Perceiving affordances in virtual reality: Influence of person and environmental properties in perception of standing on virtual grounds

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Abstract: We evaluated the perception of affordances in virtual environments (VE). In our work, we considered the affordances for standing on a virtual slanted surface. Participants were asked to judge whether a virtual slanted surface supported upright stance. The objective was to evaluate if this perception was possible in virtual reality (VR) and comparable to previous works conducted in real environments. We found that the perception of affordances for standing on a slanted surface in virtual reality is possible and comparable (with an underestimation) to previous studies conducted in real environments. We also found that participants were able to extract and to use virtual information about friction in order to judge whether a slanted surface supported an upright stance. Finally, results revealed that the person's position on the slanted surface is involved in the perception of affordances for standing on virtual grounds. Taken together, our results show quantitatively that the perception of affordances can be effective in virtual environments, and influenced by both environmental and person properties. Such a perceptual evaluation of affordances in VR could guide VE designers to improve their designs and to better understand the effect of these designs on VE users.

Keywords: *Perception of affordances, Visual perception, Posture, Slanted surface, Virtual environments, Head-mounted display*

1 Introduction

In order to successfully engage in an intended behavior, for example, to negotiate a cluttered environment, a perceiver–actor must be able to perceive the different action possibilities offered by this environment. Particular information must be available for the perceiver-actor to determine whether an action is possible or not. Such possibilities for action are known as affordances (Gibson 1979). In this context, a horizontal and rigid surface would afford walk-ability, a large aperture would afford pass-ability, and so forth. Thus, the environment is full of things that have different affordances for the organism acting in it. For the psychologist J. J. Gibson, the affordance is directly perceivable by the organism because there is information in the environment that uniquely specifies that affordance for this organism (Michaels and Carello 1981). In other words, Gibson's affordances introduce the idea of the actor-environment mutuality; the actor and the environment make an inseparable pair. This idea was different from the contemporary view of the time that the meaning of objects was created internally with further "mental calculation" of the otherwise meaningless perceptual data. Indeed, Gibson's work was focussed on direct perception, a form of perception that does not require mediation or internal processing by an actor (see Jones 2003; Chemero 2003).

The concept of affordances and J. J. Gibson's view of studying organism and environment together as a system has been one of founding pillars of ecological psychology. Although introduced in psychology, the concept influenced studies in other fields as autonomous robotics (Sahin et al. 2007; Ugur and Sahin 2010; Ugur et al. 2011; Fitzpatrick et al. 2003) and human–computer interaction (Gross et al. 2005; Norman 1988, 1999; McGrenere and Ho 2000). Regarding the human-computer interaction field, design principles have largely focused on static representations and thus have yet to fully incorporate theories of perception appropriate for the dynamic multimodal interactions inherent to virtual environment (VE) interaction. In other words, there is a need to integrate a comprehensive theory of perception into VE design. Theories of direct perception, in particular affordance theory, may prove particularly relevant to VE system design because affordance theory provides an explanation of the interaction of an organism with its environment (see Gross 2004, 2005).

The aim of the present study is to evaluate the perception of affordances when people are inside VE. In order to test the perception of affordances in such a condition, we have chosen to consider the perception of affordances for standing on a slanted surface. This perception is basic and fundamental in the interactions with our environment. In this paper, we begin with a review on the affordances in real and virtual worlds: the concept of affordance is explained, and the previous works on the perception of affordances in the context of Virtual Reality (VR) and postural activities are described. Regarding our experiments, participants were asked to judge whether a virtual slanted surface supported upright stance. In Experiment 1, we evaluated whether this perception was possible in VR and comparable to previous works conducted in real environments. The other experiments considered two dimensions involved in this perception: (a) the properties of the VE and (b) the properties of the person in the VE. The first dimension (environment) was investigated in Experiment 2 by manipulating the texture of the slanted surface (Wooden texture vs. Ice texture). The second dimension (person) was investigated in Experiment 3 by manipulating the person's position on the slanted surface. Finally, results were analyzed in relation to previous works and different practical implications were suggested for several domains.

2 Affordances in real and virtual worlds

2.1 The concept of affordance

Gibson's work, mainly centered on the field of visual perception, is at the origin of the ecological approach to perception and action as opposed to the cognitive approach found in psychology. A fundamental tenet of the ecological approach is the claim that affordances are perceived directly (Gibson 1979). In other words, the perception of affordances does not require mediation or internal processing by the perceiver. The direct perception of the affordance is possible because there is invariant information in the environment that uniquely specifies that affordance. A growing body of research has demonstrated that participants are capable of perceiving affordances to control their actions in various activities including stair climbing (Mark 1987; Warren 1984), sitting on surfaces (Mark 1987), walking through apertures (Warren and Whang 1987), and walking up slopes (Kinsella-

Shaw et al. 1992). Although these results allow a better understanding of the perception of affordances, there is still debate between researchers whether the affordance is an inherent property of the environment (Turvey 1992) or an emergent property of the animal-environment system (Stoffregen 2003). However, in both of these theoretical views, there is an agreement on the fact that the perception of affordances involves that the environmental properties (height, width, weight, distance, etc.) are not evaluated on an extrinsic scale (i.e., in physical units) but are measured on an intrinsic scale according to certain relevant properties of the perceiver-actor, such as its own height, width and running speed (Oudejans et al. 1996). Indeed, the aforementioned studies have demonstrated that perception of affordances is based on body-scaled information. In other words, actors perceive the properties of the environment in relation to themselves. In a study of the perception of stair climbing, Warren (1984) asked observers to view stairs of different heights and judge which ones they could ascend in normal fashion. Warren found that observers' judgments were consistent and accurate with respect to their actual stair-climbing capabilities; each person's maximum climbable riser height was a constant proportion (.88) of leg length. Studies of other actions identified similar invariant relationships between the critical action boundary and a relevant body part across actors of different sizes: sitting (Mark 1987), and passing through apertures (Warren and Whang 1987).

