Spatial Presence, Performance, and Behavior between Real, Remote, and Virtual Immersive Environments*

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Fig. 1. Visual display of each environment. On the left, the real environment. In the middle, the remote environment. In the right, the virtual environment.

Abstract—Spatial presence encompasses the user's ability to experience a sense of "*being there*". While particular attention was given to assess spatial presence in real and virtual environments, few have been interested in measuring it in telepresence situations. To bridge this gap, the present work introduces a study that compares the execution of a task in three conditions: a real physical environment, a remote environment via a telepresence system, and a virtual simulation of the real environment. Following a within-subject design, 27 participants performed a navigation task consisting in following a route while avoiding obstacles. Spatial presence and five related factors (affordance, enjoyment, attention allocation, reality, and cybersickness) were evaluated using a presence questionnaire. In addition, performance measures were gathered regarding environment recollection and task execution. The evaluation also included a behavioral metric measured by obstacle avoidance distance extracted from participants' trajectories. Results indicated a higher presence in the real environment, along with the best performance measures. No difference was found in spatial presence between the remote and the virtual conditions, although a higher degree of affordance and enjoyment was attributed to the virtual environment, and a higher degree of reality was attributed to the remote environment. The number of collisions was found to be lower in the remote condition compared to the virtual condition. Similarly, the avoidance distance was also bigger (and almost similar) in the real and the remote environments compared to the virtual environment indicating a greater caution of participants. These cues highlight that the behavior of participants in the remote condition was closer to their behavior in the real situation than it was in the virtual condition. Furthermore, positive correlations were found between the reality factor and two of the three performance measures, as well as with the behavioral metric. This suggests that the degree of physical existence of the space in which participants operate can influence their performance and behavior.

Index Terms—Spatial presence, remote and virtual environments, user evaluation, performance and behavioral mesures.

1 Introduction

Spatial presence is defined by Wirth et al. as "*the conviction of being located in a mediated environment*" [68]. This conviction to be physically somewhere makes spatial presence an important variable in Robotic and Virtual Reality (VR) fields where researchers aim to enhance the effectiveness of their applications. For instance, spatial presence can facilitate the transfer of information needed for the successful conduct of remote surgical operations [64], or improve the learning capability during tele- or virtual teaching [2]. It can also intensify the positive effects of the applications and their impact on users' emotional reactions such as enjoyment and satisfaction in virtual games [62], and fear and anxiety in virtual therapies [20].

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The sensation of being physically transported in an environment can be experienced by users whether the environment is real or computer-generated, and whether or not it is mediated by means of technologies [68]. Therefore, spatial presence can be classified into three subcomponents according to the different types of environments that exist [71]. Namely, if the environment is real and non-mediated the user experiences a proximal presence, also referred to as "*natural presence*" or "*non-mediated presence*" [26]. If the environment is real and mediated (i.e. considered as temporally and/or spatially distant) the user experiences a remote presence, also known as "*telepresence*" [59], and if the environment represents a non-existent, computer-generated virtual world, the user experiences a "*virtual presence*" [50].

Many researchers highlighted different factors that play significant roles in the emergence of presence, such as the level of sensory fidelity of the technology, referred to as immersion [13], the degree of affordance of the environment [43], and the user's attention allocated on a task [9]. One of the main goals of such research is to predict the variability of the user's sense of presence experienced for a specific application or within a specific environment. In that way, many studies investigated the influence of different factors on spatial presence by comparing real environments -where presence should be at its peak- with virtual environments [6, 8, 29, 33, 52, 68].

In contrast, the evaluation of spatial presence in remote environments suffered from a lack of interest, which could be due to the blurred boundary between virtual and remote environments. Indeed, both of them are mediated through similar user-interface technologies. Yet, while virtual environments have limited real-life consequences (as the results of the users' actions remain restricted to the computer-generated space), interacting in remote environments induces real-life consequences as the physical representation of the space exists. Thus, investigating spatial presence in such environments would allow assessing the impact of additional factors such as the extent to which a user considers the environment as real or "*authentic*" [58]. Moreover, by comparing remote and virtual environments with real environments, one can isolate the effect of user-interface technology and truly assess its impact on the sense of spatial presence.

To target such research questioning, this paper presents a study that evaluates the user's sense of spatial presence by comparing the execution of a task in a physical space, and the same task performed respectively in a remote (teleoperation) space and a computer-generated representation of the same physical space. Both remote and virtual environments are displayed within a head-mounted display (HMD) with almost identical visual, auditory, and control conditions. In addition to the assessment of spatial presence and some related factors using a subjective questionnaire, and objective metrics based on user performance and behavior are evaluated. Finally, the potential correlations between presence and these objective metrics are investigated.

The remainder of the paper is divided into six main sections. The first one provides an overview of related work highlighting the research focus of the paper. The second and third sections describe respectively the experimental design and the user evaluation procedure. They are followed by statistical analyses and subsequent results in the fourth section. The fifth section proposes a discussion of these results and the last section concludes and points out new perspectives.

2 Related Work

Spatial presence encompasses the user's ability to experience a sense of being physically located in any given environment [68]. Depending on the environment, some factors that influence presence, such as immersion, affordance, and realness, can be more or less significant leading to a different degree of experienced spatial presence. For this reason, it is necessary to assess presence across different environments.

2.1 Spatial presence across environments

The concept of spatial presence has been particularly studied in VR because of its usefulness in improving the impact of applications on users' emotional [20, 62]. Thus, many researchers sought to identify the factors that contribute to enhance the user's feeling of presence by comparing presence in virtual vs. real environments (the latter being considered as baselines). For instance, Usoh et al. [65] compared spatial presence in a real office and a simulated virtual environment (VE) of the same office rendered over the Virtual Research VR4 HMD. Results showed a significantly higher presence score for the real environment (as measured by the ITC-SOPI questionnaire [29]). Similarly, Mania [33] assessed presence between a seminar room and its computer-generated simulation rendered over an HMD. They found a higher sense of presence (as measured by the Slater's questionnaire [52]) in the real room. Later, Busch et al. [8] evaluated the use of a mobile navigation application in a real laboratory and its virtual simulation rendered in a five-sided CAVE-like system. Results showed no statistical differences in spatial presence (as measured by the ITC-SOPI questionnaire [29]) between both environments. Following the same process, Brade et al. [6] compared presence between a real city center and a corresponding VE rendered in a CAVE and found no significant differences between them.

In parallel, in the context of robotic and teleoperation systems, researchers mainly focused on improving the performance of users during their teleoperation tasks. They worked to design and optimize remote systems in different fields such as the spatial industry field [1], the medical-surgical field [64], and the industrial domain (e.g., assembly operations [40]) to name a few. In this respect, robotics researchers took great interest in presence due to its values in the transmission of information, especially concerning the spatial perception of a remote place [50]. Nonetheless, the evaluation of remote spatial presence suffers from a relative lack of interest compared to its equivalent in virtual environments, which can be partially due to the conflation between virtual and remote conditions. Indeed, because they are based on the same mediated user-interface technologies, they share the common feature that the relevant parts of the user's experience at some stage in the process is transmitted via a digital representation. Yet, a main difference between them is that, in the case of remote environments, a physical space exists behind this digital representation. This induces the possibility of real-life consequences (e.g., objects that can break), in contrast to virtual environments [26].

