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

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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.

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

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

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

Here, we present two human-subject studies with real–virtual human interactions involving airflow influence and VH awareness in two different MR platforms: a wide screen with rear-projected imagery and an optical see-through head-mounted display (OST-HMD). We analyzed the effects of increasing the physical–virtual connectivity via subtle airflow and isolated the perceptual effects of the physical–virtual connectivity from those of the VH's environmentally aware behavior, which included both looking toward the physical fan and holding down a fluttering piece of virtual paper. In the first study with a projection screen, we did not observe any statistically significant effects on social presence [8]. We identified several possible reasons for this, such as less participant attention towards the environment compared to the interaction scenario—a practice job interview—and the clear distinction between the virtual and real worlds established by the projection screen. Taking into consideration the lessons learned from the first study, we developed a second study, where the virtual and physical worlds were more seamlessly visually connected through a Microsoft HoloLens HMD. Here, we observed significant differences in social presence due to airflow influence and VH awareness. While both studies were designed to measure the effects of subtle environmental physical–virtual interaction on the perceived social presence with a VH, the two studies were not intended to be directly comparable—instead, we made deliberate changes to the second study based on insights and lessons learned from the first.

This paper is an extended version of a conference paper that received the Honorable Mention Award at the International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments 2018 [9]. The rest of the paper is structured as follows. Section 2 provides background information on social presence, airflow influence in physical–virtual worlds, and environmental awareness of VHs. Section 3 describes the first study with a projection-based MR environment and presents the results along with related discussion. Likewise, details of the second study with an OST-HMD-based MR environment are described and the results are discussed in Section 4. Finally, we close the paper with our conclusions across both studies in Section 5.

2. Related Work

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

2.1. Copresence, Social Presence, and Presence

There is an ongoing debate in the research community about precise definitions for *social presence* and *copresence*, as distinct from the concept of *presence*, while some use the concepts interchangeably. While presence usually refers to one's sense of "being there" in a virtual environment, the concepts of copresence and social presence might be described more specifically as how one perceives another human's presence in a sense of "being together," and how much one feels "socially connected" to the other. These concepts of social presence and copresence are an important measure of how virtual humans are perceived and have been extensively researched [10, 11, 12].

Oh et al. distinguished the concept of social presence from two other concepts of presence—telepresence and self-presence—and tried to tease out what factors could influence the perceived social presence by analyzing hundreds of papers in virtual reality and computer-medicated communication fields [13]. Zhao pointed out the confusion of different copresence concepts and tried to differentiate them [14]. He considered human copresence in two aspects: "the physical conditions in which human individuals interact and the perceptions and feelings they have of one another." Each of these aspects might be complementary to each other to determine one's perceived sense of copresence with a VH during an interaction. Slater addressed an important concept for presence, called *plausibility illusion (Psi)*. Psi "refers to the illusion that the scenario being depicted is *actually occurring*," which "requires a credible scenario and plausible interactions between the participant and objects and virtual characters *in the environment*" (emphases added) [15]. Due to the nature of Psi as it relates to interactions 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" [1, 17].

Considering the definitions addressed above, we expect that the plausibility of the context and the surrounding environment 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 [1, 17].

2.2. Physical–Virtual Influences via Airflow

Previously, airflow has been introduced as a tactile modality that can increase the sense of presence in a virtual environment 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.

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.

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

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

3.1. Materials

For the study, we implemented a female VH, "Katie," who could speak with the participants and perform upper torso gestures (e.g., hand and head gestures). The VH was rear-projected onto a screen in an office-like MR space as shown in Figure 1. The physical part of the table was positioned in front of the screen, creating a visual impression of facing a seated VH across the table. The physical table has a virtual counterpart that visually extended from the physical table into the (virtual) environment of the VH; thus, the virtual and physical parts of the table appeared to be a single table. For the VH's idle posture she had both hands on the table, and a virtual sheet of paper was also on the table. A physical rotating fan was placed alongside the table so that the wind from the fan would blow towards the virtual paper. We hid a wind sensor (Modern Device Wind Sensor Rev. P[1]) connected to an Arduino board behind a small photo frame to detect the wind from the fan (red circles in Figure 1), so that the virtual paper could flutter according to the actual wind. The sensor we used can measure a wide range of wind speeds (0–150 MPH), and there was no noticeable delay between the wind sensing and the animation triggering. Hence, this approach could provide higher fidelity and realism than with more crude setups, e.g., based on tracking the fan's pose alone. Cloth physics simulation in Unity3D was used to render the fluttering animations as naturally as possible. The VH was controlled by an experimenter (Wizard-of-Oz) behind the screen using GUI buttons, which the experimenter could use to trigger pre-defined verbal and nonverbal behaviors. The VH had neutral and pleasant facial expressions throughout the interaction.

