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ORIGINAL ARTICLE

Revisiting affordance perception in contemporary virtual reality

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Abstract
Virtual reality (VR) applications have rapidly gained renewed popularity and are extensively employed for replicating real-life scenarios that may otherwise be impractical to recreate. All such VR applications require that the environments being used provide high levels of immersion and mimic their real-world counterpart in terms of size, distance, depth, and action capabilities. Many VR applications being developed for training and entertainment require users to traverse an immersive virtual environment (IVE), where determining whether one can pass through an opening or aperture is one of the most frequently made decisions. In this experiment, we empirically compare passability judgments made in an IVE to those made in the real world. Participants judged whether they could pass through various widths of an adjustable sliding doorway in the real world and in a to-scale virtual replica viewed through an HTC Vive head-mounted display. If uncertain of their initial judgments, participants were permitted to walk towards the doorway. Results indicate that participants accurately perceive their ability to pass through doorways in both the real world and VR. However, participants in VR required more exposure to dynamic information via movement through the IVE in order to reach a real-world level of perceptual accuracy.

Keywords Affordances · Passability · Body scaling · Virtual reality

1 Introduction

In the past few years, virtual reality (VR) has made rapid headway in a wide variety of fields such as health care, manufacturing, entertainment, gaming, education, and field training. Many VR simulations employed in these fields recreate scenarios that may otherwise be impractical or infeasible to replicate in the real world, such as architectural walkthroughs, exploration tasks, combat, and other field trainings. For such virtual environments to feel realistic and provide a higher level of immersion, it is imperative that the spatial information (i.e. size and distance) perceived is veridical (Lin et al. 2015). Previous

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works have reported that viewing IVEs or augmented environments through large screen stereoscopic displays or head-mounted displays (HMD) often results in underestimations (Knapp and Loomis 2003; Jones 2008; Grechkin et al. 2010; Napieralski et al. 2011; Stefanucci et al. 2015). Hardware and software components of earlier devices were noted as probable causes of these underestimations (Thompson et al. 2004; Kenyon et al. 2008). As newer commercial HMDs with high resolution stereoscopic viewing, head-tracked motion parallax, wider field of view (FOV), and wide area tracking are developed, it is important to empirically evaluate how their improved fidelity affects users' perceptions of spatial information.

The spatial information perceived by an individual in an IVE directly informs the actions that they can perform within the environment. Actions perceived as performable by the individual in the environment are known as affordances (Gibson 1979). For example, chairs afford sitting on, gaps afford stepping over, and apertures afford passing through. In order for an individual to accurately perceive their affordances, they must perceive the geometric and dynamic characteristics of the environment relative to the geometric and dynamic properties of their own body. In this way, affordance judgments are task-relevant indices of spatial perception as they compel the perception of space by users based on their ability to perform certain actions (Gibson 1979; Geuss et al. 2010). Since the prospective judgment about whether an action can be successfully completed or not relies on size and distance estimations scaled to one's body (Stefanucci and Geuss 2009; Franchak et al. 2012), underestimations in an IVE may adversely affect affordance judgments.

Although there is a large body of previous work that examines size and distance estimations, a comparatively smaller number of studies examine how affordances are perceived in IVEs (Geuss et al. 2010, 2015; Grechkin et al. 2014). An even smaller number of looks at one of the most common affordances are utilized in real life and in IVEs, i.e. passability. Similar to the real world, VR environments involving locomotion require users to pass through hallways, doors, portals, and gaps between obstacles to get to the destination. Successfully manoeuvring through such obstacles requires the perceived affordance of passability to be comparable to that of the real world. In this expansion of our previous work (Bhargava et al. 2018), we further empirically investigate the extent to which body-scaled information that is available in real-world viewing is both available and salient in contemporary IVEs. Specifically, we compare perceptions of passability through a doorway in the real world against a virtual world replica of the same stimuli in an HTC Vive-based virtual environment.

2 Related work

Previous research about spatial perception in virtual environments suggests that size and distance estimates are generally underestimated (Knapp and Loomis 2003; Jones et al. 2008; Grechkin et al. 2010; Napieralski et al. 2011; Stefanucci et al. 2015), although these estimations have been shown to be influenced by other factors (Proffitt et al. 2003; Witt et al. 2004; Lappin et al. 2006; Witt et al. 2007; Balcetis and Dunning 2010; Stefanucci et al. 2011; Siegel and Kelly 2017). For IVEs, the underlying cause of underestimations has frequently been attributed to two sources, the restricted FOV and low fidelity of the simulation, which may cause depth compression (Renner et al. 2013).

Klein et al. (2009) found that participants underestimated distances more when viewing a virtual environment on a large screen as compared to a CAVE. The authors attributed this increased underestimation in the large screen condition to its restricted FOV. Knapp and Loomis (2003) found that FOV did not influence distance estimates; however, distances were estimated in the real world, not a virtual environment. For those studies investigating FOVs in HMDs, it was found that wider FOVs resulted in improved distance estimates (Grechkin et al. 2010; Jones et al. 2011, 2012; Li et al. 2018). In addition, size perception in virtual environments has been found to be underestimated when viewing on large screen displays (Stefanucci et al. 2015), and this underestimation was not found to improve with increased FOV (Geuss et al. 2015).

