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How Video Passthrough Headsets Influence Perception of Self and Others

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Abstract

With the increasing adoption of mixed reality (MR) headsets with video passthrough functionality, concerns over perceptual and social effects have surfaced. Building on prior qualitative findings,[1] this study quantitatively investigates the impact of video passthrough on users. Forty participants completed a body transfer task twice, once while wearing a headset in video passthrough and once without a headset. Using video passthrough induced simulator sickness, created *social absence* (another person in the physical room feels less present), altered self-reported body schema, and distorted distance perception. On the other hand, compared with past research that showed perceptual aftereffects from video passthrough, the current study found none. We discuss the broader implications for the widespread adoption of MR headsets and their impact on theories surrounding presence and body transfer.

Keywords: mixed reality, self-perception, presence, body transfer

Introduction

Mainstream technology companies are now producing headsets that blend virtual content into the physical world through *video passthrough*, arguing the technology will maximize immersion while still providing situational awareness.[2,3] Passthrough relies on stereoscopic, high resolution, low latency, and real-time video of the world displayed through headset screens.[4] This is in contrast to see-through displays, wherein users view content projected onto a transparent lens which allows users to see light from the physical world (for an early comparison of optical and video see-through, review Rolland et al.).[5]

Recent work by Bailenson et al. on the latest headsets including the Meta Quest 3 and the Apple Vision Pro compared passthrough to the physical world.[1] The authors of this work found (a) simulator sickness symptoms within less than an hour of use, (b) lapses in distance estimations, (c) social absence, where individuals in the physical world felt less real and distant, and (d) changes in one's body perception and embodiment. However, that study did not provide quantitative data. Despite the proliferation of this new technology, the comparison of how passthrough differs from physical face-to-face interactions with oneself and others remains largely underexplored. Given that these headsets are already being used in operative settings for surgical training and gait rehabilitation,[6,7] architectural visualizations,[8] and exergames,[9] the quantification of simulator sickness, body distortions, social absence, and distance underestimation effects of this technology is increasingly important.

Visually induced motion sickness can be of concern in augmented reality and virtual reality (AR/VR) applications.[10,11] Sensory conflict theory is commonly cited for simulator sickness, wherein conflicting information received from visual, vestibular, and somatosensory systems during VR use disrupts the well-trained interaction between senses.[12,13] In recent studies, only very minor simulator sickness in passthrough video exergames and training was found.[9,14] However, as these studies focused on the Microsoft HoloLens and PICO 4, researchers implored further exploration for simulator sickness in other AR and mixed reality (MR) technologies.[9,14] Drawing from sensory conflict theory, our first research question aims to address whether short doses of video passthrough can induce simulator sickness.

Moreover, researchers noted the changes in individual body perceptions, including the change to their body shape and size in video passthrough compared to without the headset.[1] These changes were attributed to video distortion and camera placement that is higher than the natural eye position. Prior work on body ownership and transfer in AR has implemented the

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classical rubber hand experiment, which illustrates that individuals in AR do not report feeling as much ownership of their rubber hand as in the real-world setting.[15] Other work using see-through head-mounted displays (HMDs) has illustrated findings that participants experience body ownership with a virtual body in a virtual mirror.[16] Our work will quantify the degree to which embodiment and body ownership are experienced in video passthrough when users view their physical bodies before a physical mirror when they have completed a set of body transfer and embodiment exercises. Studies that have explored embodiment and body transfer in VR and AR have employed a series of empirically validated exercises such as the basic body awareness therapy (BBAT) exercises and the VR avatar body transfer exercises to measure embodiment and body transfer in virtual environments.[17–19] The BBAT exercises are a series of six exercises, performed for 20 seconds each, while the participant viewed themselves in a mirror. They included exercises such as waving their hands, walking in place, stretching out their arms, and performing circular movements with one's arms. Similarly, the VR avatar body transfer exercises were a series of five exercises, performed for 30 seconds each which included focusing on one's posture, rotating their torso, and performing rocking movements with one's legs.

