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A Comparative Study Between a Large-Screen and a HMD using Wind Representations in Virtual Reality

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Abstract—In this study, we investigated the representation of wind in urban spaces through computational fluid dynamics simulations in virtual environments (VE). We compared wind perception (force and direction) as well as the sense of presence and embodiment in VE using different display technologies: Head-Mounted Displays (HMD) and large-screens, and with or without an avatar. The tactile display was found to be most effective for detecting wind characteristics and enhancing presence and embodiment in virtual scenes, regardless of display type. Wind force and overall presence showed no significant differences between projection methods, but the perception of wind direction varied, which can be attributed to the head tracking of the HMD. In addition, gender differences emerged: females had a 7.42% higher presence on large-screens, while males had a 23.13% higher presence with HMD (avatar-present). These results highlight nuances in wind perception, the influence of technology, and gender differences in VE.

Wind effects have implications for several disciplines, including engineering, architecture, and urban planning. For example, wind can affect building structures as well as users' perceptions of a space [1]. In this paper, we focus on the latter aspect and are particularly interested in how different representations of wind might affect user perception in immersive displays.

Wind representations in architectural projects are classically visualized by representing the wind flow. They can be based on the results of wind simulations or on a proposal for wind characteristics. Artistic representations of wind can also be used visually or audiovisually to show the mechanical effects of wind on the elements of the context. On the other hand, virtual reality (VR) is increasingly used in the fields of architecture and urban planning, allowing the exploration of a digital model at different scales [2]. Berger and Cristie [3] and Christmann et al. [4] investigated the question of how to make the wind visible in a VR scene through different representations.

Our main research question is as follows: How can the wind characteristics derived from a wind simulation be most effectively represented in a Virtual Reality

environment to provide information comparable to what one would experience in reality, thus enhancing the understanding of wind properties?

To answer this question, we manipulate two main aspects of wind representation in VR, namely: (1) how users visualize the virtual environment (VE), namely in a Head-Mounted Display (HMD) or on a large screen (PowerWall) and (2) how wind can be represented in the VE, in particular we are interested in the impact of modality (visual, audio, haptic) used to represent the wind.

More precisely, we compare the perception of two wind properties (force and direction) as well as the senses of presence and embodiment (using a virtual avatar for the latter) in the VE. In terms of wind representation, we use four conditions based on three different wind representations: (i) audiovisual effects of the wind on the context elements, (ii) visualization of the wind flow, (iii) tactile representation with eight digitally controlled fans, and (iv) tactile representation together with the visualization of the wind flow. We also analyzed the effects of the way the users visualized the virtual elements: via a large stereoscopic screen or via an HMD. In a previous work [6], we pointed

out that using a HMD headset would perhaps allow a more realistic sense of presence in the virtual scene with a wider FOV and that it would also suppress the view of the fans, unlike the large-screen experiment where they are visible to the user. We wanted to compare the effects of a Head-Mounted Display (HMD) on wind perception because, as Rietzler et al. [5] noted, this device obscures part of the participants' face. Moreover, when immersed through an HMD, the users' bodies can be replaced by that of an avatar, which may further impact their perception of wind.

Therefore, we wanted to compare these two modes of immersion in the virtual scene with the perception of the wind characteristics.

It should be noted that results from the large-screen come from a previous study of ours [6] and that the current study consisted of running the experiment in the HMD condition and comparing results in both visualization modes.

The main findings of this article are as follows:

- Tactile representations led participants to give responses that were closest to the input values for the wind properties (force, direction).
- Tactile representations significantly enhanced the sense of presence and embodiment.
- Surprisingly, no significant differences in tactile wind perception were found between the large-screen and the HMD, contrary to expectations due to the wind mask effect.
- Women had the strongest sense of presence in the large-screen condition, while it was in the HMD with a virtual avatar condition for men.

Consequently, our study suggests an interest in multi-modal wind representations in virtual reality to exploit the sensory effects of wind from the wind simulation results beyond the traditional wind representations using both the large-screen and the HMD.

1. Background and Related Work

Wind can be perceived by various senses. It provides audio, tactile, and thermal feedback to the human body. Its effects can also be visually perceived since it makes the elements of the context move.

1.1. Wind Flow Visualizations in Architecture, Engineering, and Urban Design Fields

In the fields of architecture, engineering and urban planning, the representations of wind differ from reality because the wind flow becomes visible in order to

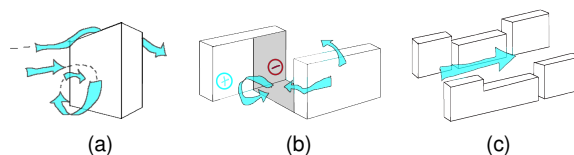


FIGURE 1. Examples of visualization of some wind effects: (a) Turbulent zone at the base of a building, (b) joining of different pressure zones, (c) channeling effect, based on Gandemer's [1] sketches.

analyze its interaction with the environment. We have identified two subsets of this visualization: (i) sketch-based representations that suggest wind properties, and (ii) visualizations of flow simulation results.

A sketch visualization of wind flow can show the behavior of the wind, its direction, the force variations (by its size) or its temperature (by its colors). Gandemer [1] presents a collection of wind effects that arise in an urban environment; see Figure 1. He explains these effects (e.g. Venturi effect, channeling effect, corner effect, etc.) and represents the wind flow as arrows showing its behavior (see Figure 1). Similarly, Lamberts et al. [7] depict different wind properties and their interaction with buildings. They used a hand-crafted representation to show these concepts.

To compare the different representations, two experimental studies were carried out in Christmann et al. [4], which aimed at evaluating different representations of air flow with a static and a dynamic representation. In the static representation, colored arrows, windsocks, and tabs were compared. One vector representation was more understandable than the other two, and the color helped to understand the force. On the other hand, the vectors could sometimes obscure the user's view. In the dynamic representation, the direction and speed of the airflows are directly represented by the movements. The authors tested artistic, schematic, and realistic representations. The schematic 3D arrow representation is easier to understand than a realistic representation of moving particles. The authors did not test streamlines, which are widely used in the literature, but believe that they could be adapted to virtual reality, although they come very close to an artistic representation.