3.2. Method

We designed a between-subjects study with three different groups: (i) **Control**, (ii) Physical–Virtual Influence (**PVI**), and (iii) Environment-Aware Behavior (**EAB**). For the **PVI** group, a virtual sheet of paper on the table in front of the VH appeared to flutter as a result of the physical fan that was located next to the participant during the interaction. The physical fan blowing the virtual paper was chosen as a subtle environmental event to strengthen the connection between physical and virtual spaces, and potentially influence the sense of social presence with the VH. For the **EAB** group, the VH would additionally occasionally exhibit attention toward the fan's effects by looking at it or holding down the virtual piece of paper to stop it from fluttering. For the **Control** group, the paper did not flutter and the VH never demonstrated any awareness of the physical fan. For all groups, participants had a conversational interaction (a simple practice job interview) with the VH. The three groups are briefly described in Table 1 and illustrated in Figure 2.

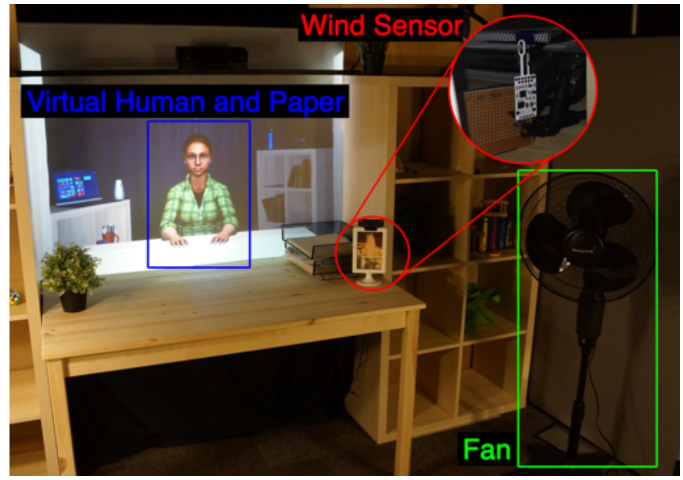

Fig. 1. Experimental setup for the first study. Participants were seated opposite from a virtual human on a physical-virtual table. A physical fan was placed next to the table but close to where the participants were seated, and a wind sensor was hidden behind a small photo frame to detect airflow that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

Table 1. Description of experimental groups: Control, Physical–Virtual Influence (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

3.3. Participants

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

3.4. Procedure

When participants arrived, we guided them to a questionnaire area. They were requested to read the informed consent and fill out a demographics questionnaire. We explained that they would have a practice job interview with a VH interviewer, "Katie," and they would play the role of an interviewee.

[1] https://moderndevice.com/product/wind-sensor-rev-p (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).

We showed them five generic questions extracted from [27]—for example, "tell me about yourself"—that the VH interviewer would be asking, and let them prepare their answers for five minutes. We did not have any specific job position for this study, so the participants were allowed to imagine their own ideal jobs, and we instructed them to practice their answers without worrying about their performance. Before the interview interaction, participants watched a video clip of a peaceful water stream for about one minute to relax. Once we began recording audio and video, the participants entered the experiment room and conducted a practice job interview with the VH. The participants were randomly assigned to one of the three experimental groups (either Control, PVI, or EAB). After the interview completed, the participants were requested to complete a post-questionnaire, which asked questions related to their perceived social presence with the VH. When they finished the post-questionnaire, they received monetary compensation of fifteen dollars for their participation.

3.5. Social Presence Measures and Hypotheses

To measure the participants' sense of social presence, we used two different Social Presence questionnaire sets from Bailenson et al. [32] and Harms and Biocca [16]. While Bailenson et al.'s questionnaire is relatively concise (five questions) and it tends to cover the VH's authenticity/realism as well as the sense of "being together," for example, one of the questions is "The person appears to be sentient, conscious, and alive to me." Harms and Biocca's questionnaire is more sophisticated, with six sub-dimensions that together characterize the overall social presence level by focusing on the quality of computer-mediated communication. The sub-dimensions are copresence, attentional allocation, perceived message understanding, perceived emotional understanding, perceived behavioral independence, and perceived emotional independence. Participants were asked all questions in seven-point Likert scales, and we used the averaged score as a representative score of social presence.