Precisely, an environment is considered remote as soon as it satisfies two criteria [21]:

1. The environment allows the **remote perception of a real physical place** either by the mediation of sensory-motor channels, the virtual representation of the physical place, or both of them using augmented reality technologies.
2. The users' **actions have real impacts** on the physical place and they are **aware** of this impact.

If the first criterion is usually met, the second one is often overlooked, creating confusion between remote and virtual environments. Nevertheless, this *awareness* criterion is crucial. Studies showed that user behaviors can be influenced by the perceptions associated with one's actions [54]. Therefore, users' awareness of the tangible impact of their actions in a remote environment may influence their behavior, and hence, their experience of spatial presence.

Furthermore, the recent technological advances including better resolution and larger field of view of HMDs combined with latency reduction make it possible to convey remote environments that provide a high-fidelity perception of the real world. Evaluating presence in such environments may highlight the impact of recent mediation technologies.

In parallel, many studies worked at identifying the measurements and the tools for the evaluation of spatial presence. These measures are described in the following.

2.2 Measurements of spatial presence

The measurements of presence can be divided into self-report (mostly using questionnaires), physiological, performance, and behavioral measures as follows.

2.2.1 Self-report measures

Self-report refers to all techniques where users are reporting their own feelings, perceptions, or behaviors during (or after) an experiment.

Many researchers proposed self-report techniques as a simple and non-intrusive way to evaluate spatial presence such as interviewing participants after they experienced an environment [17] or confronting them with the video recording of their own activity or of that of others [34]. In addition, other self-report techniques were introduced to evaluate presence such as the technique of free-modulus magnitude estimation [56], the handheld slider [16], and the presence counter [53].

Furthermore, researchers proposed post-questionnaires to assess presence. Because they are quite easy to administer and evaluate, the questionnaires have been widely used since the early days of presence research. In particular, Rosakranse and Oh identified five canonical presence questionnaires between 1998 and 2012 [45] —the Slater-Usoh-Steed (SUS) questionnaire [52], the Witmer-Singer Presence Questionnaire (PQ) [69], the igroup Presence Questionnaire (IPQ) [49], the ITC-Sense of Presence Inventory (ITC-SOPI) [29], and the Lombard and Ditton Temple Presence Inventory questionnaire (TPI) [31]. Using different items and subscales, these questionnaires provide scores that highlight different factors of presence such as immersion, affordance, enjoyment, attention allocation, and reality judgment, to name a few.

Although having been demonstrated to be sensitive and reliable, presence questionnaires do not provide a continuous measurement of presence because users complete questionnaires at the end of their experience. Furthermore, they are highly dependent on users' experience and rely on the interpretations of potentially complex concepts to generate meaningful results [51]. Therefore, objective measures have been designed to assess presence in combination with questionnaires.

2.2.2 Physiological measures

Many studies sought to establish the reliability of physiological indicators to measure presence. Dillon et al. [14] investigated the relationship of skin conductance response (SCR) and electrocardiogram (EKG) data with presence as measured by the ITC-SOPI. They run an experiment where participants viewed a video stream presented with and without stereoscopic perception. The results did not show significant correlations between physiological metrics and presence. In contrast, Meehan et al. [35] showed that in a stressful virtual immersive environment depicting a visual cliff scenario, changes in heart rate correlated positively with self-reported presence as measured by the SUS questionnaire. Other researchers investigated the reliability of this kind of measure such as brain activity [4].

Physiological measures have the advantage to be truly objective, continuous, and synchronous (i.e. recorded during the experiment). However, they require a baseline comparison for each participant, which means a considerable effort in study design. In addition, the use of additional specialized equipment to record such measures can be in itself a cause of breaks in presence [7].

2.2.3 Performance measures

The relationship between performance and presence has been of particular interest since the beginning of presence research [47]. During normal television viewing experiment, Biocca and Kim [23] reported a weak correlation between a factor of presence named "departure" and performance measured by participants' memory strength regarding commercial advertisements. Stanney et al. [57] conducted a study in which participants located in a VE had to complete the maximum amount of basic tasks. Results showed that better performances correlated with a higher sense of presence. Youngblut and Huie [70] found a significant correlation between presence as measured by the SUS questionnaire and user performance in a learning task. Sutcliffe et al. [61] investigated the relationship between presence measured using PQ questionnaire and scores of a memory recall test in which participants were asked to remember up to 10 objects. They compared three different VEs: a CAVE, a workbench, and a real room and found that the CAVE provided a better sense of presence and was remembered better.

More recently, in Stevens and Kincaid's experiment [60], participants were placed in a virtual training simulation and had to destroy as many virtual enemy forces as possible. Results showed a moderate relationship between presence measured with the PQ questionnaire and performance. Cooper et al. [12] conducted a study where participants performed a wheel change in a computer-generated environment rendered on a planar stereoscopic display screen. Results indicated a moderate relationship between task completion time and presence.

In contrast, Knerr et al. reviewed the results of 12 experiments and noted only three instances of a positive correlation between their presence questionnaire and performance [24]. Welch conducted an experiment where participants had to control a virtual car and attempt to collide with cubes [67]. The results did not show any correlation between participants' sense of presence assessed by a 1-100% rating scale and performance. Khenak et al. compared spatial presence between a real office and a remote representation of the same office rendered in an HMD [21]. The goal of the task was to point to the maximum number of images that were appearing. No correlation was found between presence (as measured by the ITC-SOPI) and performance.

These contradictory findings are urging us to continue the investigations. Our intuition is that performance measures can provide an objective indicator of spatial presence to a certain extent. However, care must be taken to rely on similar interaction techniques across environments. While some of these techniques make better use of users' innate skills (e.g. natural gesture-based interactions), other techniques are based on acquired skills from previous users' experiences (e.g. joystick interactions) to improve performance. Consequently, interaction techniques can highly affect user performances regardless of the sense of presence [11].

2.2.4 Behavioral measures

It is argued that experiencing a sense of presence contributes to bring the behavior of users in VEs closer to that which they have in the real world [44]. Schuemie et al. [48] showed that virtual and remote experiences could evoke the same reactions as real experiences at least to a certain degree of similarities (realness) between them. These reactions can be represented by postural adjustments. For example, Lepecq et al. [28] estimated body movement during an experiment in which participants walked through either a virtual or a real aperture. Results demonstrated that participants rotated their bodies likewise in both real and virtual environments. Also, the body rotation was a function of aperture and shoulder-width.

Postural changes can also be induded by socially conditioned behaviors [50]. Bailenson et al. [3] proposed the distance kept between users immersed in virtual environments and virtual agents located in the same environments as a measure of social presence. Outcomes of their studies showed that participants exhibited patterns of interpersonal distance behavior relative to virtual agents similar to those from researches with actual humans.

