# A curved-walking illusion: Effects of locomotion and presence on cybersickness

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**Abstract**

Treadmill Virtual Reality (VR) has a potential application in rehabilitation, but its adoption is hampered by commonly experienced cybersickness symptoms, and an incomplete understanding of the factors that influence relevant (learning) outcomes. Previous studies have suggested that with active locomotion (self-motion) cybersickness symptoms may be limited. Restriction of the field-of-view – e.g., via the use of video vignettes – may also reduce symptoms. Whether a VR intervention is effective may also depend on the subjective presence within the virtual environment as experienced by the user. It remains unclear, however, what the optimal conditions to prevent cybersickness and to induce high levels of presence are. In the current study we investigated the effect of self-motion (walking vs. standing) and field of view as manipulated by vignetting (on vs. off) on cybersickness, presence and memory. Thirty-two healthy adults walked two predetermined routes in two different virtual environments: During one trial participants walked on the treadmill, determining direction with a handlebar (walking condition; using a Virtuwalk-treadmill), and during the other trial (order counterbalanced between participants), participants used the handlebar while standing still to move around the virtual environment (standing condition). In a between-subjects design, half the participants experienced the virtual environments with a vignette that restricted the field-of-view, while vignetting was not applied for the other half of the participants. In contrast to expectations, cybersickness was not influenced by walking or vignetting. However, results showed a positive effect of self-motion on presence, with higher presence in the walking than no-walking condition. In addition, presence and motivation were positively correlated. Vignetting did not affect presence, but it reduced landmark memory, potentially by partially obstructing the field-of-view. The current study's findings thus suggest that self-motion is positively associated with presence, and in turn higher presence is associated with higher motivation. Vignetting did not reduce cybersickness and may not be recommended when memory of the environment is of relevance.

**Introduction**

Treadmills are often used in physical therapy with patients with gait disorders (Gaßner et al., 2022), as they encourage a healthy gait by providing the patient with a temporal and spatial framework (Bishnoi et al., 2021; Polese et al., 2013), in contrast with unsupported walking, where patients may feel the need to employ maladaptive compensatory mechanisms to walk (Bishnoi et al., 2021). Treadmills also provide better safety, the possibility of regulating the patient's weight, and control over the walking speed (Moseley et al., 2013). Such advantages over conventional walking make treadmills a great fit for physical rehabilitation where they are shown to improve gait and stride length in gait-disordered patients (Bishnoi et al., 2021).

Gait disorders negatively impact individuals' autonomy and pose a heightened risk for injury (Pirker & Katzenschlager, 2017). Estimates about their prevalence differ and range from roughly a third of those 65 years and older (Jia et al., 2019; Mahlknecht et al., 2013)], to 80% in those above 80 years old (Pirker & Katzenschlager, 2017). They also frequently occur as a comorbidity to neurological conditions, affecting most people with Parkinson's Disease (Kim et al., 2018) and around 50-80% of people with Multiple Sclerosis (Cameron & Nilsagard, 2018). Meanwhile, walking problems can gravely affect the quality of life and lead to serious injury (Larocca, 2011; Marino et al., 2019; Mahlknecht et al., 2013; Smith et al., 2021; Cameron & Wagner, 2011). The large number of people affected by gait disorders, the fact that their absolute number will increase in upcoming decades due to demographic changes (Pirker & Katzenschlager, 2017) and their negative impact on quality of life (Larocca, 2011; Marino et al., 2019; Mahlknecht et al., 2013) highlight the need for effective therapeutic interventions.

Treatment options for gait disorders may include pharmacological interventions, physical therapy or assistive devices (Pirker & Katzenschlager, 2017). Exercise programs can be the primary choice of treatment if there is no adequate pharmacological therapy (Winter et al., 2021; Pirker & Katzenschlager, 2017). Moreover, physical therapy is cost-effective, can be combined with cognitive interventions, reduces falls by increasing muscle strength and balance, and leads to the recruitment of alternative neural pathways to substitute for loss of functioning (Smith et al., 2021). Physical therapy could thus improve walking in the elderly (Marshall, 2012), patients with MS (Plummer et al., 2023; Cameron & Wagner, 2011), patients with Parkinson's disease (Granziera et al., 2021; Smith et al., 2021; Morris et al., 2010), or individuals with chronic back pain (Vanti et al., 2019).