We hypothesized that the level of social presence for each group would be different. For example, the social presence for the PVI group will be higher than the one for the Control group, and the level of social presence for the EAB group will be even higher than the one for the PVI group, i.e., Control $<<$ PVI $<$ EAB. We expected the VH's gaze direction changes and paper-holding gesture might be less significantly influential as compared to the fluttering paper because it is a subtle peripheral action.

Table 2. Descriptives for social presence responses.

		Bailenson et al.		Harms & Biocca	
Group	N	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

3.6. Results

In this study, we were curious whether observing the fluttering virtual paper would have an impact on the perceived social presence with the VH. We had expected to see positive effects on social presence for the PVI and EAB groups; however, the results did not show any supporting evidence. While there were slight differences, no statistically significant differences were observed in either social presence questionnaire among the three groups (One-way ANOVA; $F(2,28) = 0.590$, $p = 0.561$ for Bailenson et al.'s questionnaire and $F(2,28) = 0.426$, $p = 0.657$ for Harms and Biocca's questionnaire in Table 2). Based on brief interviews with participants after the study, we have some possible explanations for the lack of significant differences, which we will discuss in the next section.

3.7. Discussion

Unlike what we expected, we did not see any statistically significant effects on social presence due to the airflow influence on the virtual paper and the VH's awareness behavior towards the fan. Here we discuss some of possible explanations for this negative result based on the participants' comments.

Unawareness of the Fan Wind and Virtual Paper: We had wanted our fluttering virtual paper and fan wind to be peripheral (not central) to the experience, but they may have been *too* subtle—many participants indicated afterwards that they had not been consciously aware of the effects. Even those who were conscious of the effects seemed to pay little or no attention to them. Furthermore, based on discussion with the participants, the job interview scenario may have encouraged participants to narrowly focus on the VH, thus minimizing the potential influence of any environmental effects. Similarly, the novelty of the VH could have exacerbated the inattention to the environment and related effects.

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

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

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

Despite the lack of significant results, we obtained some insights 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 us to develop our next study, which we will describe in the next section.

4. Experiment II: Virtual Human in an HMD

In this section, we present a second study we conducted to continue the investigation of the effects of subtle physical–virtual influences and a VH's environmentally aware behavior on social presence. This study included specific modifications to overcome the shortcomings that we identified from the first study, as introduced in Section 3.7. We used a more general scenario with less intensive interaction topics, compared to the job interview task used in the first study, in which participants focused exclusively on the interaction with the VH. The environment of our second study featured real sheets of paper next to the virtual paper, allowing participants to see the implausible/plausible behavior of the virtual paper in comparison with the real sheets. Moreover, to reduce the perceived boundary between the physical and virtual spaces, we used an advanced OST-HMD, which seamlessly displays 3D virtual content as if it is spatially placed in the physical environment. Finally, we designed a new questionnaire to measure the sense of copresence while taking the surrounding environment into account. The results of the study were published in [9].

4.1. Materials

We employed the same female virtual character that was used for the first study to speak with the participants and perform upper torso gestures (e.g., hand, arm, and head gestures). For this experiment, however, she was displayed via an OST-HMD (Microsoft HoloLens), which participants wore during the interaction with the VH to reduce the noticeable boundary between the physical and virtual spaces with the seamless visual connection in augmented reality (AR). Participants and the VH were co-located in an office-like AR space as shown in Figure 3, giving the participants the impression of being seated at a table across from the VH. The physical table occluded the VH's lower body to maintain the visual plausibility. A physical rotating fan was placed next to the table in the middle of the two interlocutors so that participants could notice the fan easily, and oriented such that the airflow would occasionally blow in the direction of the virtual paper and curtains as the fan oscillated. We added virtual curtains behind the VH in addition to the virtual paper for participants to easily realize the fluttering event within the relatively small field of view (FoV) of the HMD (ca. 30 degree). The same wind sensor that we used for the first study, hidden below the table (red circles in Figure 3), would detect the airflow from the fan, allowing the virtual paper and curtains to flutter according to the real wind for the experimental conditions. We placed a couple of real papers on the table so that participants could realize implausible or plausible movement of the virtual paper compared to the real ones, e.g., the virtual paper was not fluttering while real ones were, or both virtual and real papers were fluttering together. The experimenter acted as a remote operator of the VH in a human-in-the-loop (i.e., Wizard-of-Oz) based experimental setup and triggered pre-defined verbal and nonverbal behaviors for the VH using a graphical user interface (GUI). The VH maintained a slightly pleasant facial expression throughout the interaction.