The reactions evoked by the environment can also be reflex responses to threatening stimuli [55]. For example, Usoh et al [66] conducted an experiment in which participants had to walk through a virtual pit. They analysed the path participants took to complete the task. The results showed a positive correlation between the behavioural measure extracted from the participants' trajectory and presence measured by a questionnaire. Regenbrecht et al. [42] demonstrated that anxiety (measured using the State-Trait Anxiety Index questionnaire [25]) increased with a higher presence in a VE designed to elicit fear of heights. More recently, Maïano et al. [32] found a correlation between aversive stimuli (fire, smoke screen, and alarm) represented in a virtual environment, the self-reported anxiety level of participants navigating in this environment, and the way they moved away from the "danger".

Other behavioral indicators could also be mentioned as a potential measure of presence. For instance, attention-based measures such as users' responses to virtual cues when they are presented with conflicting real cues [39] or users' reaction time when they are presented with distraction cues [5].

Behavioral measures have the advantage to be objective in comparison with self-report measures and nonintrusive in comparison with physiological measures. Yet, while being promising tools, more investigation is still needed to establish reliable measures of presence based on user reaction and behavior.

A state-of-the-art review on measurements of spatial presence shows that it is still a very active field of research and that none of the proposed methods can pretend to fully evaluate presence. Hence, the use of multiple measures when feasible is encouraged.

3 Experimental Design

The main purpose of the experiment was to compare the user's sense of spatial presence and its related factors, as well as the user's performance and behavior in three different immersive environments representing the same space: a real, a remote, and a virtual environment. In the following, each step of the design and the set-up process is detailed.

3.1 Environments

Fig. 1 shows the three environments under consideration:

- The **real environment** represents a real physical space where users are physically located and perform the task in person, without any technological mediation.
- The **remote environment** represents the same physical space, except that the users are remotely located in this space using a dedicated teleoperation system.
- The **virtual environment** reproduces as faithfully as possible the physical space in terms of visual and audio perceptions as well as in terms of navigation metaphor.

3.2 Task

The task design has been guided by several considerations derived from previous work [21], likely to heighten the sense of spatial presence, namely (a) the user moves in his/her environment and controls his/her movement, (b) he/she makes decisions based on information dynamically collected from the environment and (c) his/her actions are likely to cause irreversible/real consequences in the environment.

On this ground, a navigation task was chosen. The participants navigated into the scene by manipulating a wheelchair in each environment: a real electrical wheelchair in the real and remote environments and a virtual wheelchair in the virtual environment. More precisely, they had to navigate following a route while avoiding four obstacles, which consisted of two pyramids of cans (in the style of coconut-shy game or "chamboule-tout" in French) and two chairs.

The path route was the same for all participants but was unknown in advance by them. Instead, the path was indicated during the experiment by seven numbered signs that participants had to follow in sequence (see Fig 2). The first sign indicating the number of the second one, and so on. Furthermore, depending on the participants' vantage point, these signs were either visible or partially or totally hidden. The participants had to complete the task as fast as possible.

3.3 Apparatus

3.3.1 Physical layout

The physical space used for the experiment consisted of two areas separated by curtains. Fig 3 illustrates the 2D layout of these areas. The first area referred to as the "navigation area" in the remainder of the paper, is the actual space in which the participants would physically or remotely navigate and contained the obstacle course with the routing signs. In addition, a "safe navigation" zone was defined within this area with clear ground marking. In the second area, defined as the "operation area", the teleoperation and virtual systems were configured and implemented to allow participants to be either remotely transported in the navigation area, or virtually located in the computer-replicated environment.

A second step consisted in setting up the hardware and software components for each environment. There were four components: visual, audio, control, and tracking system.

Fig 2. (a) A real numbered sign vs. (b) a virtual sign.

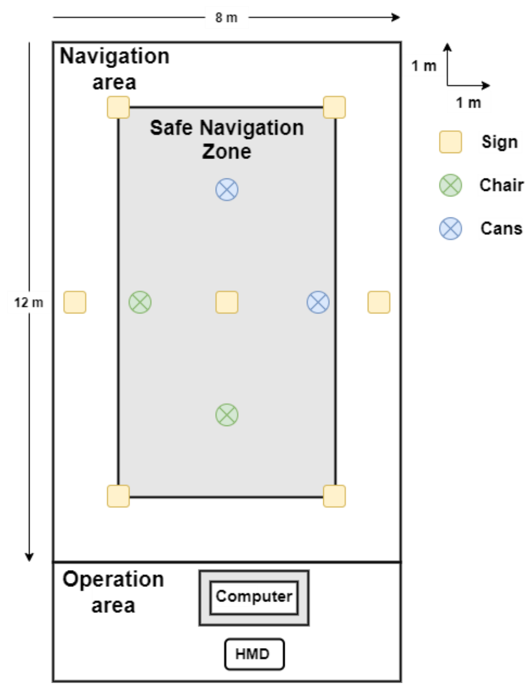

Fig 3. A 2D overview of the two areas: on the top, the Navigation area, on the bottom, the Operation area.

3.3.2 Visual set-up

Fig 4(b) shows the first-person view (FPV) in each environment. In the real environment, the participants experienced a natural visual stimulation.

In the remote condition, visual capture was performed with a Ricoh Theta-V 360° panoramic camera placed at the top of the electric wheelchair at eye level (Fig 4(a)). Images were streamed at a resolution of 3840 x 1920 at 30 Frames Per Second (FPS) to Unity's real-time rendering engine v2019.1.0f2 (rendered as a large spherical texture), then visualized with an HTC Vive Pro VR headset, providing a 90Hz refresh rate to the participants.

In the virtual environment, a computer-generated scene faithfully reproducing the space in the navigation area was rendered with a corresponding spherical texture and outputted to the same headset.

In both remote and virtual conditions, the participants' field of view was limited to about 110° because of the intrinsic headset constraints.

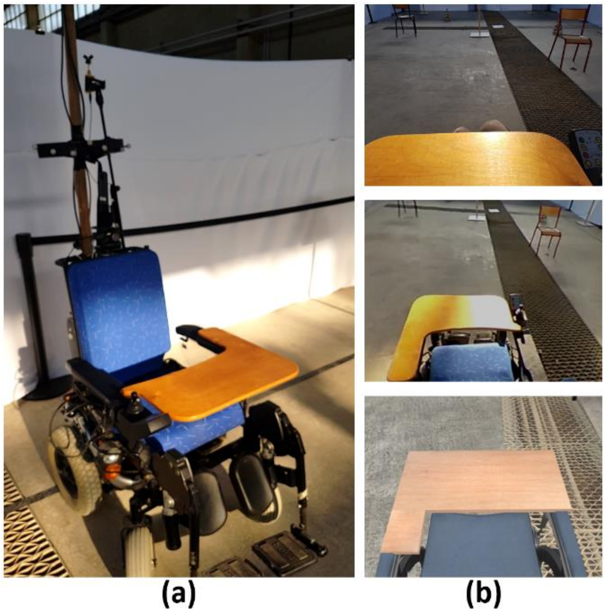

Fig 4. (a) The electric wheelchair equipped with 360° camera, 3D microphone, and tracking markers. (b) The first person view (FPV) of a participant in: (top) real environment, (middle) remote environment, (bottom) virtual environment.

3.3.3 Audio set-up

In the real environment, the participants experienced natural sound conditions, with moderate reverberation due to the nature of the experimental space (very large warehouse).