Visualizing wind simulation results not only shows wind behavior in context, but also provides quantitative data to analyze the results. It is used in various fields (with physical and digital models), e.g. in the development of cars, airplanes, buildings and much more. In physical models, wind flow gives an idea of

the behavior of the fluid even before measurements of the wind properties begin. As shown in the comprehensive overviews of flow visualization by Edmunds et al. [8], McLoughlin et al. [9] and Salzbrunn et al. [10], there are several ways to visualize the wind properties resulting from computational fluid dynamics (CFD) simulations. Post et al. [11] present four main types of visualizations: (i) direct visualization, in which raw data are conveyed most directly by representing fluid properties through colors or objects such as arrows; (ii) texture-based visualization, in which textures are used to express density or displacement; (iii) geometric visualization, in which flow is represented by objects such as streamlines; and (iv) feature-based visualization, in which data with similar features are grouped together to highlight the information of interest. Salzbrunn et al. [10] add a fifth group, (v) partition-based visualization, which provides an overall result of flow behavior and its environment. However, it is difficult to apply in a 3D representation as its visualization becomes hard to understand. On the other hand, geometric visualization is better suited for 2D, 2.5D and 3D representations [12]. Nevertheless, the proximity of the elements can lead to masking problems.

Wind visualization was also used in VR with wind simulation results. Yan et al. [13] propose a method to use the results of CFD simulations in a VR scene using Building Information Modeling (BIM) tools. Fu et al. [14] have developed an interface tool to use the ParaView context as an immersive VR environment. Hosokawa et al. [15] propose an architectural design tool to display the result of CFD simulations in a virtual scene. Both the suggestive sketches and the visualization of CFD results use the same means to investigate wind behavior: visualization of wind flow. One of the goals of our study is to evaluate this type of representation by adding wind flow visualization to the virtual scene. Recently, Gan et al. [16] created a VR view of a CFD simulation based on a 3D model of an urban area. They use their system to help non-professional users make better-informed decisions. The wind rendering can be seen in VR, but it is not assumed to be seen from the perspective of a pedestrian walking in the urban scene as in our case. An example from previous research is that of Berger and Cristie [3], who used an animation of a CFD simulation result in a VR scene. We used a similar concept in [17], where the CFD simulation result in a video was superimposed on a photo of the real space to show the wind flow behavior along the analyzed space. In the present study, we used streamlines to visualize the wind flow in the VE.

1.2. Wind Presence Suggestion by Its Mechanical Effects

Wind can be perceived through its effects on the context and can be represented in a static image or an audiovisual representation (examples exist in photographs, paintings and films). These elements can also be found in the field of computer graphics. Wang et al. [18] show the direction and strength of the wind through its influence on snowfall. Dobashi et al. [19] and Vigier et al. [20] have suggested wind properties due to cloud motion in a scene. Finally, Bakay et al. [21] represented the presence of wind on grass and Quigley et al. [22] on the deformation of trees. To account for this work, we used an audio-visual suggestion of the mechanical effects of wind to generate the reference scene condition for our experiments.

1.3. Tactile Wind Representation in Virtual Reality

Different methods are used in the literature for airflow rendering. Moon and Kim [23] proposed the Windcube, a device that surrounds users. They proposed a layout of fans divided into three different height levels. The two lower levels were made up of eight fans placed every 45°, and the superior level presented four fans. The results of their experiment show that the sense of presence increased when tactile wind rendering was on. This layout of eight fans was reused by Cardin et al. [24] and Verlinden et al. [25]. Cardin et al. [24] propose a “head-mounted wind” device, which consists of an HMD adapted with eight fans tested in a flight simulation. Verlinden et al. [25] used eight fans with a 40 cm diameter placed in a 2 m high upper structure that had a 4 m diameter. They tested their device in a sailing simulator and evaluated the sense of presence in the VR scene. Their results were consistent with the previous experiments, showing that the sense of presence was increased using the tactile wind flow.

Kojima et al. [26] adapted a helmet with small fans, tubes and an audio speaker. Their goal was to apply the wind flow directly to the ear, the most sensitive area to wind according to their previous experiment. Rietzler et al. [5] developed a pneumatic device that can rotate 270° around the user’s head, providing visual and audio content. Their results show an increase in the sense of presence and enjoyment in the VR scene using the tactile wind flow. They noted a potential problem with the HMD that masks a part of the face. This problem sets out one of our research questions: are HMD suitable for tactile wind rendering in VR?

Kulkarni et al. [27] implemented a human-scale wind tunnel using cross-approaches between numer-

ical and physical simulations. They aimed to develop a multimodal stimulation device that uses wind, temperature and odors while walking in a VE. They used two lateral ducts oriented to the oblique screens of the device, creating a vortex, and directed the wind flow towards the user according to incidence angle and speed.

Ito et al. [28] produced a demonstration integrating visual, audio, and tactile stimuli with a limited number of fans considering cross-modal effects.

Nakano et al. [29] studied the wind direction perception. They analyzed the wind incident on the front, side and back of the participants' heads. They have compared JNDs (Just Noticeable Differences) values of wind direction discrimination produced by one single fan or a uniform wind produced by a fan array [30]. They have found that the JND for a uniform wind was 5.55° if the subject concentrates and the wind is directly blown on the face with no other stimulus.

A recent study from Ito et al. [31] examined the addition of a multisensory wind simulation on VR for relaxation purposes and showed that simulated natural wind reduced mental stress compared to a situation without wind, but did not examine the perception of wind properties per view. They did, however, use a tactile simulation to simulate wind, but only in one direction. They showed that the audio-visual stimuli affected the comfort and openness of wind and emotional pleasure.

Haptic stimuli, such as wind, are used to create multisensory VR experiences and awaken the sense of embodiment. In their experiment, Chai et al. [32] combine different stimuli (thermal, wetness, and wind with airflow pressure) in a portable haptic device on the hand.

The effects of wind on the body in VR are so important that their recent work Hosoi et al. [33] aims to simulate wind stimuli without actually creating a wind source for convenience, i.e., without the need for a real wind source such as fans in a mobile home system. They induce a pseudo-wind perception using visual-acoustic-haptic cross-modal effects.