4.2. Method

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

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

In all conditions, the experiment consisted of conversational interactions based on simple and casual questions about personal preferences and experience, conducted with a VH in an

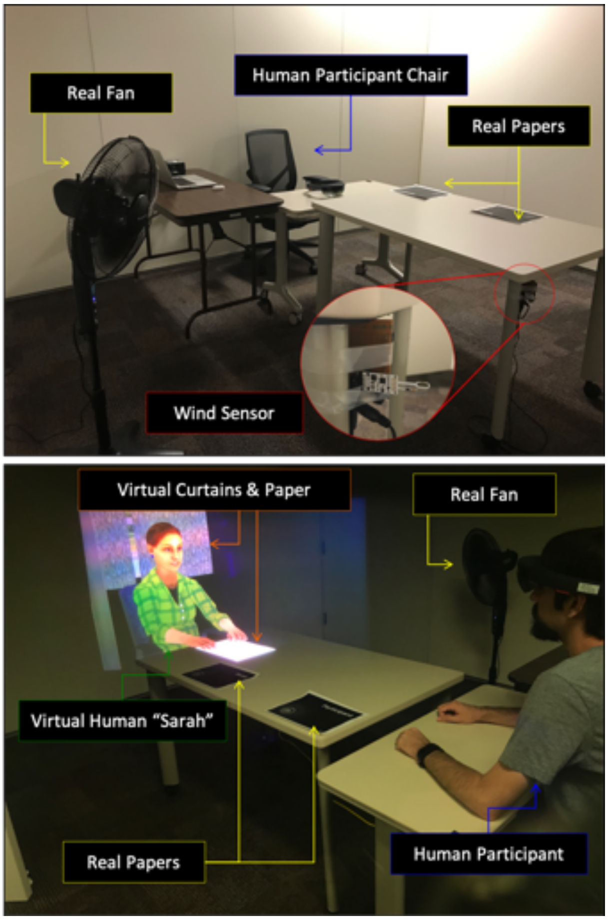

Fig. 3. Experimental setup captured from two different camera angles. Participants were seated opposite from a virtual human on a physical table. A physical fan was placed on the side between the participant and virtual human, and a wind sensor was used to detect airflow that induced a state of fluttering 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.

MR environment. For example, the VH asked participants personal questions such as, "When is your birthday?" [2] 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.

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 curious 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.

[2] 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).

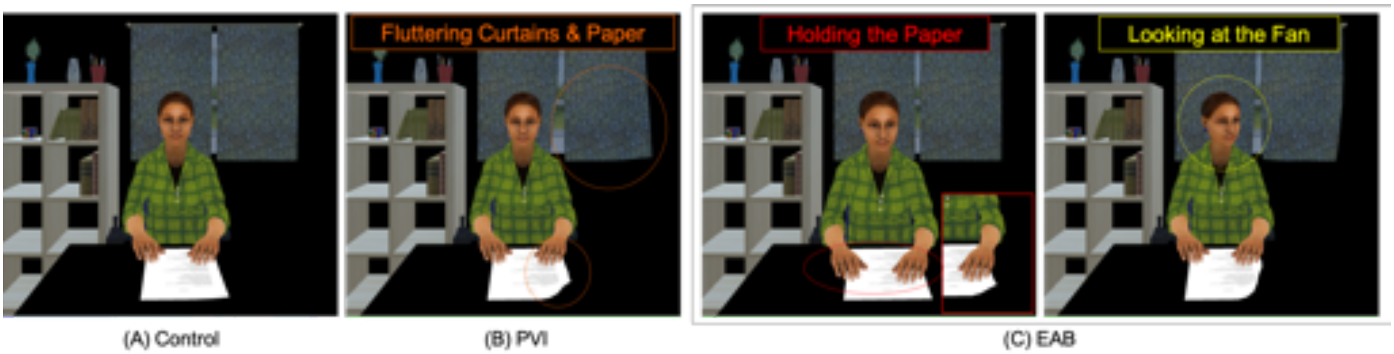

Fig. 4. Experimental conditions. (A) Control, (B) PVI (orange circles: fluttering virtual paper and curtains), and (C) EAB (red circle: holding the paper gesture, red rectangle: less fluttering after holding, yellow circle: looking at the fan).