Most of the research on size and distance estimation in VR has utilized procedures that involve verbal estimation or visually directed actions (Renner et al. 2013). Verbal estimation requires the participant to report their estimates in standardized units (i.e. feet, metres), while visually guided action requires the participant to perform a secondary movement to indicate their estimate (i.e. toss a bean bag to the perceived distance). These methods for estimating distance and size have been shown to be biased by cognitive factors (Knapp and Loomis 2003; Loomis and Philbeck 2008; Pagano and Isenhower 2008; Kuhl et al. 2010). Importantly, verbal estimates are subjective measurements of distance estimates because they rely on the participant's knowledge of standardized units of measure. As such, these distance estimates are more a measure of the participant's experience with standardized units of measure as opposed to their actual perception of distance.

An alternative method to accurately measure size and distance estimates is through affordance perception (Geuss et al. 2010). Affordances are possibilities for action (Gibson 1979), which are determined by the relationship between characteristics of the environment and properties of the organism's action system. Importantly, affordances are scaled to the individual organism, determined by each individual's morphology and physical capabilities. Individuals utilize two sources of intrinsic information when determining their affordances: First, individuals consider body scaling, which is the comparison between the geometric dimensions of the environment and the physical morphology of the body (Ishak et al. 2008). Second, individuals utilize action scaling, in which they consider their dynamic capabilities necessary to complete an action, such as flexibility, strength, or dexterity (Konczak et al. 1992; Cesari et al. 2003; Cesari 2005). Thus, affordance perception can be reconsidered as a perceptual matching task in which participants estimate the size of objects in the environment relative to their own geometric and dynamic properties. This avoids the use of arbitrary units and allows participants to estimate spatial properties of the environment in units of their own body.

For the present experiment, participants completed an affordance perception task to determine whether they could pass through doorways of various widths. (Warren and Whang 1987) showed that individuals compare their shoulder width, the widest frontal dimension, to the width of the gap to perceive passability. When asked to make yes/no judgments as to whether they could pass through doorways of various widths in the real world, participants judged the boundary between passable and impassable door widths to be a ratio of 1.3 times their shoulder width. Additionally, they found that perceptions of aperture passability are a function of the width of the door relative to the individual's static eye height. Geuss et al. (2010) asked participants to make size estimates, affordance judgments, and blind walking distance estimates of an aperture in both the real-world and virtual environments. Participants viewed two poles and used their hands to indicate the gap width between the two poles (size estimate), judged (yes/no) whether they could pass through the two poles (affordance judgment), and blindly walked to the poles (distance estimate). Differences in blind walking distance estimates were found between the real-world and the virtual environments. However, size estimates and affordance judgments did not significantly differ between the real-world and the virtual environments. Since this was a within-subject study, performing the size estimation task first may have biased responses on the affordance task. Thus, an unbiased assessment of affordance perception in IVEs is merited. Nevertheless, these findings suggest that affordance perception tasks may be a more appropriate method to assess the perceptual fidelity (Geuss et al. 2015) of a virtual environment. Moreover, Pointon et al. (2018) explored passability affordance in an augmented environment by replicating the tasks described above and observed a trend similar to Geuss et al. (2010).

While Geuss et al. (2010) used a static affordance perception task (participants stood in one spot for the duration of the task), Fath and Fajen (2011) identified multiple sources of dynamic information that can be utilized when perceiving aperture passability. They exposed participants to a virtual environment in which static eye height-scaled information was unavailable. When walking was initiated, two dynamic sources of information became available: head sway-scaled and stride length-scaled information. Participants utilized these sources of dynamic information to accurately perceive their passability boundary. In each, participants were scaling the size of the opening to intrinsic units of head sway amplitude and stride length. If static eye height-scaled information is insufficient for accurate spatial perception in VEs, the utilization of dynamic information may improve estimates. Importantly, newer VR hardware systems allow for wide area tracking that would allow a user to walk around their environment and produce dynamic sources of information. Task-specific exploration of the environment may also improve affordance perception by means of exposure to the optic flow and motion parallax produced by such movements.

More recently, Creem-Regehr et al. (2015) compared distance estimates using a high- and a low-cost HMD (Oculus Rift) and reported that the distance perception was better overall for the low-cost consumer HMD (Creem-Regehr et al. 2015). In a similar study by Kelly et al. (2017) comparing the HTC Vive to older displays, the authors reported that the use of newer HMDs reduced the underestimation of distances significantly, therefore affording more accurate space perception (Kelly et al. 2017). Buck et al. (2019) compared the action of passing through apertures in a collaborative setting using an HTC Vive (Buck et al. 2019). Although the authors investigated how dyads cross an opening together in the real world and in a collaborative IVE, they reported that gendered social dynamics were not as prevalent in VR as in the real world and participants required wider gaps to cross together in the IVE.