2.2 Affordances and virtual reality

Several researchers consider that the Gibson's ecological framework is a promising functional approach for defining the reality of experience in relation to the problem of designing virtual environments (Flash and Holden 1998; Gross et al. 2005). For example, the perception of affordances could be a potential tool for sensorimotor assessment of physical presence, that is, the feeling of being physically located in a virtual place (Lepecq et al. 2009). Therefore, Lepecq et al. (2009) investigated the walk through a virtual aperture of variable widths. In the case of presence, the subject's body orientation, while walking, was hypothesized to be adapted to the width of the aperture and to their own shoulder width. The results of this study indicated 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 (see Warren and Whang 1987). For most subjects, a behavioral transition from frontal walking to body rotation was observed as the width of the virtual aperture decreased. Finally, researchers have designed a conceptual model in order to evoke affordances in VE via sensory-stimuli substitution. Such a model can potentially guide VE designers in generating more ecologically valid designs (Gross et al. 2005).

2.3 Affordances for standing on surfaces

In the field of postural activities, different studies have shown that the stance can be an example of affordance; that is a given environment can afford stance for a given organism (Gibson 1979). In a pioneering study, (Fitzpatrick et al. 1994) examined perception of affordance for supporting upright stance. The participants were asked to judge visually or haptically (i.e., by probing the surface with a hand-held rod while blindfolded) whether a wooden slanted surface supports upright stance. In the experiments, participants stood at a distance of one meter from an inclined board, and either looked at the surface or explored the surface with the hand-held rod. Although participants were less confident and took longer to make haptic judgments in comparison to visual judgments, the perceptual boundary between supporting and not supporting did not differ for haptic and visual judgments (29.8 and 29.6 degrees respectively). The results also showed that the profiles of the responses time and confident judgments were similar for both perceptual systems: the exploration time increased and confidence decreased at the perceptual boundary. Moreover, this perceptual boundary was within a few degrees of the actual (behavioral) boundary on this behavior (approximately 30°). In a second experiment using ascending and descending methods of limits for the presentation of angles, the results also revealed that the perceptual boundaries occurred at steeper angles of inclination on descending trials than on ascending trials. This finding demonstrates a phenomenon known as enhanced contrast and suggests that perception of affordances in this task is a dynamical process (Richardson et al. 2007). In a more recent study using the same experimental paradigm, researchers have shown that the perception of affordance for supporting upright stance depended on height of center of mass (Regia-Corte and Wagman 2008; see also Malek and Wagman 2008). In this study, participants performed the task while wearing a backpack apparatus to which masses were attached in different configurations. The developmental dimension was also examined in a study evaluating how children and adults perceived affordances for upright stance. The overall superiority of the adults relative to the children indicated clearly that there are developmental changes in the ability to perceive affordances (Klevberg and Anderson 2002).

3 Objective of the study

The purpose of this article was to study the perception of affordances in VR. In order to investigate this topic empirically, we have chosen to focus our analysis on the perception of affordances for standing on a slanted surface. During the different experiments, participants were asked to judge whether a virtual slanted surface supported upright stance. In Experiment 1, we evaluated if this perception was possible in VR. In the other experiments, we analyzed this perception more precisely by considering the influence of VE and person properties. Therefore, we examined the influence of the texture of the slanted surface in Experiment 2 and the influence of the person's position in Experiment 3.

4 Experiment 1: Can we perceive affordances for standing on a slanted surface in virtual reality?

The aim of Experiment 1 was to assess the perception of affordances for standing on a slanted surface in VR and to establish a comparison with previous studies conducted in real environment. Fitzpatrick et al. (1994) investigated this perception in real environment. In their study, participants reported whether they would be able to stand on a wooden slanted surface. This perception was also evaluated by considering the time taken to reach this determination and the participant's confidence in making this determination. Results showed that the perceptual reports varied as function of inclination of the slanted surface and the boundary between inclinations that were perceived to afford standing on and those that were not (i.e., the critical angle) was within a few degrees of the actual boundary for this behaviour (an inclination of approximately 30°; see also Klevberg and Anderson 2002; Regia-Corte and Wagman 2008; Malek and Wagman 2008). Moreover, results indicated that participants took longer to answer and were less confident of their responses when the slanted surface was close to the critical angle. Consequently, the hypothesis of our experiment was that if the participant is able to perceive affordances for standing on a slanted surface in VR, we should observe: (a) an effect of inclination of the slanted surface, that is, a perceptual discrimination for the inclinations that appear to support upright stance and those that do not, and (b) a pattern of results for response time and confidence judgement similar to the one of Fitzpatrick et al. (1994).

4.1 Participants

Twelve participants (3 females and 9 males) aged from 23 to 44 (*M* = 27.5, *SD* = 5.41), took part in this experiment. All of them were right-handed, and none of them had known perception disorders. They were all naive to the purpose of the experiment.

4.2 Experimental Apparatus

The experiment was conducted in a closed room with dim light. We used the eMagin Z800 Head Mounted Display as display device, at 60 Hz and with stereoscopy enabled. The participant was upright in front of a table with the laptop computer running the application (see Fig. 1) and was wearing an opaque fabric on top of the HMD to avoid seeing the surrounding real world. The participant's head was tracked by an ART ARTtrack2 infrared tracking system with 9 surrounding cameras for 360° tracking. The available tracking space was a cylinder with a 3 m diameter and a 2.5 m height.

Fig. 1 The experimental apparatus. Left: the participant wearing the HMD and the tracking equipment. Right: the participant equipped and wearing the opaque fabric in front of the table with the laptop computer.

4.3 The Virtual Environment

In the virtual environment (see Fig. 2), the participant was inside a room (width: 8.5 m × height: 4 m × length: 8.5 m) and stood upright 1 m from a slanted surface (width: 0.76 m × length: 1.56 m × thickness: 0.02 m). There were no contextual cues in the room. The floor of the room was displayed with a grey carpet, the walls and the ceiling with a brown paint. A wooden texture was used for the slanted surface. The participant's virtual eye height (i.e., the position of the camera) corresponded to the actual participant's eye height.

