Exploring Cues and Signaling to Improve Cross-Reality Interruptions

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Figure 1: Virtual Activity Cues showing three levels of activity.

Abstract

In this paper, we report on initial work exploring the potential value of technology-mediated cues and signals to improve cross-reality interruptions. We investigated the use of color-coded visual cues (LED lights) to help a person decide when to interrupt a virtual reality (VR) user, and a gesture-based mechanism (waving at the user) to signal their desire to do so. To assess the potential value of these mechanisms we conducted a preliminary 2×3 within-subjects experimental design user study ($N = 10$) where the participants acted in the role of the interrupter. While we found that our visual cues improved participants' experiences, our gesture-based signaling mechanism did not, as users did not trust it nor consider it as intuitive as a speech-based mechanism might be. Our preliminary findings motivate further investigation of interruption cues and signaling mechanisms to inform future VR head-worn display system designs.

Keywords: virtual reality, cross-reality, interruptions

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 Introduction

Virtual reality (VR) devices immerse users in a virtual world, and yet users still occupy a real physical space that at times requires concurrent awareness or interaction. For example, a VR user may be embodied in an avatar in a virtual meeting but need to talk to someone in their real surroundings, or a real-world person may need to interrupt a VR user with a real-world issue. Such cross-reality interactions are complicated because modern VR systems are designed to isolate VR users from their real environment, while also hiding several valuable real-world cues related to the user's virtual-world activity or attention. In the real-world, interrupters typically use multiple cues to develop a *theory of mind* [2] for the interruptee that informs how the interrupter interacts with them. In other words, the interrupter attributes mental states to themselves and others and uses (potentially escalating) signaling mechanisms to coordinate an interruption with the interruptee. This closed-loop interaction is limited when people cannot interpret visual cues such as the gaze of the interruptee and the nature of the activity they are engaged in, nor signal the interruptee of their intentions. The effects can result in confusion, miscommunication, or even harm to relationships as a result of apparent violations of social norms. For short uses this might not present a problem, but as VR systems are used by more people, for personal and professional purposes, and for longer durations, facilitating such interactions across realities will become increasingly important.

Previous research has suggested allowing interrupters to signal an interruption through a natural waving gesture [11, 45]. Additionally, context awareness has been shown to be valuable when coordinating interruptions caused by notifications in VR [11], so it may be useful to provide some context about the VR user's virtual activity to the interrupter. Given these two considerations, we have arrived at the following two research questions:

RQ1 Can features that support gesture-based interactions with a VR user improve cross-reality interruptions?

RQ2 Can visual cues about whether a VR user is interruptible improve cross-reality interruptions?

To investigate these research questions we conducted a preliminary 2×3 within-subjects experimental design user study ($N = 10$) where the participants were instructed to interrupt another person (the interruptee) who was wearing a head-worn display (HWD) and ostensibly engaged in a VR task. Using a Wizard-of-Oz paradigm [14] we activated color-coded LEDs on the interruptee's HWD to provide visual cues to help the participant decide when to interrupt the VR user. The participants were told that the LED colors indicated the VR user's virtual activity, and corresponding receptiveness to interruption, in three levels: low (green), medium (yellow), and high (red) as depicted in Fig. 1. We simulated a gesture-based mechanism (waving) to allow the participants to signal the VR user that they wanted to interrupt. We timed how long participants took to interrupt the VR user, and assessed the participants' interruption experience through subjective questionnaires and a semi-structured interview.

2 Related Work

When immersed in VR, users experience the *place illusion* that they are present in the virtual world and the *plausibility illusion* that the

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virtual world is consistent and plausible [40]. Practically, these illusions are maximized by reducing the VR user's awareness of their physical surroundings. McGill et al. [28] found that immersed VR users still desire awareness of their physical space, and the awareness of other people and their proximity in the physical space is most important. Indeed, there are many unfortunate examples of VR users without sufficient awareness of their physical surroundings colliding with nearby objects and spectators [5]. In exploring alternatives to maximizing presence, researchers and HWD manufacturers have explored various cross-reality transition designs [10,41] and augmented virtuality designs [4,44], or the inclusion of physical elements in the virtual world. More specifically, researchers and HWD manufacturers have explored benefits to affording interactions across realities, e.g., by using different sensors, displays, and input modalities to provide innovative means for awareness, collaboration and shared experiences [10, 12, 18, 19, 23–25, 31, 36–38, 43].

