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ORIGINAL ARTICLE

Afforded actions as a behavioral assessment of physical presence in virtual environments

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Abstract A particular affordance was used as a potential candidate for behavioral assessment of physical presence in virtual environments. The subjects' task was to walk through a virtual aperture of variable widths. In the case of presence, the subjects' body orientation, while walking, was hypothesized to be adapted to the width of the aperture and to their own shoulder width. Results show that most subjects adapted their behavior to both their body architecture and the virtual width constraints. These subjects exhibited a behavioral transition from frontal walking to body rotation while walking through broad to narrow apertures. The same behavioral transition has already been documented in real environments (Warren and Whang in J Exp Psychol Human Percept Perform 13(3):371–383, 1987). This behavioral adjustment is thus assumed to be an objective indication of presence. Beyond these results, the present study suggests that every afforded action could be a potential tool for sensorimotor assessment of physical presence.

Keywords Presence · Behavior · Affordance · Virtual reality

1 Introduction

The notion of presence in a virtual environment (VE) is central to virtual reality research (Lombard and Jones 2007a, b). Because this notion is highly interdisciplinary, its use has long been marked by a rich and burgeoning polysemy. In an attempt to share a common terminology, the presence community research has proposed the following definition (International Society for Presence Research 2008): "Presence is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience." This definition has two main interests. First, it stresses the fundamental illusory aspect of presence. It is close to the conception according to which presence would be basically "a perceptual illusion of non-mediation'' (Lombard and Ditton 1997). Additionally, this definition contains a criterion of falsifiability (Popper 1959). According to this criterion, depending on whether or not "part or all of the individual fails to accurately acknowledge the role of the technology in the experience", it can be concluded that such experience involves presence (or not).

Beyond this minimally agreed-upon definition, what psychological and neurological processes underlie presence remains an open question. One possible way to progress on this question would be not to consider presence as a whole but rather to differentiate between different types of presence. As a multi-dimensional concept, it has generally been proposed that three main categories of dimensions could be taken into account: the dimensions "that involve perceptions of physical environments, those that involve perceptions of social interaction, and those that involve both of

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these" (International Society for Presence Research 2008). For example, Ijsselsteijn et al. (2000) distinguished between social presence (the feeling of being together and communicating with others) and physical presence (the feeling of being physically located in a place). The present work is focused on physical presence.

Considering that presence was a key aspect of virtual reality, ultimately linked to its effectiveness, researchers went on to measure it. There are multiple ways of assessing presence (van Baren and Ijsselsteijn 2004). However, three main evaluation approaches (with rich interactions) can be distinguished (Insko 2003). Historically, questionnaires have been first developed and are still being used and improved (e.g., Witmer and Singer 1998). Next to this, physiological indicators involving the autonomous nervous system activity, such as skin conductance or cardiac rhythm are used, considered as more objective than answers to questionnaires (e.g., Wiederhold et al. 2001). Finally, overt behavioral observations which are thought not to be under conscious control, such as a startle reflex or postural sway, are also used to assess presence (e.g., Freeman et al. 2000). Moreover, physiological and behavioral evaluations can be conducted during virtual reality exposure, whereas questionnaires are post-exposure measurements of presence. For both physiological indicators and overt behaviors, the basic assumption is that the more a subject feels present in a VE, the more similar his/her responses will be to those s/he would exhibit in a similar real environment (Slater 2002). This work is focused on a particular type of overt behavior as a tool to objectify physical presence.

In the present experiment, in order to assess presence in VE, we investigated spatio-temporal aspects of adaptive behavior, governed by volition and selection. In everyday life, there are numerous adaptive behaviors, which imply both an intention to act and a selection among variations of the same act. For example, walking from one place to another can be performed using different paths. The selection of a particular behavior may be constrained by the relationships between the environment and the body architecture. For example, the choice of a peculiar locomotor trajectory may result from the variety of possible paths in a cluttered environment and the size or the suppleness of the body. As such, evaluating presence in a VE may be approached using the concept of affordances (Gibson 1979). The affordances are the perceivable possibilities for action which are both provided by the environment and allowed by the actor capabilities. The idea that affordances could be used to assess physical presence has already been repeatedly suggested from various theoretical standpoints. Gibson's ecological framework has thus been presented as a promising functional approach for defining the reality of experience in relation to the problem of designing VE (Flach and Holden 1998). In a similar Gibsonian vein, it has been proposed that presence is equivalent to successfully supported action in the environment, whether the environment is virtual or real, local or remote in relation to the actor (Zahorik and Jenison 1998). In a situated cognition perspective on presence, it has been argued that physical presence depends on integration of aspects relevant to movement and perception, as well as on how these aspects interact with the possibilities for action afforded in the interaction with the VE (Carassa et al. 2005). In a mental model approach of physical presence, it has been recently proposed that such presence is a bistable experience, during which perceived self-location and perceived action possibilities (i.e., affordances) are connected to a mediated spatial environment, and mental capacities are bound by the mediated environment instead of reality (Wirth et al. 2007). Even more recently, Schubert (2009) considers that affordances determine physical presence and calls for the need to study affordances in an embodied conceptualization of physical presence.