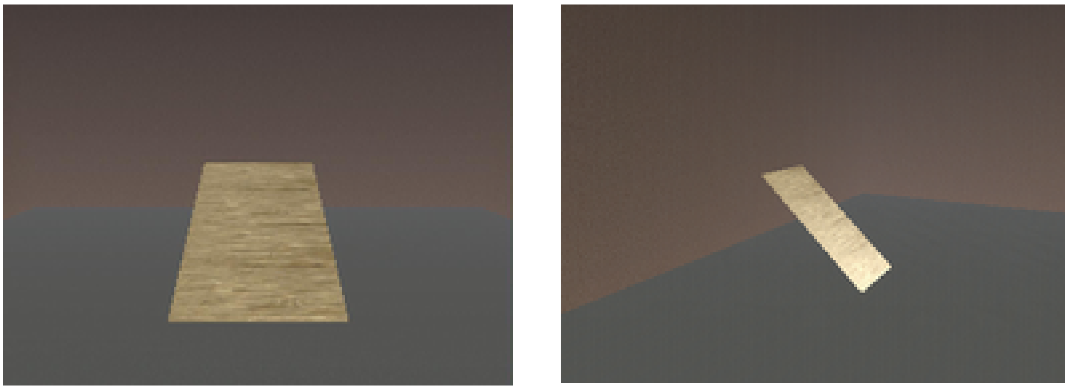

Fig. 2 The virtual environment was made up of a room with a wooden slanted surface. Left: the participant's view. Right: a side view.

4.4 Procedure

The participant's task in this experiment was to determine whether a wooden surface with a given inclination would support normal upright posture. Normal upright posture was defined as standing with the feet flat (i.e., not on the toes) without bending at the hip or knees. Before the experiment, each participant was briefed about the task and was instructed to stay upright during experiment. The participant was allowed to move the head in order to explore the virtual environment. Once equipped with the HMD and the opaque fabric (see Fig. 1), the participant was led in front of the table with the laptop. The experimenter pressed the Enter key to start the presentation of the virtual environment with the slanted surface; and pressed again the Enter key when participant began responding in order to measure his (her) response time. The experimenter recorded the perceptual response (i.e., "yes" the surface would support upright posture or "no", it would not). Participants also reported their confidence in their judgments on a scale ranging from very uncertain/not at all confident (1) to absolutely certain/very confident (7). The response time began with the presentation of the virtual environment and stopped when participant began answering. Participants could view the surface for as long as they wished to determine whether they would be able to stand on the slanted surface. After recording the responses, the experimenter pressed the Enter key then a black screen appeared and the application displayed the next trial. The method of constant stimuli was used for the measure of the critical inclination. Seven angles of inclination 12°, 17°, 22°, 27°, 33°, 39°, and 45° were presented during the experiment. Each angle was randomly presented six times, resulting in 42 trials per participant. The duration of the experiment was approximatively 15 minutes.

4.5 Results

4.5.1 Analysis on the Percent of "Yes" Responses

For each participant, the percentage of trials that received a "yes" response was calculated for each of 7 angles of inclination. An alpha-level of 0.05 was adopted. A 7 (Angle of inclination) repeated-measures ANOVA on percentage of "yes" responses revealed a significant main effect, $F(6,66) = 103.8$, $p < 0.001$ (see Fig. 3). The mean percentage of "yes" responses for the seven slopes was 100, 86.11, 45.83, 19.44, 5.56, 4.17, and 1.39, indicating that participants made a distinction between those inclines that appeared to support upright stance and those that did not.

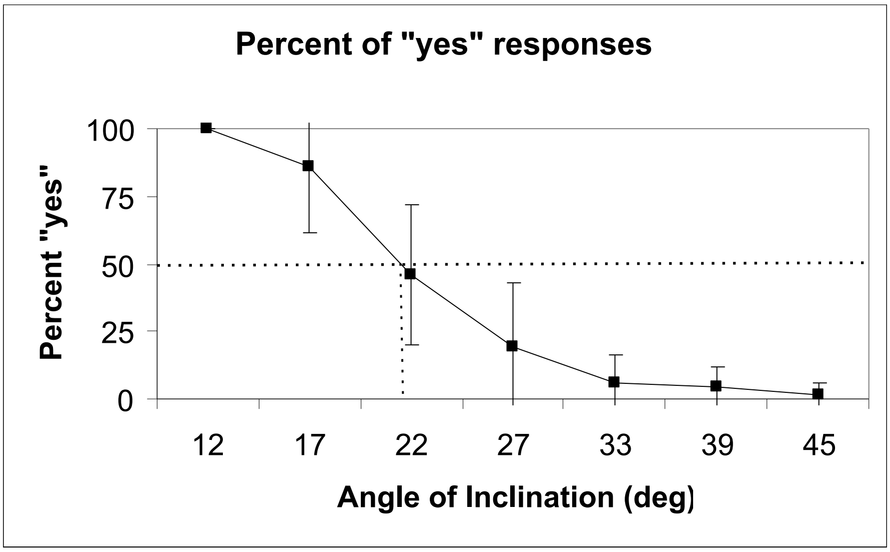

Fig. 3 Mean percentage of “yes” responses (the surface would support upright stance) as a function of angle of inclination of the slanted surface. Bars represent *SD*.

To get an accurate measure of the critical angle, the percentage of “yes” responses for each angle of inclination was analyzed using a logistic function expressed by the following equation (Bootsma et al. 1992; O’Regan and Humbert 1989; Peper et al. 1994; Cornus et al. 1999):

$$\%\text{ of "yes" responses} = \frac{100}{\left(1 + e^{-k(c-x)}\right)}$$

In the logistic equation, 100% was the maximum percentage of “yes” responses (i.e., the participants always judged to be able to stand on the slanted surface), x, the angle of inclination in degrees. C was the 50% point, that is, the angle of the slanted surface at which the participant changed his or her judgment from “yes, I can stand on the slanted surface” to “no, I can’t”. In other words, this point was the critical angle for standing on the slanted surface with an upright posture. K was the slope approaching that point. The analysis revealed that the 50% point occurred at an angle of inclination of 21.98° ($k = 0.32$; $r^2 = 0.84$) with lower and upper fiducial limits of 21.06° and 22.91°.

4.5.2 Analysis on Response Time

For each participant, the mean response time (in seconds) was computed on the 6 trials for each angle of inclination. A 7 (Angle of inclination) repeated-measures ANOVA on the mean response time showed a significant main effect, $F(6,66) = 9.23$, $p < 0.001$ (see Fig. 4), indicating that participants took longer to explore surfaces close to the transition point between supporting and not supporting upright posture. Mean response times for the seven angles of inclination were 3.15, 4.93, 5.29, 4.14, 3.47, 2.84, and 2.48 s, respectively.