Tolley et al. [34] presented a "WindyWall", a 90-fan array to allow users to explore wind simulations. They were interested in how people perceive the wind flow coming from simulations. Their results show that users are more sensitive to horizontal patterns.

2. Materials and Methods

We propose to compare those three kinds of representations: (i) wind flow visualizations, (ii) suggestions of wind presence by its effects on the context and

(iii) tactile wind representations. The state-of-the-art experiment on tactile wind rendering served as a basis for the implementation of our device in the VR space. We use our experimental device first to evaluate the perception of wind force and direction as well as the sense of presence and embodiment in a VR scene.

This study was approved by Nantes University's ethical committee (ref. n°19092022 19/09/2022). Our experiment is divided into two stages depending on the device type. First, we did an experiment using a stereoscopic large-screen. The screen dimensions are 1.80m high by 2.40m wide (see Figure 2a). We used a tablet with a dedicated application to evaluate the wind's perceived direction and force. We also studied the sense of presence in the VR scene. This large-screen experiment was reported in [6] and [35]. Then, we reproduce the previous experiment using an HMD HTC VIVE (see Figure 2c). Indeed, since the HMD hides a part of the participant's face and thus part of the incident wind, we wanted to study its impact. We also added a virtual avatar and evaluated the sense of embodiment in the HMD condition. Indeed, in the first-person perspective, participants could look down on their virtual bodies thus we added a gender-matched virtual body to represent them in the VE. The reason for adding a body was that if participants could embody their avatar in the VE, the perception of the wind on their virtual body could increase their perception of the wind.

The goal of our experiments was to analyze the effects of three different wind representations in terms of perception of its properties (direction and force) and on the senses of presence and embodiment in a VE, depending on the display technology used to visualize the VE (stereoscopic large-screen vs. HMD). We focused on the following representations: (i) the audiovisual representation of the mechanical effects of wind on contextual elements, (ii) the visualization of wind flow, and (iii) the tactile rendering of wind using digitally controlled fans. We specify that we were not looking for accuracy in terms of rendering the wind properties, but a suggestion of their variations.

2.1. Apparatus

We reuse the setup of fans and the VE from [6]. The arrangement of fans was based on that proposed by Verlinden et al. [25] since we were looking for a wind incidence on the participants' heads and bodies. In their paper, Verlinden et al. [25] used eight fans at the top of the experimental room. We decided to locate them at ground level (see Figure 2b) as participants were to be oriented to look up to see the buildings and wind flow

in the VR scene. We used the following fan model: Pro-Breeze 20" chrome floor fan (ProBreeze, London, UK). Each fan has 4 predefined speeds: Off = 0 m/s, speed 1 (s1) = 2.2 m/s, speed 2 (s2) = 2.6 m/s, and speed 3 (s3) = 3.3 m/s; measured at the participant position in the VR room. They were located around the user at a distance of 1.32 m (see Figure 2a). This distance was determined empirically based on constraints on the dimensions of the test room as well as the speed and timing of wind perception, which were influenced by the distance to the fan location. Using preliminary experiments measuring wind speed, we were able to determine this distance as a compromise between the wind speed measured at the user's position and the perception latency.

Regarding the sound, we equipped the participants with Plantronics-Backbeat Go 410 (Poly, San Jose, USA) Bluetooth in-ear headphones which had a double function: (i) to allow for the sound rendering of the virtual scene, and (ii) to reduce the ambient noise of the room (resulting from the fans operation, relays, projector, etc.) with their active noise cancellation function. Their size was chosen so as not to prevent the tactile influence of wind on the ears of the participants.

In terms of scene projection, our experiments were divided by the use of a stereoscopic large-screen and an HMD HTC VIVE. For the last one, we used the VIVE controllers which were used in one hand to choose the questionnaires' answers, and in the other hand, to track the participants' hands to control the virtual avatar.

2.2. Digital Fan Control

To integrate the tactile rendering of the wind, we implemented communication between the virtual scene from Unity3D (V.2018.3.9f1, Unity Technologies, San Francisco, CA, USA) and the fans using a Velleman-VMA101 (Velleman Group nv, Gavere, Belgique) card and a relay module. We modified the housing of the speed control buttons for each fan so that we could digitally control their activation and speed.

2.3. Virtual Environment

We used wind simulation data (coming from CFD simulation results [36]) to produce two visualizations in Paraview software (V5.5.0, Kitware, Clifton Park, USA). The processing of this data is detailed in [6].

To evaluate the effects of using a virtual avatar in our experiment, we evaluated a group of participants who used it during the evaluation. We used one female and one male avatar from the open source avatar Microsoft Rocketbox library [37]. We used the Finallk component in Unity3D to map the users' upper body

movements onto the avatars. We implemented two animations for the avatars lower body: (i) a walking animation that was triggered when the avatar was in motion, and (ii) an idle position. Three trackers were defined: the HMD for the head position and the controllers for the hands position. As the participants followed a predefined path in the virtual environment, and because the displacement took place automatically in the scene, participants' lower limbs were not tracked as it could create a discrepancy between their real legs movements and the animation of the avatar. This allowed us to control the participants' exposure to the wind and ensure that they all experienced the exact same conditions allowing for a fair comparison between the conditions and results analysis. In the HMD condition, participants could see their avatars through reflective surfaces on the virtual model or look directly at their virtual body. Of course, while participants could not control their displacement in the VE and were asked to keep their legs still, they were free to move their head in order to explore the environment as they wished, unlike the large-screen condition where there was no head-tracking implemented. The predefined paths are shown in the supplementary material.

2.4. Experimental Design

Our study was conducted with three independent variables. The first one (**I1**) was the wind representation since we ensured that participants were different between the HMD conditions and the previously run large-screen experiment, with four different levels:

- R** The Reference scene composed of an audiovisual representation of the mechanical effects of wind on the elements of the context. The direction and wind force were given by the spatialized sound of the wind. The presence of wind was also suggested by the movement of tree leaves and clouds (see 3a).
- V** The Reference scene (R) + Visual representation of the wind flow, as found in the representations used in architecture (see 3b).
- T** The Reference scene (R) + Tactile wind rendering with digitally controlled fans.
- V+T** The Reference scene (R) + Visual representation of the wind flow (V) + Tactile restitution (T).