When a VR user's primary task does not involve cross-reality interactions, a real-world person initiating an interaction with them can be modeled as a cross-reality interruption. VR HWD manufacturers have implemented ways to present interruptions to users. For instance, the Oculus Quest 2 can render a silhouette of a nearby real-world person inside the VR user's virtual environment (VE) when the interrupter enters the user's defined play space [1]. Additionally, the HTC Vive's "Knock Knock" feature allows a person in the real world to signal an interruption by pressing a button on a tethered VR computer's keyboard [7]. Researchers have explored other methods to present real-world interrupters to VR users, including through notifications [11,46] and representing the interrupter to the VR user through positional visualization techniques [11,21,30,39] or through avatar representations inside the VE [11, 13, 21, 28, 30, 44]. In particular, Gottsacker et al. [13] studied how different representations of interrupters affected the interrupted user's experience and found that avatars that fit with the VE were best, and that users may prefer a visual augmentation of the avatar to understand the interrupter is present in the physical world but not the virtual one.

These mechanisms provide awareness of the interrupter for the VR user. It is also important to study this interaction from the interrupter's perspective. Prior work has shown that interrupters are often concerned about disrupting or surprising a VR user, and they use cues about the VR user's physical movements and audio from their HWD to determine good times to interrupt [9,35]. It has also been shown that interrupters do not always feel comfortable interrupting someone who appears deeply engaged in VR for fear of disrupting or surprising the VR user [9,35], but interrupters feel more comfortable when they know the VR user [33]. Prior work has explored methods of communicating more information to real-world interactors about both the virtual and physical context of VR users, which could be useful in facilitating cross-reality interruptions from the interrupter's perspective. To share virtual context with real-world people, researchers have used screens attached to a VR HWD displaying the VE [15,17], displays external to the VR HWD [16], and augmented reality (AR) [37,43]. To allow nearby people to observe physical cues occluded by VR HWDs, researchers have investigated making a VR HWD more transparent by displaying a VR user's eyes to people nearby [26,27]. To design improved cross-reality interruptions, the work presented in this paper draws both on work about sharing a VR user's mental and virtual context with real-world people, and work on interacting across realities.

3 EXPERIMENT

We conducted a full-factorial 2×3 within-subjects design study contextualized in a workplace scenario. The study protocol was approved by the institutional review board of our university. Participants were instructed to interrupt a "co-worker" (an experimenter) who was engaged in a VR task. As described in Sect. 3.1, there were two signaling conditions (hand-waving gesture, none), and there were three *Virtual Activity Cue* conditions (VAC-NONE, VAC-EARLY, VAC-LATE) conveyed with colored LEDs on the co-worker's HWD as shown in Fig. 1. As described in Sect. 3.3, we collected both qualitative and quantitative measures to assess the effects of the conditions as described in Sect. 4.

3.1 Experimental Conditions

The 2×3 experimental conditions tested different methods of interrupting a VR user and different portrayals of the VR user's virtual activity to the interruptee. The order of the six conditions was counterbalanced using an incomplete Latin square to reduce potential carryover effects. In all conditions the experimenter played the role of the VR user, i.e. the co-worker and interruptee.

3.1.1 Gesture System Availability (GEST)

Previous work has shown that interrupters of VR users are comfortable interrupting with speech or touch in friendly settings [33,35]. Other researchers have developed methods for signaling a real-world interruption to a VR user using notifications [11,32,46], avatars [11, 13, 21, 28, 30, 44], or other visualization techniques [11, 21, 30, 39]. Researchers have also suggested using a gesture-based system to detect an interrupter's hand wave and signal an interruption to a VR user [11,45], but such a system has not been evaluated.

To simulate a gesture-based interruption system, we used a Wizard-of-Oz technique [14] where the experimenter used the Oculus Quest 2's passthrough view mode [31] to observe participants. When the experimenter saw participants wave, the experimenter pretended that a Gesture System mounted on the HWD had recognized the wave and notified them of the participant's desire to interrupt. The experimenter then proceeded to discreetly deactivate the LEDs and take the HWD off. In the experimental conditions where the simulated Gesture System was available to participants (GEST-A), participants were instructed to use the Gesture System on the headset of the experimenter to initiate the interruption. When the Gesture System was not available (GEST-NA), participants were instructed not to use the Gesture System but were not given any instructions on how to interrupt.

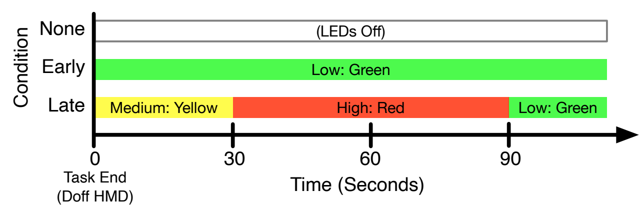


Figure 2: Experiment trial steps and visual activity cue timing.