The current study also examines how the perceptual system is impacted while wearing video passthrough and the *aftereffects* that occur once the headset is removed.[20] Previous research has examined aftereffects in see-through video. Biocca and Roland showed users would underreach for objects while wearing a see-through HMD and that once the headset was taken off they would overcompensate by overreaching for the objects.[21] More recently, scholars have directly examined video passthrough and found that distances were underestimated in a blind throwing task in video passthrough compared to without a headset.[22] Those authors largely attributed this to the limited field-of-view of the headset. Similar results were found by Park et al. who showed significant decreases in spatial task accuracy in video see-through compared to without it.[23] Moreover, other works have also found that visuomotor tasks resulted in significant changes in cognitive performance and processing, particularly when there is movement involved in the task.[24,25] However, to date, to our knowledge, there has been no quantitative research that examines the *aftereffects* of passthrough video. Therefore, we seek to understand how users experience differences in distance perception in video passthrough compared to the physical world, how these effects change with time in the HMD, and the aftereffects of HMD removal.

Recent work has illustrated the influence of see-through VR use, that is, the Microsoft HoloLens, in social interactions.[26] Miller et al. found that users in a headset felt less social connectedness and less social presence to their interaction partners compared to those not using an AR headset in passthrough, a phenomenon scholars now refer to as *social absence*.[1,26] Therefore, this study also tests how social absence differs in MR compared to without headset in an experimenter–participant setting.

Materials and Methods

This study was approved by the Institutional Review Board at Stanford University (protocol #: 66462).

Hardware

Participants used the Meta Quest 3 headset (515 g) with 2064 × 2208 pixels per eye, 110 × 96-degree field-of-view, 39 milliseconds latency, 120 Hz refresh rate, and full-color passthrough. Hand controllers were not used during the study.

Procedure

The study employed a repeated measures design. Throughout the study, while participants were in the headset, they were viewing the physical room via the Quest 3′s passthrough viewing mode. No applications or visual digital overlays were present in the participants' field of view. Following their completion of the pre-experiment survey consisting of demographic questions and past VR and passthrough-related experiences, participants were randomly assigned to a (a) *passthrough followed by no headset condition* or a (b) *no headset followed by passthrough condition* to counterbalance order effects. In both conditions, participants performed BBAT and VR avatar body transfer exercises to elicit a feeling of body awareness and a sense of embodiment (Figure 1).[17–19] Specific instructions given to participants are elaborated in Supplementary Appendix SA1. This was followed by a blind walk task[27] to assess how accurately participants could estimate distances (Figure 2). In total, participants wore the headset for 4 minutes for these exercises.

A researcher was present in the room with the participant who helped the participant put on the headset before the trials and take off the headset following the trials. This researcher stood 2 m to the right of the participant and was responsible for guiding participants through the various tasks. During the blind walk task, they helped ensure participants were starting at the same point and measured how far participants were from the target.

After completing the first (*passthrough or no passthrough*) condition, participants completed a post-experiment questionnaire inquiring about simulator sickness, presence, embodiment, change in perceived body schema, and body distortions. They were then exposed to the second (*passthrough or no passthrough*) condition and performed the body transfer exercises; following which, they answered identical questions on

FIG. 1. The participant wears an MR head-mounted display and participates in body transfer exercises for 4 minutes. MR, mixed reality.

FIG. 2. The participant wears an MR head-mounted display and engages in a blind walk task to the point circled that is 3.12 m away from them. They performed the blind walk task four times (i: in headset, ii: directly after removing headset, iii: without a headset, and iv: without a headset for three more trials after initial no headset).

simulator sickness, presence, embodiment, change in perceived body schema, and body distortions.

Participants

Before the experiment, we ran sample size calculation using G*Power with a power of 0.8, effect size of 0.5, and an alpha error probability of 0.05, which resulted in a power of 34 participants. This effect size that was used in our a-priori power calculations was derived from prior meta-analyses that look into movement-related outcomes,[28] AR technologies,[29] and AR-related student learning.[30]

We recruited participants via Stanford University's Department of Communication subject pool and online outreach. Participants were remunerated with a $25 gift card or granted course credit. A total of 40 participants consented. Participants were of ages 18–25 (*n* = 30), 25–30 (*n* = 6), 30–35 (*n* = 3), 35–40 (*n* = 1), identified as women (*n* = 29), men (*n* = 10), and declined to answer (*n* = 1). Participants were freshmen (*n* = 1), sophomores (*n* = 8), juniors (*n* = 5), seniors (*n* = 8), graduate students (*n* = 14), and other education levels (*n* = 3). Participants stated that they never had prior VR experience (*n* = 10), rarely experienced VR environments (*n* = 27), sometimes experienced VR environments (*n* = 2), and experienced VR environments several times a week (*n* = 1). Similarly, participants stated that they never experienced passthrough (*n* = 26), rarely experienced passthrough (*n* = 12), sometimes experienced passthrough (*n* = 1), and experienced passthrough several times a week (*n* = 1). Participants who did not consent to having their video recorded were filtered out of the video analysis portion of the study (*n* = 3). Table 1 presents additional participant demographic information.