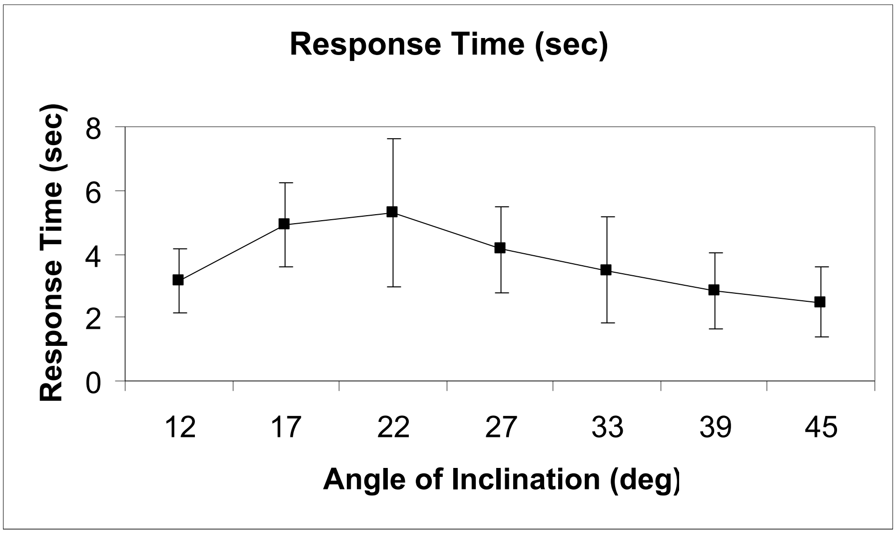

Fig. 4 Mean response time (in seconds) as a function of angle of inclination. Bars represent *SD*.

As in Fitzpatrick et al. (1994), the increase of response time near the transition point and its decrease on either side of the transition would be confirmed by a significant polynomial regression with a positive coefficient on the x term (i.e., angle) and a negative coefficient on the x^2 term (angle^2). Thus, a polynomial regression was conducted on the mean response time. The resulting equation was $y = 1.65 + 0.2439*x - 0.0052*x^2$, $r^2 = 0.22$, $F(2,81) = 11.23$, $p < 0.001$. This result confirmed that more time was needed for inclinations close to the perceptual transition.

4.5.3 Analysis on Confidence Judgment

For each participant, the mean confidence judgment was computed on the 6 trials for each angle of inclination. A 7 (Angle of inclination) repeated-measures ANOVA on the mean confidence judgment also revealed a significant main effect, $F(6,66) = 21.78$, $p < 0.001$ (see Fig. 5), indicating that participants were less confident of their responses close to the transition point. Mean confidence judgments for the seven angles of inclination were 5.83, 4.51, 3.69, 4.72, 5.94, 6.40, and 6.78 respectively.

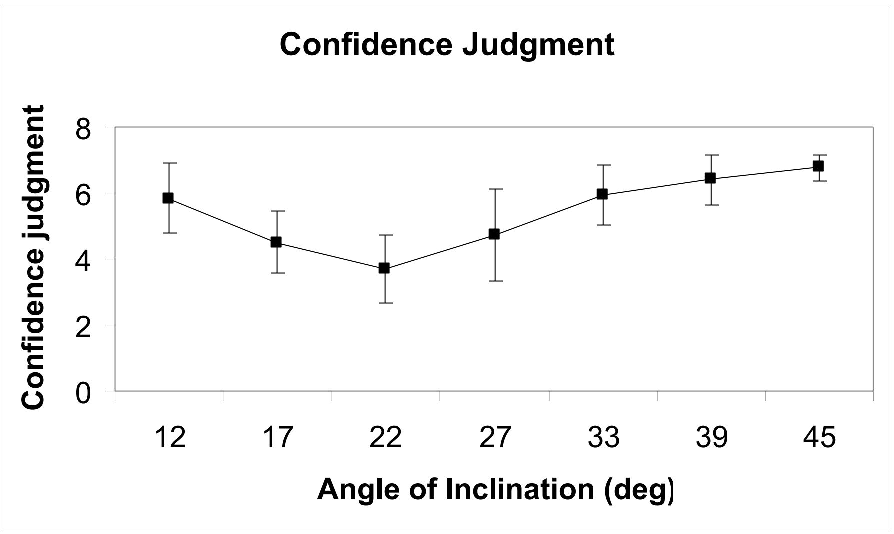

Fig. 5 Mean confidence rating (1 indicates not confident; 7 indicates very confident) as a function of angle of inclination. Bars represent *SD*.

As in Fitzpatrick et al. (1994), the decrease of confidence near the transition point and its increase on either side of the transition would be confirmed by a negative x term and a positive x^2 term in a significant polynomial regression. Results confirmed that participants were least confident in their perceptual responses the closer the presented angle was to the transition point: $y = 7.47 - 0.248*x + 0.0054*x^2$, $r^2 = 0.39$, $F(2,81) = 25.79$, $p < 0.001$.

4.6 Summary of Results

As in the Fitzpatrick et al's (1994) study conducted in real environment, results showed that participants were able to discriminate the inclinations that appeared to support upright stance and those that did not in VR. Moreover, the analysis revealed that the 50% point (or the critical angle for an upright posture) occurred at an angle of inclination of 21.98° and the pattern of results for the response time and the confidence judgment was consistent with this result by showing that participants took longer to answer and were less confident of their responses when the inclination was close to the critical angle. Thus, these results revealed that the perception of affordances for standing on a slanted surface in VR is possible and comparable to previous studies conducted in real environments.

5 Experiment 2: Influence of VE properties in perceiving affordances for standing on a slanted surface in virtual reality

The aim of Experiment 2 was to evaluate the perception of affordances for standing on a slanted surface by considering the properties of the VE. In this experiment, we considered the texture of the slanted surface as pertinent property (see our previous study, Regia-Corte et al. 2010). To prevent an object from slipping down a slope, frictional force must be strong enough to overcome the pull of gravity. The amount of frictional force that is created depends on the coefficient of friction between the object and the surface of the slope. Thus, two contrasted textures (high-friction: Wooden vs. low-friction: Ice) were used for the slanted surface. The hypothesis of this experiment was that if the texture is involved in the perception of affordances for standing on a slanted surface in VR, we should observe an effect of the texture on the perceptual boundary (or critical angle): with a perceptual boundary lower with the Ice texture than with the Wooden texture.