3.1.2 Virtual Activity Cues (VAC)

Previous research has shown that individuals near VR users desire an increased awareness of the VR user's virtual surroundings and activities [35]. Several methods have been developed for sharing a VR user's activities with surrounding people, including casting a video stream of the VR experience to phones and web browsers [22], displaying the VR view on the HWD itself [15–17] or projected nearby [20], and using smartphone AR to peer into a VR user's VE [29]. However, VR users may require a level of privacy for their virtual activities and desire that their view or virtual environment not be shared with people around them, especially if users are unaware of bystanders' presence. Additionally, it may not be convenient for an interrupter to access another device to obtain information about the VR user's interruptibility. With this in mind, we prototyped simple Virtual Activity Cues to convey a minimum level of information about the VR user's interruptibility attached directly to the VR HWD.

Table 1: Cross-Reality Interruption Experience Questionnaire. The sub-scales are: *Interrupt Experience* and *Perception of Interruptee*. Each question is assessed on a 7-point scale *(1: not at all, 7: very much)*. Scales with an * are inverted for analysis.

Sub-scale	*Construct*	*Question*
Interrupt Experience	Comfort	How *comfortable* did you feel when you were interrupting the researcher?
	Hesitancy*	How *hesitant* did you feel when you were interrupting the researcher?
	Control	How much *control* did you have over the interruption?
	Confidence	How *confident* did you feel when you were interrupting the researcher?
	Uncertainty*	How *uncertain* did you feel when you were interrupting the researcher?
	Anxiety*	How *anxious* did you feel when you were interrupting the researcher?
Perception of Interruptee	Responsiveness	How *responsive* was the researcher to your interruption?
	Friendliness	How *friendly* did the researcher seem when you interrupted them?
	Openness	How *open to being interrupted* did the researcher seem?
	Responsiveness	How *quickly* did the researcher respond to your interruption?
	Interruptibility	Do what extent did you feel you could interrupt the researcher?

To test different Virtual Activity Cues, we attached LEDs to the outside of the experimenter's HWD as shown in Fig. 1. These lights provided visual cues about the experimenter's simulated virtual activity level through green, yellow, and red lights which respectively corresponded to low, medium, and high virtual activity levels. In this experiment, the order and duration of the LED colors for each condition were pre-programmed per the timing shown in Fig. 2. During the interrupt step of each trial participants experienced one of three conditions with visual cues indicating the experimenter's current virtual activity level: VAC-NONE, VAC-EARLY, VAC-LATE. In the VAC-NONE condition, the LEDs on the experimenter's HWD were off the entire time. In the VAC-EARLY condition, when the participant completed their task and removed their HWD the LEDs immediately turned green, indicating a low activity status. In the VAC-LATE condition, after the participant removed their HWD, the LEDs turned yellow indicating a moderate activity level for 30 seconds; then the lights turned red indicating a high activity level for 60 seconds (1 minute); then the LEDs turned green.

3.2 Study Procedure

After reading a consent form and affirming the participant's informed consent, an experimenter introduced the study and explained that the person in an HWD seated across the room (a second experimenter) was a co-worker who was using VR for their own tasks, but would instruct the participant on each of their tasks. Participants were then shown a scripted demonstration during which the LEDs on the co-worker's HWD changed colors as the co-worker pretended to be engaged in different tasks while announcing them out loud. For example, the lights would be green while the experimenter said "Now I am browsing for a file," or red when the experimenter said "Now I am focusing on reading." After putting on an HWD (Oculus Quest 2) the participants completed six VR tasks of stacking virtual blocks in 16-block configurations in a virtual office environment. Once they completed building the correct structure, a virtual screen informed them they successfully completed the task. Then, another virtual screen informed participants they must remove their HWD and interrupt the HWD-wearing co-worker (experimenter) to find out their next task. The screen instructed participants whether or not to use the *Gesture System* to interrupt. Participants then walked over to the co-worker, observed the Virtual Activity Cues on the HWD if they were active, and interrupted. The co-worker then removed their HWD and had a short conversation with participants, asking what color structure they just made, and instructing them in what color to build the next structure. Finally, participants completed a questionnaire about the interruption experience. The participants then began the next trial, putting on the HWD and beginning their next block stacking task. After the sixth interruption and interruption experience questionnaire, the trials concluded and participants filled out a demographics questionnaire. At the end the experimenters conducted a semi-structured interview about the experience.