In the present study, we empirically evaluated how intrinsic factors like body scaling translate to a virtual environment, without a self-avatar, by utilizing an affordance perception task similar to (Geuss et al. 2010). We compared perceptions of passability through a sliding doorway aperture in the real world to an accurate replica of the same stimuli in an HTC Vive-based virtual environment. Unlike prior work, participants were permitted to walk towards the aperture if they were uncertain of their ability to pass through the door. This allowed them to utilize dynamic information when making their affordance judgments. The virtual world sliding doorway apparatus and experiment room were carefully created and calibrated to exactly match the size and scale of the real-world counterpart using a conjunction of

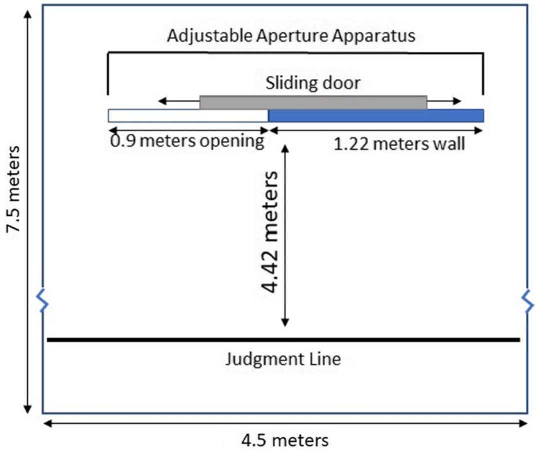

Fig. 1 Experimental setup with details of the adjustable aperture

tracking, scaling, and adjustment techniques described later in the paper.

3 Study design

3.1 Experiment setup

The study utilizes a between-subject design with a real-world (RW) condition and an immersive VR condition. No viewing restrictions were introduced in the real-world condition in order to examine passability judgements in natural setting of the real-world viewing and to maintain ecological validity. The VR condition encompassed viewing that was typical of best existing, popular, commercial VR systems (HTC Vive, Oculus Rift and Touch) and did not have any additional tracking technology or rendering enhancements such as self-avatars. In this manner, we aim to capture a baseline measure of passability perception between typical VR and RW viewing situations, before examining the importance of other intrinsic (self-representations) or external reference information on participants' perceptual judgments. Participants' position in the IVE was marked on the floor by a circle which was updated based on the position of the HMD. The conditions were set up in this manner as we wanted to compare a typical real-life scenario to a typical VR setup that many commercial HMD VR systems provide out of the box. The experiments were conducted in a 7.5 × 4.5 m room (see Fig. 1). A sliding doorway was used for both the conditions. The doorway was adjusted to produce 14 predetermined widths (33 cms to 72 cms in 3 cm increments), 3 times each, in random order for a total of 42 trials. The sliding doorway and a judgment line were positioned on opposite sides of the room 4.42 metres apart. A curtain was hung behind the door to block any background visuals that could be seen through the opening, as they might provide additional perceptual cues. We used a heavy curtain and hung it in such a manner that the sliding door did not come in contact with it at any point and was not deformed due to air flow.

A 3D replica of the physical room and the experiment apparatus matching in size and scale was modelled using Maya for use in the VR condition. Images matching the patterns from the physical space were used to texture the door, curtain, walls, etc., see Fig. 2. The virtual curtain was rendered statically and did not change from trial to trial. The Unity 3D game engine was used to render the simulation at 90 frames per second on a HTC Vive HMD (110° horizontal FOV) utilizing a desktop computer with a dedicated NVIDIA GeForce GTX 1080 graphics card and an Intel i7 processor. The same physical room was used for both conditions, and the virtual environment was mapped exactly onto the physical space.

Although it is possible that the background clutter in the real world may have provided additional depth cues, it occupied a small area of the field of view of the participant and previous research suggests that the size and scale of the environment affect perception (Nguyen et al. 2009). Therefore, we verified the overlap and the visual angle subtended between the real and virtual environments to make sure they produced the same visual effect. The verification of the one-to-one mapping of the virtual environment onto the physical space was a 2-step process involving tactile feedback from

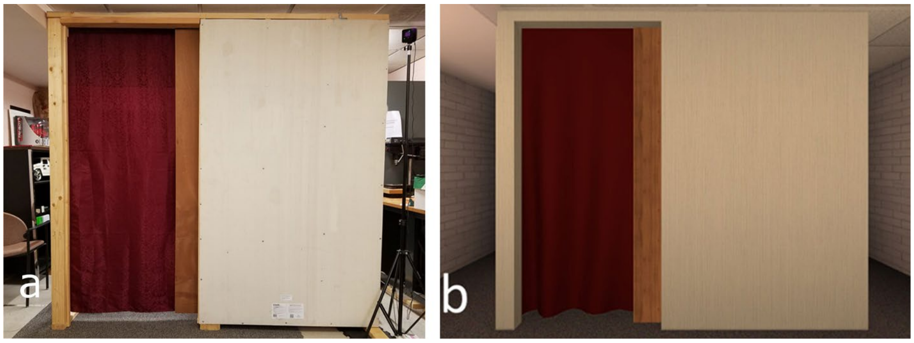

Fig. 2 **a** Real-world widest aperture (72 cms), **b** VR replica of the widest aperture (72 cms)

the HTC Vive controllers, tracker recordings, and the visual angle subtended in the HMD. For the first step, we touched the virtual aperture at multiple locations with the controller and checked for tactile feedback. If a tactile feedback was received, we checked if the location overlapped with the exact location on the real door and verified the tracker logs. In case a tactile feedback was not received or the location was off, an offset was calculated based on the controller's position and the door's position. This offset was applied to the tracking space in unity. The second step involved verifying the visual angle subtended. We visually aligned the Vive controller to an edge of the door in the virtual world first and then took off the HMD to see if the real controller visually aligned with the same edge of the real door. This process was repeated for all horizontal and vertical edges of the door from different viewing distances and aperture widths.

3.2 Participants

A total of 35 participants were recruited from Clemson University, 17 in real world and 18 in VR, for this experiment with 25 females and 10 males. The age ranged from 17 to 33 years with an average of 20.4 years. All participants were checked for normal or corrected to normal vision. The participants were either paid $10 or given course credit.