5.1 Participants

Twelve participants (2 females and 10 males) aged from 20 to 29 (*M* = 24.9, *SD* = 2.8), took part in this experiment. All of them were right-handed, and none of them had known perception disorders. They were all naive to the purpose of the experiment.

5.2 Experimental Apparatus

We used the same experimental apparatus as in Experiment 1.

5.3 The Virtual Environment

We used the same virtual environment as in Experiment 1 except that two different textures were used for the slanted surface: a Wooden texture or an Ice texture (see Fig. 6). In this experiment, the participant controlled the inclination of the slanted surface with the keyboard of the laptop computer.

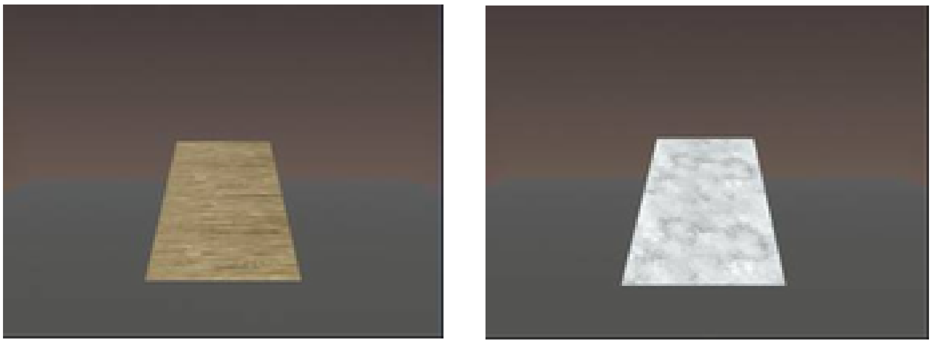

Fig. 6 The virtual environment was made up of a room with a slanted surface. Two different textures were used for the slanted surface: a Wooden texture (left) and an Ice texture (right).The participant controlled the inclination of the slanted surface with the keyboard of the laptop computer.

5.4 Procedure

The task in this experiment was to adjust the angle of inclination of the virtual slanted surface until the participant felt that it was just barely possible for him (her) to stand on that surface with a normal upright posture. Before the experiment, each participant was briefed about the task and was instructed to stay upright during experiment. The participant was allowed to move the head in order to explore the virtual environment. Once equipped with the HMD and the opaque fabric, the participant was led in front of the table with the laptop and the participant’s right hand was placed on the keyboard. The participant used their right hand fingers to press the computer keys. The participant could adjust the angle of the slanted surface with three keys: the up arrow to increase the inclination, the down arrow to decrease the inclination and the Enter key to validate the response. The resolution for one press on the up-down arrows was 0.25° and a continuous press on the keys was possible to adjust the inclination (5° / sec).

The method of adjustment was used for the measure of the critical inclination. For each trial, the angle of inclination of the surface was initially set at either the lowest angle of inclination (i.e., 0°) or the highest angle of inclination (i.e., 90°) and the participants adjusted the angle of inclination until they felt that the surface was set at the steepest angle that would support upright posture. Participants could view the surface for as long as they wished to determine whether they would be able to stand on the slanted surface. Once participants were satisfied with position of the surface, they pressed the Enter key to validate the response then a confirmation message appeared with a black screen and asked to press again the Enter key to confirm the response or to press the Space bar to return to the task. When the response was confirmed, the value of the inclination was recorded and the application displayed the next trial. During the experiment, two different textures were used for the slanted surface: a Wooden texture and an Ice texture. No information was communicated to the participant about the texture of the slanted surface. Participants completed all the two texture conditions (Wooden and Ice) and the order of the conditions was counterbalanced across participants. Thus, half of the participants completed the Wooden texture condition first, and the other half of the participants completed the Ice texture condition first. In each condition, participants completed two ascending trials (in which the angle of inclination was initially set at 0°) and two descending trials (in which the angle of inclination was initially set at 90°). Ascending and descending trials alternated within a given condition, and the order of the sequence (i.e., whether an ascending or a descending trial was presented first in a given condition) was counterbalanced across participants. Thus, half of the participants completed the ascending trial first, and the other half of the participants completed the descending trial first. In this experiment, participants completed a total of 8 trials (2 texture conditions × 2 directions × 2 trials per condition). The duration of the experiment was approximatively 10 minutes.

5.5 Results

The mean angle of inclination chosen by the participants was considered as the perceptual boundary. For the analysis, an alpha-level of 0.05 was adopted. A 2 (Texture: wooden vs. ice) × 2 (Direction: ascending vs. descending) repeated-measures ANOVA was conducted on these perceptual boundaries. The ANOVA revealed a significant effect of texture, $F(1,11) = 8.07$, $p = 0.016$ (see Fig. 7), the perceptual boundary with the Ice texture ($M = 22.13°$, $SD = 8.52°$) was significantly lower than with the Wooden texture ($M = 27.60°$, $SD = 10.57°$).

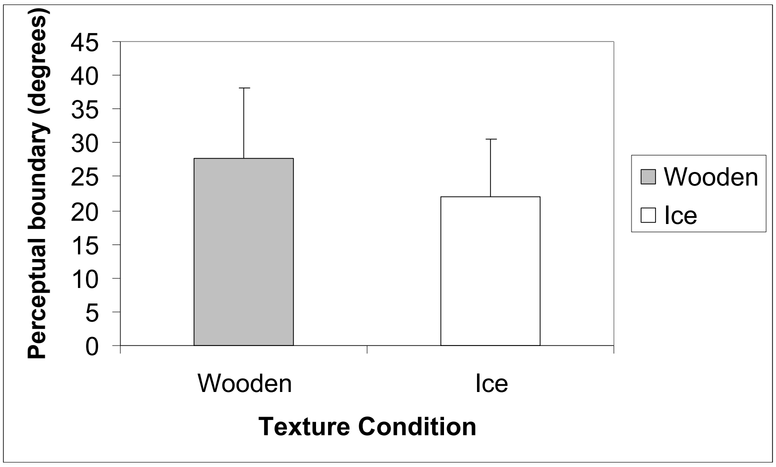

Fig. 7 Mean perceptual boundary (or critical angle in degrees for standing on the slanted surface) as a function of the texture condition (Wooden and Ice). Bars represent *SD*.