3.3 Measures

To test our hypotheses, we collected the following data.

3.3.1 Interruption Experience

To examine the participants' experience of interrupting a VR user in a cross-reality context, we devised the questions shown in Table 1 inspired by questions in related research studies [9,13]. The sub-scales are *Interrupt Experience* and *Perception of Interruptee*. We formed these sub-scales by conceptually grouping aspects of an interruption experience. The *Interrupt Experience* sub-scale captures participants' feelings toward the interruption process. The *Perception of Interruptee* sub-scale captures how participants perceived the interruptee's feelings toward the interruption and toward the participant themselves.

3.3.2 Time to Interrupt

To measure how much time each interruption took, a secondary experimenter started a stopwatch timer when the participant removed their headset and stopped the timer when the participant interrupted the primary experimenter. This measure provides insight into how hesitant participants were during each interruption.

3.3.3 Data Analysis Approach

We tested the normality assumption required for parametic analysis methods through the Shapiro-Wilk test and checking the QQ plots. The questionnaire data was normally distributed, so we analyzed the within-subjects data with a repeated measures ANOVA and Tukey multiple comparisons at the 5% significance level with Bonferroni correction. Mauchly's test indicated sphericity of this data could be assumed. We used the non-parametric Friedman test for the *Time to Interrupt* data because it was not normally distributed. For our subjective cross-reality interruption experience questions, we computed the Cronbach's alpha for our *Interrupt Experience* and *Perception of Interruptee* constructs to be 0.934 and 0.835 respectively, suggesting our conceptually-grouped constructs had sufficiently high internal consistency to be analyzed in aggregate.

3.4 Qualitative Inquiry

We conducted semi-structured interviews with each participant after they completed all experimental trials. We audio-recorded these interviews and used the Otter.ai [1] web-based transcription software to transcribe the recordings. We then validated all of the transcripts and corrected any errors. We applied inductive thematic analysis [3] to identify emergent themes from the interview data. This analysis followed Braun & Clarke's six-phase framework [3], in which the first and second authors familiarized themselves with the recordings. Then, we generated initial codes based on interesting features found across all interviews. Next, we grouped the codes to search for initial themes in the data, which we then reviewed across the entire dataset.

[1]https://otter.ai/

We named and defined the themes in an iterative fashion until the overall story communicated by the themes was clear. Our report of the themes is found in the next section.

3.5 Participants

We recruited 10 participants from two AR/VR research labs at our university (3 identified as women and 7 identified as men; ages between 22 and 31, $M = 28.4$, $SD = 4.1$; 1 undergraduate student, 1 post-doctoral researcher, 1 lab manager, and 7 PhD students). As these participants were co-workers with the experimenters and comprise a small sample size, we consider this experiment a pilot study that we intend to run as a full study in the near future.

4 Results

In this section, we present the quantitative and qualitative results of our experiment.

4.1 Quantitative Results

In this section, we report the results of our statistical tests. We plan to collect a larger sample in the future to gain greater statistical power and test hypotheses relating to participants' interruption experiences and behaviors.

4.1.1 Interruption Experience

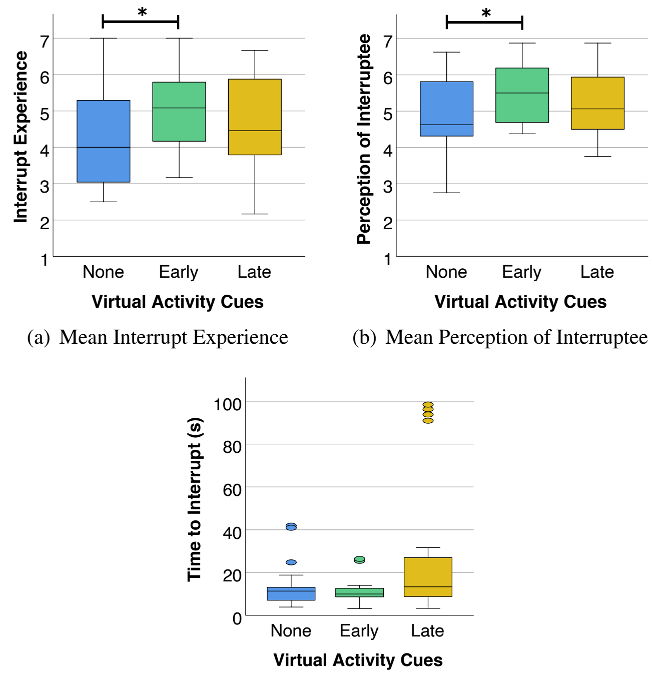
Fig. 3 shows the aggregated means for our *Interrupt Experience* and *Perception of Interruptee* sub-scales of the cross-reality interruption experience questions when participants saw no Virtual Activity Cues (VAC-None), immediately saw the low Virtual Activity Cues (VAC-Early), or first saw the medium Virtual Activity Cues (VAC-Late). We found a significant effect of Virtual Activity Cues on *Perception of Interruptee*, $F(2,16) = 6.6$, $p = 0.008$, $\eta_p^2 = 0.102$. Additionally, post-hoc tests show there was a significant difference in *Perception of Interruptee* ($p = 0.034$) between the VAC-None and VAC-Early conditions. The effect of Virtual Activity Cues on *Interrupt Experience* sub-scale was not significant, $F(2,16) = 3.6$, p=0.051, $\eta_p^2 = 0.101$. Because the p-value was close to significant for our limited sample size, we ran pairwise comparison tests, and we found a significant difference in *Interrupt Experience* ($p = 0.024$) between VAC-None and VAC-Early. There were no significant effects of Gesture System on the interrupter's experience.