Our inclusion criteria required participants to be above 18 years of age, be healthy at the time of the experiment, and have the ability to provide informed consent. Those outside this were excluded from the study.

Measures

Distance perception. Participants engaged in a blind walk task where they were instructed to walk toward a target they had seen previously in the lab with their eyes closed (a) three times in passthrough, (b) three times directly following the use of passthrough, (c) three times without headset, and (d) three trials without headset after the initial three without headset trials. The participant wore an MR head-mounted display and engaged in a blind walk task to a point that was 3.12 m away from their marked starting point. The target width was 12 cm. A researcher measured the difference in distance between where participants perceived the target to be and its actual location. This target was measured using a tape measure on one axis.[27]

TABLE 1. DEMOGRAPHIC CHARACTERISTICS OF PARTICIPANTS ($N = 40$)

	N
Age	
18–25	30
25–30	6
30–35	3
35–40	1
Gender	
Woman	29
Men	10
Decline to Answer	1
Race/ethnicity	
African, African American, or Black	5
Asian or Asian American	13
Hispanic or Latinx	5
Middle Eastern	2
White	7
Mixed	6
Decline to answer	2
Year in School	
College Freshman	1
College Sophomore	8
College Junior	5
College Senior	8
Graduate Student	14
Other	3
Prior Virtual Reality Experience	
Never	10
Rarely	27
Sometimes	2
Several times a week	1
Prior passthrough experience	
Never	26
Rarely	12
Sometimes	1
Several times a week	1

Simulator sickness questionnaire. Simulator sickness was assessed using the simulator sickness questionnaire (SSQ) (Cronbach's $\alpha = 0.87$).[31,32] The questionnaire is made up of three subscales, namely, "Nausea," "Oculomotor," and "Disorientation," and 16 items on a 4-point scale (0 = "None" and 3 = "Severe"). Scores for each subscale, as well as total scores, can be associated with negligible (<5), minimal (5–10), significant (10–15), and concerning (15–20), with above 20 being considered bad.[33]

Embodiment questionnaire. Sense of embodiment, which is the level of embodiment one feels in their body, was measured using an adapted avatar embodiment questionnaire (Cronbach's $\alpha = 0.89$).[34] Of the 16-item 7-point scale (1 = "Never" and 7 = "Always"), we selected 9 items that were later modified to be suitable for the passthrough scenario (Supplementary Appendix SA2).

Change in perceived body schema. Change in perceived body schema or the change that participants perceive and feel toward the spatial representation of their body, was measured using six items on a 7-point scale from the virtual embodiment questionnaire (1 = "Strongly disagree" and 7 = "Strongly agree") (Cronbach's $\alpha = 0.77$).[35]

Body distortion. Body distortion, or how distorted participants believe their bodies looked in the virtual environment and in the physical environment, was measured with four items on a 5-point scale where 1 = "Not at all" and 5 = "Extremely" (Cronbach's $\alpha = 0.79$) (Supplementary Appendix SA3).

Presence. Presence was measured using a 5-point (1 = "Not at all" and 5 = "Extremely") adapted Virtual Human Interaction Lab Presence scale (2022) with three subscales namely, social presence (Cronbach's $\alpha = 0.86$), self-presence (Cronbach's $\alpha = 0.63$), and spatial presence (Cronbach's $\alpha = 0.91$) (Supplementary Appendix SA4).[36–38]

Results

The means and standard deviations of all dependent variables by condition are shown in Table 2. We first used the Shapiro–Wilk normality test to assess data distribution across variables and conditions. Prior to running the analysis of covariance (ANCOVA) tests, we ensured that all the assumptions for the test were met.[39] As the data were nonparametric and not normally distributed, we transformed the data using log transformations to run the ANCOVA tests. We included covariate and control variables, namely, gender, age, school year, and condition order into our ANCOVA model for each outcome variable reported below. All results reported were controlled for covariates and demographic variables, but the findings are significant both with and without controlling for these variables.

To account for outliers in variables after log transformations, we followed the winsorizing median statistical technique that computes the median of that variable and replaces outliers with the observations closest to them. Findings were the same with and without the statistical transformation of outliers.