The ANOVA also revealed a significant effect of direction, *F*(1,11) = 6.83, *p* = 0.024 (see Fig. 8), the perceptual boundary occurred at a steeper angle of inclination when the surface was descending (*M* = 26.09°, *SD* = 9.89°), than when the surface was ascending (*M* = 23.65°, *SD* = 8.34°). The interaction between texture and direction was not significant (*F*(1,11) = 1.38, *p* = 0.26).

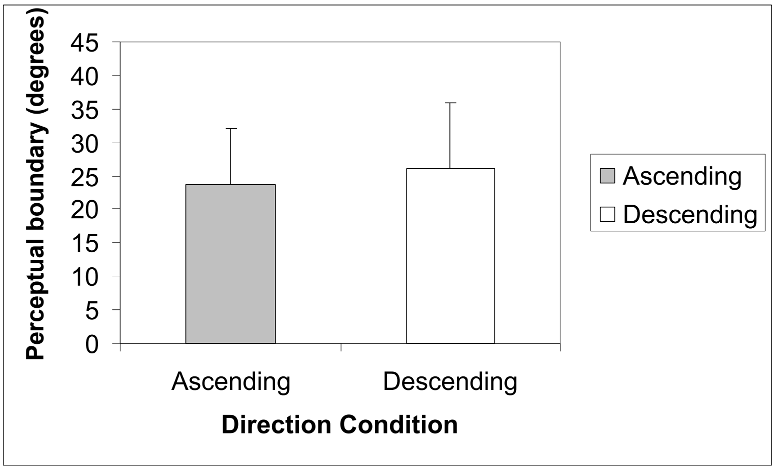

Fig. 8 Mean perceptual boundary (or critical angle in degrees for standing on the slanted surface) as a function of the direction condition (Ascending and Descending). Bars represent *SD*.

5.6 Summary of Results

In this experiment, the texture of the slanted surface was manipulated. Results showed that the perceptual boundary with the Ice texture (22.13°) was significantly lower than with the Wooden texture (27.60°). This result revealed that the virtual information about friction was detected and used in VE. Thus, participants were able to differentiate visually a low-friction texture (Ice) from a high-friction texture (Wooden). In other words, this result indicated that the texture of the slanted surface was involved in perceiving affordances for standing on this surface in VR. Furthermore, as in the previous works conducted in real environments, our results also revealed that the perceptual boundaries occurred at steeper angles of inclination on descending trials than on ascending trials. This finding demonstrates a phenomenon known as enhanced contrast (Richardson et al. 2007) and suggests that perception of affordances in this task is a dynamical process. Finally, this last result reinforces the similarity observed between the perception of affordances in VE and in real environments.

6 Experiment 3: Influence of person properties in perceiving affordances for standing on a slanted surface in virtual reality

The aim of Experiment 3 was to evaluate the perception of affordances for standing on a slanted surface by considering the properties of the person in the VE. In this experiment, we considered the person's position on the slanted surface as pertinent property. The person's position is the location on the slanted surface considered by the person during his (her) perceptual judgement. This person's property was not analyzed in previous studies conducted in real environments. For our experiment, it is important to notice that the different locations on the slanted surface involve different aspects for the participant. Thus, for example, a high location is more dangerous for the physical integrity than a low location. Consequently, in Experiment 3, the perception of whether a slanted surface supported upright stance was investigated by using a postural zone differently positioned on the slanted surface. When this postural zone was displayed on the surface, the participant had to consider this information of position during his (her) perceptual judgement. In other words, the participant had to visualize him- or herself being inside the postural zone when it was displayed. Thus, three postural zone conditions (No zone vs. Low zone vs. High zone) were used during experiment. The hypothesis of this experiment was that if the person's position is involved in the perception of affordances for standing on a slanted surface in

VR, we should observe an effect of the postural zone on the perceptual boundary (or critical angle): with a perceptual boundary lower in the High zone condition (dangerous) than in the Low zone condition (not dangerous).

6.1 Participants

The participants of this experiment were the same as for the Experiment 2.

6.2 Experimental Apparatus

We used the same experimental apparatus as in the Experiments 1 and 2.

6.3 The Virtual Environment

We used the same virtual environment as in the Experiments 1 and 2 except that in this experiment, it was possible to display a postural zone on the slanted surface and to change its position in relation to the bottom of the slanted surface (see Fig. 9). This postural zone was delimited by a white rectangle (width: 60 cm × height: 30 cm). Three different zone conditions were used during the experiment: a No zone condition (where no postural zone was displayed), a Low zone condition (positioned at 20 cm from the bottom) and a High zone condition (positioned at 1.36 m from the bottom). A wooden texture was used for the slanted surface. The participant controlled the inclination of the slanted surface with the keyboard of the laptop computer.

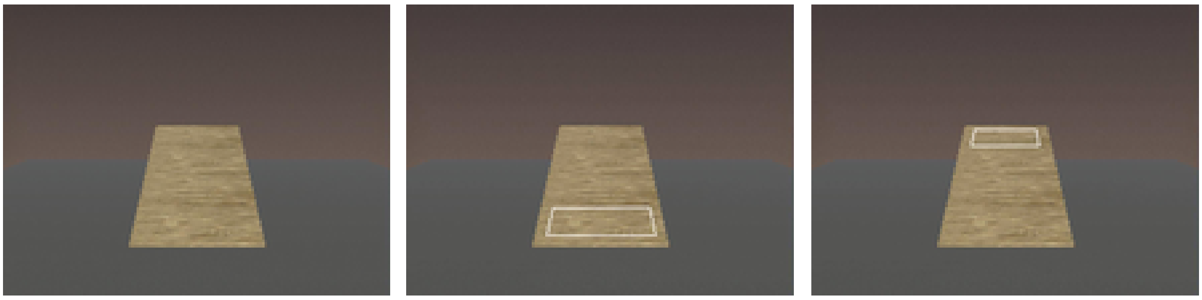

Fig. 9 The virtual environment was made up of a room with a wooden slanted surface. Three different zone conditions were used during the experiment: a No zone condition (left), a Low zone condition (center) and a High zone condition (right). The participant controlled the inclination of the slanted surface with the keyboard of the laptop computer.