To reproduce a similar auditory stimulation in the remote environment, a 1st-order Ambisonic microphone (Tetramic microphone by CoreSound) placed at the top of the electrical wheelchair was used to capture sound in the navigation area (see Fig 4(a)). This sound was then rendered binaurally over the HTC Vive headphones in the Operation area. A patch designed in the Max/MSP[1] environment managed the entire audio processing pipeline. In particular, the SPAT library [10] performed the conversion from the Tetramic's recording A-format to the more common Ambix format, and subsequently the decoding operation from ambisonic to binaural rendering using the virtual speaker array approach [37]. The SPAT also added 1.2 seconds of reverberation to simulate the acoustics of the navigation area. The source aperture was fixed to 90°.

In the virtual environment, the sounds were computer-generated based on prior audio recordings of the wheelchair while navigating (e.g. hitting the cans and the chairs) in the physical space. It was then rendered binaurally over the HTC Vive headphones. Pre-tests showed that the hearing perception in the remote and virtual environments to be very similar.

3.3.4 Control set-up

In the real environment, participants were seated in the electric wheelchair located in the navigation area and controlled it directly using an integrated joystick placed on its right arm.

In both remote and virtual conditions, the participants were seated in an armchair -of the same size as the wheelchair- located in the operation area and equipped with a near-identical joystick placed in the same position.

In the remote condition, the wheelchair was remotely driven using a dedicated serial protocol implemented on the teleoperation computer to which the joystick was connected. Finally, control of the computer-generated wheelchair in the virtual condition was implemented in Unity software using its built-in physics engine.

[1] https://cycling74.com/products/max/

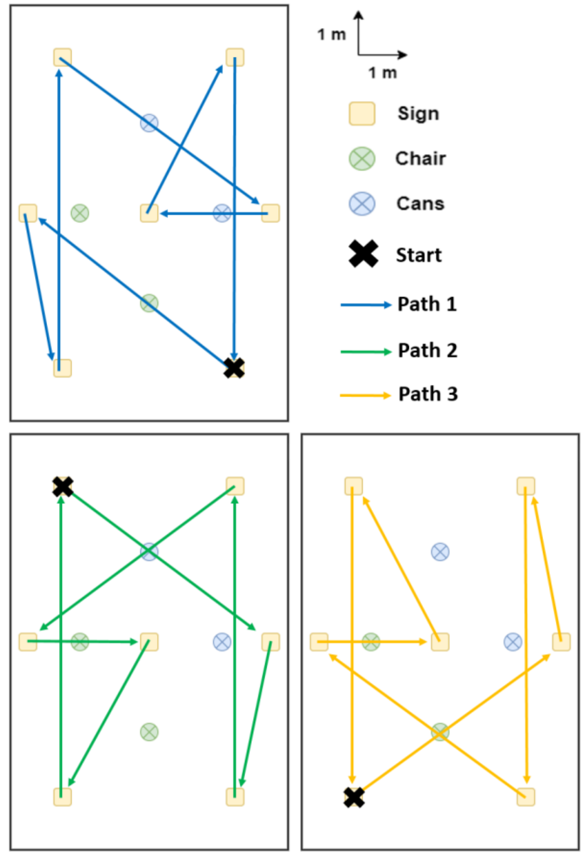

Fig 5. Illustration of the three paths followed by all participants.

3.3.5 Tracking set-up

In the Navigation area, an infrared tracking system consisting of an eight-camera ARTTrack5[2] tracking network was set-up to record the motion of the wheelchair in the real and remote conditions. Infrared markers were fixed on the electric wheelchair (Fig 4(a)). The trajectories of the wheelchair were recorded at 60Hz with millimetric accuracy. Special care was taken so that tracking data was available everywhere in the safe navigation zone.

Regarding the virtual environment, wheelchair tracking was logged in Unity using world coordinate frame, then transformed into the local coordinate frame to match real data.

3.4 Independent variables

A within-subjects design study was run with two fixed variables:

[ENV] The type of environment with three modalities labeled *REAL*, *REMOTE*, and *VIRTUAL* representing respectively the condition where the participant are performing the task directly in the navigation area, the condition where they are performing the task remotely from the operation area, and the condition where they are performing the task in the virtual environment. This variable represented the factor to be evaluated during the experiment. Besides, the *REAL* condition was considered as a baseline against which the two other conditions would be compared.

[PATH] The type of path the participants had to follow during the task. Three modalities were representing three different paths with the same geometrical characteristics (length of the path, number of turns and their angles, number of times an obstacle is encountered, etc.). This variable was not considered as a factor in the evaluation. Rather, it was an extra variable that needed to be controlled to avoid biasing the results (see Fig 5 for an illustration of the three paths).

[2] https://ar-tracking.com/products/tracking-systems/arttrack5/

The order of both variables was counterbalanced across participants using Latin Square Design for [ENV] and randomization for [PATH] in order to mitigate possible learning effects.

4 USER EVALUATION

The evaluation was approved by the local ethics and research committee of our university.

Before the evaluation, it was anticipated that the real environment would outperform the remote and virtual environments in terms of presence experienced and performance. In addition, outcomes from the real environment were intended to be closer to those from the remote condition than to those from the virtual environment. This assumption is based on the idea that, because the remote environment represents the same physical space with the same real implications and consequences, it should lead participants to behave in the same way as if they were actually in the physical space. Conversely, presence and behavioral metrics should be more "disrupted" in the virtual environment.

4.1 Participants

Twenty-seven participants took part in the evaluation (18 males, nine females) with ages ranging from 21 to 40 years (mean = 27.7, SD = 5.7). The only criteria to participate was to have a normal or corrected-to-normal vision and non-impaired hearing. All participants freely volunteered for the experiment, without any financial compensation. Among them, 23 were right-handed, three were left-handed, and one reported to be ambidextrous. The majority of them (19 participants) were students from our university, while the others were staff from our laboratory, all coming from different scientific fields. Furthermore, regarding the level of experience in VR, four participants had never used an HMD before and reported no experience in VR systems, four reported that they were beginners, 15 reported intermediate expertise, and four considered themselves experts.

4.2 Procedure

Upon their arrival at the site of the experiment, participants signed an informed consent form containing written instructions about the experiment. Thus, all participants were informed that it was a study on spatial presence and that their performance and behaviour would be recorded. However, they did not know about the hypotheses of the study. They also filled out a background information document. Then, depending on their order, participants sat on the electric wheelchair located in the navigation area (in case of *REAL* condition) or on the fixed armchair located in the operation area and wore the HMD (in case of *REMOTE* or *VIRTUAL* conditions). Finally, regardless of the condition and the handedness, participants were asked to put their right hand on the joystick. The experiment could then begin. It was divided into three phases as follows:

Training. This phase consisted of a simplified course without obstacles. First, the experimenters gave a short verbal explanation about how to navigate and asked participants to freely discover the environment. No fixed time was imposed during this acclimatization phase. All the participants were encouraged to explore the space so that they became familiar with the set-up. When they were ready, the experimenter explained the task to perform and gave some instructions to follow (stay within the safe navigation zone, finish the course as fast as possible, avoid hitting the obstacles, and finally memorize the location of the signs).

