtual objects were associated with a stronger sense of presence, which participants attributed to feelings of oppressiveness or spatial dominance. Overall, these results indicate that presence increases when the virtual object is interactive, larger in size, and opaque.

Objective measures suggested that the representation factors (interactivity, transparency, and size) did not reliably modulate

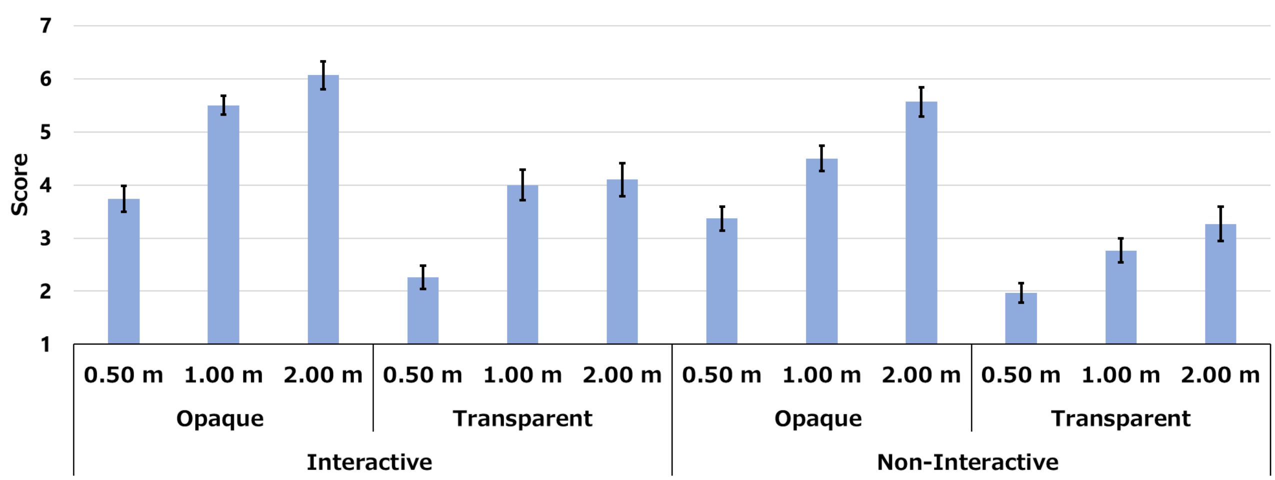

Figure 7. The mean presence score for the room-scale virtual object

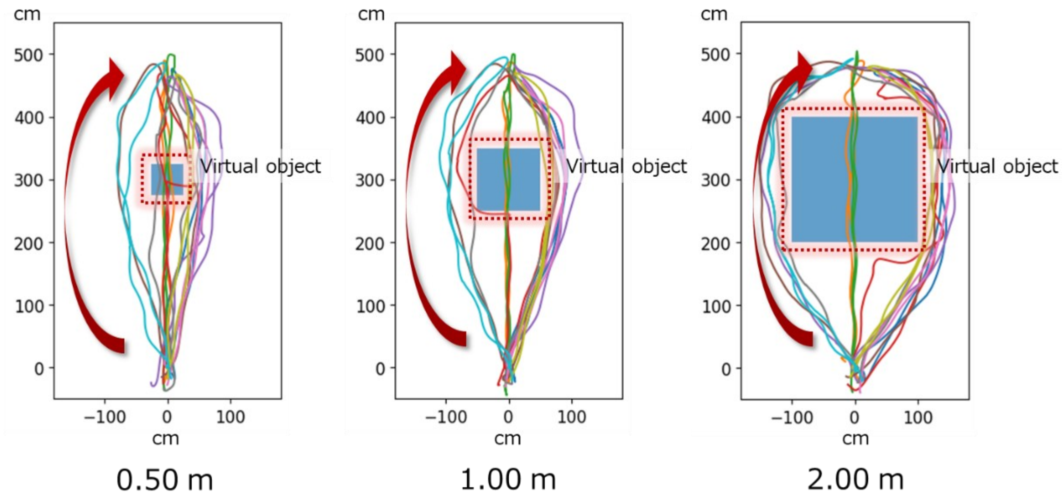

Figure 8. *The head trajectories seen from the top view for each size*

avoidance behavior, consistent with the Experiment 1 results. In post-experiment interviews, many participants reported discomfort or resistance when the virtual object approached or intersected the face, or when the body appeared to pass through the object. These experiences likely contributed to the avoidance tendencies observed in the room-scale setting.

Overall, our findings suggest that interaction scale may influence behavioral responses. Participants rarely avoided the virtual object in the desk-scale task, whereas avoidance was more frequently observed in the room-scale indoor task. Coordinate data and video observations indicate that participants tended to avoid situations in which the virtual object interfered with the head or feet during walking, but they were less concerned when interference involved the hands or arms. Taken together, these results suggest that users' behavioral responses to virtual objects may depend not only on object representation, but also on which body parts are implicated during interaction (e.g., whole-body locomotion vs. manual reaching).

Conclusion

This study investigated how virtual object representation (interactivity, transparency, and size) influences user experience and behavior in mixed reality. Our results can be summarized as follows:

- Perceived presence of the virtual object was higher for interactive, opaque, and larger objects.
- Avoidance/displacement behavior toward the virtual object did not show reliable differences across these representation factors.
- Behavioral responses may depend on interaction scale (e.g., desk-scale vs. room-scale).

By evaluating both subjective experience and behavioral responses, this study suggests that interaction scale may play a key role in shaping how users behave around virtual objects. However, the specific factors that drive behavioral change remain to be clarified. Identifying these factors is an important direction for designing human-centered MR interfaces that appropriately account for users' embodied responses in mixed environments.

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Author Biography

Yusuke Ohira received the B.A. and M.A. degree in Human Sciences from Waseda University, Japan, in 2023 and 2025, respectively. Currently, he is a Ph.D. candidate in the department of intermedia art and science, Waseda University. His current research interests include in mixed reality, machine learning, and user experience. He is a student member of the virtual reality society of Japan.

Kazuki Deguchi is a Master's Student at Waseda University, Japan. He received B.A. in Human Sciences from Waseda University, in 2024. His research focuses psycho-physiological effects in advanced technology, e.g. VR, XR, and statistics, e.g. sports data analytics.

Yoshihiro Banchi is an Assistant Professor at Waseda University, Japan. He received Ph.D., M.A. from Waseda University, in 2020, 2018. His research focuses ergonomics and data science on psyco-physiological effects in advanced technology, e.g. VR, XR, self-driving car

Takashi Kawai is a Professor at Waseda University, Japan. He received Ph.D., M.A., B.A. in Human Sciences from Waseda University, in 1998, 1995, 1993. His research focuses ergonomics in immersion technologies, e.g. 3D, VR, XR. He is a Certified Professional Ergonomist. Currently he is in charging of Japan Committee Chair of Advanced Imaging Society, Executive Committee of International Ergonomics Association, and Conference Chair of Stereoscopic Displays and Application.