



## Blowing in the Wind: Increasing Social Presence with a Virtual Human via Environmental Airflow Interaction in Mixed Reality

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### ARTICLE INFO

#### Article history:

Received June 6, 2019

**Keywords:** Mixed Reality, Augmented Reality, Virtual Humans, Social Presence, Copresence, Physical-Virtual Interaction, Environment-Aware Behavior, Airflow, Physical-Virtual Coherence, User Study

### ABSTRACT

In this paper, we describe two human-subject studies in which we explored and investigated the effects of subtle multimodal interaction on social presence with a virtual human (VH) in mixed reality (MR). In the studies, participants interacted with a VH, which was co-located with them across a table, with two different platforms: a projection based MR environment and an optical see-through head-mounted display (OST-HMD) based MR environment. While the two studies were not intended to be directly comparable, the second study with an OST-HMD was carefully designed based on the insights and lessons learned from the first projection-based study. For both studies, we compared two levels of gradually increased multimodal interaction: (i) virtual objects being affected by real airflow (e.g., as commonly experienced with fans during warm weather), and (ii) a VH showing awareness of this airflow. We hypothesized that our two levels of treatment would increase the sense of being together with the VH gradually, i.e., participants would report higher social presence with airflow influence than without it, and the social presence would be even higher when the VH showed awareness of the airflow. We observed an increased social presence in the second study when both physical–virtual interaction via airflow and VH awareness behaviors were present, but we observed no clear difference in participant-reported social presence with the VH in the first study. As the considered environmental factors are incidental to the direct interaction with the real human, i.e., they are not significant or necessary for the interaction task, they can provide a reasonably generalizable approach to increase social presence in HMD-based MR environments beyond the specific scenario and environment described here.

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### 1. Introduction

The sense of *social presence* or *copresence*—one's sense of “being (socially) connected” or “being together”—is an important concept in most research on natural social interaction between real and virtual humans (VHs), which investigates the social influence that VHs can exert over users [1]. To increase the

sense of social presence with VHs, researchers have primarily focused on improving the visual/aural fidelity of the VH, e.g., its appearance [2] and verbal behaviors [3]. However, the surroundings in the space where the interlocutors, i.e., a VH and a real human, interact with each other could be also a significant factor influencing the sense of social presence. In this manner, Allwood considered that the environment is the fourth major parameter that characterizes a social activity (after purpose, roles, and instrumentation) [4].

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1 The physical environment is particularly important in mixed  
 2 reality (MR), where virtual content is visually merged with  
 3 the real-world surroundings. In such environments, humans  
 4 can expect natural and seamless interaction between the virtual  
 5 content and the physical environment. For instance, Microsoft's HoloLens addresses this challenge by employing a re-  
 6 constructed virtual representation of the surrounding physical  
 7 environment [5]. On top of the spatial coherence between virtual  
 8 content (including VHs) and the physical environment [6],  
 9 our goal is to explore and understand how and in what ways the  
 10 surrounding environment is contributing to human perception  
 11 of natural interaction and whether we can leverage any such  
 12 knowledge to increase the sense of social presence with VHs.

13 Related work by Lee et al. [7] suggests that subtle movements  
 14 of a computer-mediated physical object between real humans  
 15 and a VH can improve their sense of social presence. In  
 16 their experiment, they used a wobbly table which spanned the  
 17 real and virtual spaces so that participants could see and feel  
 18 movements of the table caused by the VH and also cause it to  
 19 move. Although this is a prime example of physical–virtual  
 20 influence, in order to generalize this approach it would be im-  
 21 portant to understand if similar effects can be induced via sub-  
 22 tler environmental events, such as those that are merely observ-  
 23 able but which a real human would not actively participate in  
 24 or directly interact with. Also, despite the positive results, there  
 25 was still some ambiguity as to which aspect of the wobbly table  
 26 setup was causing the increase in social presence; it could have  
 27 been the tight physical–virtual connectivity via visual-motor  
 28 synchrony, but it also could have been the VH's reactive behav-  
 29 iors exhibiting awareness of the wobbling. Thus, we want to  
 30 further investigate the possible effects of subtle environmental  
 31 physical–virtual interaction on social presence in real–virtual  
 32 human interactions using the following two conditions:

- 34 • the virtual world is affected by events in the real world  
 35 related to airflow caused by a physical fan, and
- 36 • the virtual human shows non-verbal awareness of the real-  
 37 world airflow.

38 Here, we present two human-subject studies with real–virtual  
 39 human interactions involving airflow influence and VH aware-  
 40 ness in two different MR platforms: a wide screen with rear-  
 41 projected imagery and an optical see-through head-mounted  
 42 display (OST-HMD). We analyzed the effects of increasing  
 43 the physical–virtual connectivity via subtle airflow and isolated  
 44 the perceptual effects of the physical–virtual connectivity from  
 45 those of the VH's environmentally aware behavior, which in-  
 46 cluded both looking toward the physical fan and holding down  
 47 a fluttering piece of virtual paper. In the first study with a pro-  
 48 jection screen, we did not observe any statistically significant  
 49 effects on social presence [8]. We identified several possible  
 50 reasons for this, such as less participant attention towards the  
 51 environment compared to the interaction scenario—a practice  
 52 job interview—and the clear distinction between the virtual and  
 53 real worlds established by the projection screen. Taking into  
 54 consideration the lessons learned from the first study, we de-  
 55 veloped a second study, where the virtual and physical worlds  
 56 were more seamlessly visually connected through a Microsoft  
 57 HoloLens HMD. Here, we observed significant differences in

58 social presence due to airflow influence and VH awareness.  
 59 While both studies were designed to measure the effects of sub-  
 60 tle environmental physical–virtual interaction on the perceived  
 61 social presence with a VH, the two studies were not intended to  
 62 be directly comparable—instead, we made deliberate changes  
 63 to the second study based on insights and lessons learned from  
 64 the first.

65 This paper is an extended version of a conference paper  
 66 that received the Honorable Mention Award at the International  
 67 Conference on Artificial Reality and Telexistence and Euro-  
 68 graphics Symposium on Virtual Environments 2018 [9]. The  
 69 rest of the paper is structured as follows. Section 2 provides  
 70 background information on social presence, airflow influence in  
 71 physical–virtual worlds, and environmental awareness of VHs.  
 72 Section 3 describes the first study with a projection-based MR  
 73 environment and presents the results along with related discus-  
 74 sion. Likewise, details of the second study with an OST-HMD-  
 75 based MR environment are described and the results are dis-  
 76 cussed in Section 4. Finally, we close the paper with our con-  
 77 clusions across both studies in Section 5.

## 2. Related Work

78 This section provides background information on definitions  
 79 of social presence and related concepts, the sense of airflow in  
 80 virtual environments, and environment-aware behavior of VHs.  
 81

### 2.1. Copresence, Social Presence, and Presence

82 There is an ongoing debate in the research community about  
 83 precise definitions for *social presence* and *copresence*, as dis-  
 84 tinct from the concept of *presence*, while some use the concepts  
 85 interchangeably. While presence usually refers to one's sense of  
 86 “being there” in a virtual environment, the concepts of copres-  
 87 ence and social presence might be described more specifically  
 88 as how one perceives another human's presence in a sense of  
 89 “being together,” and how much one feels “socially connected”  
 90 to the other. These concepts of social presence and copresence  
 91 are an important measure of how virtual humans are perceived  
 92 and have been extensively researched [10, 11, 12].