Task. During this phase, participants completed the course as quickly as possible without hitting the obstacles.

Post-assessment. Once the task was completed, participants were asked to complete the Spatial Presence in Immersive Environments (SPIE) questionnaire [22]. This questionnaire is based on the previous most used questionnaires (namely ITC-SOPI, PQ, and IPQ questionnaires) and highlights different scales that could discriminate between remote and virtual environments. In addition, participants were asked to remember the location of the seven numbered signs in the environment (the limit of working memory is generally 7 plus or minus 2 chunks of information [36]).

The duration of the evaluation was between 15 and 20 minutes for each environment. Consequently, the total duration to complete the experiment was about 60 minutes.

4.3 Data collection

In total, 81 trials were registered: 3 [ENV] x 27 participants. For each trial, task completion time, number of obstacles collided, and trajectories of the wheelchair were logged. Responses to the questionnaire and the memory test were also collected. Consequently, the study comprised 11 different measures, which can be grouped as follows.

4.3.1 Subjective measures

Responses to the 5-point Likert scale SPIE (1 = strongly disagree, 5 = strongly agree) yielded scores for each of the six components of the questionnaire:

(1) SP: perceived spatial presence.
(2) AFF: affordance of the environment.
(3) ENJ: enjoyment of the participant.
(4) REAL: realness attributed to the environment.
(5) ATT: attention allocated to the task.
(6) CYB: perceived cybersickness.

4.3.2 Objective measures

Three performance measures were registered:

(1) MEMORY: the number of corrected answers to the memory test.
(2) TIME: the task completion time.
(3) COLLISION: the number of obstacles collided.

In addition, two behavioral metrics were extracted from the trajectory of the wheelchair:

(4) CLEAR_DIST: the clearance (avoidance) distance, i.e. the minimum distance between the path and the obstacles.
(5) CURVE_ABS: the curvilinear abscissa around obstacles.

CLEAR_DIST was calculated –for each of the four obstacles- as the minimum Euclidean distance between the path and the obstacles in the environment. It provides a measure of the passing distance from obstacles, i.e. how close the path came to each obstacle at its nearest point [15].

CURVE_ABS (s) was calculated at each point on the path as:

$$s = \sqrt{\frac{X^2}{t} + \frac{Z^2}{t}} \times t \qquad (1)$$

Where t is the time, and X and Z are wheelchair position coordinates in a horizontal plane. Then, the mean values of CURVE_ABS were computed around each obstacle, in a range set to $2 \times \overline{CLEAR\_DIST}$.

4.4 Hypotheses

It was expected that [ENV] condition would significantly affect the reported responses to the questionnaire as well as the performance and behavioral measures. More precisely, it was hypothesized that:

H1(a): SP, AFF, ENJ, REAL, and ATT scales will be the highest, and CYB scale the lowest in *REAL* condition.
H1(b): SP, AFF, ENJ, REAL, and ATT scales will be higher, and CYB scale lower in *REMOTE* condition compared to *VIRTUAL* condition.
H2(a): MEMORY score will be the highest in *REAL* condition.
H2(b): MEMORY score will higher be in *REMOTE* condition compared to *VIRTUAL* condition.
H3(a): TIME score will be the highest in *REAL* condition.
H3(b): TIME score will higher be in *REMOTE* condition compared to *VIRTUAL* condition.
H4(a): COLLISION score will be the lowest in *REAL* condition.
H4(b): COLLISION score will be lower in *REMOTE* condition compared to *VIRTUAL* condition.

H5:	CLEAR_DIST in *REAL* condition will be more similar to *RM* condition than to *VIRTUAL* condition.
H6:	CURVE_ABS in *REAL* condition will be more similar to *REMOTE* condition than to *VIRTUAL* condition.

5 Statistical Results

In the following, the means and standard deviations are abbreviated by M and σ respectively. Homogeneity of data was evaluated using the modified robust Brown-Forsythe Levene test. The normality of the data was analyzed using visual inspections of the normal QQ-plots in combination with Shapiro-Wilk tests. When data were non-normally distributed, a log_{10}-transformation was applied to satisfy the assumption of parametric tests. If the data was not homogeneous or not normally distributed, non-parametric equivalent tests were substituted.

All the analyses were performed using R version 3.6.0.

The result of the statistical parametric and nonparametric tests for each measure is reported. For statistically significant effects ($p < .05$), Cohen's d effect size estimate r was computed with threshold values 0.1 (small), 0.3 (medium), and 0.5 (large).

The remainder of this section is divided into three parts. The first part describes the effect of [ENV] condition on the subjective scales of the questionnaire. The second part describes the effect of the environments on objective performance and behavioral measures. The third part presents the correlation between the subjective scales and the objective metrics.

5.1 Effect on subjective SPIE questionnaire

The means of the five scales SP, AFF, ENJ, REAL, and ATT were found higher while the CYB scale was found lower in *REAL* condition (see Fig 6). SP scale mean was very high (above 4.5) in absolute terms. A Shapiro-Wilk normality test on the mean values of the scales indicated that they were not-normally distributed (SP: W = .91; $p = .000$, AFF: W = .95; $p = .005$, ENJ: W = .95; $p = .005$, *REAL*: W = .91; $p = .000$, ATT: W = .76; $p = .000$, CYB: W = .90; $p = .000$).

A Friedman test was carried out to compare the mean values for all environments. A significant difference between them for all the scales was found, except ATT scale (**SP: $\chi^2(2) = 29.36$, $p < .000$**, **AFF: $\chi^2(2) = 27.43$, $p < .000$**, **ENJ: $\chi^2(2) = 23.77$, $p < .000$**, **REAL: $\chi^2(2) = 28.06$, $p < .000$**, ATT: $\chi^2(2) = 2.06$, $p = 0.36$, **CYB: $\chi^2(2) = 21.08$, $p < .000$**). Then, Wilcoxon signed-rank dependent tests with continuity correction were conducted. The results are reported in Table 1.

Results showed that *REAL* condition outperformed the *REMOTE* and *VIRTUAL* conditions in all the scales, which supported H1(a). However, the results between *REMOTE* and *VIRTUAL* conditions were more contrasted: *VIRTUAL* condition scored higher on AFF and ENJ scales, while *REMOTE* condition obtained better scores on REAL scale. In addition, no significant differences between them on SP and CYB scales were found. Consequently, H1(b) was partially rejected.

5.2 Effect on objective measures

Fig 7 shows the mean value plots for the performance measures (MEMORY, TIME, and COLLISION) and the behavioral indicator (CLEAR_DIST). No significant results regarding CURVE_ABS were found, therefore, they are not reported here.

5.2.1 Performance measures

Regarding MEMORY, the mean scores were approximately the same in all three conditions (around 4.5 correct answers). A Shapiro-Wilk normality test indicated that they were not normally distributed (W = .85; $p < .000$). Therefore, a Friedman test was carried out that showed no significant differences between the environments ($\chi^2(2) = 1.33$, $p = .52$).