3.3 Procedure

In both conditions, participants read and signed a consent form and were asked to fill out a small demographic survey. Then, their height and shoulder widths were measured in centimetres. Visual acuity was also measured using a modified Snellen visual acuity test.[1] Interpupillary distance (IPD) and stereo acuity[2] were also measured for each participant in the VR condition. All participants had normal 20/20 visual acuity and were able to perceive stereo normally.

After filling out the surveys and recording the measurements, participants were instructed on how to make judgments and were asked to stand behind the judgment line. They were instructed, for every door width presented, to communicate to the experimenter if they could pass through it without turning their shoulders. They were allowed to walk closer to the door in a straight line if uncertain but were not permitted to walk through it. Walking was allowed to maintain consistency with natural interaction and to provide participants with ample spatial information by incorporating motion parallax and optic flow, especially in the IVE. Since walking through the door was not allowed, they never receive feedback about the accuracy of their judgments. For each trial, we recorded the participant's judgment (yes or no), the door width presented, if they walked closer to the door (0 or 1), and the distance between the door and the participant if they walked. These were recorded using a pen and a paper for the real-world condition and using a keystroke logging script for the VR condition.

The protocol followed was slightly different in the two conditions and is explained below in detail. Participants were allowed to take breaks, especially in the VR condition, as some of them were experiencing VR for the first time.

3.3.1 Real world (RW)

After the participant was instructed on how to make judgments, he/she was asked to close their eyes. The experimenter then adjusted the sliding door to a random width. For every trial, the door was slid back and forth thrice before sliding to the actual width to avoid any bias from the sound of the door sliding. Once the door was at the desired width for that trial, the participant was asked to open their eyes and make a judgment. If the participant was uncertain of their judgment, he/she could walk towards the door until they were certain. If the participant walked during a trial, the distance between his/her feet and the door was recorded. The participant was then instructed to walk back to the line and close their eyes for the next trial. The procedure above was repeated for 42 trials.

3.3.2 Virtual reality (VR)

In the VR condition, before the participants were asked to stand behind the line, their IPD was measured and they were tested for stereo perception. The experimenter then gave participants some information about the HMD, adjusted the IPD to match the participants' measured eye separation, and helped them don the HMD. To familiarize participants with the depth cues present within the IVE, a small acclimation phase was added. The acclimation phase included participants being situated in a virtual room similar to the testing room, but without the virtual apparatus. They were asked to walk up to a virtual cube randomly placed in the room and read out loud a number that was placed on one of its surfaces. They repeated this task 6 times, and the cube was randomly placed at a different location each time with a randomly generated number on it. This forced them to naturally walk with the HMD to the objects and read the information they contained. After the acclimation phase, participants were given the same instructions as in the real-world condition in the testing phase. In the VR condition, instead of having the participant close their eyes, a virtual curtain blocked their view as the aperture's width was adjusted for the next trial. When the participants' view was restored, they had to

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[1] http://www.allaboutvision.com/eye-test/snellen-chart.pdf.

[2] https://www.good-lite.com/cw3/Assets/documents/100050_StereoFlyManual.pdf.

make a judgment about the aperture's passability. The testing phase procedure above was then repeated for 42 trials.

3.4 Research questions and hypotheses

The research questions addressed in this study were as follows:

1. Are perceptions of aperture passability different in the real world and IVEs?
2. To what extent do participants in IVEs require task-specific exploration of the environment in order to perceive their passability?

Our hypotheses in this study were as follows:

H1 Participants in both the real-world and virtual reality conditions will scale their perceptions of passability to their individual shoulder widths
H2 Participants in the real-world condition will produce more accurate judgments than those in the virtual reality condition
H3 Participants in the virtual reality condition will be more uncertain of their judgments and thus walk towards the door more often than participants in the real-world condition
H4 On trials where participants walked, participants in the virtual reality condition will require more task-relevant exploration of the environment (i.e. they will walk farther) than participants in the real world

3.5 Variable transformation

For each trial, a binary *judgment* variable was computed, such that judgments of the door being passable were coded as 1 and judgments of the door being impassable were coded as 0. Second, a binary *movement* variable was created such that trials where participants walked towards the door prior to making their judgment were coded as 1, and trials where participants did not walk towards the door were coded as 0. Third, a binary *accuracy* variable was created to address whether participants correctly judged each door to be passable or impassable. When participants judged a door that was larger than their shoulders to be passable, or a door that was smaller than their shoulders to be impassable, they made a correct judgment (coded 1). When participants judged a door that was larger than their shoulders to be impassable, or a door that was smaller than their shoulders to be passable, they made an incorrect judgment (coded 0). It was necessary to dichotomize this categorical variable that otherwise had four categories due to the unequal distribution of occasions in some of those categories.

For each participant, every presented door width was converted into a *passability ratio* calculated by dividing the door width by the individual participant's shoulder width. Thus, a passability ratio of 1 indicates that the door width and the participant's shoulder width are equal. A passability ratio less than 1 indicates that the door width is smaller than the participant's shoulder width (and should thus be impassable), while a passability ratio greater than 1 indicates that the door width is larger than the participant's shoulder width (and should thus be passable).

Lastly, after viewing raw data scatter plots, a quadratic term was created for the passability ratio variable. A significant quadratic effect would indicate that a quadratic function fits the data better than a traditional linear function.