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	N	18
Control	1.53	3.25	Chi-Square	7.300
PVI	2.19	3.67	df	2
EAB	2.28	3.67	Asymp. Sig.	**.026**

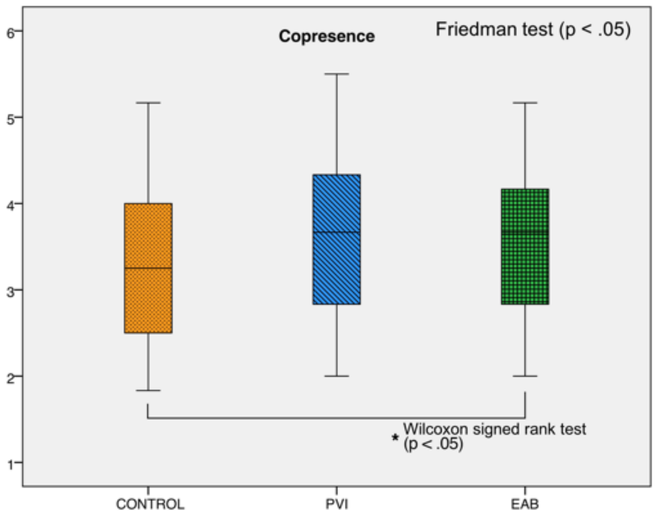

Fig. 5. Copresence scores for the three experimental conditions. The PVI's median value was the highest followed by EAB and the Control condition.

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

After the participants experienced all three conditions, we asked them in which condition they felt the VH was the most interactive with the surrounding environment and for their preference among the conditions. The results show that the participants perceived the VH in the EAB condition as the most interactive with respect to the real environment, and the PVI condition was preferred the most (see Figure 6). The Control condition was evaluated as the least interactive and the least preferred while there were a few participants who did not perceive a difference among the conditions.

4.7. Discussion

Based on our results, we found a significant main effect on copresence by introducing airflow and VH awareness behavior in a shared MR environment. Our finding suggests that peripheral environmental events, such as fan-blowing objects and observing them, impact one's sense of copresence with the VH that they interact with, and this could provide a useful reference for practitioners who want to increase the copresence level by 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^{a}	$-.094^{b}$	-1.988^{a}
Asymp. Sig.	.191	.925	**.047**

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

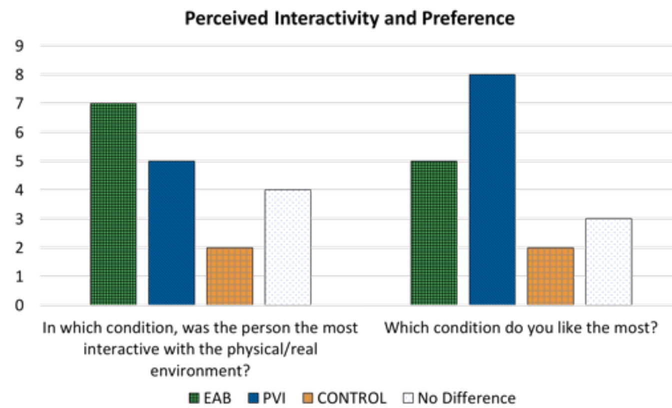

Fig. 6. Perceived interactivity and preference. The y-axis is the number of participants who chose the condition for the questions.

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.

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

In addition, our results suggest that the influence by the subtle indirect physical–virtual interaction could be observed and compared more clearly when the physical–virtual events appear to be implausible and incoherent with the surrounding environment. In this sense, the statistically significant main effect in the present study could be partially explained by the use of an optical see-through AR HMD, which can increase the user's expectations related to the physical–virtual interactivity, contrary to a projection screen displaying the VH in the first study. Regarding the coherency, we intentionally placed real paper on the table so that participants could compare the fluttering movement between the real paper and the virtual paper. Without the real paper, it is unlikely that we would have been able to show strong effects related to the virtual paper's behavior because paper can be static for other reasons, e.g., insufficient wind. In general, our adjustments based on the previous experience in the first study seemed to help reveal the significant effects for this study, such as the change of interaction scenario, the use of optical see-through AR HMD, the modified questionnaire, and emphasizing the implausibility.

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

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

5. Conclusion

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

Our experiments investigated the effects of subtle environmental events and VH behaviors on the sense of social presence, extending related research involving physical–virtual environmental influences, such as the wobbly table [7]. Our results help to clarify the findings in this related work, in which the specific source of the observed increase in social presence could not be clearly identified.

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

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