93 Oh et al. distinguished the concept of social presence  
 94 from two other concepts of presence—telepresence and self-  
 95 presence—and tried to tease out what factors could influence  
 96 the perceived social presence by analyzing hundreds of pa-  
 97 pers in virtual reality and computer-mediated communication  
 98 fields [13]. Zhao pointed out the confusion of different copres-  
 99 ence concepts and tried to differentiate them [14]. He consid-  
 100 ered human copresence in two aspects: “the physical conditions  
 101 in which human individuals interact and the perceptions and  
 102 feelings they have of one another.” Each of these aspects might  
 103 be complementary to each other to determine one's perceived  
 104 sense of copresence with a VH during an interaction. Slater ad-  
 105 dressed an important concept for presence, called *plausibility*  
 106 *illusion* (*Psi*). *Psi* “refers to the illusion that the scenario be-  
 107 ing depicted is *actually occurring*,” which “requires a credible  
 108 scenario and plausible interactions between the participant and  
 109 objects and virtual characters *in the environment*” (emphases

1 added) [15]. Due to the nature of Psi as it relates to interactions  
 2 between real and virtual objects and humans, it could be highly related to the concepts of social presence and copresence as well. Harms and Biocca considered copresence as one of several sub-dimensions that embody social presence [16], and Blascovich et al. defined social presence both as a “psychological state in which the individual perceives himself or herself as existing within an *interpersonal environment*” (emphasis added) and “the degree to which one believes that he or she is in the presence of, and dynamically interacting with, other veritable human beings” [11, 17].

12 Considering the definitions addressed above, we expect that the plausibility of the context and the surrounding environment  
 13 where the social interaction takes place could be important factors in the sense of social presence or copresence, for example, due to enhanced mutual awareness [18] or a shared interpersonal environment [11, 17].

## 18 2.2. Physical–Virtual Influences via Airflow

19 Previously, airflow has been introduced as a tactile modality that can increase the sense of presence in a virtual environment  
 20 by associating one’s physical feeling of wind in the real space with the context in that virtual environment. For example, Dinh et al. evaluated multimodal (including wind) effects on presence and memory while navigating a virtual environment, and found significant improvements on both variables [19]. Moon et al. developed the “WindCube,” which consists of multiple small fans in a frame, allowing users to feel the wind while experiencing a virtual environment [20]. Similarly, Hülsmann et al. implemented a multimodal CAVE system employing the sense of wind and warmth, and suggested a positive influence on the sense of presence [21]. Also, Feng et al. used wind along with vibration cues in a virtual navigating scenario using an HMD [22]. Lehmann et al. conducted a user study about the sense of presence while experiencing a ski simulation with wind sensations [23], and they reported a higher sense of presence with the wind. Deligiannidis et al. investigated the relationship between the wind sensation and user task performance using a scooter riding simulation, “VR Scooter,” in virtual reality (VR) [24]. They found that participants completed the riding task faster and reported more positive user experience when they experienced the virtual scooter simulation with wind sensations.

43 Although there is some previous work supporting the positive effects of airflow on perceived presence and task performance in VR, there is still a lack of research about the effects of airflow on the sense of social presence with VHs, particularly in MR. We believe it could be beneficial to increase the sense of social presence with VHs by achieving a tight physical–virtual connection via airflow that influences both virtual and real objects in an MR environment, and we investigate how subtle and indirect experience of such an airflow can affect the sense of social presence with a VH. For example, users might report a higher sense of social presence with a VH when they observe real wind blowing virtual objects in a shared MR environment, which could be visually plausible as well as induce an impression that the VH might have the same perception of the wind as the real human.

## 2.3. Virtual Humans and Environmentally Aware Behavior

VHs are used in many social interaction settings, such as educational, medical, or interview training scenarios. For instance, Dieker et al. made use of several virtual characters to train prospective teachers [25]. Chuah et al. developed interactive VHs with a physical lower body for medical training and concluded that increasing the physicality of VHs could increase social presence [11]. Rizzo et al. evaluated a fully autonomous VH platform called “SimSensei” that could recognize a user’s verbal and nonverbal behaviors for identifying mental illnesses, and showed its potential in different medical and military applications [26]. Huang et al. developed the “Rapport Agent,” which could interact with users autonomously, for an interview scenario, and measured the level of social presence with the VH as a rapport measure [12]. Hoque et al. used an interactive and expressive VH and showed its effectiveness in practicing job interviews [27]. Many VHs, including the examples above, are displayed on TV or projection screens, and some researchers have investigated approaches for adding user interactivity with VHs in other modalities, e.g., detecting touches on the VH’s face and rendering responsive VH behaviors [28]. Although previous research has shown promising results, the level of social presence with VHs is still very different from that between real humans.

To make up the gap, researchers and practitioners have primarily focused on improving the visual and aural fidelity of VHs, e.g., appearance [2] and verbal behaviors [3]. However, a VH’s nonverbal behaviors, such as expressing awareness of objects or events in the *physical* space, could also potentially enhance the physical–virtual connection and be perceived as a plausible reaction in MR environments. For example, Andrist et al. presented bidirectional gaze between a VH and a user and towards physical objects on a table, while interacting with the VH [29], and found that the gaze behavior supported more effective communication. Similarly, Kim et al. evaluated a VH’s joint attention and gaze behavior with participants’ expectations and found increased social presence [30]. Kim et al. found that a VH exhibiting awareness of the surrounding environment and influencing physical objects, e.g., appearing to turn on a real lamp, could improve the trustworthiness of the VH and the user’s perceived social presence with it [31].

This environmentally aware behavior in physical environments tends to be overlooked in VHs in augmented and virtual reality due to the nature of virtuality (i.e., lack of physicality); however, VHs that exhibit awareness of the physical surrounding objects and events in MR might be perceived as more compelling and increase the sense of social presence.

## 3. Experiment I: Virtual Human on a Projection Screen

We seek to emphasize the inter-space physical–virtual connection through a different modality than the traditional visual and aural senses, possibly exceeding one’s expectation for virtual content in a real environment. To this end, we conducted two user studies to explore the influence of environmental events on social interaction between real and virtual humans in different MR settings.

1 The intent of these experiments was to explore how and in  
 2 what ways the surrounding environment can be an important  
 3 factor in human perceptions of interactions with VHs. We also  
 4 seek to leverage any knowledge gained to increase the sense  
 5 of social presence with VHs. For both studies, we specifically  
 6 tested two different treatments to see the effects on social pres-  
 7 ence: (i) enhanced physical–virtual connectivity/influence via  
 8 a *real* fan blowing on *virtual* objects such as a virtual piece  
 9 of paper and virtual curtains, and (ii) the VH’s corresponding  
 10 *awareness* of the environmental factor as she looks at the fan  
 11 and holds a fluttering piece of paper.

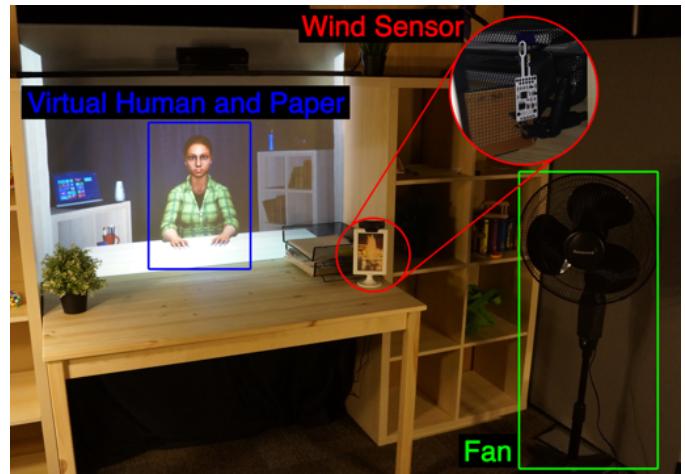
12 In this section, we describe the first study, which was con-  
 13 ducted in a projector-based MR environment where the VH  
 14 and virtual environment were displayed via a wide projection  
 15 screen. The second study, which incorporates lessons from the  
 16 first study, will be described in Section 4.