4.1.2 Interrupt Timing

We measured the *Time to Interrupt* of each interruption as the amount of time from when participants removed their VR HWD to the moment they interrupted the VR researcher. A boxplot showing the *Time to Interrupt* by Virtual Activity Cues is shown in Fig. 3. We did not find significant effects of Gesture System on *Time to Interrupt*, $\chi^2(1) = 0.533, p = 0.47$. We did not find a significant difference between VAC-None and VAC-Early, $\chi^2(1) = 3.2, p = 0.074$ or between VAC-None and VAC-Late, $\chi^2(1) = 1.8, p = 0.180$. We observed that two participants waited for the Virtual Activity Cues to turn green before interrupting the co-worker, leading to long times of over 90 seconds to interrupt in the VAC-Late condition. Their four experimental trial data points for the VAC-Late condition are the outliers shown in the upper right of Figure Fig. 3(c). The other participants interrupted at similar times for all trials, regardless of the color of the lights.

4.2 Qualitative Findings

Interrupters' mental state attribution is inhibited by VR HWDs In social interactions, people develop a *theory of mind*, or attribute mental states to others. Two participants reported relying solely on the Virtual Activity Cues to assess the co-worker's interruptibility, and the other eight participants expressed difficulties related to fully understanding the co-worker's state of mind. These eight participants reported trouble understanding both the co-worker's (a) cognitive load or engagement in their task and (b) awareness of the interrupter. In the first group, two participants reported being confused by the LED cues because they perceived a conflict between the VR user's physical movements and the activity level reported. The other six participants in this group noted a desire to see the VR user's eye gaze to help assess how engaged he was with his virtual task. In the second group, five participants reported a desire for feedback from the interruption system when they interacted using the Gesture System because they wanted to know the VR user was aware of their presence. Of the eight participants reporting difficulty attributing an aspect of the VR user's mental state, three participants appreciated having additional information about the co-worker's activity provided by the Virtual Activity Cues.



(a) Mean Interrupt Experience (b) Mean Perception of Interruptee (c) Time to Interrupt

Figure 3: Quantitative results. Boxplots of (a) Interrupt Experience, and (b) Perception of Interruptee sub-scales of the interruption experience questions (higher is better), and (c) Time to Interrupt by Virtual Activity Cues. The whiskers indicate post-hoc test results (* p<0.05).

5 Discussion

Cross-reality interactions are socially complex. Our results suggest that VR complicates workplace cross-reality interruptions because the device inhibits interrupters in forming a theory of mind [2] by preventing interrupters from making confident judgments about the VR user's activity and interruptibility. While it has been reported that in-the-wild VR users do not find cross-reality interruptions to be very disruptive [35], our results suggest that the barriers of VR devices impair how interrupters may interact with VR users. Prior work has shown that interrupters can identify good times to interrupt based on task switches [9]. However, our study involved a VR user engaged in a virtual activity that did not elicit many physical cues that could be used to determine when the user switched tasks.

The Gesture System did not improve this interaction as other research has suggested [11,45]. Several participants found it interesting, but did not trust it to work at first, so a novelty effect [42] could explain its insignificant effects. Other research has found that interrupters of VR users are comfortable interrupting using their voice [33,35], so participants may not desire a gesture-based system.