4 Results

4.1 Hierarchical linear model (HLM)

Since the experiment uses a repeated measure design, there was considerable nesting in the variables. That is, since each participant completed 42 trials, a portion of the variance in their responses can be attributed to a common source—the fact that the *same participant* was responding to each trial. This created multiple levels of variance. In a mixed-model regression, Level 1 (within-participant) variables represent those that change from trial to trial (for this study: passability ratio and trial number). Level 1 variables explain residual variance from the regression line, indicated by the difference between actual values and predicted values for each trial. Level 2 (between-participant) variables represent those that change from participant to participant (for this study, condition). Level 2 variables explain intercept variance, indicated by the difference between the overall regression intercept and the intercepts of each participant's individual regression equation. Level 1 by Level 2 interactions occur when within-participant effects are moderated by between-participant variables. These cross-level interactions explain slope variance, indicated by the difference between the overall regression slope and the slope of each participant's individual regression line.

In order to confirm that there was nesting in the data, the intraclass correlation (ICC) was calculated from the baseline model. The ICC is a ratio of between-subject variance/total variance. Results showed that 42% of the total variance in participant responses resided between participants, and 58% of the total variance resided within participants. This confirms the nestedness of the data and supports the mixed-model approach.

Typical statistical analyses, such as those involving disaggregation or aggregation of data, cannot simultaneously account for multiple levels of variance (i.e. relationships between and across levels) (Bryk and Raudenbush 1992; Hofmann 1997). Hierarchical linear modelling (HLM) is a method that can appropriately identify differences that occur at between-subject levels and within-subject levels (Bryk and Raudenbush 1992; Hofmann 1997; Woltman et al. 2012). In addition, HLM requires fewer assumptions and is more tolerant of missing data and differences in group sizes (Bryk and Raudenbush 1992; Woltman et al. 2012). Therefore, to account for variance at every level, HLM was used for this analysis. For a more detailed explanation of HLM, see Hofmann (1997).

When using HLM, it is important to hold the regression coefficient of the intercept constant across all models. In order to do this, all continuous variables were grand mean centred. Thus, the intercept coefficient of the regression equation represents the predicted outcome when all continuous variables are held at their average.

Additionally, the use of dichotomous dependent variables produced a nonlinear cubic distribution. Since nonlinearity violates an assumption of linear regression, the raw scores were transformed into logit values, which have a linear distribution. By using a binary logistic regression (Peng et al. 2002), the model will predict the linear logit value, which can later be transformed into the odds and probability of an event occurring. Interpretation of main effects will utilize the odds ratio; instead of having an additive effect on the logit, the odds ratio has a multiplicative effect on the odds (i.e. a one-unit increase in the predictor results in the odds being multiplied by the odds ratio).

Effect sizes for each fixed effect will be presented as the change in R2 (proportion of explained variance) comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 can be interpreted as the percentage of variance accounted for by the fixed effect.

4.2 Judgment

To investigate whether virtual reality alters the perception of door passability, a binary logistic regression was run with judgment as the dependent variable. Participants judged each doorway to be either passable or impassable. Table 1 shows results of the model predicting passable judgments.

As expected, the passability ratio (presented door width/shoulder width) significantly predicted judgments and accounted for 75% of the variance in judgments. Participants became more likely to judge a presented door width passable as it increased with respect to their shoulder widths. Notably, participants' passability judgments in the VR condition were not significantly different from the ones in the real-world condition ($F = .48$, $p = .49$). The perceived critical boundary (the smallest ratio judged as passable) was 1.03 for the real-world condition and 1.0 for the virtual reality condition.

Table 1 Full model fixed coefficients and standard errors predicting judgment

Predictors	Coefficients (SE)	sr^2
Fixed effects		
Intercept	3.30 (.81)	–
Passability ratio	28.47 (1.97)***	.75
Condition	.77 (1.12)	–
Passability ratio × condition	−4.42 (4.01)	–

*$p < .05$; **$p < .01$; *** $p < .001$

Table 2 Full model fixed coefficients and standard errors predicting movement

Predictors	Coefficients (SE)	sr^2
Fixed effects		
Intercept	−3.09 (.30)	–
Trial	−.04 (.01)***	.04
Passability ratio	34.83 (5.54)***	.05
Passability ratio squared	−16.95 (2.61)***	.26
Condition	−.31 (.36)	–
Passability ratio squared × condition	−1.30 (.57)*	.02

*$p < .05$; **$p < .01$; ***$p < .001$

4.3 Movement

To further investigate the effect of virtual reality on a participant's perception of affordances, a binary logistic regression was run with movement as the dependent variable. Recall that for each trial, participants were asked to walk towards the door if they were uncertain of their passability judgment. See Table 2 for results of the model predicting when participants walked towards the door prior to making their judgment.

In predicting the likelihood of movement, the main effect of trial showed that participants were less likely to walk towards the door over time. For each additional trial, the odds of walking towards the door were reduced by a multiplicative factor of .96. Again, there was a main effect of the passability ratio. However, upon inspection of the plotted data, a quadratic term was included in the model. The significant effect of passability ratio squared suggests that the relationship between movement and the passability ratio is best explained by a quadratic function rather than a linear one. That is, the probability of walking was highest when the passability ratio was close to 1 and lowest when the passability ratio was very high or very low (see Fig. 3).