The main hypothesis of our study is that the degree of presence in a VE can be evaluated by its actual affordances for action, which can be experimentally tested. For example, a subject may have to lengthen the stride while stepping over a street gutter or to rotate the body while walking through a narrow aperture (Warren and Whang 1987). These adaptive behaviors pertain to body-scaled motor adjustments. For a street gutter of constant width, the tendency to lengthen the step is more pronounced if the legs are short. Similarly, for an aperture of constant width, the tendency to rotate the body is more marked for larger shoulder widths. These body-scaled behaviors, such as the shoulder rotation pattern involved in walking through an aperture, present various theoretical and methodological interests. From a theoretical point of view, it is important to determine where such behavior takes place along a continuum of controllability ranging from uncontrollable "hard-wired" behaviors to self-controlled volitive behaviors. In the first case indeed, this uncontrollable "hard-wired" behavior would always occur, whether the subject feels present or not. In the second case, the behavior would reflect a deliberate spatially guided postural locomotor behavior devoted to obstacle avoidance. This behavior would thus depend on the subject's belief according to which there is some obstacle to avoid. Since the subject's belief reflects, at some level, a failure to accurately acknowledge the role of the technology in the experience, this belief is compatible with the assumption of physical presence. Where does "shoulder rotation" take place along the continuum of controllability? First, it seems excluded that this behavior belongs to the uncontrollable "hard-wired" category. Indeed, navigating through apertures is learned through trial and error-learning during ontogenesis. For example, it is known that children may dangerously push their head between the spindles of a crib or piece of playground equipment (Tinsworth and McDonald 2001; Ishak et al. 2008). Even adults might slightly misjudge their ability to pass through doorways while walking (Gordon and Rosenblum 2004; Warren and Whang 1987). Second, navigating through an aperture involves posturo-locomotor behavior. At some level, locomotion is clearly an automatic activity. Possibly, the postural component of this activity (shoulder rotation while locomoting) may also become automatic in the repetitive exposure to obstacle avoidance. The point here is, even if this postural locomotor behavior is an automatic one, it can be voluntarily modified. For example, locomotion as an automatic behavior can be voluntarily modified in terms of speed or direction. In short, shoulder rotation while walking is probably an automatic activity which can be voluntarily modified. As a controllable activity, the "shoulder rotation pattern involved in walking through an aperture" provides a test sensitive to physical presence. Additionally, from a methodological point of view, such body-scaled behaviors present a triple interest. First, they can be potentially elicited within VEs. Second, they happen at the very time during which presence occurs. In other words, they are not postponed, but they are contemporaneous with the psychological state involving presence. Finally, their variations due to the interplay of body architecture and virtual constraints are objectively measurable. As such, they can provide a behavioral evaluation of presence.

Surprisingly, there is very little research in which afforded actions were used to assess presence in VE. Objectifying presence via body scaled motor adjustment while walking through an aperture has already been attempted (Stappers et al. 1999). However, this study failed to demonstrate that virtual and real apertures were experienced in the same way. While walking through a real aperture, subjects classically exhibit a behavioral transition from frontal walking (when the aperture is large enough) to body rotation (when the aperture is too narrow) (Warren and Whang 1987; Higuchi et al. 2006). In addition, subjects with large shoulders exhibit greater angles of shoulder rotation than small subjects. However, when the same shoulder rotations are plotted against a relevant body-scaled ratio (aperture width/shoulder width), the difference between subjects of different sizes vanishes. This suggests that, in real conditions, "large" and "small" subjects behave similarly relative to their own body size (Warren and Whang 1987; Higuchi et al. 2006). On the other hand, in VE, there was no evidence that the subjects could relate the size of the aperture to their own shoulder width. Instead, in the study of Stappers et al (1999), body rotation was observed for every aperture size, even when no body rotation was required to pass through the aperture. This initial failure may explain why affordances have been so poorly investigated in physical presence research (Lombard and Jones 2007a, b).

Stappers' et al. (1999) negative results might also have been due to the use of helmet-mounted displays, suffering from a reduced field of vision and the residual presence of a head-fixed visual reference frame (Mars et al. 2005). Thus, we undertook a similar study with a four-sided cave-like system, enabling us to stimulate the subject's entire visual field (Cruz-Neira et al. 1993). We designed an experimental study, in which subjects had to walk through a virtual aperture whose width was manipulated. Continuous monitoring of their movements while walking forward through the virtual aperture was achieved, in order to evaluate the adequacy of their body adjustments to the size of the aperture and to their own shoulder size. The core hypothesis of our study was that, if subjects experienced presence then they should exhibit in VEs the basic behavioral properties already observed in corresponding real environments (Slater 2002). Three expectations were investigated in this respect (Warren and Whang 1987; Higuchi et al. 2006). The first one was that subjects should exhibit a behavioral transition from frontal walking (large aperture) to body rotation (narrow aperture) while walking through the virtual door. In order to check this expectation, we examined whether their eventual shoulder rotation was adapted to the width of the virtual aperture. Secondly, the subjects were also expected not to collide with the sides of the virtual door. In order to investigate this point, we examined the spatial accuracy with which walking through the virtual aperture was performed. Thirdly, it was expected that not only the subjects with large shoulders should show greater angles of shoulder rotation than small subjects, but also that both types of subjects should behave similarly with respect to their own body size. In order to check this expectation, we compared the critical aperture widths and the critical body-scaled (aperture width/shoulder width) ratios from which "large" and "small" subjects exhibit a behavioral transition from frontal walking to body rotation while walking through the virtual aperture.