A video of the experimental conditions can be consulted at the following link (accessed on 16 June 2024) <https://youtu.be/eMKBUAsbaIM> from [35].

The second one (**I2**) was the sense of presence, and finally (**I3**) the type of device used to visualize the VE, i.e., the large-screen or the HMD.

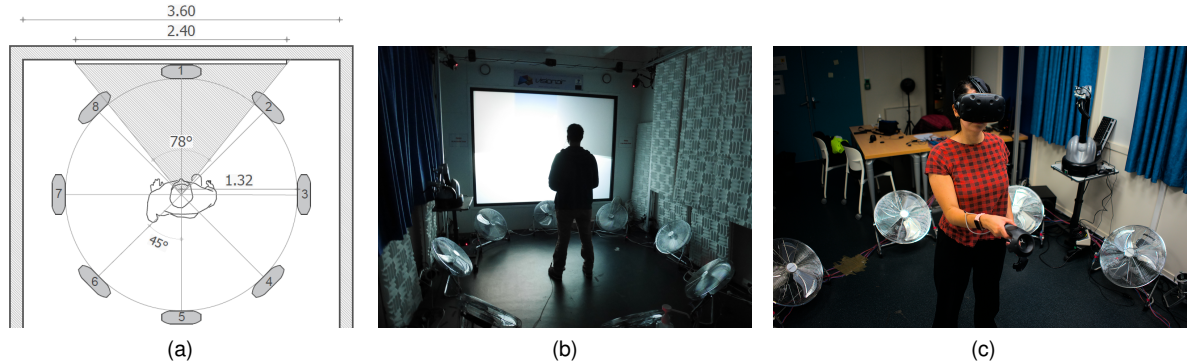


FIGURE 2. (a) Fan layout composed of eight fans located around participants in the VR room, units in meters. Image from [6]. (b) A participant in the VR room using the large stereoscopic screen. Image from [35]. (c) A participant in the VR room using the HMD HTC VIVE.

There were five dependent variables: the wind properties perception (**D1** direction and **D2** force), **D3** the sense of presence, **D4** the sense of embodiment and **D5** the avatar use in the virtual reality scene.

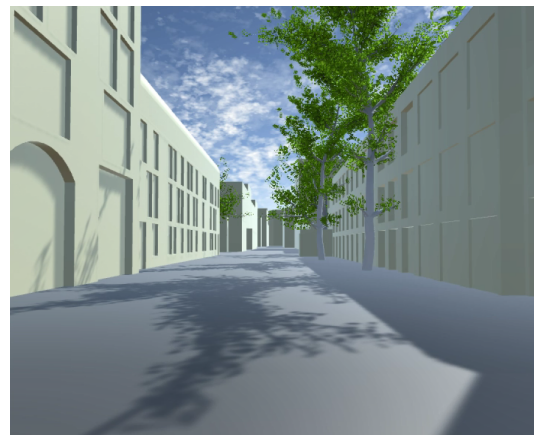
We used a within-subjects design for **I1** and a between-subjects design for **I2** and **I3**.

37 volunteers participated in our large-screen experiment (17 women, 20 men) aged from 22 to 61 years (mean=35, SD=9.6), and 61 volunteers (26 women, 35 men) aged from 18 to 60 years (mean = 30.15, SD = 12.2) in our HMD experiment. Note that this last was divided into two groups: with and without virtual avatar; 30 (14 women, 16 men) and 31 (12 women 19 men) volunteers respectively. The majority of the participants were students and staff members of the university and of the laboratory. They did not know the purpose of the experiment and were not compensated for their participation, as is common practice in our institution.

2.5. Hypotheses

Considering previous research, and based on our experimental design, we made the following hypotheses:

- H1** R is more accurate for wind direction perception using the HMD compared to the large-screen projection. As the participants' head movements are tracked with the HMD, the source of the wind sound can be easily understood.
- H2** V is more accurate for wind direction understanding using the HMD compared to the large-screen projection. The fact of being able to rotate the camera in the virtual scene can allow us to analyze the path of the streamlines and to better understand their behavior.
- H3** T has similar behavior with both the large-screen



(a)



(b)

FIGURE 3. (a) Reference scene, the first course presented to participants (image from [6]). (b) The visual wind-flow representation.

projection and the HMD. Since the fans used in both experiments have effects on both the participant's head and body, we consider that the wind properties can be understood with both types of devices.

- H4** The use of the virtual avatar increases the sense of presence in the VE. According to Slater [38] the representation, presence and actions of virtual bodies can increase the illusion in the VE.
- H5** Tactile representations increase the sense of embodiment in the VE. Previous studies [39], [40] showed that tactile feedback improves the sense of embodiment in a VE. We assumed the wind stimuli to be consistent with previous work.

2.6. Procedure

Each participant came to the virtual reality room where the procedure was explained. They had to take four different virtual paths in the same street with three stops, detailed in [35]. Each path was characterized by a type of wind representation and was presented to participants (using the large-screen) in the following order: R - V - T - V+T. To reduce the possible order effects from the large-screen experiment, participants using HMD followed the experiment starting by R representation and the others were presented randomized. Note that these paths were predefined to prevent the resulting latency between the moment the fans are turned on and the participant's perception of the wind. Before starting, participants were given noise-canceling headphones. Participants of the large-screen experiment used a tablet for the evaluation while those of the HMD experiment used the HTC VIVE controllers. The camera viewpoint was based on the participant's height. Then, they were located at the center of the group of fans. A reference wind value was played (sound and tactile) before starting to let the participants identify the maximal values of wind force. Then, participants using the avatars were located in front of a mirror in the VR scene to allow them to become familiar with their virtual bodies. During the path there were some reflective surfaces to observe their virtual avatar, they could also do it in direct vision.

The tablet had an application that indicated the number of the stops to be evaluated and allowed the participants of the large-screen experiment to specify the wind direction in a circle and the wind force in a slider from 0 (corresponding to no wind) to 10 (corresponding to the maximum reference value). We used the same elements (the circle and slider) for the participants of the HMD experiment, but they were presented as panels within the virtual scene. These

evaluations were to be made based on the resulting wind behavior (direction and force) at the stop points, which remained constant during the evaluation. At the end of each path, the participants had to evaluate their sense of presence in the VR scene with the SUS questionnaire [41] and the participants with the avatars also evaluated a sense of embodiment questionnaire [42]. Then they continued the experiment with another type of representation. The sessions lasted about 30 minutes per participant.