### 17 3.1. Materials

18 For the study, we implemented a female VH, “Katie,” who  
 19 could speak with the participants and perform upper torso ges-  
 20 tures (e.g., hand and head gestures). The VH was rear-projected  
 21 onto a screen in an office-like MR space as shown in Figure 1. The physical part of the table was positioned in front  
 22 of the screen, creating a visual impression of facing a seated  
 23 VH across the table. The physical table has a virtual coun-  
 24 terpart that visually extended from the physical table into the  
 25 (virtual) environment of the VH; thus, the virtual and physical  
 26 parts of the table appeared to be a single table. For the VH’s  
 27 idle posture she had both hands on the table, and a virtual sheet  
 28 of paper was also on the table. A physical rotating fan was  
 29 placed alongside the table so that the wind from the fan would  
 30 blow towards the virtual paper. We hid a wind sensor (Modern  
 31 Device Wind Sensor Rev. P<sup>1</sup>) connected to an Arduino board  
 32 behind a small photo frame to detect the wind from the fan (red  
 33 circles in Figure 1), so that the virtual paper could flutter ac-  
 34 cording to the actual wind. The sensor we used can measure a  
 35 wide range of wind speeds (0–150 MPH), and there was no no-  
 36 ticeable delay between the wind sensing and the animation trig-  
 37 gering. Hence, this approach could provide higher fidelity and  
 38 realism than with more crude setups, e.g., based on tracking the  
 39 fan’s pose alone. Cloth physics simulation in Unity3D was used  
 40 to render the fluttering animations as naturally as possible. The  
 41 VH was controlled by an experimenter (Wizard-of-Oz) behind  
 42 the screen using GUI buttons, which the experimenter could  
 43 use to trigger pre-defined verbal and nonverbal behaviors. The  
 44 VH had neutral and pleasant facial expressions throughout the  
 45 interaction.

### 47 3.2. Method

48 We designed a between-subjects study with three different  
 49 groups: (i) **Control**, (ii) Physical–Virtual Influence (**PVI**), and  
 50 (iii) Environment-Aware Behavior (**EAB**). For the **PVI** group,  
 51 a virtual sheet of paper on the table in front of the VH appeared



52 **Fig. 1. Experimental setup for the first study.** Participants were seated  
 53 opposite from a virtual human on a physical-virtual table. A physical fan  
 54 was placed next to the table but close to where the participants were seated,  
 55 and a wind sensor was hidden behind a small photo frame to detect airflow  
 56 that induced a state of fluttering in the virtual paper.

57 **Table 1. Description of experimental groups: Control, Physical–Virtual In-  
 58 fluence (PVI), and Environment-Aware Behavior (EAB).**

Group	Physical Fan	Virtual Paper Fluttering	Virtual Human’s Awareness Behavior
Control	ON	NO	NO
PVI	ON	YES	NO
EAB	ON	YES	YES

59 to flutter as a result of the physical fan that was located next to  
 60 the participant during the interaction. The physical fan blowing  
 61 the virtual paper was chosen as a subtle environmental event to  
 62 strengthen the connection between physical and virtual spaces,  
 63 and potentially influence the sense of social presence with the  
 64 VH. For the **EAB** group, the VH would additionally occasionally  
 65 exhibit attention toward the fan’s effects by looking at it or  
 66 holding down the virtual piece of paper to stop it from fluttering.  
 67 For the **Control** group, the paper did not flutter and the  
 68 VH never demonstrated any awareness of the physical fan. For  
 69 all groups, participants had a conversational interaction (a sim-  
 70 ple practice job interview) with the VH. The three groups are  
 71 briefly described in Table 1 and illustrated in Figure 2.

### 72 3.3. Participants

73 We recruited participants within our university community.  
 74 31 undergraduate/graduate students participated in the exper-  
 75 iment (Control: 10, PVI: 10, and EAB: 11). The participants  
 76 were 9 females and 22 males (age M: 22.35, SD: 3.36, range:  
 77 18–29). All participants received fifteen US dollars for their  
 78 participation (duration: 30 min).

### 79 3.4. Procedure

80 When participants arrived, we guided them to a question-  
 81 naire area. They were requested to read the informed con-  
 82 sent and fill out a demographics questionnaire. We explained  
 83 that they would have a practice job interview with a VH inter-  
 84 viewer, “Katie,” and they would play the role of an interviewee.

<sup>1</sup><https://moderndevice.com/product/wind-sensor-rev-1/>  
 (Accessed 2019-02-21)



**Fig. 2. Experimental groups. (A) Control, (B) PVI (red circle: fluttering virtual paper), and (C) EAB (blue circle: looking at the fan, blue rectangle: holding the paper gesture).**

1 We showed them five generic questions extracted from [27]—  
 2 for example, “tell me about yourself”—that the VH interviewer  
 3 would be asking, and let them prepare their answers for five  
 4 minutes. We did not have any specific job position for this  
 5 study, so the participants were allowed to imagine their own  
 6 ideal jobs, and we instructed them to practice their answers  
 7 without worrying about their performance. Before the inter-  
 8 view interaction, participants watched a video clip of a peace-  
 9 ful water stream for about one minute to relax. Once we began  
 10 recording audio and video, the participants entered the exper-  
 11 iment room and conducted a practice job interview with the  
 12 VH. The participants were randomly assigned to one of the  
 13 three experimental groups (either Control, PVI, or EAB). Af-  
 14 ter the interview completed, the participants were requested to  
 15 complete a post-questionnaire, which asked questions related  
 16 to their perceived social presence with the VH. When they fin-  
 17 ished the post-questionnaire, they received monetary compen-  
 18 sation of fifteen dollars for their participation.

### 19 3.5. Social Presence Measures and Hypotheses

20 To measure the participants’ sense of social presence, we  
 21 used two different Social Presence questionnaire sets from  
 22 Bailenson et al. [32] and Harms and Biocca [16]. While Bailen-  
 23 son et al.’s questionnaire is relatively concise (five questions)  
 24 and it tends to cover the VH’s authenticity/realism as well as the  
 25 sense of “being together,” for example, one of the questions is  
 26 “The person appears to be sentient, conscious, and alive to me.”  
 27 Harms and Biocca’s questionnaire is more sophisticated, with  
 28 six sub-dimensions that together characterize the overall social  
 29 presence level by focusing on the quality of computer-mediated  
 30 communication. The sub-dimensions are copresence, atten-  
 31 tional allocation, perceived message understanding, perceived  
 32 emotional understanding, perceived behavioral independence,  
 33 and perceived emotional independence. Participants were asked  
 34 all questions in seven-point Likert scales, and we used the aver-  
 35 aged score as a representative score of social presence.

36 We hypothesized that the level of social presence for each  
 37 group would be different. For example, the social presence  
 38 for the PVI group will be higher than the one for the Control  
 39 group, and the level of social presence for the EAB group will  
 40 be even higher than the one for the PVI group, i.e., Control <<  
 41 PVI < EAB. We expected the VH’s gaze direction changes and

**Table 2. Descriptives for social presence responses.**

Group	N	Bailenson et al.		Harms & Biocca	
		Mean	SD	Mean	SD
Control	10	4.780	0.520	5.111	0.635
PVI	10	4.560	0.759	4.922	0.386
EAB	11	4.891	0.797	4.939	0.477

42 paper-holding gesture might be less significantly influential as  
 43 compared to the fluttering paper because it is a subtle peripheral  
 44 action.

### 45 3.6. Results

46 In this study, we were curious whether observing the flutter-  
 47 ing virtual paper would have an impact on the perceived so-  
 48 cial presence with the VH. We had expected to see positive ef-  
 49 ffects on social presence for the PVI and EAB groups; however,  
 50 the results did not show any supporting evidence. While there  
 51 were slight differences, no statistically significant differences  
 52 were observed in either social presence questionnaire among  
 53 the three groups (One-way ANOVA;  $F(2,28) = 0.590$ ,  $p =$   
 54  $0.561$  for Bailenson et al.’s questionnaire and  $F(2,28) = 0.426$ ,  
 55  $p = 0.657$  for Harms and Biocca’s questionnaire in Table 2).  
 56 Based on brief interviews with participants after the study, we  
 57 have some possible explanations for the lack of significant dif-  
 58 ferences, which we will discuss in the next section.