Even in their simple state of showing the user's activity level as a proxy for interruptibility in the form of lights varied in three different colors, our results suggest Virtual Activity Cues are beneficial for filling in some of the interpersonal gaps created by the HWD. However, participants interpreted both the cues and urgency of their interruption task differently. Some used the VR user's slight physical movements to judge his activity level in addition to the LED cues, which at times led to internal conflict about the interruption process. Additionally, some participants interpreted the yellow cues as a good time to interrupt, while others only interrupted when they were green. It would be interesting to study how participants' decisions to interrupt would change if the yellow "moderate" activity cue were eliminated from the Virtual Activity Cues prototype entirely. Further, it is necessary to more broadly and deeply analyze participants' rationale for deciding when to interrupt.

Limitations and Future Work One limitation of our study is the sample: our small group of participants all have regular experience with VR and were personally familiar with the experimenters. All participants work in the AR/VR research space, and 8 out of 10 of them were students. Relatedly, our experiment suffers from demand characteristics [6], meaning participants were more likely to offer positive feedback about the interruption facilitation prototype we introduced than negative feedback. While it will be difficult to remove demand characteristics from the experiment entirely, a larger and more diverse sample may offset them. Because most cross-reality interruptions tend to occur between people who know each other [35], we plan to recruit participants in pairs similar to related interruption studies [33]. To ensure ecological validity of the study, we will recruit pairs that work together.

Additionally, we plan to refine our experimental design to focus solely on the cues about the virtual world rather than including the gesture-based interruption mechanism. This design space for communicating VR user interruptibility remains large. There are several open research questions regarding the level of virtual context information interrupters desire, the best ways to communicate that information, how interrupters use it in their interruption process, and trade-offs with VR users' privacy. In this preliminary study, we chose to simulate simple VR user activity patterns. These are not representative of all VR user activity patterns, so our planned future work includes more variations in the order and duration for which different cues are shown (e.g., cues that show high activity immediately, and cues that transition between different activity levels more frequently). Moreover, several participants noted that it was difficult to tell the difference between green and yellow LED lights on the Virtual Activity Cues system. Perception studies on color sensitivity offer a possible explanation for this in that the color yellow is the least attention-grabbing color, and green is the most [8, 34]. In future studies, we may test a different color scheme and try communicating the virtual activity level in another dimension as well. For example, there could be three rows of lights stacked on top of each other on the front of the HWD, and each row could be responsible for a certain activity level, similar to a stoplight. This design would also make the Virtual Activity Cues more accessible to people who are color blind.

Last, some of the measures used in this study had limitations. Specifically, a stopwatch was used to record participants' time to interrupt, so the timing data should be considered approximate. Our future user study will consider the timing data alongside behavioral observations to better capture participants' hesitancy when interrupting. Also, the questions used to capture participants' subjective cross-reality interruption experience are not validated. Constructing a validated cross-reality interruption questionnaire is an opportunity for future research and may be useful to the research community given the demonstrated interest in such interactions.

6 CONCLUSION

As VR devices are used by more people and for longer durations, it is important to understand how certain social norms will be affected. In this paper, we present a 2×3 within-subjects experimental design user study (N=10) to study the complications of cross-reality interruptions of VR users and how such complications may be ameliorated. We tested different interruption interfaces and found that the Virtual Activity Cues were helpful in facilitating interruptions of VR users, as they provided access to contextual information about the VR user that is obscured by the hardware. We also found that the VR HWD occludes common contextual cues about the VR user's interruptibility, which in turn inhibits an interrupter's theory of mind, or their social ability to attribute mental states to another person. Because interruptions are interpersonal interactions, there are differences in how people interpret interruptibility and decide to interrupt. This work is an important step in understanding the interpersonal complications and trade-offs involved in cross-reality workplaces where traditional social norms face challenges.

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REFERENCES

[1] H. Baker. Oculus Quest 2 'Space Sense' Guardian Intrusion Feature Found in v32 Firmware. https://uploadvr.com/space-sense-quest-2/, September 13, 2021. [Accessed 2021-10-22].

[2] S. Baron-Cohen. Precursors to a theory of mind: Understanding attention in others. *Natural theories of mind: Evolution, development and simulation of everyday mindreading*, 1:233–251, 1991.

[3] V. Braun and V. Clarke. Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2):77–101, 2006.

[4] G. Bruder, F. Steinicke, K. Rothaus, and K. Hinrichs. Enhancing Presence in Head-Mounted Display Environments by Visual Body Feedback Using Head-Mounted Cameras. In *Proceedings of the International Conference on CyberWorlds*, pp. 43–50, 2009.