6.4 Procedure

The task and the method in this experiment were the same that in the Experiment 2 except that when the postural zone was displayed on the slanted surface, the participant had to consider this zone for the adjustment of his (her) critical angle for an upright posture. During the experiment, three different zone conditions were used for the slanted surface: No zone, Low zone and High zone. Participants completed all the three zone conditions and the order of the conditions was counterbalanced across participants. A full counterbalancing with six possible orders was used. Participants were randomly assigned to each of the six possible orders of conditions. In each zone condition, participants completed two ascending trials (in which the angle of inclination was initially set at 0°) and two descending trials (in which the angle of inclination was initially set at 90°). Ascending and descending trials alternated within a given condition, and the order of the sequence (i.e., whether an ascending or a descending trial was presented first in a given condition) was counterbalanced across participants. Thus, half of the participants completed the ascending trial first, and the other half of the participants completed the descending trial first. In this experiment, participants completed a total of 12 trials (3 zone conditions × 2 directions × 2 trials per condition). The duration of the experiment was approximatively 12 minutes.

6.5 Results

The mean angle of inclination chosen by the participants was considered as the perceptual boundary. For the analysis, an alpha-level of 0.05 was adopted. A 3 (Zone condition: No zone vs. Low zone vs. High zone) × 2 (Direction: ascending vs. descending) repeated-measures ANOVA was conducted on these perceptual boundaries. The ANOVA revealed a significant effect of the zone condition, $F(2,22) = 6.74$, $p = 0.005$ (see Fig. 10).

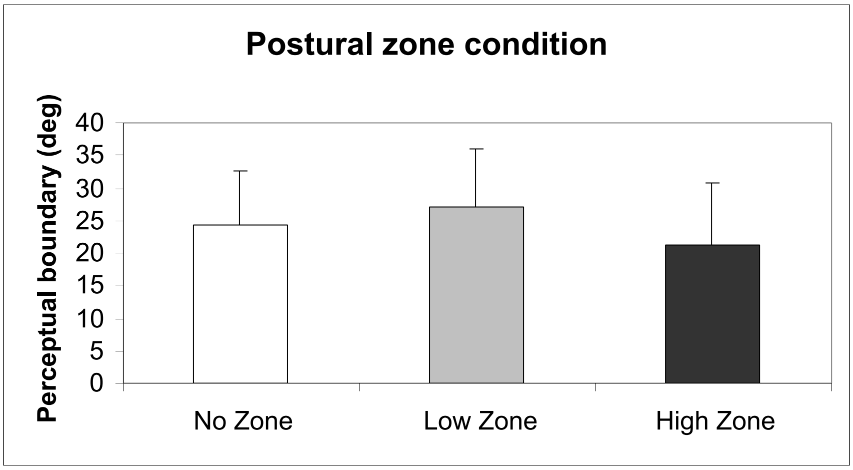

Fig. 10 Mean perceptual boundary (or critical angle in degrees for standing on the slanted surface) as a function of the zone condition (No zone, Low zone and High zone). Bars represent SD.

For the different comparison analysis, a correction for experiment-wise error was realized by using Bonferroni-adjusted alpha level ($p = 0.05$ divided by the number of tests). Thus, in order to compare the three zone conditions (No zone, Low zone and High zone), the alpha level was adjusted to $p = 0.0167$. Follow-up t test revealed that the perceptual boundary in the Low zone condition ($M = 27.04°$, $SD = 9.02°$) was significantly higher than in the High zone condition ($M = 21.10°$, $SD = 9.52°$), $t(11) = 3.86$, $p = 0.002$. By contrast, the analysis indicated that the perceptual boundary in the No zone condition ($M = 24.41°$, $SD = 8.26°$) was not significantly different from the perceptual boundaries in the Low zone condition ($t(11) = -1.82$, $p = 0.096$) and in the High zone condition ($t(11) = 1.79$, $p = 0.10$). The ANOVA also indicated a tendency for the direction, $F(1,11) = 4.77$, $p = 0.052$, the perceptual boundary occurred at a marginally steeper angle of inclination when the surface was descending ($M = 25.46°$, $SD = 9.08°$), than when the surface was ascending ($M = 22.91°$, $SD = 8.05°$). The interaction between zone condition and direction was not significant ($F(1,11) = 2.30$, $p = 0.12$).

6.6 Summary of Results

The analysis revealed that the postural zone on the slanted surface had an effect in perceiving affordances for an upright posture: the perceptual boundary in the High zone condition was significantly lower than in the Low zone condition. Thus, these results indicated that the person's position on the slanted surface was involved in the perception of affordances for standing on this surface in VR.

The absence of significant differences between the No zone condition and the two other conditions (Low zone and High zone) could be explained by the fact that when no postural zone was displayed on the slanted surface, participants were free to consider different postural positions on the slanted surface (i.e., low, high, or middle) during their perceptual judgments. Finally, consistent with Experiment 2 and previous studies, our results also indicated a tendency for which the perceptual boundaries occurred at steeper angles of inclination on descending trials than on ascending trials (enhanced contrast).

7 General discussion

This paper analyzed the perception of affordances for standing on a slanted surface in VR. During the different experiments, participants were asked to judge whether a virtual slanted surface supported upright stance. Interestingly, participants showed a natural ability to perceive affordances in VR although they have no prior experience with the virtual slanted surface displayed. These results are interesting because they are consistent with the previous research conducted in real environments but also because they reveal several specificities.