3. Results

In this section, we present descriptive and inferential statistical analyses of the perception of the wind properties (direction and force), the sense of presence, and embodiment in the VE.

3.1. Statistical Analysis

We considered the difference between the initial simulated parameters of the wind in the scene (rendered in various experimental conditions) and the user answers for the wind properties and the sense of presence.

A square-root transformation was applied to the data to normalize the absolute values of the answers. The resulting values, concerning wind properties (direction and force), presence, and embodiment, were analyzed using a multilevel linear model. The model includes the variable to be explained (direction difference, force difference, presence or embodiment), the explanatory variable (the type of representation), and the participant factor as a random effect. The assumption of normality was tested with the Shapiro–Wilk test at the 5% level and a visual check of the normal distribution of the data residuals. A Tukey's posthoc test was performed to compare all the conditions of the categorical variable. The statistical analysis was conducted using RStudio software (V2021.9.2.382, RStudio Team, Boston, Ma, USA), with the function `lme` of the `nlme` package (V3.1-153). The `glht` (multcomp package (V1.4-18)) function was used for pairwise comparisons and the `shapiro.test` (stats package (V4.1.2)) function for the assumption of normality. Raw data visualization are provided as supplementary material.

3.2. Wind Direction

Large-Screen experiment: The type of representation had a significant effect on the estimation of wind direction using the large-screen, $\chi^2(3) = 66.87$, $p < 0.001$. Orthogonal contrast revealed that the direction error of absolute values (difference between the expected

response and the value given by the participants) was significantly reduced for T compared to R, $b = 3.05, t(108) = 8.22, p < 0.001$, and compared to V, $b = 1.67, t(108) = 4.52, p < 0.001$. There was no significant difference in direction error between T and V+T, $b = 0.34, t(108) = 0.93, p = 0.35$. To compare the significant pairwise differences, we produced a post-hoc test as set out below (see Figure 4a):

- Compared to R, direction error was significantly reduced for T ($p < 0.001$), V+T ($p < 0.001$) and V ($p = 0.001$).
- Compared to V, direction error was significantly reduced for T ($p < 0.001$) and V+T ($p < 0.001$) representations.
- There was no significant difference in direction error using V+T compared to T ($p = 0.78$).

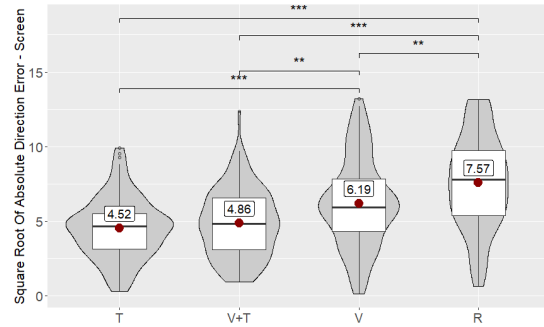
The effects of gender ($\chi^2(1) = 0.55, p = 0.45$), age ($\chi^2(1) = 0.015, p = 0.90$) (evaluated between two groups: older and younger than median value ($\bar{X} = 31$ for large-screen and $\bar{X} = 25$ for HMD)) and the experience in Virtual Reality declared by the participants ($\chi^2(4) = 1.75, p = 0.78$), did not present any significant difference in wind direction perception using the large-screen projection.

HMD experiment: The type of representation had a significant effect on the estimation of wind direction using the HMD device, $\chi^2(3) = 56.31, p < 0.001$. Orthogonal contrast revealed that the direction error of absolute values was significantly reduced for T compared to R, $b = 2.15, t(132) = 7.05, p < 0.001$, and compared to V, $b = 1.25, t(132) = 4.13, p < 0.001$. There was no significant difference in direction error between T and V+T, $b = 0.05, t(132) = 0.17, p = 0.86$. To compare the significant pairwise differences, we produced a posthoc test (see Figure 4b):

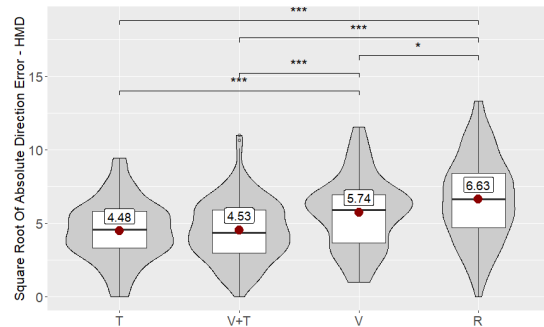
- Compared to R, direction error was significantly reduced for T ($p < 0.001$), V+T ($p < 0.001$), and V ($p = 0.017$).
- Compared to V, direction error was significantly reduced for T ($p < 0.001$) and V+T ($p < 0.001$) representations.
- There was no significant difference in direction error using V+T compared to T ($p = 0.99$).

The use of the virtual avatar did not present any significant difference in the wind direction perception, such that $\chi^2(1) = 1, p = 0.31$.

Type of Device Comparison: The experimental condition had a significant effect on the estimation of wind direction, such that $\chi^2(1) = 5.41, p = 0.02$. Orthogonal contrast revealed that the direction error of absolute values was significantly reduced for



(a) Large-screen.



(b) HMD.

FIGURE 4. Box plot and violin plot of the square root of the absolute wind direction estimation error through the four different representations (a) with large-Screen and (b) HMD. The red dot is the mean value. Horizontal lines represent the quartiles. The violin plot shows the frequency of results. Stars present the level of significance (* : $p < 0.05$, ** : $p < 0.01$, *** : $p < 0.001$).

the HMD device compared to the large-screen, $b = -0.43, t(80) = -2.36, p = 0.02$.

Regarding the device type results by the type of wind representation, we found that direction error of absolute values was significantly reduced for HMD compared to the large-screen in R condition $p = 0.03$, but there were no differences in T ($p = 0.87$), V ($p = 0.19$) and V+T ($p = 0.28$) conditions.