Again, there was no main effect of condition on a participant's likelihood to walk towards the door ($F = .77$, $p = .39$). However, condition was a significant moderator of the quadratic ratio term. Figure 3 shows that at high and low values

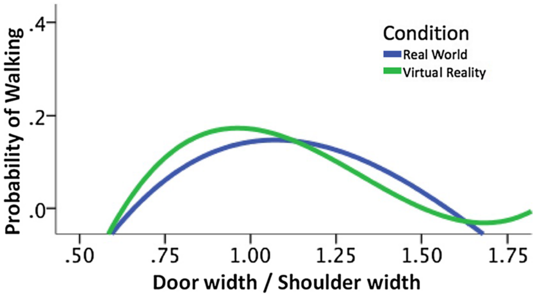

Fig. 3 Interaction of passability ratio by condition predicting the probability of walking towards the door

Table 3 Full model fixed coefficients and standard errors predicting distance

Predictors	Coefficients (SE)	sr^2
Fixed effects		
Intercept	142.54 (19.78)	–
Passability ratio	− 847.71** (312.57)	.06
Passability ratio squared	347.22* (135.99)	.06
Condition	56.33* (27.35)	.10
Passability ratio × condition	101.17 (147.04)	–
Passability ratio squared × condition	− 31.28 (61.08)	–

$*p < .05$; $**p < .01$; $***p < .001$

of the ratio, participants were unlikely to walk for both the VR and real-world conditions. However, participants in VR were more likely to walk towards the door for ratios slightly less than 1, while participants in the real world were more likely to walk towards the door for ratios slightly above 1.

4.4 Distance

Next, we selected only the cases in which participants walked towards the door ($n = 140$ trials), and ran an HLM regression to assess the effects of virtual reality on the distance walked. Recall that for this variable, a small distance from the door indicates that the participant walked farther before making their judgment with certainty, and a large distance from the door indicates that the participants walked a short distance before making their judgment. Table 3 shows results for the model predicting the participant's distance from the door at the time of their judgment.

There was a significant main effect of passability ratio which accounted for 6% of the residual variance in the model. Again, plots of the data suggested a quadratic trend, so the passability ratio squared term was included in the model. This suggested that the distance from the door was smallest when the ratio was close to 1 (see Fig. 4). Additionally, there was a significant main effect of condition, such that participants in the virtual reality condition ($M = 133.67$ cm, SD = 18.25) were closer to the door when they made a judgment as compared to the ones in the real-world condition ($M = 190.01$ cm, SD = 20.42). The effect of condition accounted for 10.3% of the intercept variance in the model.

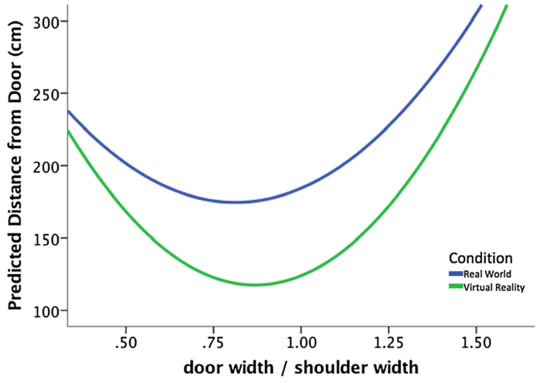

Fig. 4 Predicted distances from the door plotted against the participant's passability ratio, displaying a quadratic effect of passability ratio and a main effect of condition

Table 4 Full model fixed coefficients and standard errors predicting incorrect judgments

Predictors	Coefficients (SE)	sr^2
Fixed effects		
Intercept	− 7.38 (.81)	–
Trial	.01 (.01)	–
Passability ratio	165.99 (17.24)***	.06
Passability ratio squared	− .81.34 (8.43)***	.78
Movement	− 1.16 .27)***	.04
Condition	− .10 (.37)	–
Trial × condition	.03 (.01)*	.01
Passability ratio × condition	− 1.79 (1.78)	–
Passability Ratio × movement	− 58.21 (37.51)	–
Passability ratio squared × condition	− 1.40 (.98)	–
Passability ratio squared × movement	− 1.38 (1.20)	–

$*p < .05$; $**p < .01$; $***p < .001$

4.5 Accuracy

To test whether virtual reality affected participants' accuracy of judgments, a binary logistic regression was run with judgment accuracy as the dependent variable. Table 4 shows results from the model predicting incorrect judgments.

There was a significant main effect for both the linear and quadratic passability ratio terms, accounting for over 78% of the variance in accuracy. Participants were much more likely to make an incorrect judgment when the door width was

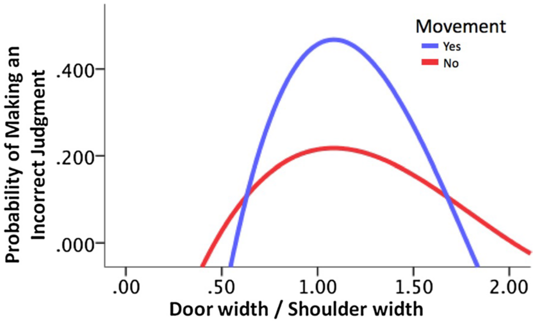

Fig. 5 Predicted probability of making an incorrect judgment plotted against the participant's passability ratio, showing the quadratic effect of passability ratio and the main effect of movement

close to the participant's shoulder width (see Fig. 5). Additionally, the main effect of movement was significant. Participants were more likely to be incorrect when they chose to walk towards the door (probability of incorrect judgment $M = .3$, $\mathrm{SD} = .25$) than when they did not walk towards the door ($M = .09$, $\mathrm{SD} = .16$), $t(151) = -9.53$, $p < .001$. Although condition was not a significant predictor of accuracy, it was a significant moderator of the effect of trial. In the virtual reality condition, there was no improvement in accuracy across trials. But for the real-world condition, accuracy improved over time; every increase in trial number resulted in the odds of an incorrect judgment decreasing by a multiplicative factor of .97.