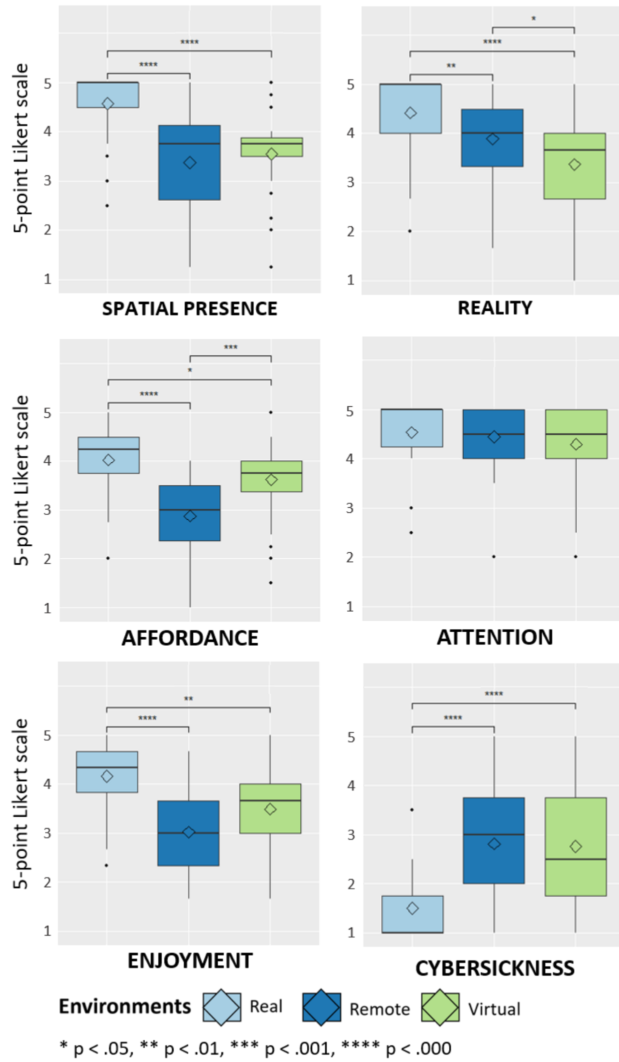

Fig 6. Effect of the environments on the scales of the SPIE questionnaire. The diamond symbol, the line across the box, and the dots represent respectively the mean, the median, and the outliers.

Table 1. Results Wilcoxon signed-rank tests on the questionnaire scales. Statistically significances are colored in green.

	REAL* vs. *REMOTE	***REAL* vs. *VIRTUAL***	***REMOTE* vs. *VIRTUAL***
SP	V = 348; $p < .000$; r = 1.35	V = 288; $p < .000$; r = 1.31	V = 123; $p = .46$
AFF	V = 345; $p < .000$; r = 1.49	V = 195; $p < .05$; r = 0.52	V = 23; $p < .000$; r = 0.91
ENJ	V = 253; $p < .000$; r = 1.43	V = 226; $p < .01$; r = 0.84	V = 62; $p < .05$; r = 0.53
REAL	V = 216; $p < .000$; r = 0.64	V = 294; $p < .000$; r = 1.13	V = 259; $p < .01$; r = 0.56
CYB	V = 9; $p < .000$; r = 1.37	V = 12; $p < .000$; r = 1.31	V = 156; $p = .86$

MEMORY measure was also evaluated for the first condition only, regardless of the environment in which the participants performed the task. The mean scores were also approximately the same between the conditions, with a slight drop (mean of 4 correct answers). Similarly, a Friedman test showed no significant results. Thus, H2(a) and H2(b) were rejected.

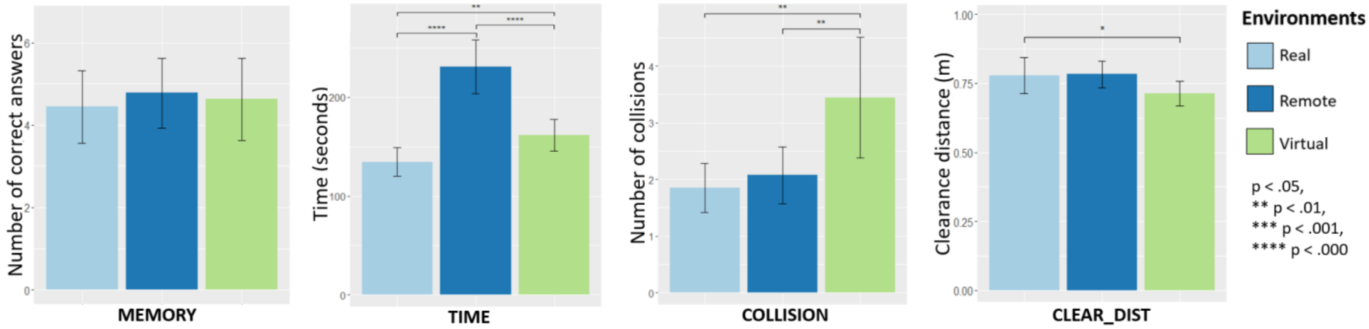

Fig 7. Effect of the environments on objective measures. Bar plots indicate mean values. Error bars indicate confidence intervals.

Concerning TIME measure, the mean value for each condition was M_{RL} = 134.62s (σ_{RL} = 36.9s), M_{RM} = 230.77s (σ_{RM} = 69.12s), M_{VL} = 161.59s (σ_{VL} = 40.65s). The log_{10}-transformed completion time was normally distributed (W = .98; *p = .35*) and homogenous (t = 0.39, *p = 0.99*). Therefore, a one-way ANOVA was run that showed a statistical significant difference between the environments (**F(2, 52) = 48.35, *p < .000***). Consequently, paired t-tests were carried out with a Bonferroni correction applied to compare between each condition. Results indicated a significant difference between *REAL* and *REMOTE* conditions **(t(26) = -8.89, *p < .000*, r = 1.81)** and *REAL* and *VIRTUAL* conditions **(t(26) = -3.7, *p < .01*, r = 0.73)** with *REAL* outperforming both *REMOTE* and *VIRTUAL* conditions (supporting H3(a)). In addition, a significant difference was found between *REMOTE* and *VIRTUAL* **(t(26) = 6.48, *p < .000*, r = 1.23)** with *VIRTUAL* outperforming *REMOTE* condition (H3(b) not supported).

Concerning COLLISION measure, the average values were M_{REAL} = 1.85 collisions (σ_{REAL} = 1.1 collisions), M_{REMOTE} = 2.07 collisions (σ_{REMOTE} = 1.27 collisions), $M_{VIRTUAL}$ = 3.44 collisions ($\sigma_{VIRTUAL}$ = 2.69 collisions). A Shapiro-Wilk test indicated that the data was not-normally distributed even after applying a log_{10}-transformation (W = 0.84, *p < .000*). Thus, a Friedman test was used that showed a significant difference between the environments (**χ^2(2) = 7.98, *p < .05***). Wilcoxon signed-rank dependent tests were then conducted. Results showed statistical significant differences between *REAL* and *VIRTUAL* conditions (**V = 64; *p < .01*; r = 0.77**), but no significant difference between *REAL* and *REMOTE* conditions (**V = 66; *p = 0.4***). Therefore, H4(a) was only partially supported. In addition, the difference was significant between *REMOTE* and *VIRTUAL* conditions (**V = 42; *p < .01*; r = 0.65**) with *REMOTE* outperforming *VIRTUAL*, which supported hypothesis H4(b).