Simulator sickness

An analysis of the covariance test was used to compare each simulator sickness category. Significant findings were found when comparing each category. Results from the subscales of the three subscales of the SSQ, namely, (a) nausea, (b) oculomotor, and (c) disorientation, show that nausea in passthrough ($M = 12.48$, standard deviation [SD] = 12.41) was significantly higher than without a headset ($M = 3.93$, $SD = 4.84$), [F (1, 56) = 12.85, $p < 0.01$]. Oculomotor in passthrough ($M = 20.60$, $SD = 17.39$) was significantly higher than without a headset ($M = 6.89$, $SD = 7.73$), [F (1, 57) = 8.61, $p < 0.01$]. Disorientation in passthrough ($M = 45.06$, $SD = 38.62$) was significantly higher than without a headset ($M = 10.61$, $SD = 27.84$), [F (1, 56) = 14.36, $p < 0.001$]. Total simulator sickness, which was calculated on the entire measure, in passthrough ($M = 26.87$, $SD = 22.22$) was significantly higher than without a headset ($M = 9.44$, $SD = 9.21$), [F (1, 55) = 13.06, $p < 0.001$]. These findings indicate that passthrough, even in short doses, can create simulator sickness (Figure 3).

Body schema and body distortions

With reference to our second research question, the ANCOVA showed no significant differences between participants' sense of

TABLE 2. MEANS AND STANDARD DEVIATION TABLE OF DEPENDENT VARIABLES IN THE PASSTHROUGH AND NO HEADSET CONDITION ($N = 40$)

Variables	*In Passthrough—Means (SD) (Minimum Value–Maximum Value)*	*No Headset—Means (SD) (Minimum Value–Maximum Value)*
Embodiment	3.15 (1.35) (1.00–6.71)	2.96 (1.55)(1.05–5.98)
Appearance	2.67 (1.33) (1.00–6.67)	2.71 (1.46) (1.20–6.40)
Response	2.70 (1.60) (1.00–7.00)	2.24 (1.55)* (1.00–6.50)
Ownership	3.87 (1.42) (1.00–6.67)	3.67 (1.84) (1.00–7.00)
Multisensory	3.33 (1.64) (1.00–6.50)	3.29 (1.93) (1.00–7.00)
Perceived change in body schema	3.06 (1.53) (1.00–6.00)	2.21 (1.28)* (1.00–5.00)
Body distortion	2.01 (0.95) (1.00–4.00)	1.13 (0.28)*** (1.00–2.00)
Presence		
Social presence	2.48 (0.99) (1.00–4.33)	3.08 (1.22)*** (1.00–5.00)
Self-presence	3.62 (0.83) (2.00–5.00)	3.90 (0.91) (1.00–5.00)
Spatial presence	2.51 (1.18) (1.00–4.50)	1.36 (0.70)*** (1.00–3.50)
Simulator sickness		
Nausea	12.48 (12.41) (0.00–38.16)	3.93 (4.84)* (0.00–9.54)
Oculomotor	20.60 (17.39) (0.00–75.80)	6.89 (7.73)** (0.00–22.74)
Disorientation	45.06 (38.62) (0.00–125.28)	10.61 (27.84)*** (0.00–41.76)
Total simulator sickness	26.87 (22.22) (0.00–86.02)	9.44 (9.21)**(0.00–26.18)

$^{*}p < 0.05$.
$^{**}p < 0.01$.
$^{***}p < 0.001$.