5 Discussion

In the following section, we will discuss our findings based on the ordinal structure of each trial. Upon presentation of a door width, participants determined if they could make a passability judgment with certainty. (1) If uncertain, participants initiated movement towards the door. (2) On trials in which participants initiated movement, they were instructed to continue walking until they were certain of their passability, and then stop. (3) Once participants stopped moving, they gave a verbal judgment of their ability to pass through the door. (4) Offline, experimenters calculated the accuracy of each judgment by comparing the participant's shoulder width to the presented door width.

5.1 Movement

Overall, the likelihood of walking towards the door—an index of uncertainty in participants' initial static judgment—was equal in both the real world and in VR. This suggests that static information that informs affordance perception in VR adequately replicates the same static information that is available in the real world. Interestingly, this occurred despite the absence of a self-avatar in the VR condition. As mentioned before, perceptions of aperture passability rely largely on geometric perceptual matching. That is, perceiving one's ability to pass through a doorway relies on the relation between one's shoulder width and the width of the opening (Warren 1984; Warren and Whang 1987). Since participants in VR had no virtual shoulders to reference when determining their passability, they could not directly compare virtual shoulder width and virtual door width. Despite that, passability judgments in VR were made with the same certainty as those made in the real world. While virtual shoulder width was not optically available in VR, static eye height information was available and true to the participants' eye height in the real world. This information was likely utilized to determine passability (Warren 1984; Warren and Whang 1987). This result is not supportive of our third hypothesis, but is a positive outcome for contemporary VR technology's ability to replicate real-world sources of information.

When the presented door widths were close to the participant's shoulder width (and thus their critical passability boundary), participants were more likely to be uncertain of their judgment and walk towards the door. As shown in Fig. 3, participants in VR were more likely to walk towards the door when the door was slightly smaller than their shoulder width, while participants in the real world were more likely to walk towards the door for door widths slightly larger than their shoulder width. Participants in the real world walked most often when the door width was 1.2 times their shoulder width. This ratio value closely replicates the perceptual boundary for verbal judgments of passability in the real world found by Warren & Whang (1987). However, the finding that in VR, participants walk towards the door most often when the door is slightly smaller (.9) than their shoulder widths is unexpected. We present two possible explanations. First, perhaps participants in VR are perceiving the door to be larger than it is. In this case, a presented ratio of .9 was perceived as a ratio of 1. We find this unlikely due to the robust body of research indicating size underestimation in IVEs (Stefanucci 2012; Stefanucci et al. 2015; Renner et al. 2013), along with findings from the present study that passability judgments were equivalent in VR and the real world. A second possible explanation is that doorways smaller than one's shoulder width present harmful consequences for misperception compared to doors larger than one's shoulder width. To wrongfully perceive a smaller door as passable would result in possible collision with the door, while there is no consequence for wrongfully perceiving a larger door as impassable. Thus, perhaps participants in VR were more cautious of their judgments in potentially harmful scenarios. Compared to previous VR work that utilized two poles to create an aperture (Geuss 2010; Fath and Fajen 2011), this experiment used a virtual replica of a wooden doorway, which increased both its ecological validity and its potential for harm given a collision. Further research is necessary to investigate the ultimate cause of this finding.

5.2 Distance from door

Although there was no difference between VR and the real world in the likelihood of initiating a walk towards the door, there were differences once they walked. On all walking trials, participants initiated their walk because they were uncertain of their ability to pass through the door. In this instance, the available static information (eye height scaling) was insufficient, and walking exposed the participants to additional sources of dynamic information. These sources include the motion parallax of the door relative to the environment and intrinsic scaling of the door relative to kinematic properties of the participant's self-produced head sway and stride length (Fath and Fajen 2011). Participants in VR walked further before making their judgment than did participants in the real world. Thus, participants in VR required more exposure to sources of dynamic information before gaining certainty in their passability judgment than did those in the real world. This supports our fourth hypothesis and falls in line with past research that suggests continuous visual feedback when walking through an IVE may improve judgments of size and distance by allowing participants to rescale perceived space (Kelly et al. 2013, 2014; Siegel and Kelly 2017). In the case of this experiment, interaction with the IVE improved participants' certainty of passability judgments, and participants in VR required more dynamic exploration of the environment to reach certainty than did participants in the real world.

5.3 Judgment

Despite walking differences between the real-world condition and the virtual reality condition, there were no differences in participants' judgments of perceived passability. It's possible that additional explorations of the optic flow in the VR condition allowed performance to equal that of the real-world condition. As the *passability ratio* increased (i.e. as the width of the opening became wider than the participants' shoulder width), the probability of judging the doorway as passable increased in both the real-world condition and virtual reality condition. This finding suggests that individuals engage in body scaling in both the real world and VR when determining if they can pass through a doorway.