3.3. Wind Force

Large-Screen experiment: The type of representation had a significant effect on the estimation of wind force using the large-screen, $\chi^2(3) = 13.54, p = 0.0036$. Orthogonal contrast revealed that force error (difference between the expected response and the value given by the participants) was significantly reduced for T compared to R, $b = 0.18, t(108) = 2.64, p = 0.0094$. There was no significant difference in force error in

T compared to V, $b = 0.14, t(108) = 1.99, p = 0.05$, and to V+T, $b = -0.039, t(108) = -0.56, p = 0.57$. To compare the significant pairwise differences, we produced a posthoc test (see Figure 5a):

- Compared to R, force error was significantly reduced for T ($p = 0.039$) and V+T ($p = 0.0068$).
- Compared to V, force error was significantly reduced for V+T ($p = 0.049$).
- Compared to V, the wind force error was not significantly different either with R ($p = 0.91$) nor T ($p = 0.18$).
- There was no significant difference in force error for T compared to V+T ($p = 0.94$).

The effects of gender ($\chi^2(1) = 0.01, p = 0.9$), age ($\chi^2(1) = 1.68, p = 0.19$), and the experience in virtual reality declared by the participants ($\chi^2(4) = 2.33, p = 0.67$) did not present any significant difference on wind force perception.

HMD experiment: The type of representation had a significant effect on the estimation of wind force using the HMD device, $\chi^2(3) = 36.92, (p < 0.001)$. Orthogonal contrast revealed that force error (difference between the expected response and the value given by the participants) was significantly reduced for T compared to R, $b = 0.38, t(147) = 5.22, p < 0.001$ and compared to V $b = 0.34, t(147) = 4.67, p < 0.001$. There was no significant difference in force error in T compared to V+T, $b = 0.065, t(147) = 0.904, p = 0.36$. To compare the significant pairwise differences, we produced a posthoc test (see Figure 5b):

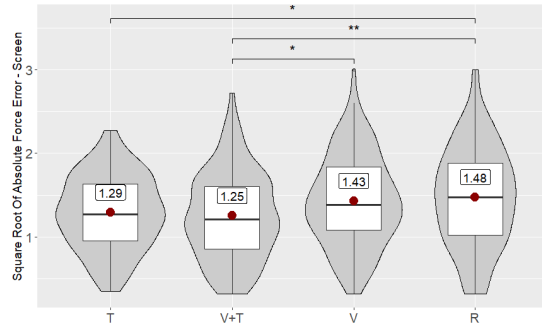
- Compared to the R, force error was significantly reduced for T ($p < 0.001$) and V+T ($p < 0.001$).
- Compared to the V, force error was significantly reduced for T ($p < 0.001$) and V+T ($p < 0.001$).
- Compared to V, the wind force error was not significantly different either with R ($p = 0.96$).
- There was no significant difference in force error for T compared to V+T ($p = 0.80$).

The use of the virtual avatar did not present any significant difference on the wind force perception, such that $\chi^2(1) = 0.81, p = 0.36$.

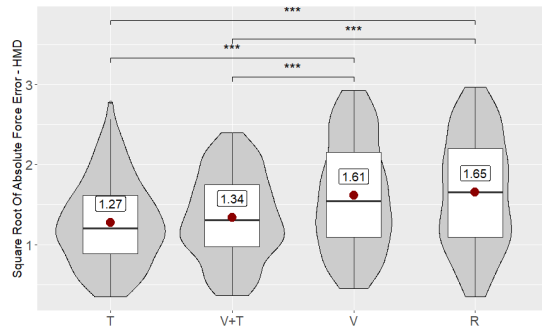
Type of Device Comparison: The experimental condition did not have a significant effect on the estimation of wind force, such that $\chi^2(1) = 2.87, p = 0.089$.

3.4. Sense of Presence

Large-Screen Experiment: The type of representation had a significant effect on the estimation of the sense of presence using the large-Screen, $\chi^2(3) = 53.543, p < 0.001$. Orthogonal contrast revealed that the sense of presence was significantly increased in T



(a) Large-screen condition.



(b) HMD condition.

FIGURE 5. Box plot and violin plot of the square root of the absolute wind force error through the four different representations (a) with large-screen and (b) HMD. The red dot is the mean value. Horizontal lines represent the quartiles. The violin plot shows the frequency of results. Stars present the level of significance (* : $p < 0.05$, ** : $p < 0.01$, *** : $p < 0.001$).

compared to R, $b = -0.17, t(108) = -5.60, p < 0.001$, V, $b = -0.24, t(108) = -7.66, p < 0.001$ and V+T, $b = -0.08, t(108) = -2.78, p = 0.006$. To compare the significant pairwise differences, we produced a posthoc test (see Figure 6a):

- Sense of presence was significantly increased for T compared to R ($p < 0.001$), V ($p < 0.001$) and V+T ($p = 0.024$).
- Sense of presence was significantly increased for V+T compared to R ($p = 0.023$) and compared to V ($p < 0.001$).
- There was no significant difference in the sense of presence for V compared to R ($p = 0.15$).

The participants' gender presented a significant difference in the sense of presence in the VE $\chi^2(1) = 6.73, p < 0.009$. Orthogonal contrast revealed that the sense of presence was significantly lower in men compared to women $b = -0.15, t(35) = -2.69, p < 0.01$ (see Figure 7).

The age ($\chi^2(1) = 0.22, p = 0.63$) and experience in virtual reality declared by the participants ($\chi^2(4) = 6.97, p = 0.13$) did not have any significant impact on the sense of presence.

HMD Experiment: The type of representation had a significant effect on the estimation of the sense of presence using the HMD device, $\chi^2(3) = 92.19, p < 0.001$. Orthogonal contrast revealed that the sense of presence was significantly increased in T compared to R, $b = -0.55, t(180) = -5.01, p < 0.001$, V, $b = -1.16, t(180) = -10.54, p < 0.001$ and V+T, $b = -0.33, t(180) = -3.07, p = 0.002$. To compare the significant pairwise differences, we produced a posthoc (see Figure 6b):

- Sense of presence was significantly increased for T compared to R ($p < 0.001$), V ($p < 0.001$) and V+T ($p = 0.010$).
- Sense of presence was significantly increased for V+T compared to V ($p < 0.001$).
- Sense of presence was significantly reduced for V compared to R ($p < 0.001$).
- There was no significant difference in the sense of presence for V+T compared to R ($p = 0.20$).