[5] E. Dao, A. Muresan, K. Hornbæk, and J. Knibbe. Bad breakdowns, useful seams, and face slapping: Analysis of VR fails on YouTube. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2021.

[6] N. Dell, V. Vaidyanathan, I. Medhi, E. Cutrell, and W. Thies. "Yours is better!": Participant response bias in HCI. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems*, CHI '12, p. 1321–1330. Association for Computing Machinery, New York, NY, USA, 2012.

[7] J. Durbin. Vive 'knock knock' lets you know people in the real world still care about you. https://uploadvr.com/new-knock-knock-feature-lets-you-know-someone-needs-attention/, May 16, 2016. [Accessed 2021-03-15].

[8] S. Etchebehere and E. Fedorovskaya. On the role of color in visual saliency. *Electronic Imaging*, 2017(14):58–63, 2017.

[9] C. George, P. Janssen, D. Heuss, and F. Alt. Should I interrupt or not? Understanding interruptions in head-mounted display settings. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, pp. 497–510, 2019.

[10] C. George, A. N. Tien, and H. Hussmann. Seamless, bi-directional transitions along the reality-virtuality continuum: A conceptualization and prototype exploration. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality*, pp. 412–424, 2020.

[11] S. Ghosh, L. Winston, N. Panchal, P. Kimura-Thollander, J. Hotnog, D. Cheong, G. Reyes, and G. D. Abowd. NotifiVR: Exploring interruptions and notifications in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1447–1456, 2018.

[12] M. Gottsacker. Balancing Realities by Improving Cross-Reality Interactions. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 944–945. IEEE, 2022.

[13] M. Gottsacker, N. Norouzi, K. Kim, G. Bruder, and G. Welch. Diegetic Representations for Seamless Cross-Reality Interruptions. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 310–319. IEEE, 2021.

[14] P. Green and L. Wei-Haas. The Rapid Development of User Interfaces: Experience with the Wizard of Oz Method. In *Proceedings of the Human Factors Society—29th ANNUAL MEETING*, pp. 470–474, 1985.

[15] J. Gugenheimer, D. Dobbelstein, C. Winkler, G. Haas, and E. Rukzio. FaceTouch: Enabling touch interaction in display fixed UIs for mobile virtual reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pp. 49–60, 2016.

[16] J. Gugenheimer, E. Stemasov, J. Frommel, and E. Rukzio. ShareVR: Enabling co-located experiences for virtual reality between hmd and non-hmd users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 4021–4033, 2017.

[17] J. Gugenheimer, E. Stemasov, H. Sareen, and E. Rukzio. Facedisplay: Towards asymmetric multi-user interaction for nomadic virtual reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–13, 2018.

[18] J. Hartmann, C. Holz, E. Ofek, and A. D. Wilson. RealityCheck: Blending virtual environments with situated physical reality. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems*, pp. 347:1–12, 2019.

[19] D. Heaney. Valve index now has 3D-correct camera passthrough. `https://uploadvr.com/valve-index-room-view-3d`, June 19, 2020. [Accessed 2021-10-22].

[20] D. Hepperle, A. Siess, and M. Wölfel. Staging Virtual Reality Exhibits for Bystander Involvement in Semi-public Spaces. In A. Brooks and E. I. Brooks, eds., *Interactivity, Game Creation, Design, Learning, and Innovation*, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, pp. 261–272. Springer International Publishing, 2020.

[21] Y. Kudo, A. Tang, K. Fujita, I. Endo, K. Takashima, and Y. Kitamura. Towards balancing VR immersion and bystander awareness. *Proc. ACM Hum. Comput. Interact.*, 5(ISS):1–22, 2021.

[22] B. Lang. Quest is getting a third-person spectator view for casting. `https://www.roadtovr.com/oculus-quest-third-person-spectator-view-camera-casting/`, June 4, 2021. [Accessed 2022-06-20].

[23] B. Lang. Vive focus 2.0 update brings bevy of new features: Phone mirroring, pass-through video & more. `https://www.roadtovr.com/vive-focus-system-update-2-0-phone-mirroring-pass-through-video-and-more`, May 27, 2018. [Accessed 2021-10-22].

[24] M. Lee, N. Norouzi, G. Bruder, P. J. Wisniewski, and G. F. Welch. The physical-virtual table: Exploring the effects of a virtual human's physical influence on social interaction. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, pp. 25:1–11, 2018.

[25] C. Mai, S. A. Bartsch, and L. Rieger. Evaluating shared surfaces for co-located mixed-presence collaboration. In *Proceedings of the International Conference on Mobile and Ubiquitous Multimedia*, p. 1–5, 2018.