2 Method

2.1 Subjects

Nineteen male subjects voluntarily participated in the experiment, ranging in age from 18 to 30 years (mean = 21.6; SD = 3.1). The rationale for including males only was morphological. In males, the body rotation while walking through an aperture is known to depend upon the shoulder width, i.e., the widest frontal body dimension

(Warren and Whang 1987). In females, the same behavior is potentially more complex since it could depend not only on the shoulder width but also on the bust size. The 19 male subjects had normal or corrected to normal vision. They were free from any known locomotor disorder. They were naïve as to the purpose of the experiment. They were not a priori selected regarding their stature. Their standing height ranged from 159 to 194 cm (mean = 178.4; SD = 8.9). Their shoulder width ranged from 40 to 55 cm (mean = 45.6; SD = 3.1). Their inter-pupillary distance ranged from 57 to 69.5 mm (mean = 63.6; SD = 3.2). Their stereoscopic acuity, as assessed using the Randot® Graded Circles test (Stereo Optical Company Inc, Chicago, IL, USA) ranged from 20 to 140 s of arc (median = 20; upper and lower quartiles were 50 and 20; interquartile range = 30).

2.2 Apparatus

The experiment was conducted inside a cave-like virtual reality system (Fig. 1). The hardware consisted of four projection surfaces: the front, left and right vertical walls and the horizontal floor. The three walls (3 m wide and 4 m high) were back-projected acrylic screens. The floor (a square with a side of 3 m) was directly projected from above. The height of the display (4 m) was defined in order to avoid the need for a ceiling projection surface, while optimizing visual immersion. Only the top and the rear faces of our cave were not projection surfaces.

Each projection surface received images with 1,400 × 1,050 pixels resolution. The screens were seamlessly joined to provide a visually continuous projection surface. Stereoscopic projection of VEs was achieved by two DLP® (Digital Light Processing) projectors attached to each projection surface. Each projector addressed one eye. Stereoscopic separation between left and right eye images was ensured by colorimetric separation (Infitec® technological solution). Infitec filters were installed in the projectors, while the subject was wearing glasses with the same filters. This guaranteed perfect separation of images between the two eyes. Finally, a head tracking system (ArtTrack®), using infrared recognition of passive markers placed on the subject's glasses, was used to record the subject's head position and orientation and to update in real time (60 Hz frame rate) the stereoscopic images relative to the subject's point of view (Fig. 3). Additionally, passive markers were symmetrically placed on the subject's shoulders. The whole projection system was controlled by a cluster of five PCs (one master + four slaves). Each slave PC was attached to a couple of projectors devoted to a projection surface. Surrounding spatialized sound stimulation was achieved by means of a 7.1 sound system. We used Virtools® solution to build and control virtual scenarios, for experimental control and data recording.

2.3 The virtual environment

The VE was designed using 3D modeling software (3DSmax®). It was then imported into Virtools for building and running the experimental scenario. The VE was composed of two adjoining rooms connected via a sliding door (Fig. 2). The first room was empty and was marked with a starting point (light-gray disk displayed on the floor). The second room was furnished (in order to provide static and dynamic depth cues) and was marked with an arrival point (dark-gray disk). The sliding door consisted of two mobile surfaces (height = 204 cm, thickness = 25 cm) that could be closed or opened by lateral translation. The opening and the closing of the door were accompanied with different rattle sounds. The sliding door formed an aperture whose width was variable and ranged from 40 to 80 cm, by 5 cm steps. The nine possible aperture widths were 40, 45, 50,

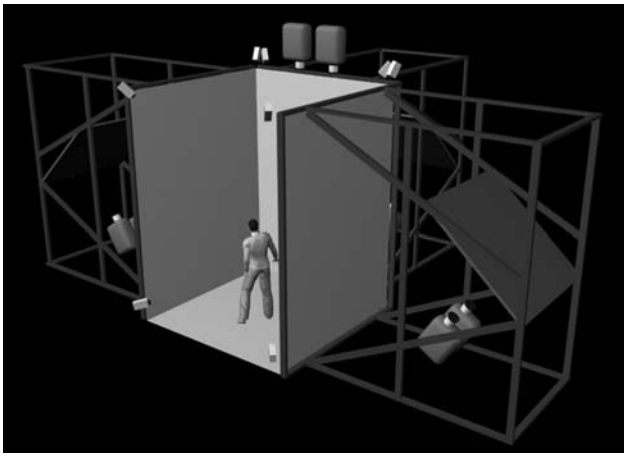

Fig. 1 Schematic representation of the VR system

Fig. 2 The virtual rooms and the sliding door

55, 60, 65, 70, 75 and 80 cm. The starting point, the center of the door and the arrival point were aligned. The distance from the starting point to the door and from the door to the arrival point was 110 and 90 cm, respectively. The center of the door was located at the center of the cave (along front–back and left–right axes).

2.4 Procedure

Each subject was briefed in an independent room adjoining the room containing the cave. Several anthropometric and perceptual measures were performed in that room. The standing height was canonically measured using a stadiometer. Shoulder width, the widest frontal body dimension, was measured with an anthropometer from the tip of the left humerus (humeral greater tubercle) to the tip of the right humerus with the shoulders relaxed, in a standing subject. The inter-pupillary distance was measured with a corneal reflection pupillometer. This measure was taken into account in order to generate stereoscopic images and hence individually optimize spatial perception from binocular vision.