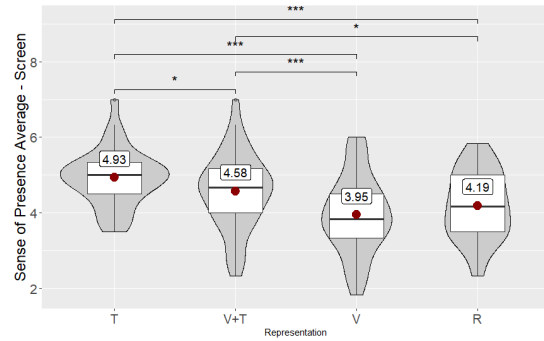
Type of Projection Comparison: The experimental condition did not have a significant effect on the sense of presence, $\chi^2(1) = 2.85, p = 0.091$.

Use of the Virtual Avatar: The experimental condition did not have a significant effect on the sense of presence, $\chi^2(1) = 1.24, p = 0.26$.

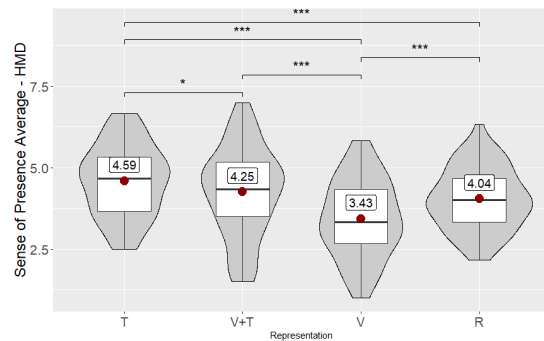
Use of the Virtual Avatar by Gender: The experimental condition had a significant effect on the sense of presence, $\chi^2(1) = 5.61, p = 0.017$. Orthogonal contrast revealed that the sense of presence was significantly increased in men compared to women using the virtual avatar, $b = 0.85, t(28) = 2.4, p = 0.019$ (see Figure 8). While there was not a significant effect on the sense of presence divided by gender without the virtual avatar, $\chi^2(1) = 0.61, p = 0.64$.

3.5. Embodiment

The Sense of Embodiment (SoE) was only evaluated in the HMD experiment since participants did not have an avatar in the Large-Screen experiment. The type of representation had a significant effect on the estimation of the embodiment in the VE, $\chi^2(3) = 132.04, p < 0.001$. Orthogonal contrast revealed that the sense of embodiment was significantly increased for T compared to R, $b = -1.25, t(87) = -11.66, p < 0.001$, and compared to V, $b = -1.34, t(87) = -12.53, p < 0.001$. There was no significant difference in the embodiment sense in T compared to V+T, $b = -0.13, t(87) =$



(a) Large-screen Experiment.



(b) HMD Experiment.

FIGURE 6. Box plot and violin plot of the square root of the average sense of presence through the four different representations (a) with large-screen and (b) HMD. The higher the value, the higher the sense of presence. The red dot is the mean value. Horizontal lines represent the quartiles. The violin plot shows the frequency of results. Stars present the level of significance (* : $p < 0.05$, ** : $p < 0.01$, *** : $p < 0.001$).



FIGURE 7. Box plot and violin plot of the effects of gender on the sense of presence using the large-screen. Stars present the level of significance (** = $p < 0.01$).



FIGURE 8. Box plot and violin plot of the effects of gender on the sense of presence using the HMD and the virtual avatar. Stars present the level of significance ($* = p < 0.05$).



FIGURE 10. Box plot and violin plot of the effects of gender on the sense of embodiment. Stars present the level of significance ($*** = p < 0.001$).

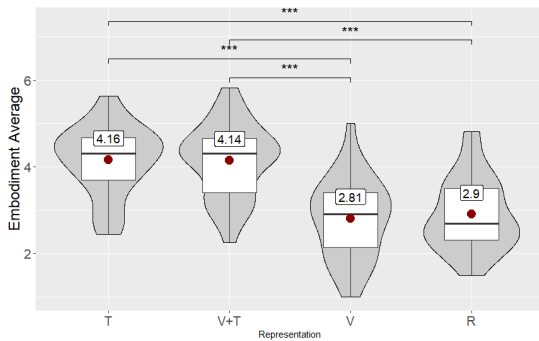


FIGURE 9. Box plot and violin plot of the effects of the type of representation on the sense of embodiment. Stars present the level of significance ($*** = p < 0.001$).

$-0.014, p = 0.89$. To compare the significant pairwise differences, we produced a posthoc test (see Figure 9):

- The SoE was significantly increased for T compared to V ($p < 0.001$) and R ($p < 0.001$).
- The SoE was significantly increased for V+T compared to V ($p < 0.001$) and R ($p < 0.001$).
- There was no significant difference in the SoE neither between R and V conditions ($p = 0.81$) nor between T and V+T ($p = 0.99$).

The participants' gender presented significant differences in the sense of embodiment in the VR scene $\chi^2(1) = 5.74, p = 0.016$. Orthogonal contrast revealed that the sense of embodiment was significantly lower in women compared to men $b = 0.62, t(28) = 2.49, p = 0.018$ (see Figure 10).

3.6. Wind Perception

Note that this condition was only evaluated in the HMD experiment. The type of representation had a signifi-

cant effect on the wind perception in the VE, $\chi^2(3) = 173.28, p < 0.001$. Orthogonal contrast revealed that the wind perception realism was significantly increased for T compared to R, $b = -2.32, t(180) = -11.04, p < 0.001$, to V, $b = -3.11, t(180) = -14.77, p < 0.001$ and compared to V+T, $b = -0.62, t(180) = -2.95, p = 0.003$. To compare the significant pairwise differences, we produced a posthoc test:

- Wind perception realism was significantly increased for T compared to V ($p < 0.001$), R ($p < 0.001$) and V+T ($p < 0.015$).
- Wind perception realism was significantly increased for V+T compared to V ($p < 0.001$) and R ($p < 0.001$).
- Wind perception realism was significantly decreased for V compared to R ($p < 0.001$).