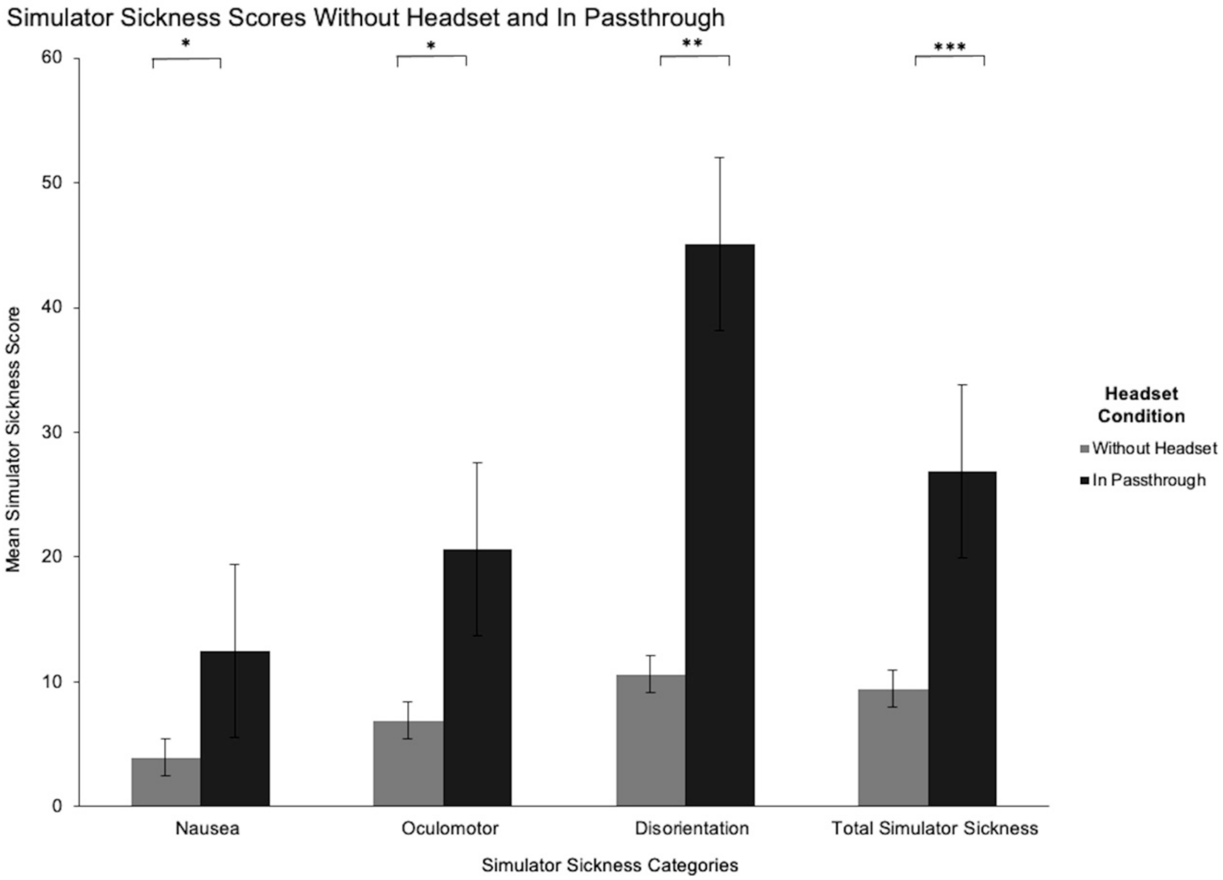

FIG. 3. A bar plot illustrating simulator sickness scores in passthrough and without a headset by simulator sickness categories.

embodiment in video passthrough ($M = 3.15$, $SD = 1.35$) or the physical environment ($M = 2.97$, $SD = 1.55$) ($F(1, 72) = 0.71$, $p = 0.40$].

However, participants did experience a significantly higher change in their perceived body schema in video passthrough ($M = 3.06$, $SD = 1.53$) compared to those without headsets ($M = 2.21$, $SD = 1.28$) [$F(1, 74) = 7.85$, $p < 0.05$]. Participants also reported experiencing significantly higher body distortions in video passthrough ($M = 2.01$, $SD = 0.95$) compared to those without headsets ($M = 1.13$, $SD = 0.28$) [$F(1, 57) = 18.03$, $p < 0.001$] (Table 2).[a,b]

Distance underestimation

A linear mixed-effects model was used to account for trial time as a continuous variable, since each participant did three trials per headset trial type (in passthrough, directly following passthrough, no headset, and no headset following initial three trials) and condition order in which HMD was used. There were no changes in the pattern of results by trial time and order.

Participants exhibited significant underestimation of distances, while in passthrough compared to the three blocks where they estimated distance without a headset (the first three trials and the second three trials from the without condition, and the second block after wearing the headset in the headset condition). Comparing distance underestimation in passthrough and directly following passthrough (participants remove their headset directly after using it), the average participant who just removed their headset underestimated distance less by 21.27 cm in the real world than in passthrough (standard error [SE] = 3.48 cm) ($p < 0.001$) (Figure 4). Comparing the amount of distance underestimation in passthrough and no headset (the two blocks where participants did not use the headset at all), we found that there were significant differences. In comparison to being in passthrough viewing mode, the average participant who did not wear a headset experienced less distance underestimation by 8.85 cm ($SE = 3.54$ cm) ($p < 0.05$) (Figure 4).