### 59 3.7. Discussion

60 Unlike what we expected, we did not see any statistically sig-  
 61 nificant effects on social presence due to the airflow influence  
 62 on the virtual paper and the VH’s awareness behavior towards  
 63 the fan. Here we discuss some of possible explanations for this  
 64 negative result based on the participants’ comments.

65 **Unawareness of the Fan Wind and Virtual Paper:** We had  
 66 wanted our fluttering virtual paper and fan wind to be peripher-  
 67 al (not central) to the experience, but they may have been *too*  
 68 subtle—many participants indicated afterwards that they had  
 69 not been consciously aware of the effects. Even those who were  
 70 conscious of the effects seemed to pay little or no attention to  
 71 them. Furthermore, based on discussion with the participants,  
 72 the job interview scenario may have encouraged participants to

1 narrowly focus on the VH, thus minimizing the potential influence  
 2 of any environmental effects. Similarly, the novelty of the  
 3 VH could have exacerbated the inattention to the environment  
 4 and related effects.

5 **Maintained Plausibility:** We had originally considered the  
 6 *absence* of movement of paper as *implausible* in the presence of  
 7 the fan, and intended to use that implausibility to measure the  
 8 effect of the physical–virtual influence (real fan affecting virtual  
 9 paper). However in retrospect we realize that non-movement  
 10 of the paper could be perceived as entirely *plausible*—the fan  
 11 might or might not affect a piece of paper on a nearby table,  
 12 and therefore the treatment was potentially ineffectual for our  
 13 intended purpose. In other words, none of the groups (Control,  
 14 PVI, and EAB) might have seen anything “wrong” with the virtual  
 15 paper’s behavior.

16 **Boundary between Physical and Virtual Spaces:** One thing  
 17 that we also noticed from participants’ comments was that the  
 18 projected images on the screen did not provide sufficient depth  
 19 perception because it was not stereoscopic. This might have  
 20 emphasized the separation between the physical and virtual  
 21 spaces across the table and led the participants to merely think  
 22 of an ad-hoc technical setting for the wind influence rather than  
 23 perceiving it as natural causality.

24 **Social Presence Questionnaires:** In attempting to understand  
 25 why we did not see the expected effects, we came to realize that existing social presence questionnaires do not currently  
 26 consider the aspects of the surrounding environment where the  
 27 social interaction takes place; rather, they mainly solely focus  
 28 on the interactivity/connectivity between two or more interlocutors.  
 29 Given that several definitions of social presence indicate  
 30 that the environmental aspects could be important, adding questions  
 31 about the environment (or more generally the social context)  
 32 could potentially provide a more accurate measure.

33 Despite the lack of significant results, we obtained some insights  
 34 from this study. Given that we still believed the environment and awareness behaviors of the environment could increase social presence with VHs, the lessons from this study led  
 35 us to develop our next study, which we will describe in the next  
 36 section.

## 40 4. Experiment II: Virtual Human in an HMD

41 In this section, we present a second study we conducted  
 42 to continue the investigation of the effects of subtle physical–  
 43 virtual influences and a VH’s environmentally aware behavior  
 44 on social presence. This study included specific modifications  
 45 to overcome the shortcomings that we identified from the first  
 46 study, as introduced in Section 3.7. We used a more general  
 47 scenario with less intensive interaction topics, compared to the  
 48 job interview task used in the first study, in which participants  
 49 focused exclusively on the interaction with the VH. The environment  
 50 of our second study featured real sheets of paper next  
 51 to the virtual paper, allowing participants to see the implausible/  
 52 plausible behavior of the virtual paper in comparison with  
 53 the real sheets. Moreover, to reduce the perceived boundary  
 54 between the physical and virtual spaces, we used an advanced  
 55 OST-HMD, which seamlessly displays 3D virtual content as if

56 it is spatially placed in the physical environment. Finally, we  
 57 designed a new questionnaire to measure the sense of copresence  
 58 while taking the surrounding environment into account.  
 59 The results of the study were published in [9].

### 60 4.1. Materials

61 We employed the same female virtual character that was used  
 62 for the first study to speak with the participants and perform upper  
 63 torso gestures (e.g., hand, arm, and head gestures). For this  
 64 experiment, however, she was displayed via an OST-HMD (Micro-  
 65 soft HoloLens), which participants wore during the interaction  
 66 with the VH to reduce the noticeable boundary between the  
 67 physical and virtual spaces with the seamless visual connection  
 68 in augmented reality (AR). Participants and the VH were co-  
 69 located in an office-like AR space as shown in Figure 3, giving  
 70 the participants the impression of being seated at a table across  
 71 from the VH. The physical table occluded the VH’s lower body  
 72 to maintain the visual plausibility. A physical rotating fan was  
 73 placed next to the table in the middle of the two interlocutors so  
 74 that participants could notice the fan easily, and oriented such  
 75 that the airflow would occasionally blow in the direction of the  
 76 virtual paper and curtains as the fan oscillated. We added virtual  
 77 curtains behind the VH in addition to the virtual paper for  
 78 participants to easily realize the fluttering event within the rel-  
 79 atively small field of view (FoV) of the HMD (ca. 30 degree).  
 80 The same wind sensor that we used for the first study, hidden  
 81 below the table (red circles in Figure 3), would detect the air-  
 82 flow from the fan, allowing the virtual paper and curtains to flutter  
 83 according to the real wind for the experimental conditions.  
 84 We placed a couple of real papers on the table so that participants  
 85 could realize implausible or plausible movement of the  
 86 virtual paper compared to the real ones, e.g., the virtual paper  
 87 was not fluttering while real ones were, or both virtual and real  
 88 papers were fluttering together. The experimenter acted as a re-  
 89 mote operator of the VH in a human-in-the-loop (i.e., Wizard-  
 90 of-Oz) based experimental setup and triggered pre-defined ver-  
 91 bal and nonverbal behaviors for the VH using a graphical user  
 92 interface (GUI). The VH maintained a slightly pleasant facial  
 93 expression throughout the interaction.

### 94 4.2. Method

95 To investigate the effects of the physical–virtual interaction  
 96 via airflow and the VH’s awareness behavior, we wanted to  
 97 give the participants a chance to directly compare how they felt  
 98 about the VH in different experimental conditions. A within-  
 99 subject design is the most effective approach to control for in-  
 100 dividual experience/gender/personality factors with respect to  
 101 the interaction with the VH. Thus, we used a within-subjects  
 102 design with three conditions, which participants experienced in  
 103 a counter-balanced order. The three conditions were the same  
 104 as the ones that we used for the first study (see Table 1):

- 105 • **Control** condition,
- 106 • **Physical–Virtual Influence (PVI)** condition, and
- 107 • **Environment-Aware Behavior (EAB)** condition.

108 In all conditions, the experiment consisted of conversational  
 109 interactions based on simple and casual questions about per-  
 110 sonal preferences and experience, conducted with a VH in an

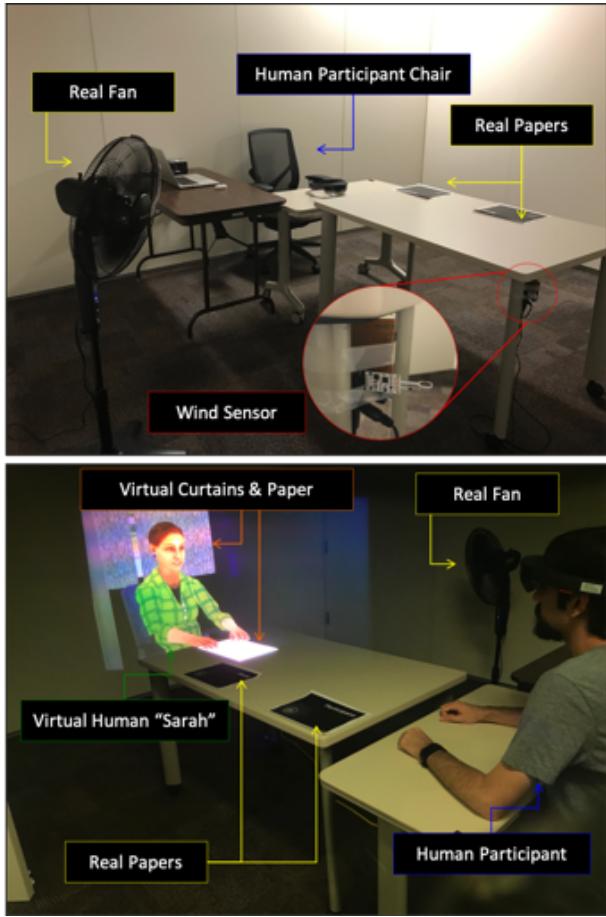


Fig. 3. Experimental setup captured from two different camera angles. Participants were seated opposite from a virtual human on a physical table. A physical fan was placed on the side between the participant and virtual human, and a wind sensor was used to detect airflow that induced a state of fluttering in the virtual paper and curtains. Real papers were placed on the table so that the participants could compare the virtual paper with the real papers when the airflow blew them.