5.4 Accuracy

For trials where participants decided to walk, the likelihood of making an incorrect judgment was higher. That is, participants were less likely to make an accurate affordance perception when they chose to walk towards the door. This was expected, however, because participants walked towards the door on trials that were close to the passability boundary, and thus, they were less certain of their judgments.

Importantly, no significant effect of condition was observed. That is, the likelihood of making an incorrect judgment was similar in the real-world condition and virtual reality condition. This finding does not support our second hypothesis that participants in the real-world condition will produce more accurate judgments than participants in the virtual reality condition. While previous research has thoroughly documented issues of depth compression and subsequent underestimation in virtual environments (Renner et al. 2013), the lack of difference in accuracy between conditions found in the present study suggests that participants in the virtual reality condition did not experience depth compression. As such, it is possible that advancements in newer VR hardware have successfully mitigated the issue of depth compression. More specifically, this may be attributed to the wider FOV in the HTC Vive. The FOV for the HTC Vive is similar to that used by Jones (2012) who found that estimates improved when FOV was wider. Similar findings were also reported by Creem-Regehr et al. (2015) and Kelly et al. (2017) when evaluating distance estimations with newer HMDs.

Additionally, the use of a virtual sliding doorway that both mimicked a real-world scenario and matched the sliding doorway used in the real-world condition may explain the similarity in performance between the real-world and virtual reality conditions. For instance, Interrante et al. (2006) claim that maintaining high fidelity between the real-world and virtual environments (i.e. matching the virtual environment to the real world) reduces issues of depth compression. Thus, our findings are in agreement with those documented by Interrante et al. (2006). Lastly, the similarity in accuracy between the real world and virtual reality is consistent with (Geuss et al. 2015) research, suggesting that affordance perception tasks are more appropriate measures of size and distance, as they result in similar performance between the real world and VR.

Further analysis revealed that as the trials progressed, the likelihood of making an incorrect judgment decreased in the real-world condition. For the virtual reality condition, however, the likelihood of making an incorrect judgment remained similar as the trials progressed. Though the overall likelihood of making an incorrect judgment was similar for both conditions, the significant interaction between condition and trial suggests there was a learning effect in the real-world condition, but not for the virtual reality condition. Previous research has found that individuals' gaits in virtual environments are less stable than in the real world (Janeh et al. 2017). More specifically, individuals have been shown to walk slower, take shorter steps, and take more steps in virtual environments (Janeh et al. 2017). It is possible that our participants in the virtual reality condition experienced reduced gait stability, which inhibited a learning effect.

6 Conclusion and future work

The present study sought to revisit spatial perception in IVEs to determine if the advancements of newer VR hardware (wider FOV, high resolution fidelity, and wide area tracking) reduce or eliminate underestimation. Participants were presented with various door widths in VR or the real world and judged whether they could pass through the door. If uncertain of their ability to pass through the door, participants were instructed to walk towards the door (but not through it) until they were certain of their response. This movement towards the door provided task-specific exploration of the environment that allowed them to pick up additional sources of intrinsically scaled dynamic information. This allowed us to compare affordance perception (as a surrogate for size estimation), accuracy, certainty, and reliance on dynamic information between VR and the real world.

Overall, participants in VR were no different from participants in the real world in terms of aperture passability judgments, accuracy of judgments, and certainty of judgments. This suggests that overall, the information necessary to determine one's affordances (size and distance of the aperture relative to one's own geometric and dynamic properties) is available and salient in VR. However, in order to achieve a comparable level of judgment accuracy to that of the real world, VR participants required additional exposure to dynamic sources of information by walking closer to the door. Further, even though participants never received explicit or experiential feedback about the accuracy of their judgments, participants in the real world improved in accuracy over time, while participants in VR did not. Ultimately, improvements in resolution, graphic fidelity, and FOV offered by newer VR hardware allow users to accurately perceive their action capabilities.

Some key takeaways for developers of complex virtual reality applications with environments involving locomotion are provided here. When developing virtual replicas of a real-world environment, it is beneficial to use devices that provide a wider FOV and the ability to physically navigate towards the aperture. It may be additionally beneficial to create a highly realistic environment so that performance on tasks in both the real-world and virtual environments is comparable. For VR applications, games, and other immersive training scenarios that require users to manoeuvre through obstacles, it may be useful to provide more optic flow via inclusion of arbitrary objects and increased travelable distance. This will be especially useful in scenarios where improvements in affordance judgments are desired, such as walking rehabilitation, athletic training for hurdle races, and combat training for stealth missions involving manoeuvring through pits.

A limitation of our work is that the technique used to calibrate the room relies on the underlying HTC Vive libraries to render the tracked objects and graphics accurately within the tracking boundary. Though this technique provided satisfactory results for our study, further testing should be conducted to ensure that it is robust and without fault. Another limitation is that we did not investigate the effects of embodied viewing afforded by self-avatars. As previously mentioned, participants in the virtual reality condition engaged in more task-relevant exploration of the environment, suggesting that the static information available to them was insufficient. Addition of a self-avatar will increase the static information available and may influence individuals' perceptions of passability. Therefore, in future research, we aim to investigate the effects of self-avatars on passability judgments in IVEs. We plan to explore how passability judgments are affected when the dimensions of the self-avatar like height, width, etc. are modified in an IVE. Finally, we plan to explore the effects of visual fidelity of the environment and aperture, as well as the HMD's FOV on passability judgments in an IVE.

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