The aim of Experiment 1 was to evaluate whether the perception of affordances for standing on a slanted surface was possible in VR and comparable to previous works conducted in real environments. In this experiment, participants reported whether they would be able to stand on a virtual wooden surface with an upright posture. Results showed that participants were able to discriminate the inclinations that appeared to support upright stance and those that did not in VR. Response time and confidence judgment were consistent with this result by showing an increase of response time and a decrease of confidence judgment when the inclination was close to the critical angle. However, the observation of results indicated that the critical angle for an upright posture in VR (21.98°) appeared to be lower in comparison to those of previous studies conducted in real environments (approximatively 30°). This underestimation is an interesting and paradoxical result. Indeed, we can imagine that people inside VE are aware to be in an unrealistic world where their physical integrity is not involved and where it is possible to risk dangerous behaviors. However, this underestimation indicated, on the contrary, that participants were more careful in VE. One possible explanation for this paradoxical result would be the presence of a time effect on the perception: at the beginning, the VE as a new environment involves a safety first effect with an underestimation of action possibilities. But during time and practice inside the VE, participants become more adapted and confident with a virtual perception reaching the real perception. And finally, participants adopt risky and dangerous behaviors leading to an overestimation of action possibilities. Thus, it would be interesting for the future research to consider the time factor in order to test this hypothesis. It is important to notice that previous studies have shown that distances appear to be compressed in immersive virtual environments presented via head mounted display systems, relative to in the real world (Steinicke et al. 2009). Thus, the underestimation observed in our study could indicate that the perception of affordances in VR would be also affected by the effect of compression. On the other hand, it is possible that some properties of the HMD configuration were involved in this perception. These topics could be investigated more precisely in future experimental work.

The aim of Experiment 2 was to evaluate the role of VE properties in perceiving affordances by manipulating the texture of the slanted surface. In this experiment, the participant adjusted the angle of inclination of the virtual slanted surface until he (she) felt that it was just barely possible for him (her) to stand on that surface with a normal upright posture. The analysis showed that the perceptual boundary with the Ice texture (22.13°) was significantly lower than with the Wooden texture (27.60°). Thus, this result revealed that the virtual information about friction was detected and used in VE. Participants were able to differentiate visually a low-friction texture (Ice) from a high-friction texture (Wooden). In other words, this result indicated that the texture of the slanted surface was involved in perceiving affordances for standing on this surface in VR. It suggests that participants can be influenced by the properties of the virtual environment (here the visual textures), and can extract and use such information when perceiving affordances of virtual objects. Furthermore, as in the previous works conducted in real environments, our results also revealed that the perceptual boundaries occurred at steeper angles of inclination on descending trials than on ascending trials. This finding demonstrates a phenomenon known as enhanced contrast (Richardson et al. 2007) and suggests that perception of affordances in this task is a dynamical process. This last result reinforces the similarity observed between the perception of affordances in VE and in real environments.

The comparison of results for Experiments 1 and 2 indicated an important difference between perceptual boundaries. Indeed, results of Experiment 2 showed higher critical angles for both conditions compared to the result in Experiment 1. Thus, even the critical angle for the ice texture was slightly steeper than the critical angle for the wooden texture in Experiment 1. However, such a comparison is not really pertinent in our case since the psychophysical methods used in each experiment were not the same (method of stimuli constant in Experiment 1 and method of adjustment in Experiment 2). Finally, this difference and the incoherence observed can be attributed to the technical aspect resulting from the use of each method, such as the verbal responses in Experiment 1 and the possibility for the participant to move the slanted surface in Experiment 2.

The aim of Experiment 3 was to evaluate the role of person properties in perceiving affordances by manipulating the person's position on the slanted surface. In this experiment, the task and the method were the same as in the Experiment 2 except that a postural zone was displayed on the slanted surface and the participant had to consider this zone for the adjustment of his (her) critical angle for an upright posture. Three postural zone conditions were used during experiment: No zone, Low zone, and High zone. The analysis revealed that the postural zone on the slanted surface had an effect in perceiving affordances for an upright posture: the perceptual boundary in the High zone condition (21.10°) was significantly lower than in the Low zone condition (27.04°). Thus, these results indicated that the person's position on the slanted surface was involved in the perception of affordances for standing on this surface in VR. These results might first be related to previous studies conducted in order to evaluate the role of the person's emotional state (e.g., anxiety) in the perception of affordances. For example, Pijpers et al. (2006) used a climber wall and determined perceived and actual maximal overhead reaching height under different anxiety conditions, which were created by placing the same climbing route high and low on the wall. Anxiety was found to reduce both perceived and actual maximal reaching height. On the other hand, Jiang and colleagues (Jiang and Mark 1994; Jiang et al. 1993) found that when individuals had to judge whether they could step over a gap, their estimates of crossable gap width decreased as gap depth increased. This finding seems to refer to a process similar to that addressed in the Pijpers et al.'s (2006) study in that increased gap depth led to increased anxiety, which in turn affected the perception of gap crossing capability. Consequently, these studies indicate that the use of postural zones in our experiment may have modified the person's emotional state (i.e., anxiety or vertigo) which in turn affected the perception of affordances for standing on the surface. Hence, we can suppose that the lower perceptual boundary observed in the High zone condition in comparison to the one in the Low zone condition could be explained by the fact that more anxiety was felt in the High zone condition than in the Low zone condition. Future research could investigate this point by using physiological measures and an "anxiety thermometer" (see Houtman and Bakker 1989) during the experiment. Regarding the practical implications of our study, the results suggest various applications. People with motor impairments or balance disorders might improve their postural ability with specific activities in VR where they are confronted to different affordances. On the other hand, other practical implications would be in the context of urban projects, where the immersion in the 3D representations of buildings would allow to localize the uncomfortable affordances. The results observed in the present work call for additional investigations devoted to evaluate the perception of different affordances in VR (walking up slopes, stair climbing, gap crossing, and object reaching). It would also be interesting to conduct these investigations by considering different perceptual modalities (vision, haptic and audition) and their interactions.

Conclusion

The aim of this work was to evaluate the perception of affordances in VR taking as an example standing on a slanted surface. Therefore, we have conducted different experiments where participants judged whether a virtual slanted surface supports upright stance. Results indicated that the perception of affordances for standing on a slanted surface in VR is possible and comparable (with an underestimation) to previous studies conducted in real environments. Participants were also able to differentiate visually a low-friction texture (Ice) from a high-friction texture (Wooden) and to use this virtual information about friction in the perception of affordances for standing on a slanted surface. Finally, our study indicated that the person's position is an important factor involved in the perception of affordances for standing on a slanted surface in VR. Taken together our results show quantitatively that the perception of affordances can be effective in virtual environments, and influenced by both environmental and person properties. They introduce and validate the paradigm of postural affordance of standing on a slanted surface for future studies on affordances in VR. Thus, future research might evaluate the influence of other parameters such as the type of display or some characteristics of participants.

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