5.2.2 Behavioral measure

The mean values of CLEAR_DIST were respectively M_{REAL} = 0.78 m (σ_{REAL} = 0.12 m), M_{REMOTE} = 0.78 m (σ_{REMOTE} = 0.16 m), $M_{VIRTUAL}$ = 0.71 m ($\sigma_{VIRTUAL}$ = 0.11 m).

The data was normally distributed (W = .98; *p = .31*) and homogenous (t = 0.73, *p = 0.81*). Therefore, a one-way ANOVA was run that showed a statistical significant difference between the environments (**F(2, 52) = 3.02, *p < .05***). Then, paired t-tests with Bonferroni correction were run showing a significant difference between *REAL* and *VIRTUAL* conditions (**t(26) = 2.41, *p < .05*, r = 0.58**), whereas no statistically significant results were found between *REAL* and *REMOTE* conditions (t(26) = -0.17, *p = .87*). These results were in line with H5. Yet, no significant difference was found between *REMOTE* and *VIRTUAL* conditions (t(26) = 1.7, *p = .1*).

5.3 Correlation between the subjective scales of SPIE and the objective measures

Pearson correlation tests were run between SP-, AFF-, REAL-, ENJ-, ATT, and CYB-scales of the questionnaire and the performance measures, namely, MEMORY, TIME, and COLLISION, as well as with the behavioral metric CLEAR_DIST. Table 2 highlights the significant correlations between them.

Table 2. Statistically significant Pearson correlations between the questionnaire scales and the other measures (correlation > 0.3 are colored in green, no = no correlation).

	MEMORY	TIME	COLLISION	CLEAR_DIST
SP	0.25 (p <.05)	-0.42 (p <.000)	-0.23 (p <.05)	no
AFF	0.31 (p <.01)	-0.49 (p <.000)	no	no
REAL	no	-0.22	-0.26 (p <.05)	0.24 (p <.05)
ENJ	0.29 (p <.01)	-0.33 (p <.01)	-0.22 (p <.05)	no
ATT	0.24 (p <.05)	no	no	no
CYB	0.27 (p <.01)	0.28 (p <.01)	0.27 (p <.01)	no

Concerning performance measures, all the scales were significantly correlated with MEMORY (except REAL-scale), with TIME (except AFF-scale), as well as with COLLISION (except AFF- and ATT-scales) variables. With regard to CLEAR_DIST metric, a small correlation was found only with REAL-scale.

6 Discussion

The comparative analysis between the real, remote and virtual environments was performed on the six scales of the SPIE questionnaire (spatial presence, affordance, reality attributed to the environment, enjoyment, attention allocated to the task, and cybersickness), as well as on the three objective performance measures (memory scores, task completion time, and the number of collisions), and the behavioral indicator defined as the avoidance collision distance from the obstacles.

6.1 Subjective responses to SPIE questionnaire

The real environment is by definition the natural space in which people are located and with which they are interacting in their daily lives. As expected, it recorded the best rating regarding the level of affordance[3].

However, contrary to what was hypothesized, the remote environment was rated as providing the lowest affordance. One reason for this could be the higher expectations of participants regarding their embodiment. Many of them reported that not seeing themselves in the wheelchair in the remote condition (see Fig 4(b)) was very disruptive compared to the virtual condition where the absence of avatar was less annoying. These expectations could highly influence the relation between the body of participants and the environment on which affordance is based [43]. This highlights the importance of using avatars in future studies as they enable embodiment by promising users the affordance of "real" bodies [38].

[3] For the sake of clarity, the spatial presence component will be discussed at the end of this section.

Special care should be given to the fidelity of these avatars in representing the actual self of users [19].

Another explanation of the low degree of affordance in the remote condition could be that the “jerks” of the real wheelchair (due to friction with the ground) were visually reflected in the HMD without being physically experienced by the participants. This discrepancy between what was perceived and what was experienced could highly affect affordance. Therefore, forthcoming studies should integrate haptic stimuli to prevent this kind of bias.

As with affordance, the enjoyment scale was rated the best in the real environment and the worst in the remote one. Some informal interviews showed the great enthusiasm of participants while directly driving the wheelchair in the real condition because of the “*weird but funny*” nature of the experience (none of the participants were physically disabled so that they had little or no experience in wheelchair driving). In the remote condition, this sensation of enjoyment was reduced because of some reluctance to control the wheelchair using such a teleoperation system. Moreover, this system tended to reduce participants’ confidence in controlling the wheelchair: a lot of them were more afraid of breaking something in the remote situation than in the direct driving experience.

Concerning the degree of attention allocated by the participants to the task, no difference was found between the three environments, which can be easily explained by the similarity of both task and content in all environments.

In contrast, a significantly lower degree of cybersickness was found in the real environment compared to both remote and virtual environments. However, no difference was found between the remote and virtual environments that were rated with almost a similar degree of cybersickness. This probably reflects the use of identical mediation systems (identical visual and audio rendering as well as same navigation metaphor). In addition, the average rating assigned to both environments in absolute term was medium (2.7 points), which illustrates the ability of participants to perform the task in overall good conditions and highlights the increase of quality of such virtual and teleoperation systems. Furthermore, these results demonstrate the importance of relying on similar user interfaces when comparing between different environments.

Concerning the reality scale, participants attributed the highest degree to the real environment and the lowest degree to the virtual environment supporting our hypothesis. It was expected that the remote environment would be rated as more real in comparison with the virtual one because of the physical existence of space. Thus, even though both remote and virtual environments relied on the same user interface to mediate the action space, participants’ awareness of the physicality of this space in the remote condition probably led them to assign a higher degree of reality to it.

Most importantly, the sense of spatial presence was rated as the highest in the real environment compared to both remote and virtual environments. This result is in agreement with many studies that compared real and virtual environments [65]. However, it goes against the outcomes of one of previous findings where participants experienced a sense of hyper-presence in a remote condition compared to a real baseline [21]. This could be due to the dynamic nature of the navigation task in the present study that resulted in significant perception discrepancy between the real and the remote environments, with haptic stimuli experienced only in the real condition (whereas in the previous study, the perception of both environments was almost similar because participants relied on visual and audio stimuli only).

Furthermore, it was expected that the remote environment would induce a higher sense of presence than the virtual environment. Yet, no significant differences were found between them. This result may be partially explained by the positive influence of affordance and enjoyment on participants’ sense of presence that were rated higher in the virtual environment. In other words, the influence of the physical existence of the space represented by the reality scale, as discussed above, was not enough to tip the scales in favor of the remote environment. Nevertheless, more investigations are required to confirm or affirm this hypothesis.

6.2 Objective performance and behavioral results

In this study, the objective outcomes were based on both performance and behavior indicators.

Concerning performance, no difference was found in the average memory score between the three environments. It was expected that at least the real environment would register a better memory performance due to its higher level of immersion (larger field of view, natural sound) [41]. Nevertheless, this result may be related to the similar degree of attention allocated to the task in the three environments: participants focused the same way during the experiment regardless of the environment resulting in the same overall memory score.