[26] C. Mai, L. Rambold, and M. Khamis. TransparentHMD: revealing the HMD user's face to bystanders. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*, pp. 515–520, 2017.

[27] N. Matsuda, B. Wheelwright, J. Hegland, and D. Lanman. Reverse Pass-Through VR. In *ACM SIGGRAPH 2021 Emerging Technologies*, pp. 1–4. 2021.

[28] M. Mcgill, D. Boland, R. Murray-Smith, and S. Brewster. A dose of reality: Overcoming usability challenges in VR head-mounted displays. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems*, pp. 2143–2152, 2015.

[29] M. McGill, J. Gugenheimer, and E. Freeman. A quest for co-located mixed reality: Aligning and assessing SLAM tracking for same-space multi-user experiences. In *26th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–10, 2020.

[30] D. Medeiros, R. dos Anjos, N. Pantidi, K. Huang, M. Sousa, C. Anslow, and J. Jorge. Promoting reality awareness in virtual reality through proxemics. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 21–30. IEEE, 2021.

[31] Oculus. Oculus release notes. `https://support.oculus.com/release-notes/`, March 23, 2020. [Accessed 2021-03-15].

[32] J. O'Hagan and J. R. Williamson. Reality aware VR headsets. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays*, pp. 9–17, 2020.

[33] J. O'Hagan, J. R. Williamson, and M. Khamis. Bystander interruption of VR users. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays*, PerDis '20, p. 19–27. Association for Computing Machinery, New York, NY, USA, 2020.

[34] N. Olguntürk, C. Yener, and D. Guvenc. Effects of hue, saturation, and brightness: Part 2 - attention. *Color Research & Application*, 29:20 – 28, 12 2003.

[35] J. O'Hagan, J. R. Williamson, M. McGill, and M. Khamis. Safety, power imbalances, ethics and proxy sex: Surveying in-the-wild interactions between VR users and bystanders. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 211–220. IEEE, 2021.

[36] A. Peña-Ríos, V. Callaghan, M. Gardner, and M. J. Alhaddad. Using mixed-reality to develop smart environments. In *Proceedings of the International Conference on Intelligent Environments*, pp. 182–189, 2014.

[37] T. Piumsomboon, Y. Lee, G. Lee, and M. Billinghurst. CoVAR: a collaborative virtual and augmented reality system for remote collaboration. In *SIGGRAPH Asia 2017 Emerging Technologies*, pp. 1–2. 2017.

[38] D. F. Reilly, H. Rouzati, A. Wu, J. Y. Hwang, J. Brudvik, and W. K. Edwards. TwinSpace: An infrastructure for cross-reality team spaces. In *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology*, p. 119–128, 2010.

[39] A. L. Simeone. The VR motion tracker: visualising movement of non-participants in desktop virtual reality experiences. In *Proceedings of the IEEE Workshop on Everyday Virtual Reality*, pp. 1–4, 2016.

[40] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1535):3549–3557, 2009.

[41] F. Steinicke, G. Bruder, K. H. Hinrichs, and A. Steed. Gradual transitions and their effects on presence and distance estimation. *Computers & Graphics*, 34:26–33, 2010.

[42] J. Sung, H. I. Christensen, and R. E. Grinter. Robots in the wild: Understanding long-term use. In *Proceedings of the 4th ACM/IEEE International Conference on Human Robot Interaction*, HRI '09, p. 45–52. Association for Computing Machinery, New York, NY, USA, 2009.

[43] S. Thanyadit, P. Punpongsanon, and T.-C. Pong. ObserVAR: Visualization system for observing virtual reality users using augmented reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 258–268. IEEE, 2019.

[44] J. von Willich, M. Funk, F. Müller, K. Marky, J. Riemann, and M. Mühlhäuser. You invaded my tracking space! using augmented virtuality for spotting passersby in room-scale virtual reality. In *Proceedings of the ACM Conference on Designing Interactive Systems*, p. 487–496, 2019.

[45] J. R. Williamson, M. McGill, and K. Outram. PlaneVR: Social acceptability of virtual reality for aeroplane passengers. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems*, p. 1–14, 2019.

[46] A. Zenner, M. Speicher, S. Klingner, D. Degraen, F. Daiber, and A. Krüger. Immersive notification framework: Adaptive & plausible notifications in virtual reality. In *Extended Abstracts of the ACM CHI Conference on Human Factors in Computing Systems*, p. 1–6, 2018.