1 MR environment. For example, the VH asked participants personal questions such as, "When is your birthday?"<sup>2</sup> Thirty questions were prepared and divided into three sets of ten ordered questions, each with a similar overall pattern of question themes or topics. Each question set was randomly assigned to the three conditions. The interaction between the participants and the VH was straightforward and did not have conversational dynamics. The experimenter simply triggered the VH's verbal and nonverbal behaviors via GUI buttons throughout the interaction with the participants, so the experimenter's influence was minimized.

12 In the **PVI** condition, virtual paper on the table in front of the VH and virtual curtains behind her fluttered as a result of the physical fan located to the side of the VH and the participant. Participants could also see real papers fluttering on the table and compare them to the virtual paper (see Figure 3). We were cu-

rious whether this subtle environmental event could strengthen the connection between the physical and virtual spaces and potentially influence perceived social presence, even though participants were not directly involved in the fan-blowing event.

In the **EAB** condition, the VH would additionally occasionally exhibit attention toward the fan by looking at it or putting her hand on the virtual paper to stop the fluttering. The VH did not make any verbal acknowledgment about the fan wind. As gaze has been considered an informative cue to convey the direction of interest [33], we chose to demonstrate the VH's awareness of the fan in a subtle way through the use of gaze behavior and the paper holding gesture.

In the **Control** condition, the virtual paper did not flutter and the VH never demonstrated any awareness of the physical fan, although the fan was on and the real papers on the table did flutter due to the wind. A brief description of the three conditions is shown in Figure 4.

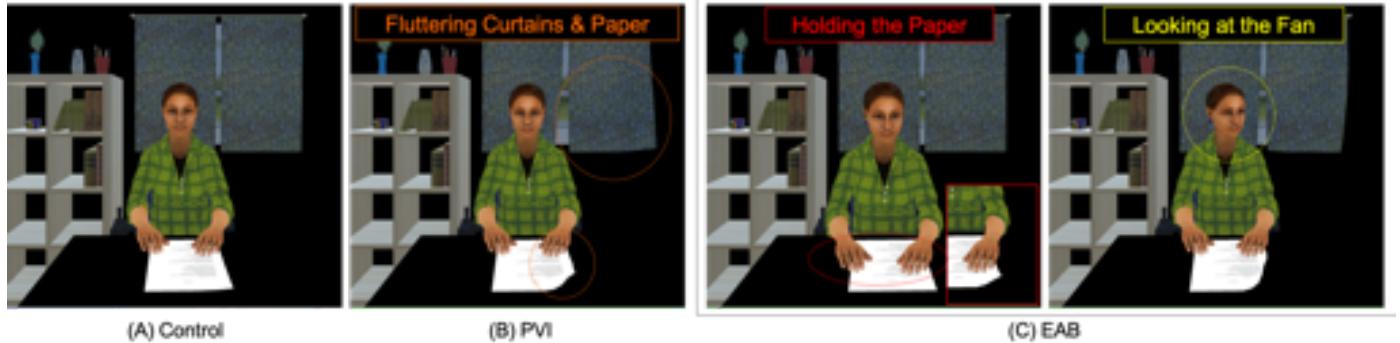
#### 4.3. Participants

We recruited 18 participants (8 females and 10 males; age  $M = 21.44$ ,  $SD = 4.49$ , range: 18–37) from our university community for the study. Seven of them had prior experience with VR/AR headsets, but the number of experiences was less than five times. The rest of them did not have any VR/AR headset experiences. All participants received fifteen dollars for their participation as a monetary compensation after the experiment (duration: 40–50 min).

#### 4.4. Procedure

Once participants arrived, they received an informed consent document and filled out a demographics questionnaire. We measured their interpupillary distance (IPD), which was applied to the HoloLens. In the within-subjects design, participants experienced the three experimental conditions in a counterbalanced order. We explained to participants that they would be interacting with a VH three times, and be asked to complete a post-questionnaire after each interaction to assess their sense of social presence with the VH. Once participants donned the HoloLens, they initially saw virtual blinds placed between themselves and the VH; they were instructed to begin interacting with the VH once the blinds moved up. In this way, we wanted to prevent the participants from feeling that the VH suddenly appeared when they donned the headset, which might influence their sense of social presence with the VH. During the interaction, the VH verbally asked participants ten casual questions on personal experience or preference as described above (see Section 4.2), and participants verbally responded yes/no or brief answers to the questions. After experiencing each experimental condition, they were guided to complete a questionnaire measuring the level of perceived social presence with the VH. After participants completed all three conditions, they filled out a final post-questionnaire regarding their preference among the three interactions and in which condition they felt the VH was the most interactive. Next, they participated in a brief interview with the experimenter to confirm their perception of the manipulations and provide their overall comments about their interactions with the VH. Finally, they received a monetary compensation for their participation and then departed.

<sup>2</sup>For the conversational interaction with the VH, thirty questions were extracted from <http://allysrandomage.blogspot.com/2007/06/101-random-questions.html> (Accessed 2019-02-21).



**Fig. 4.** Experimental conditions. (A) Control, (B) PVI (orange circles: fluttering virtual paper and curtains), and (C) EAB (red circle: holding the paper gesture, red rectangle: less fluttering after holding, yellow circle: looking at the fan).

#### 4.5. Social Presence Measure and Hypotheses

Various subjective questionnaires have been introduced to measure social presence with VHs, e.g., [16, 32, 34]. These questionnaires usually cover and combine multiple aspects together, such as a sense of copresence (i.e., being together in the same place), a degree of social connection (i.e., how closely they communicate/interact with each other), and a sense of realism (i.e., the VH's human-likeness). While such a combined questionnaire is beneficial when the goal is to measure overall perception of the VH, we realized that these questionnaires do not sufficiently reflect a participant's perception of the surrounding environment and its relationship to interactions with co-located interlocutors, which should be carefully considered to understand the sense of social presence in the interaction.

Here, we wanted to avoid this shortcoming and involve the surrounding environment in measuring the participant's perception while particularly focusing on the sense of copresence, e.g., being (physically) together in the same space, which might be mainly affected by our experimental manipulations, i.e., the physical–virtual influence by airflow and the VH's environmentally aware behavior. Thus, we prepared seven questions relevant to this sense of being together, extracting some of questions from existing questionnaires (see Table 3). CP 1–3 were modified from Bailenson et al. [32] and CP 4 was modified from Basdogan et al. [34]. We also added three of our own questions, CP 5, CP 6-1, and CP 6-2. The absolute difference between CP 6-1 and CP 6-2 was calculated and used as a single value, which indicates that the participant and the VH are in the same place. In other words, the smaller absolute difference between CP 6-1 and CP 6-2 means that the participant felt more that he/she and the VH were in the same place somewhere in between the virtual space and the physical space. All questions used 7-point Likert scales, and we computed the averaged score as a representative score of copresence.