In contrast, average task completion time revealed that participants were faster in the real environment. Thus, the higher degree of immersion in the real condition could increase participants’ performance [63]. On the other hand, participants were the slowest in the remote environment, which goes against what was hypothesized. The most likely explanation is that the participants were extremely careful “not breaking anything” when remotely navigating with the real wheelchair, and drastically reduced their speed as a consequence.

This assumption is supported by the number of observed collisions that was lower in both real and remote environments vs. the virtual environment. Moreover, no difference in terms of collisions was found between the real and the remote condition. Therefore, participants paid more attention not to collide with obstacles when the space was real (i.e. existing), regardless of being physically or remotely located in this space.

This tends to be confirmed by the behavioral indicator extracted from the trajectory of the wheelchair: the avoidance distance value was highest (and almost similar) in both real and remote environments compared to the virtual environment. This suggests that participants were less prudent when the space was computer-generated, being aware that their actions would have no real consequences. Nevertheless, it goes against another study that found an increase of the clearance distance when participants were facing virtual obstacles compared to real ones [46].

Yet, our results show the influence of the actual existence of the space in which participants are physically or remotely located on their performance and behavior. This influence of *physical existence* was also highlighted in an augmented-reality study on co-presence (“being together”[18]) : in a face-to-face tabletop game with a virtual avatar, participants felt higher co-presence when the avatar was moving a physical token than when the token moved was virtual [27].

Summarizing the results of the comparative analyses, the real environment fared better than both remote and virtual environments, except for the degree of attention allocation and the memory scores where no differences were found. These results confirm the hypotheses H1(a), H2(a), and H4(a).

Outcomes were more mixed when comparing remote and virtual environments. Regarding subjective results, no difference in actual presence was found. In addition, a higher level of affordance and enjoyment was allocated to the virtual environment, contradicting H1(b). In contrast, the remote environment was attributed a higher degree of reality as expected. Furthermore, participants’ performance showed a shorter task completion time in the virtual environment rejecting H3(b), but a lower collision rate in the remote environment supporting H4(b).

Finally, the behavioral indicator represented by the clearance distance highlighted that participants’ behavior in the remote environment was closer to their behavior in the real environment than it was in the virtual environment. This outcome supports H5.

6.3 Correlation between subjective and objective results

Previous papers raised the question of existing correlations between the sense of presence and performance and behavioral measurements (see Related Work section). In trying to answer this question, the correlations between the subjective scales of the SPIE questionnaire and the objective measures recorded in the experiment were computed.

No correlation was found with the clearance distance behavioral indicator. However, a positive correlation was found between the subjective rating of spatial presence and performance measures. In particular, the more the participants rated themselves as present in the environment, the more they remembered the space, the less time they took to complete the task, and the fewer obstacles they collided. This result echoes some recent studies that tended to argue that presence and performance are related [12, 57], while it contradicts other studies [21, 67]. More investigation is then necessary to truly determine the relationship between presence and performance.

The degree of affordance was positively correlated with both memory score and task completion time. Affordance refers to the possibility to act in the environment in accordance with users' expectations [43]. Therefore, it would appear logical that a better environment affordance induces better performance. Yet, affordance was not correlated with the number of collisions considered as a performance measure. This seemingly contradictory finding calls for further evaluations to better understand the relationship between affordance and performance measures.

Similarly to spatial presence, enjoyment was found to be positively correlated with all performance measures (memory scores, task completion time, and the number of collisions). It suggests a positive influence of users' interest in the task on their performance [30].

In contrast, attention scale was positively correlated only with memory scores. As it was hypothesized above, this correlation indicates that the more attention the participants allocated on the task during the experiment, the better they remembered the features of this environment (in this case, the location of the signs).

Most importantly, a correlation was found between the degree of reality attributed to the environments and task completion time, the number of collisions, and clearance distance. Thus, the more the participants were aware of the reality of the space, the more they were careful, keeping more distance between them and the obstacles, so as to avoid them. This correlation provides evidence of a perceived difference between remote and virtual environments and the impact of this difference on performance and behavior.

Finally, it was found that a higher degree of cybersickness correlates with longer task completion time and more collisions. However, it was positively correlated with memory scores. This could be because a longer time spent in the environments to complete the task, allowing participants to better remember the details of the working space.

Taken together, such correlations provide promising results on the use of more objective tools such as performance measures and behavioral indicators in combination with questionnaires. Yet, more investigations are needed to truly understand the reliability of this tools to assess spatial presence.

6.4 Limitations of the study

Despite our efforts to properly run the study, some limitations may have affected our results. First, participants were not wheelchair users, so that a "novelty" effect of using such a set-up in the real condition might have biased the experience of participants and influenced their assessment of presence and its sub-components. Therefore, it would be interesting to conduct a follow-up study where participants are in fact, wheelchair users and to compare the results obtained.

Then, the study may have suffered from the influence of a visual delay in the remote condition due to the 360° panoramic camera's restitution. Even if no participant complained about it, this latency has probably reduced the performance. This is a common limitation of the current teleoperation systems that researchers and designers have to work on.

Last but not least, no avatar was provided in both remote and virtual conditions. This difference with the real baseline condition could lead to a confound of the participant's leg not being visible, which might break fair comparison. In future studies, physical mannequins and virtual avatars must be used respectively in remote systems and computer-generated configurations.

7 Conclusion

This paper presented a user study that compared the execution of a task within a real physical space with the same task performed in a remote and a virtual environment displayed over an HMD, representing respectively a remote configuration and a virtual representation of the same physical space. Participants had to complete a circuit while avoiding obstacles. The primary objective of the study was to assess the sense of spatial presence (as measured by the SPIE questionnaire [21]) in all three conditions. In addition, objectives metrics were recorded based on the participants' performance to remember details from the scene, to complete the task and to avoid obstacles, as well as on their behavior obtained by extracting the obstacle avoidance distance from trajectories of the wheelchair.

Results from the questionnaire indicated a higher presence in the real environment while no difference was found between the remote and the virtual environments. Performance measures (shorter time and fewer collisions) confirmed the real environment as a robust baseline across all measures. The number of collisions was found to be lower in the remote environment compared to the virtual one. This result indicates a greater caution of participants not to collide obstacles when the space was perceived as real. This assumption is supported by a bigger avoidance distance in the real and remote environments compared to the virtual environment. Furthermore, it highlighted that participants' behavior in the remote environment was closer to their behavior in the real one than it was in the virtual environment.

In addition, positive correlations were found between spatial presence and performance measures, but not between presence and the behavioral indicator. These results are promising regarding the reliability of performance tools to assess presence while encouraging the use of complementary measurements.

Also worth mentioning are the correlations that were found between the degree of reality attributed to the environment and some performance and behavioral measures. Because this feature was higher in the real and remote environments, one can assume that the physical existence of the space in which participants are located could lead them to be more cautious, influencing their performance and behavior. If further studies are required to confirm these findings, these results provide strong evidence of existing differences between the perception of remote and virtual environments and incite further comparisons between them.

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