Inside the immersive environment, the subject was equipped with INFITEC stereo glasses and with reflective markers on the glasses and on both shoulders (Fig. 3). The shoulder markers were symmetrically placed over the trapezius muscles (between the neck and the shoulder) and not on the heads of the right and left humeri. This particular placement was designed to avoid subjective widening of the shoulders (Berlucchi and Aglioti 1997; Holmes and Spence 2006). These equipments allowed 3D tracking of the subject's cyclopean point of gaze (for real-time updating of the visual scene) and recording of shoulders' positions (for offline analysis of the subject's posture) by the ART® system. These trackings and recordings were performed with respect to three axes. These were left–right or X axis, front–back or Z axis and up–down or Y axis (for a subject facing the front wall).

Once equipped, the subject was conducted from the welcome room into the cave. In order to optimize immersion into the VE, the eyes-closed subjects were guided by the experimenter into the VE and required to open their eyes only when facing the front wall from the starting point, while the VE was displayed. In this way, they could see the VE only throughout the experimental session.

The initial scene (Fig. 2) showed the sliding doors wide open (aperture = 250 cm). Then the doors were closed, leaving an aperture whose width was one of the nine predetermined values. This closing was accompanied by a spatialized rattling sound at the doors location. Facing the front wall, the subject stood on the starting point. He was prevented from walking forward since he was restrained by the shoulders by the experimenter located behind him. The subject was then required to walk straight from the starting point to the arrival point and to stop at this point (Fig. 4). This neutral directive aimed to avoid any behavior induction by instructional semantic effects. To allow him to do so, the experimenter liberated the subject from any physical constraints. The unconstrained walking speed should be normal and comfortable. Once at the arrival point, the subject was required to stand still, facing the front wall and not to make a U-turn. The subject was informed that the sliding door behind him would open wide. This opening was accompanied by a spatialized rattling sound located behind the subject. When the sliding door was opened, the

Fig. 3 Representation of the subject's equipment, with markers attached to stereo glasses and a set of markers on each shoulder

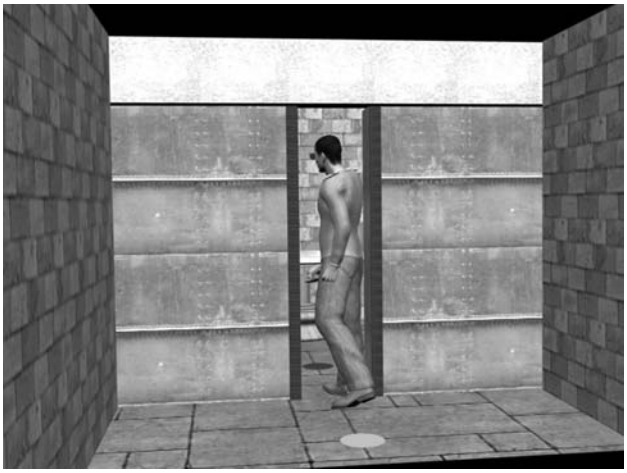

Fig. 4 Schematic representation of a subject walking through the virtual aperture

subject walked backwards from the arrival point to the starting point. The experimenter held the subject by the shoulders in order to guide him during this backward walk. This backward walk with the doors wide opened was designed to avoid possible cognitive conflict that may have arisen if the subject had walked through or hit the virtual walls that delimited the door. Once at the starting point, the subject was required to precisely face the front wall. The doors were then closed, leaving an aperture whose width was one of nine predetermined values. A new trial could then begin.

During an experimental session, subjects run a series of trials, with the following logic. The aperture could be one of nine widths: 40, 45, 50, 55, 60, 65, 70, 75, 80 cm. A block of trials involved nine trials (one trial per width). Each subject performed three blocks (i.e., 3 × 9 = 27 trials). For each block, the order of presentation of the nine widths was randomized.

2.5 Dependant variables

From the recorded successive positions of the shoulder markers, while the subjects walked through the virtual aperture, three dependant variables were computed for each trial: the maximal absolute shoulder rotation, the minimal distance between each shoulder and each lateral side of the door, and the presence of a collision between each shoulder and any lateral side of the door.

3 Results

3.1 Shoulder rotation during walking through the aperture

We here assess the hypothesis that, if subjects experienced presence, they should exhibit a behavioral transition from frontal walking to body rotation as the width of the virtual aperture diminishes. It is thus minimally expected that the body rotation should increase as aperture width decreases. Out of the 19 subjects who completed the experiment, 17 subjects adapted their body orientation to the aperture width. Their mean absolute maximum angle of shoulder rotation is plotted as a function of aperture width (Fig. 5). An ANOVA (blocks × apertures) was conducted on individual means of shoulder rotation. This ANOVA revealed a main effect of aperture width ($F_{8,128} = 89.62$, $p < 0.001$) and a main effect of blocks ($F_{2,32} = 4.03$, $p < 0.03$) without interactions. The main result here is that the magnitude of body rotation significantly increases as aperture width decreases. Additionally, the magnitude of body rotation increases with the repetition of experimental blocks.