We maintained our hypotheses from the first study about the level of copresence (see Section 3.5):

- **H1:** the sense of copresence with the VH for the PVI condition will be higher than for the Control condition.
- **H2:** the sense of copresence with the VH for the EAB will be even higher than for the PVI.

**Table 3.** Copresence questionnaire used in the experiment.

**CP: Copresence (Sense of Being Together in the Same Place)**

CP 1. I perceived that I was in the presence of the person in the room with me. (1: Strongly Disagree, 7: Strongly Agree)  
 CP 2. I felt the person was watching me and was aware of my presence. (1: Strongly Disagree, 7: Strongly Agree)  
 CP 3. I would feel startled if the person came closer to me. (1: Strongly Disagree, 7: Strongly Agree)  
 CP 4. To what extent did you have a sense of being with the person? (1: Not at all, 7: Very much)  
 CP 5. To what extent was this like you were in the same room with the person? (1: Not at all, 7: Very much)  
 \*CP 6-1. I felt I was in the \_\_\_ space. (1: Virtual, 7: Physical)  
 \*CP 6-2. I felt the person was in the \_\_\_ space. (1: Virtual, 7: Physical)

\*The absolute difference of user responses to CP 6-1 and CP 6-2 was used as a single value.

#### 4.6. Results

For the analysis, we computed the average of six scores from the seven questionnaire responses (see Table 3). The internal consistency of the six scores was high as shown by Cronbach's alpha ( $\alpha = .716$ ). Considering sample size, dependency, and ordinal characteristics of the questionnaire responses, a non-parametric Friedman test was used for the analysis of the participants' responses on the copresence questions with a significance level at  $\alpha = .05$ . We found a significant main effect of the experimental conditions on the participants' estimated copresence,  $\chi^2(2) = 7.300, p = .026$  (Table 4).

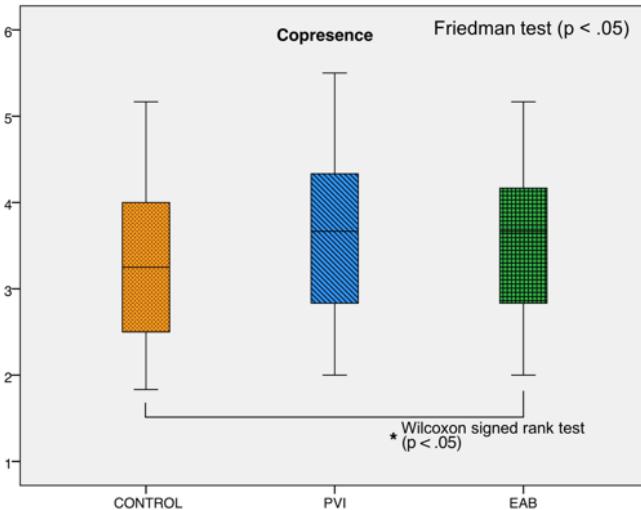
Median (IQR) copresence levels for the Control, the PVI, and the EAB running trials were 3.25 (2.42 to 4.04), 3.67 (2.79 to 4.38), and 3.67 (2.67 to 4.29), respectively (see Figure 5). For the post-hoc analysis, Wilcoxon signed-rank tests were conducted. We found a significant difference between the Control and the EAB conditions ( $Z = -1.988, p = .047$ ), while no significant differences were found between the Control and the PVI conditions ( $Z = -1.309, p = .191$ ), and between the PVI and the EAB conditions ( $Z = -0.094, p = .925$ ) (see Table 5).

This indicates that the sense of copresence was higher when the VH's environment-aware behavior is present along with the physical–virtual airflow interactivity, compared to when those

**Table 4. Friedman test results for copresence.**

Friedman test		
Condition	Mean Rank	Median
Control	1.53	3.25
PVI	2.19	3.67
EAB	2.28	3.67

N 18  
Chi-Square 7.300  
df 2  
Asymp. Sig. **.026**

**Fig. 5. Copresence scores for the three experimental conditions. The PVI's median value was the highest followed by EAB and the Control condition.**

1 manipulations were absent. The magnitudes suggest a higher  
2 copresence for the PVI and the EAB conditions than the Control  
3 condition. Our original hypotheses H1 and H2 were not fully  
4 supported by the results, i.e., we did not see significant differ-  
5 ences among all the conditions. However, our results partially  
6 support H2 in that participants felt a higher sense of copresence  
7 when the VH exhibited awareness behaviors accompanied by  
8 the physical airflow affecting virtual objects.

9 After the participants experienced all three conditions, we  
10 asked them in which condition they felt the VH was the most  
11 interactive with the surrounding environment and for their pref-  
12 erence among the conditions. The results show that the par-  
13 ticipants perceived the VH in the EAB condition as the most  
14 interactive with respect to the real environment, and the PVI  
15 condition was preferred the most (see Figure 6). The Control  
16 condition was evaluated as the least interactive and the least  
17 preferred while there were a few participants who did not per-  
18 ceive a difference among the conditions.

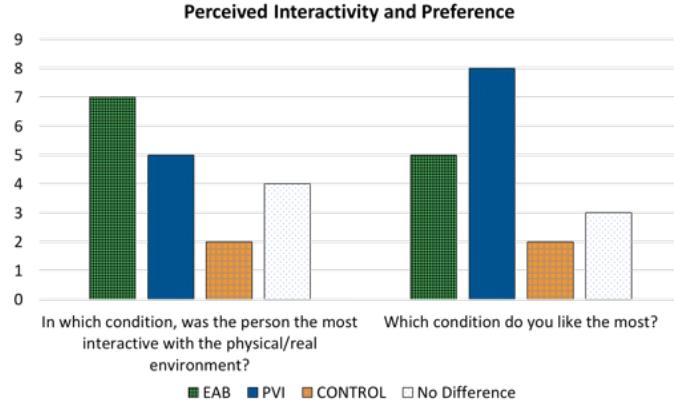
#### 19 4.7. Discussion

20 Based on our results, we found a significant main effect on  
21 copresence by introducing airflow and VH awareness behavior  
22 in a shared MR environment. Our finding suggests that periph-  
23 eral environmental events, such as fan-blowing objects and ob-  
24 serving them, impact one's sense of copresence with the VH  
25 that they interact with, and this could provide a useful reference  
26 for practitioners who want to increase the copresence level by  
27 physical-virtual environmental influences.

**Table 5. Results from Wilcoxon signed-rank tests for copresence.**

Wilcoxon signed-rank tests			
	PVI-Control	EAB-PVI	EAB-Control
Z	-1.309 <sup>a</sup>	-.094 <sup>b</sup>	-1.988 <sup>a</sup>
Asymp. Sig.	.191	.925	<b>.047</b>

a. Based on negative ranks, b. Based on positive ranks.

**Fig. 6. Perceived interactivity and preference. The y-axis is the number of participants who chose the condition for the questions.**

Our results suggest a higher copresence for the PVI and the EAB compared to the Control condition, particularly between the Control and the EAB conditions with statistical significance, which is also supported by our participants' informal comments after the experiment. Most participants indicated that they noticed the influence of physical airflow on the virtual paper and curtains, and the VH's awareness behaviors. Here are a few of the participants' comments that we collected in this experiment:

**Comment 1:** "It (airflow) made the environment feel more real. It definitely helped."

**Comment 2:** "It (airflow) made me feel like I was really in the same room (with the VH)."

**Comment 3:** "Oh, that's cool. It's almost like they were blending the physical world and the virtual world. ... I could see that (real) paper fluttering when her (virtual) paper fluttered on the desk. It seemed like a continuum."

The post-hoc pair-wise analysis showed that the sense of copresence was significantly higher in the EAB condition compared to the Control condition. This indicates that the VH's awareness behaviors played a role in improving the sense of copresence on top of the physical-virtual airflow simulation.