The participants' gender did not present a significant difference in the evaluation of the wind perception $\chi^2(1) = 0.024, p = 0.87$.

4. Limitations, Discussion and Future Work

We point out that we cannot generalize with our sample population, which is clearly limited in number and diversity. In order to generalize the results of our study to a broader population, we would need to repeat the two experiments with a more diverse population.

Our results show that, between the different types of representations, the Tactile (T) condition was the most suitable in terms of wind properties (direction and force) and it was also the one that increased the most the senses of presence and embodiment in both large-screen and HMD device. During the experiment, the participants did not report any problems related to

cybersickness.

Note that in our experiments we did not have the possibility to control room temperature, which can influence wind perception. This should be implemented in a future experiment to reproduce the atmosphere of a place in a more representative way. Nevertheless, the two experiments were run approximately at the same time of the year (September 2019 for [35] and October 2022 for the current study).

4.1. Device Type

Regarding the device type, we observed a significant difference in evaluation of the wind direction between the large-screen and the HMD. Results show a better understanding using the HMD. We analyzed this difference with each representation and we found that the only significant difference was present in the R condition, where the wind direction perceived was closer to the input value using the HMD. It can be explained by the fact that the head movements were tracked with the HMD, facilitating the identification of the wind sound source localization, which supports hypothesis H1 but does not support H2.

In our Large-screen experiment, we decided to use that device instead of a HMD since the latter covers a part of participants' faces and therefore could affect wind perception. We reproduced the experiment using the HMD to test this assumption. The results of the experiments show that wind representations were well interpreted by the participants using both the large-screen and the HMD, supporting H3. There were no significant differences between the two types of projections neither for the wind force evaluation nor the sense of presence in the VR scene. The only difference was present in the wind direction evaluation, as explained before, in the R condition.

Note that the participants were only allowed to rotate the virtual camera in the HMD evaluation, as rotating the camera on the large-screen resulted in a change in wind direction and thus latency problems in wind perception.

One limitation in our large-screen experiment was the order of presentation of the four conditions, which was the same for all participants and could lead to an order effect. In the HMD experiment, we presented condition R first and the remaining three conditions were randomized to reduce this potential effect.

4.2. Use of the Virtual Avatar

The use of the virtual avatar did not affect the sense of presence in our evaluation, which refutes H5. However, when we differentiate the effects of the virtual avatar

by gender, we find a significant difference between women and men that is not present without the use of the virtual avatar. The results showed that men's sense of presence was increased by using the virtual avatar in the VE, which is consistent with the study by Schwind et al. [43]. They found that women showed a lower sense of presence than men when using virtual human hands, especially when using male hands. In contrast, when using non-human hands, the sense of presence was higher in women. They also observed that women perceived visual features of the virtual hands. We also used a non-textured street model in our experiments. In our Large-Screen experiment, the sense of presence was higher for women. When using the HMD without the virtual avatar, there was no significant difference between the genders in terms of sense of presence. However, when using the virtual avatar, the sense of presence was stronger in men than in women. Previous studies have shown differences between genders in VR, Fribourg et al. [44] found that women tended to require a higher level of avatar aspect compared to men. Banakou and Chorianopoulos [45] found in their experiment that women interacted more with male avatars when the female avatars were more attractive, suggesting a self-confidence effect from the avatar's appearance.

4.3. Sense of Presence and Sense of Embodiment

Sense of presence results were similar with both the large-screen and the HMD device. Condition T showed a higher level of presence in the VR scene, which is consistent with previous studies such as [23], [25], [5]. The use of the streamlines reduced the feeling of presence when using HMDs. This can be explained by adding elements that cannot be seen in the real world. We did not find a significant difference when comparing the large-screen with the HMD.

Our results showed that conditions using a tactile representation (T and V+T) increased the sense of embodiment in the VE, supporting hypothesis H5.

As for the sense of presence and embodiment, our question concerning the wind perception in the VE shows a higher score in conditions using the tactile representation (T and T+V). T presented the higher result showing significant differences with the others representation. The condition V+T was close to T (presenting a significant difference), evidencing that even with the streamlines the realism of the wind representation remains high when the tactile condition is present. Condition V presented the lowest score.

Unexpectedly, the results of our experiment show

that, men experienced a higher sense of presence (using the virtual avatar) and sense of embodiment than women. We did not have any research hypothesis on such differences since there is no consensus on such results in the literature, where we can find some results mentioning that men have a higher sense of presence than women [46] while other report no statistical difference between gender [47] or even report inverse results where women had a higher sense of presence than men [48].

As for the sense of embodiment, we also had no prior hypothesis on a gender difference between men and women as prior research did not point out to a clear consensus (see e.g., [49] where there was no statistical difference between men and women in terms of sense of embodiment).

4.4. Wind Perception

Concerning the wind-flow visualization, we only explored a streamlined animation to make the wind visible. Other types of wind-flow visualization, e.g. as presented by Christmann et al. [4] such as vectors or particles, can vary from arrows to expressive representations. Their use could bring other elements to analyze in the different stages of an architectural project, or even integrate the wind representations to a BIM project as studied by Gan et al. [16].

5. Conclusions

We explored different types of wind representations of an urban space coming from a CFD result in a virtual environment. Our study was divided into two different stages mainly characterized by the device type. For the first one, we used a large-screen device, to avoid an obstacle in the participants' faces that could affect the wind perception. In the second one, we evaluated the effects of the HMD on wind perception. Our results show that wind properties, coming from a CFD simulation can be expressed and understood by different types of representation beyond the wind-flow visualization used in classical representations. According to our results, and our experimental conditions, the tactile representation was the most helpful in identifying wind properties and increasing the sense of presence and embodiment in the VR scene, using both the large-screen and HMD devices. This is an interesting fact because the HMD adds the possibility to explore the model around the avatar turning the head without disturbing the wind perception.

Aware of the impact of other physical phenomena such as temperature on the wind resulting in urban

spaces, we intend to implement this variable in a future experiment, taking advantage of the controlled environment of a VR experiment room.

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