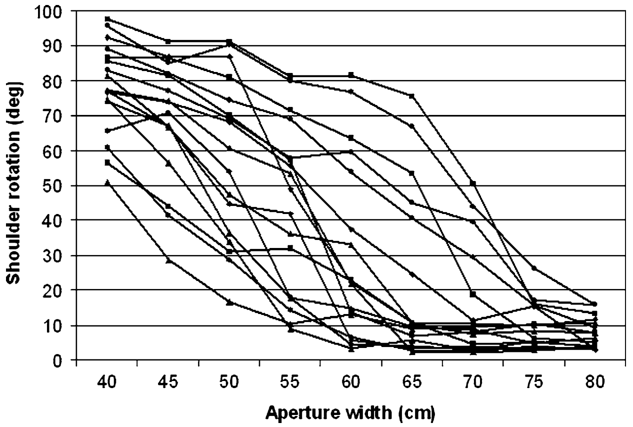

Fig. 5 Individual mean absolute max angle of shoulder rotation as a function of aperture width for the seventeen subjects who adapted their body orientation to the aperture width

3.2 Spatial accuracy of walking through the aperture

Under the presence hypothesis, walking through the aperture should also be spatially accurate enough to allow avoiding collisions against the sides of the door. Two analyses check this expectation.

A first analysis examines the number of collisions against the (left or right) lateral sides of the door upon the number of walkings through the door (Table 1). For the 17 subjects who adapted their body rotation to the aperture width, they were 51 (i.e., 17 × 3) passages per each aperture width. Almost all these passages were collision-free whatever the aperture width. Only some very rare collisions occurred for the narrow apertures (40, 45 and 50 cm). Over the 459 (i.e., 51 × 9) passages performed by the 17 subjects, all aperture width conditions pooled, there were six collisions. In these collisions, the shoulder exceeded the door limit by a distance ranging from 4 to 26 mm (median = 7 mm).

A second analysis examines the minimal security distance between the shoulders and the lateral sides of the door during walking through the aperture performed by the 17 subjects who adapted their body orientation to the aperture width. Figure 6 plots the location of each side of the door and of each shoulder along the left–right or X axis as a function of the aperture width. The locations of the shoulders were the most extreme left position for the left shoulder and the most extreme right position for the right shoulder recorded during the walking through the aperture. Each shoulder position was recorded from the moment it entered the door until the moment it left the door. ANOVAs (blocks × apertures) were conducted on the means of minimal security distance for each body side. These ANOVAs revealed that the minimal security distance did not vary with aperture width for most apertures (65, 60, 55, 50, 45 and 40 cm) neither for the left ($F_{5,80} = 0.53$, ns) nor for the right side ($F_{5,80} = 0.44$, ns). This absence of effect is illustrated (Fig. 6) by the parallelism

Table 1 Number of collisions against the left and the right side of the door upon the number of passages for each aperture width

Side of the door	Aperture width (cm)								
	40	45	50	55	60	65	70	75	80
Left	0/51	0/51	0/51	0/51	0/51	0/51	0/51	0/51	0/51
Right	2/51	1/51	3/51	0/51	0/51	0/51	0/51	0/51	0/51

The results are given for the 17 subjects who adapted their body orientation to the aperture width

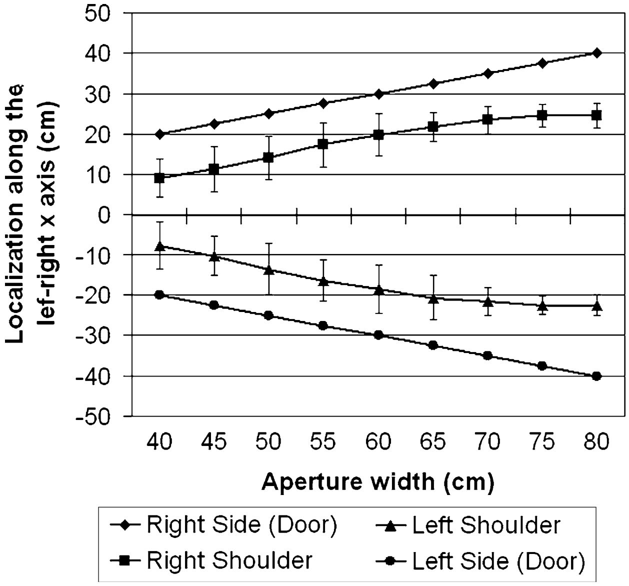

Fig. 6 Minimal security distance between the shoulders and the lateral sides of the door during the walking through the aperture as a function of aperture width. The minimal security distance is the interval between the location of the (left or right) door side and the location (mean ± 1 standard deviation) of the (left or right) shoulder

between the locations of the (left or right) side of the door and the locations of the (left or right) shoulder for these apertures (65, 60, 55, 50, 45 and 40 cm). However, the minimal security distance decreased with aperture width for larger apertures (80, 75 and 70 cm) both for the left ($F_{2,32} = 29.78$, $p < 0.001$) and for the right side ($F_{2,32} = 15.57$, $p < 0.001$). This effect is illustrated (Fig. 6) by the non-parallelism between the locations of the (left or right) side of the door and the locations of the (left or right) shoulder for larger apertures (80, 75 and 70 cm). Finally, the symmetrical position of the two shoulders above and below 0 (the center of the door) indicates that the subjects centered their passages toward the middle of the door whatever the aperture width.