It is further interesting to see that the participants seemed to have preferred the PVI condition over the EAB condition. This trend might be explained by the fact that in the EAB condition the VH occasionally looked at the fan during the conversation, which could cause participants to feel as if their conversation partner was distracted by the environmental event and not paying full attention to them. While the EAB condition helped to bridge the gap between the real and virtual spaces, it also made the VH's behavior more subject to interpretations of natural behavior in the real world.

1 As expected, observing the subtle airflow caused by a physical fan without active participation/involvement was not quite  
 2 as effective as the wobbly table experience in [7], which directly  
 3 involved participants in the interaction. Compared to the direct  
 4 involvement of the human participants in the wobbly table  
 5 movement, the fluttering virtual paper and airflow were not de-  
 6 signed to be an integral part of the interaction between the par-  
 7 ticipants and the VH in our experiment. This might also have  
 8 made the VH's reactive nonverbal behaviors to the fan/paper  
 9 less essential for the interaction and less influential to the par-  
 10 ticipants. However, while it would be possible to create a simi-  
 11 lar level of involvement, e.g., by letting participants position the  
 12 fan or using hand-held fans, it is encouraging to see that even  
 13 our subtle indirect factors in this experiment had a significant  
 14 effect on copresence.  
 15

16 In addition, our results suggest that the influence by the sub-  
 17 tle indirect physical–virtual interaction could be observed and  
 18 compared more clearly when the physical–virtual events appear  
 19 to be implausible and incoherent with the surrounding environ-  
 20 ment. In this sense, the statistically significant main effect in  
 21 the present study could be partially explained by the use of an  
 22 optical see-through AR HMD, which can increase the user's  
 23 expectations related to the physical–virtual interactivity, con-  
 24 trary to a projection screen displaying the VH in the first study.  
 25 Regarding the coherency, we intentionally placed real paper on  
 26 the table so that participants could compare the fluttering move-  
 27 ment between the real paper and the virtual paper. Without the  
 28 real paper, it is unlikely that we would have been able to show  
 29 strong effects related to the virtual paper's behavior because pa-  
 30 per can be static for other reasons, e.g., insufficient wind. In  
 31 general, our adjustments based on the previous experience in  
 32 the first study seemed to help reveal the significant effects for  
 33 this study, such as the change of interaction scenario, the use of  
 34 optical see-through AR HMD, the modified questionnaire, and  
 35 emphasizing the implausibility.

36 One general factor that might have limited the effect of the  
 37 airflow and the VH's reactive awareness behavior on the per-  
 38 ceived sense of copresence with the VH in this experiment  
 39 could be related to the narrow FOV of the HoloLens. Partic-  
 40 ipants were not continuously able to see both the VH and the  
 41 paper/fan while they were looking at objects in the environment.  
 42 Also, the VH's body could be cropped by the narrow FOV such  
 43 that participants could see only a portion of the upper body of  
 44 the VH, impacting the overall copresence level [35].

45 Our results are interesting in that we investigated the effects  
 46 of a less researched modality, i.e., wind, which enables a sub-  
 47 tle stimulus on the sense of copresence. We chose the wind  
 48 modality because it has not been researched in depth in MR  
 49 environments so far despite the fact that events caused by wind are  
 50 common occurrences in our real life and potentially powerful in  
 51 influencing one's perception of virtual content. Our approach to  
 52 reinforce the connectivity between the real and virtual worlds  
 53 by using wind is not limited to copresence research with VHs,  
 54 but could be employed in various MR applications.

## 5. Conclusion

56 System evaluation with perception studies involving human  
 57 subjects has become a more common practice in the field of  
 58 MR and intelligent virtual agents [36] [37] [38]. In this paper, we  
 59 described a series of two human-subject studies in which we  
 60 analyzed the effects that environmental physical–virtual inter-  
 61 action and awareness behaviors can have on the sense of social  
 62 presence with a VH in MR. The second study was designed to  
 63 address specific shortcomings from the first. We demon-  
 64 strated that a VH's awareness behavior along with subtle environ-  
 65 mental events related to airflow caused by a physical fan can lead  
 66 to higher subjective estimates of social presence with the VH.  
 67 Whereas we did not find a significant improvement of social  
 68 presence due to physical–virtual airflow interaction in a typical  
 69 projection-based MR environment in the first study, our results  
 70 with an OST-HMD in the second study, which we carefully re-  
 71 designed based on the lessons from the first study, showed that  
 72 the airflow effects and responsive behavior played an important  
 73 role in increasing perceived copresence with the VH.

74 Our experiments investigated the effects of subtle environ-  
 75 mental events and VH behaviors on the sense of social pres-  
 76 ence, extending related research involving physical–virtual en-  
 77 vironmental influences, such as the wobbly table [7]. Our  
 78 results help to clarify the findings in this related work, in which  
 79 the specific source of the observed increase in social presence  
 80 could not be clearly identified.

81 As MR technology converges with different advanced fields,  
 82 such as ubiquitous computing and artificial intelligence (AI),  
 83 the virtual entities in MR are becoming more intelligent and in-  
 84 teractive with the physical environment [31] [39] [40]. In future  
 85 work, we plan to develop VH systems that can more dynami-  
 86 cally interact with physical objects through Internet of Things  
 87 (IoT) technology, and investigate various modalities to increase  
 88 the dynamics and fidelity of interaction between the real and  
 89 virtual spaces in MR, which can be applied to a social context  
 90 with VHs.

## Acknowledgments

91 This material includes work supported in part by the Na-  
 92 tional Science Foundation under Grant Number 1564065 (Dr.  
 93 Ephraim P. Glinert, IIS) and Grant Number 1800961 (Dr. Tonya  
 94 Smith-Jackson, IIS), the Office of Naval Research under Grant  
 95 Number N00014-17-1-2927 (Dr. Peter Squire, Code 34), and  
 96 the AdventHealth Endowed Chair in Healthcare Simulation  
 97 (Prof. Welch). Any opinions, findings, and conclusions or rec-  
 98 ommendations expressed in this material are those of the au-  
 99 thor(s) and do not necessarily reflect the views of the supporting  
 100 institutions.

## References

102  
 103 [1] Blascovich, J. Social Influence within Immersive Virtual Environments. In: Schroeder, R, editor. *The Social Life of Avatars. Computer Supported  
 104 Cooperative Work*; Springer London; 2002, p. 127–145.  
 105

[2] Garau, M, Slater, M, Vinayagamoorthy, V, Brogni, A, Steed, A, Sasse, MA. The Impact of Avatar Realism and Eye Gaze Control on Perceived Quality of Communication in a Shared Immersive Virtual Environment. In: ACM SIGCHI Conference on Human Factors in Computing Systems. 2003, p. 529–536.

[3] Morency, LP, de Kok, I, Gratch, J. A probabilistic multimodal approach for predicting listener backchannels. Autonomous Agents and Multi-Agent Systems 2009;20(1):70–84.

[4] Allwood, J. An activity based approach to pragmatics. In: Bunt, H, Black, W, editors. *Abduction, Belief and Context in Dialogue: Studies in Computational Pragmatics*. John Benjamins Publishing Company; 2000, p. 47–80.

[5] Microsoft. Spatial mapping (windows mixed reality). [https://developer.microsoft.com/en-us/windows/mixed-reality/spatial\\_mapping](https://developer.microsoft.com/en-us/windows/mixed-reality/spatial_mapping); 2017.

[6] Kim, K, Maloney, D, Bruder, G, Bailenson, JN, Welch, GF. The effects of virtual human's spatial and behavioral coherence with physical objects on social presence in AR. Computer Animation and Virtual Worlds 2017;28(3-4):e1771.

[7] Lee, M, Kim, K, Daher, S, Raji, A, Schubert, R, Bailenson, J, et al. The Wobbly Table: Increased Social Presence via Subtle Incidental Movement of a Real-Virtual Table. In: Proceedings of IEEE Virtual Reality. 2016, p. 11–17.

[8] Kim, K, Schubert, R, Welch, G. Exploring the Impact of Environmental Effects on Social Presence with a Virtual Human. Lecture Notes in Artificial Intelligence (Proceedings of International Conference on Intelligent Virtual Agents) 2016;10011:470–474.