Social absence

To answer our fourth research question that explores the relationship between social presence scores and without a headset and in passthrough, we ran an ANCOVA.[c] The results showed that without a headset ($M = 2.48$, $SD = 0.99$), social presence was higher than in video passthrough ($M = 3.08$, $SD = 1.22$), [$F(1, 74) = 4.36$, $p < 0.05$].[d] Median values show an increase of 30.55% in social presence ratings without wearing the headset compared to in video passthrough.

Discussion

While prior literature has shed light on the influence of MR content on user psychology,[9,40,41] few have directly

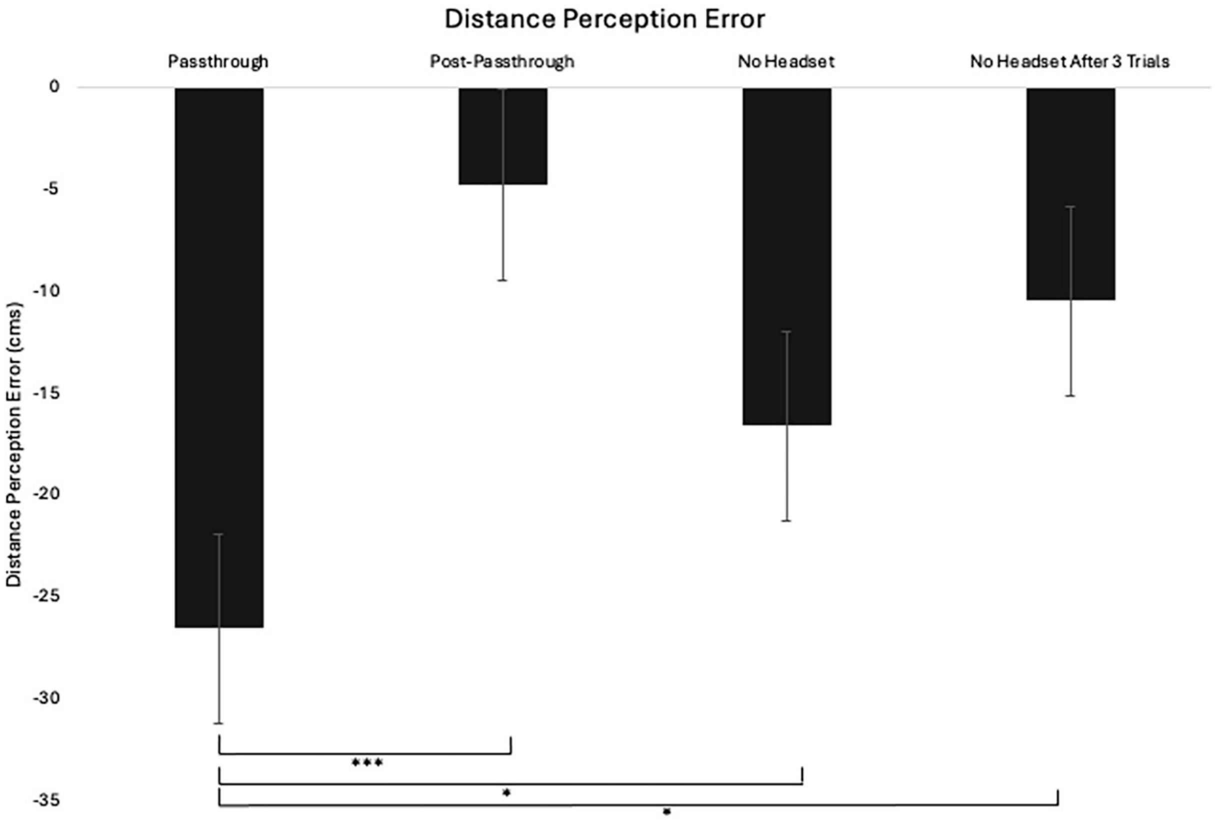

FIG. 4. Differences in distance underestimation in video passthrough and without headset.

compared face-to-face interaction to the video passthrough as a medium.[1]