3.3 Critical aperture widths and "aperture/shoulder" ratios

The two previous analyses demonstrated that, for 17 subjects, the shoulder rotation was related to the width of the virtual aperture and the spatial accuracy of the walking through the aperture was almost optimal. These analyses reflected that these subjects accurately obey the virtual width constraints. This new analysis additionally examined whether shoulder rotation was conjointly determined by both the aperture width and the shoulder width. Under the presence hypothesis, it was expected that, while the subjects with large shoulders should show greater angles of shoulder rotation than small subjects, both types of subjects should however behave similarly with respect to their own body size.

To assess this expectation, the population of 17 subjects was then divided into three groups (small, medium and large) based on their shoulder width. The shoulder width ranged from 40 to 45 cm for the small group (n = 6 subjects), and from 46 to 55 cm for the large group (n = 6 subjects). The shoulder width was above 45 cm and below 46 cm for the medium group (n = 5 subjects). Hereafter, we focused on the comparison between "small" and "large" subjects.

As expected, the "large" subjects have greater ($F_{1,10} = 6.03$, $p = 0.034$) angles of shoulder rotation than the "small" subjects (Fig. 7a) for intermediate apertures (55, 60, 65, 70, 75 cm). On the contrary, there was no effect of shoulder width when the subjects walked through narrow (40, 45, 50 cm) apertures ($F_{1,10} = 0.55$, $p = 0.47$) or when they walked through the broadest (80 cm) aperture ($F_{1,10} = 0.59$, $p = 0.45$). These results were probably due to the interplay between aperture widths and shoulder widths. When there was no constraint upon shoulder rotation (broadest aperture), "large" and "small" subjects displayed similar absence of shoulder rotation (i.e., frontal walking). Similarly, when the constraints were maximal (narrowest apertures), "large" and "small" subjects exhibited non-different shoulder rotations. Finally, "large" and "small" subjects showed different shoulder rotations when the constraints were variable (intermediate apertures).

Interestingly, the difference between groups tended to diminish when the same shoulder rotation data were replotted against the "aperture width/shoulder width" (body-scaled) ratio, hereafter referred to as A/S ratio (Fig. 7b). Thus, rescaling of the virtual aperture as a function of a relevant body characteristic eliminates group differences, suggesting that "small" and "large" subjects behave similarly relative to their own body size.

In order to test this hypothesis, we computed the critical aperture width and critical A/S ratio from which subjects exhibit a behavioral transition from frontal walking to body rotation while walking through the aperture. This was done under the following assumptions. Each subject was considered to use "frontal walking" while walking through the largest aperture (80 cm). The eventual body rotation

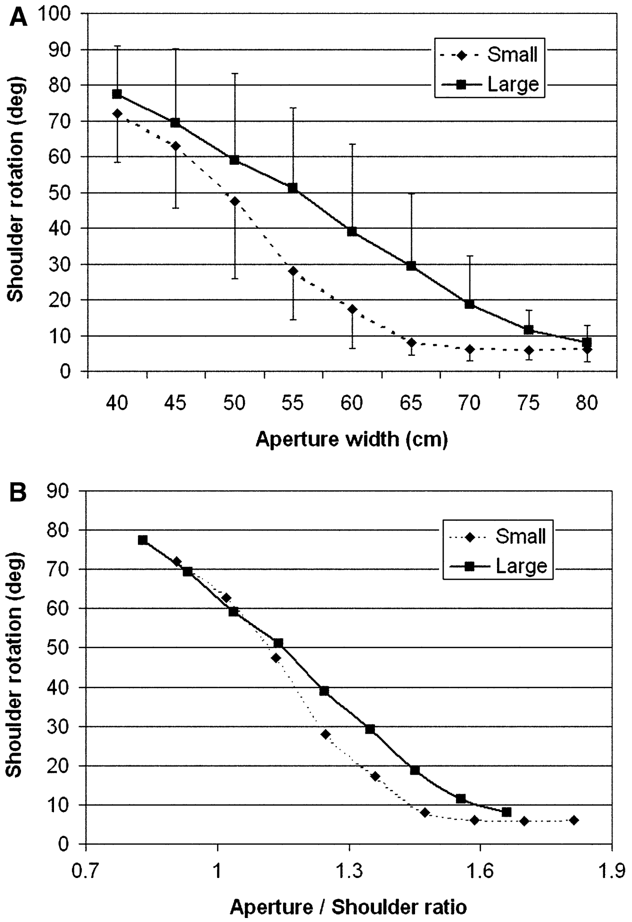

Fig. 7 Average max angle of shoulder rotation (± 1 standard deviation), for "large" and "small" subjects, as a function of aperture width (a) and as a function of the body-scaled ratio of aperture width divided by shoulder width (b)

Table 2 Mean and standard deviations of critical aperture widths and critical A/S ratios in small and large subjects

Actors	Critical aperture width (cm)		Critical A/S ratio	
	Mean	SD	Mean	SD
Small (n = 6)	52.5	4.18	1.22	0.14
Large (n = 6)	62.5	8.22	1.29	0.15