[9] Kim, K, Bruder, G, Welch, GF. Blowing in the Wind: Increasing Co-presence with a Virtual Human via Airflow Influence in Augmented Reality. In: International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments. 2018, p. 183–190.

[10] Bailenson, JN, Beall, AC, Loomis, J, Blascovich, J, Turk, M. Transformed Social Interaction, Augmented Gaze, and Social Influence in Immersive Virtual Environments. Human Communication Research 2005;31(4):511–537.

[11] Chuah, JH, Robb, A, White, C, Wendling, A, Lampotang, S, Kopper, R, et al. Exploring Agent Physicality and Social Presence for Medical Team Training. Presence: Teleoperators and Virtual Environments 2013;22(2):141–170.

[12] Huang, L, Morency, LP, Gratch, J. Virtual Rapport 2.0. Lecture Notes in Artificial Intelligence (Proceedings of International Conference on Intelligent Virtual Agents) 2011;6895:68–79.

[13] Oh, CS, Bailenson, JN, Welch, GF. A Systematic Review of Social Presence: Definition, Antecedents, and Implications. Frontiers in Robotics and AI 2018;5(114):1–35.

[14] Zhao, S. Toward a taxonomy of copresence. Presence: Teleoperators and Virtual Environments 2003;12(5):445–455.

[15] Slater, M. Place Illusion and Plausibility can Lead to Realistic Behaviour in Immersive Virtual Environments. Philosophical Transactions of the Royal Society of London Series B, Biological Sciences 2009;364(1535):3549–3557.

[16] Harms, C, Biocca, F. Internal consistency and reliability of the networked minds measure of social presence. In: Seventh Annual International Presence Workshop. 2004, p. 246–251.

[17] Blascovich, J, Loomis, J, Beall, AC, Swinth, KR, Hoyt, CL, Bailenson, JN. Immersive virtual environment technology as a methodological tool for social psychology. Psychological Inquiry 2002;13(2):103–124.

[18] Goffman, E. *Behavior in Public Places: Notes on the Social Organization of Gatherings*. New York: The Free Press; 1963.

[19] Dinh, HQ, Walker, N, Song, C, Kobayashi, A, Hodges, LF. Evaluating the Importance of Multi-Sensory Input on Memory and the Sense of Presence in Virtual Environments. In: IEEE Virtual Reality. 1999, p. 222–228.

[20] Moon, T, Kim, GJ. Design and Evaluation of a Wind Display for Virtual Reality. In: Proceedings of the ACM Symposium on Virtual Reality Software and Technology. 2004, p. 122–128.

[21] Hülsmann, F, Fröhlich, J, Mattar, N, Wachsmuth, I. Wind and Warmth in Virtual Reality: Implementation and Evaluation. In: Proceedings of the Virtual Reality International Conference. 2014, p. 28:1–8.

[22] Feng, M, Dey, A, Lindeman, RW. The Effect of Multi-Sensory Cues on Performance and Experience During Walking in Immersive Virtual Environments. In: Proceedings of IEEE Virtual Reality. 2016, p. 173–174.

[23] Lehmann, A, Geiger, C, Wöldecke, B, Stöcklein, J. Poster: Design and Evaluation of 3D Content with Wind Output. In: Proceedings of IEEE Symposium on 3D User Interfaces. 2009, p. 151–152.

[24] Deligiannidis, L, Jacob, RJ. The VR scooter: Wind and tactile feedback improve user performance. In: Proceedings of IEEE Symposium on 3D User Interfaces. 2006, p. 143–150.

[25] Dieker, LA, Rodriguez, JA, Lignugaris/Kraft, B, Hynes, MC, Hughes, CE. The Potential of Simulated Environments in Teacher Education: Current and Future Possibilities. Teacher Education and Special Education: The Journal of the Teacher Education Division of the Council for Exceptional Children 2013;37(1):21–33.

[26] Rizzo, A, Scherer, S, Devault, D, Gratch, J, Artstein, R, Hartholt, A, et al. Detection and Computational Analysis of Psychological Signals Using a Virtual Human Interviewing Agent. International Journal of Disability and Human Development 2014;15(3).

[27] Hoque, M, Courgeon, M, Martin, JC, Mutlu, B, Picard, RW. Mach: My automated conversation coach. In: Proceedings of ACM International Joint Conference on Pervasive and Ubiquitous Computing. 2013, p. 697–706.

[28] Hochreiter, J, Daher, S, Nagendran, A, Gonzalez, L, Welch, G. Optical Touch Sensing on Nonparametric Rear-Projection Surfaces for Interactive Physical-Virtual Experiences. Presence: Teleoperators and Virtual Environments 2016;25(1):33–46.

[29] Andrist, S, Gleicher, M, Mutlu, B. Looking Coordinated: Bidirectional Gaze Mechanisms for Collaborative Interaction with Virtual Characters. In: Proceedings of the ACM CHI Conference on Human Factors in Computing Systems. 2017, p. 2571–2582.

[30] Kim, K, Nagendran, A, Bailenson, J, Welch, G. Expectancy Violations Related to a Virtual Human's Joint Gaze Behavior in Real-Virtual Human Interactions. In: Proceedings of the International Conference on Computer Animation and Social Agents. 2015, p. 5–8.

[31] Kim, K, Boelling, L, Haesler, S, Bailenson, JN, Bruder, G, Welch, GF. Does a Digital Assistant Need a Body? The Influence of Visual Embodiment and Social Behavior on the Perception of Intelligent Virtual Agents in AR. In: Proceedings of IEEE International Symposium on Mixed and Augmented Reality. 2018, p. 105–114.

[32] Bailenson, JN, Blascovich, J, Beall, AC, Loomis, JM. Interpersonal distance in immersive virtual environments. Personality and Social Psychology Bulletin 2003;29(7):819–833.

[33] Frischen, A, Bayliss, AP, Tipper, SP. Gaze Cueing of Attention: Visual Attention, Social Cognition, and Individual Differences. Psychological Bulletin 2007;133(4):694–724.

[34] Basdogan, C, Ho, CH, Srinivasan, MA, Slater, M. An experimental study on the role of touch in shared virtual environments. ACM Transactions on Computer-Human Interaction 2000;7(4):443–460.

[35] Lee, M, Bruder, G, Höllerer, T, Welch, G. Effects of Unaugmented Periphery and Vibrotactile Feedback on Proxemics with Virtual Humans in AR. IEEE Transactions on Visualization and Computer Graphics 2018;24(4):1525–1534.

[36] Kim, K, Billinghurst, M, Bruder, G, Been-Lirn Duh, H, Welch, GF. Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017). IEEE Transactions on Visualization and Computer Graphics Special Issue on IEEE International Symposium on Mixed and Augmented Reality 2018;24(11):2947–2962.

[37] Norouzi, N, Kim, K, Hochreiter, J, Lee, M, Daher, S, Bruder, G, et al. A Systematic Survey of 15 Years of User Studies Published in the Intelligent Virtual Agents Conference. In: ACM International Conference on Intelligent Virtual Agents. 2018, p. 17–22.

[38] Dey, A, Billinghurst, M, Lindeman, RW, Swan, JE. A Systematic Review of 10 Years of Augmented Reality Usability Studies: 2005 to 2014. Frontiers in Robotics and AI 2018;5(37):1–28.

[39] Lee, M, Norouzi, N, Bruder, G, Wisniewski, PJ, Welch, GF. The Physical-Virtual Table: Exploring the Effects of a Virtual Human's Physical Influence on Social Interaction. In: Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology. 2018, p. 1–11.

[40] Norouzi, N, Bruder, G, Belna, B, Mutter, S, Turgut, D, Welch, G. A Systematic Review of the Convergence of Augmented Reality, Intelligent Virtual Agents, and the Internet of Things. In: Springer Transactions on Computational Science Computational Intelligence. 2019, p. 1–24.