The body transfer exercises that participants performed early on in our study procedure were aimed to induce a sense of embodiment and body awareness.[18,19] Following these exercises,[18,19] our findings indicated that while there were no differences in participants' embodiment in their physical bodies both in passthrough and without headset, there was a change in users' perceived body schema and body distortion while in passthrough compared to the physical reality. This could be a result of the curvature of the small screens in the headset and the algorithmic process of integrating multiple cameras, which cause a discrepancy in the location of the user's real eyes and the camera display's location.[5] These distortions create changes in body perceptions and should be given attention, particularly given the growing number of MR interventions on body image.[42,43]

Even in short doses of 4 minutes and without any virtual effects layered over the real world, simulator sickness occurred, with disorientation being the largest symptom. We also extend prior literature in support of sensory conflict theory, suggesting that MR headsets give rise to incongruencies of conflicting information and desynchronized sensory outputs, which may be attributed to technical features such as lower refresh rates and resolution compared to the human eye.[44] However, while our work builds on the precedent that simulator sickness is low before headset use,[31,45,46] scholars also argue that a nonzero baseline may be incorrect,[47,48] given that responses to the SSQ may vary between populations, particularly for those with medical conditions. In the current study, we only looked at post SSQs, and likely used a tool that was blunter than other work which computes a pre–post measure.[47] Future research should account for baseline SSQ levels, particularly as passthrough becomes more common in medical applications.[6] Research on ways to counter simulator sickness in virtual environments has alluded to technical modifications such as reducing the visual field-of-view, minimizing the time lag between actions performed in the virtual environment and visual and/or motion responses, simulated reference frames as well as adaptation and training.[49–53] With reference to sensory conflict theory, it is likely that sickness occurs mostly when the user has yet to establish coping strategies to deal with sensory incongruences which they can adapt to following repeated exposure.[54] In addition, future work would benefit from looking into how long these simulator sickness effects last to verify the findings by Kim et al.[11]

With reference to the perceptual effects of distance underestimation in passthrough, our findings implore the need for caution in the use of video passthrough in motion due to higher distance underestimation while in headset compared to without it and can be attributed to the weight and field-of-view of video passthrough as well as the geometric distortions in the display graphics.[22,55–58] Depth cameras and eye height manipulations, which have been cited to improve depth perception, should be tested for feasibility in aiding distance underestimation and facilitating improved cognitive processing in future studies.[59,60] We also found no significant aftereffects from a very short headset experience. Given that we only evaluated participants' distance perception on their blind walk task, future work would benefit from studying how the type of task influences cognitive processing and performance in the visuomotor domain.[24,25]

Finally, on exploring the social implications of MR headsets as they relate to social absence.[61,62] In essence, passthrough video turns a face-to-face interaction into a Zoom call, where real people become mediated by video. Possible explanations for this could include the low field-of-view in a headset compared to without one and the lower visual fidelity of the physical surroundings in passthrough viewing mode. Given that our findings illustrate social absence only as it relates to the experimenter and passthrough user, future work should seek to explore how users experience this phenomenon in dyadic and group interactions and test out the mechanisms under which social facilitation and inhibition processes may occur.[26]

Conclusion

This study provides initial quantitative evidence that even with the advances of video passthrough in the most recent MR headsets, perceptual and social effects will limit the headsets from becoming an everyday medium that augments physical world interactions. We call the need for further research into the longitudinal and long-term effects of video passthrough immersion to better understand how physiological indicators such as simulator sickness and psychological factors such as social absence can be minimized.

Notes

a. Results from our Shapiro–Wilk test for normality illustrated that values for embodiment ($W = 0.921$, $p < 0.01$), perceived body schema ($W = 0.85$, $p < 0.001$), and body distortions ($W = 0.52$, $p < 0.001$) was significantly different from a normal distribution, therefore, a log transformation was employed.
b. Our analysis, using a Wilcoxon signed-rank test, revealed the same pattern of results without transformations of data.
c. Results from our Shapiro–Wilk test for normality illustrated that values for social presence ($W = 0.93$, $p < 0.05$) were significantly different from a normal distribution, therefore a log transformation was employed.
d. Our analysis, using a Wilcoxon signed-rank test, revealed the same pattern of results without transformations of data.

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Authors' Contributions

M.S.: conceiving and designing the study, collecting data, analyzing and interpreting results, writing up and editing article. J.B.: conceiving and designing the study, interpreting results, writing up and editing article.

Author Disclosure Statement

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Supplementary Material

Supplementary Appendix SA1
Supplementary Appendix SA2
Supplementary Appendix SA3
Supplementary Appendix SA4

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