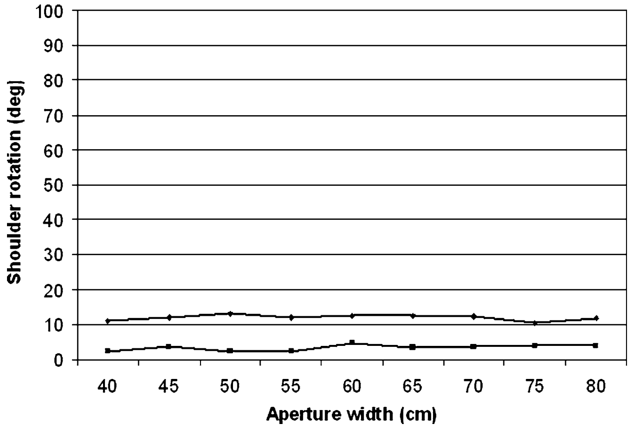

Fig. 8 Individual mean absolute max angle of shoulder rotation as a function of aperture width for the two subjects who exhibited frontal walking whatever the aperture width

exhibited at each narrower aperture (75, 70, 65, 60, 55, 50, 45, 40 cm) was statistically assessed by comparison with frontal walking through the largest aperture. For each subject, following descendant width values, the first aperture giving rise to a significant difference with frontal walking (as assessed using paired *t* tests) defined the critical aperture width or the critical A/S ratio.

Mean critical aperture widths and critical A/S ratios are given in Table 2. The difference between the critical widths for the "small" group (52.5 cm) and "large" group (62.5 cm) was statistically significant, as assessed by Student's *t* test ($t_{10} = -2.65$, $p < 0.02$). However, when these values were expressed intrinsically, the A/S ratios are quite similar: 1.22 for the "small" group and 1.29 for the "large" group, and not statistically different ($t_{10} = -0.83$, ns). The critical A/S ratios observed here in VE are quite similar to that measured in real environment (Warren and Whang 1987). These results lend strong support to the view according to which, in real environment (Warren and Whang 1987) as well as in VE, "small" and "large" subjects behave similarly relative to their own body size.

3.4 Non-adaptive behavior in two subjects

Out of the 19 subjects who completed the experiment, 2 subjects did not adapt their body orientation to the aperture width. They did not rotate the shoulders at all while walking through the virtual aperture. During each trial, they systematically exhibited frontal walking whatever the aperture width (Fig. 8). Because of this systematic frontal walking, they unavoidably collided against the sides of the virtual door. For geometrical reasons, these collisions occurred at the narrowest apertures. Given that these two subjects were 46.5 and 42 cm large (shoulder width) on the one hand, and that they performed straight frontal walking from the starting point to the arrival point on the other hand, they had occasional unilateral (left or right side) collisions for 45 and 50 cm aperture widths or even systematic bilateral (left and right sides) collisions for 40 cm aperture width. Interestingly, it should be noted that the peculiar behavior of these two subjects is not due to insufficient stereoscopic vision. The stereoscopic acuity of each of these two subjects corresponded to the median stereoscopic acuity (20 s of arc) of the whole population studied.

4 Discussion

The results of this study indicate that the locomotor postural patterns of subjects having to walk through a virtual aperture strongly resemble those of subjects who have to walk through a real aperture (Warren and Whang 1987; Higuchi et al. 2006). For most subjects indeed, a behavioral transition from frontal walking to body rotation was observed as the width of the virtual aperture diminishes. Most subjects also walked through the virtual aperture of different widths with great accuracy. Additionally, subjects with wider shoulders were observed to rotate their body more than subjects with small shoulder widths. Finally, the differences between "small" and "large" subjects tended to vanish when body rotation was considered with respect to a body-scaled ratio (aperture width/shoulder width). Indeed, while the behavioral transition from frontal walking to body rotation occurred at different critical aperture widths (expressed in centimeters) in "small" versus "large" subjects, the same behavioral transition occurred at the same critical body-scaled ratio (aperture width/shoulder width) in both types of subjects. All these conclusions are common to our study performed in VE and to Warren and Whang's study (1987) completed in real conditions. We thus suggest that all these facts together constitute a strong behavioral indicator of physical presence. Indeed, all these facts fulfill the basic assumption that the more a subject feels present in a VE, the more similar his responses will be to those he would exhibit in a similar real environment (Slater 2002).

Furthermore, the present results show that, out of 19 naïve subjects, 17 always systematically responded to the experimental setup (rotating their body to pass through the aperture without hitting the sides), while being only asked to step forward. This result demonstrates the immersive characteristics of the VR setup, including real-time interaction between the subject's movement and sensorial updating of the VE, 3D cues (stereoscopic vision, motion parallax), surrounding visual and auditory stimulation. Here, it should be noted that they are multiple methodological differences between our study and that of Stappers et al. (1999) which first attempted to evidence that walking through an aperture of variable widths share basic properties between virtual and real conditions, and as such might potentially constitute a behavioral index of physical presence. It is then difficult to explain with precision why the present study solves the problem that has led to unsuccessful demonstration in this previous research. Future research will investigate more precisely the role of these different factors. From the literature, it can be suggested that self-generated motion cues associated with large field stimulation (Ijsselsteijn et al. 2001), as well as converging multi-sensorial stimulation (here sound and vision) contribute to the sensation of presence (Slater 2002).

The fact that 17 of our subjects behave in coherence with the VE can be then considered as evidence that our experimental setup was efficient in making the subjects believe that they were actually facing a real door, necessitating shoulder rotation to pass through. In short, most subjects behave as if they believed in the tangibility of the visual world. In this regard, it can be hypothesized that the belief in the tangibility of the door would be based on the experience of the actual tangibility of the ground. In our experiment, the visible parts of the virtual world are heterogeneous in terms of potential tangibility. Some parts, like the horizontal ground surface, are both visible and tangible. Other parts, like the vertical sides of the door, are visible but not tangible. It may be that the property of tangibility would be extended to all visual parts. This extension would be cognitively possible for two reasons. First, the subjects experienced by walking the tangibility of the visual floor. Second, the subjects never experienced the non-tangibility of the door. The systematic confirmation of the tangibility of the floor associated to the systematic lack of disconfirmation of the non-tangibility of the door may feed the belief in a general tangibility of the visual virtual world.

The achievement of walking through apertures in real environment presupposes the involvement of at least two distinct perceptions: visual perception (for aperture width) and the self-perception of body stature (for shoulder width) (Warren and Whang 1987; Higuchi et al. 2006). The fact that most subjects managed to adequately walk through apertures in our VE, suggests that both perceptions were preserved during this action. In other words, our study suggests that our VE not only provided an exact metric regarding the environment, but also that this VE did not alter the perception of metric regarding the body. It is thus possible that this type of VE, which represent canonical views of the reality (in terms of usual size, orientation and motion), let unchanged the kinesthetic and proprioceptive processes by which the self-perception of the body is routinely achieved in normal earth environment.

However, it remains that two subjects never responded to our experimental setup. They systematically adopted frontal walking while they walked through the aperture whatever its size. They systematically collided against both sides of the door of the narrowest width. What happened with these two subjects? Here a couple of (non-exclusive) hypotheses can be evoked, which will certainly require further studies. We tried our best to optimize immersion, including having subjects blindfolded until they were "inside" the VE and never letting them look backwards. Doing that, we tried to minimize "real world" stimulation. However, it might be that some uncontrolled variables (e.g., the unavoidable junction between screen surfaces) and/or subject behavior (looking up momentarily to the ceiling) has destroyed the sensation of presence inside the VE. This hypothesis points toward limitations of the immersive setup (one subject told us that he did not see the reason why he would react to immaterial, transparent surfaces). In addition, we might also consider the hypothesis that subjects' cognitive and personality characteristics, such as field-dependency (Sas and O'Hare 2003; Hecht and Reiner 2007) come into play, when it comes to the subjective and integrative balance between different sensorial streams. Finally, it should be noted that the absence of the expected response in subjects suggests that the behavioral index ("shoulder rotation") was not a compulsory uncontrollable behavior.

Now, the present study needs to be completed by additional investigations, in order to further support the validity of the studied behavior ("shoulder adjustment") as a measurement of physical presence. Generally speaking, these complementary investigations should regard various metrological properties of presence measurement by the way of this behavioral index. In particular, these investigations should assess the sensitivity of the measure. So far, the experiment demonstrates that most (17 of 19) subjects adapted their body orientation to the aperture width. This suggests that most subjects feel strong presence with this scenario. However, this sole result only informs us about the strong power to induce presence of this simple scenario generated by a sophisticated VE. In order to assess the sensitivity of this behavioral index in measuring felt presence, it is also necessary to demonstrate that different scenario ranked according to their power to induce physical presence, cause various responses from this behavioral index. In particular, this behavior is expected to occur less frequently, in fewer participants or with less accuracy in a condition with a low inducing level of presence than in a condition with a high one. It is our intention to perform this kind of research in order to potentially strengthen the validity of the particular afforded behavior used here as a measurement tool for physical presence.

To sum up, presence was assessed in the present study by a particular motor adjustment which links the size of a body feature (shoulder width) to the size of some characteristics in the environment (width of the door). This kind of adjustment pertains to body-scaled motor adjustment. In other words, these motor adjustments constitute some "realized affordances". According to Gibson (1979), an affordance is an action possibility which is provided to an organism depending both on the organism properties and environment properties. In short, the present study suggests that eliciting "acted affordances" in virtual reality research could contribute to the behavioral assessment of presence in VEs. Since any "acted affordance" implies measurable variations (e.g., magnitude of body rotation) of a given action (e.g., walking through an aperture) and that these variations depend on both some body characteristics (e.g., the shoulder width) and some VE feature (e.g., the width of the aperture), we propose that any "acted affordance" can provide a sensorimotor evaluation of presence. For example, it is possible to investigate the behavior which involves bending one's head forward while walking through either a virtual or real door whose height is variable. Unlike the behavioral index studied here ("shoulder adjustment") with males only, this new afforded action ("to lower one's head") could be equally assessed in both genders and thus would allow better generalization over the population.

As a conclusion, the present study behaviorally objectivates physical presence in VR by the way of an afforded action. In both the real and the virtual world, human navigation through apertures is expectedly co-determined by the individual body architecture characteristics and the spatial metrics of the aperture. As a behavioral assessment of physical presence in VR, the present research calls for additional investigations devoted to evaluate the psychometric validity of this kind of measurement.

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