An innovative technology that holds promise for effective use in physical therapy is Virtual Reality (VR). VR is an umbrella term for a diverse range of technologies that all enable the creation of artificial environments with which the user may interact in real-time (Fuchs et al., 2011). Virtual environments (VEs) can be presented via head-mounted displays (HMD), which enable users to move around freely. Since walking distances are limited in the spaces that VR is used in, treadmills are used to expand the movement in virtual space while minimizing the use of real-world space. Treadmill-based VR shows advantages over conventional walking such as by increasing motivation in gait-disordered and healthy populations (Winter et al., 2021; Mouatt et al., 2019). Using treadmill-based VR also has added benefits for walking speed in chronic stroke patients (Rodrigues-Baroni et al., 2014; Kim & Kaneko, 2023), stride length (Hao et al., 2022) and exercise satisfaction (Ahmad et al., 2024).

However, the mass-adaptability of VR is hampered by a side effect known as cybersickness or visually induced motion sickness (Teixeira et al., 2020; Nilsson et al., 2018) which includes symptoms of nausea, dizziness, and headaches (Saredakis et al., 2020; Ng et al., 2020). A prominent explanation for cybersickness is sensory conflict theory (Oh & Son, 2022; Ng et al., 2020), which posits that it originates in a mismatch of the incoming sensory information with the prediction of this information constructed by the internal model of the Central Nervous System based on prior experiences (Nürnberger et al., 2021). Estimates of the prevalence of cybersickness differ greatly from 20-80% (Kim et al., 2021; Oh & Son, 2022), to 60% of users (Garrido et al., 2022) due to the extreme variety of VR systems and virtual environments available today (Biswas et al., 2024) and inter-individual differences in susceptibility (Tian et al., 2022). Generally, however, cybersickness remains an issue in most systems (Oh & Son, 2022; Biswas et al., 2024; Kim et al., 2021).

It has been suggested that increased self-motion in VR interactions may reduce cybersickness symptoms, as compared to controller-based navigation through the virtual environment (Chance et al., 1998; Sousa et al., 2022; Lee et al., 2017) but only if the real-world user movement and the perceived movement in the virtual environment match closely (Ng et al., 2020; Lee et al., 2017). There is scarce evidence that walking on a treadmill was found to decrease cybersickness (Lee et al., 2017) but that omni-directional treadmills increase cybersickness compared to uni-directional treadmills (Bashir et al., 2023). Evidence on the effects of treadmill-based VR on cybersickness compared to stationary VR is rare and needs to be expanded upon.

Another source for cybersickness may be the visual stream of the environment passing by on the peripherals of the HMD during movement (Wu & Rosenberg, 2022), referred to as optical flow or vection. To block vection from sight, vignettes are used which are blackened or blurred bands sitting like a frame on the visual field (Lin et al., 2002; Lin et al., 2020; Budhiraja et al., 2017; Oh & Son, 2022). Lin et al. (2002) found a significant reduction of cybersickness for vignettes reducing the field of view (FoV) to 100° and 60° but not to for a smaller vignette reducing the FoV to 140°. Similarly, Oh & Son (2022) found no nausea-diminishing effects of FoV-reductions to 90° or 60° but for an FoV reduction to 30°. Adaptive vignettes which blurred the edges of the VR display only during times of increased movement and vection occurrence were found to significantly reduce cybersickness too (Budhiraja et al., 2017; Wu & Rosenberg, 2022). Such effects of vignettes are not always found (Norouzi et al., 2018) which highlights the need for further research particularly in active walking setups, such as treadmill-based VR, where the increased movement during exercise may amplify vection.

Besides a possible application in physical therapy, the use of VR also has applicable value to improve the ecological validity of existing neuropsychological testing procedures for memory, which are usually pen and pencil tests (Pieri et al., 2023). Innovative VR tests for memory already exist (Picard et al., 2017; Kim et al., 2023; Pieri et al., 2023) but they do not always correlate with traditional neuropsychological measures for the same concepts (Borghetti et al., 2023). This shows that an apparent lack of knowledge on how memory works in VR and identifies a need for further investigation into memory in VR.

One factor that may impact memory processes in VR is the amount of self-motion of its users. The idea of embodied cognition suggests that motor systems may impact cognition (Madan & Singhal, 2012). One causal mechanism for such findings may be the memory specificity principle (Tulving & Thompson, 1973), which stipulates that memories are encoded with contextual information that can be used as cues to access them. Increased self-motion may supply additional proprioceptive and tactile cues during encoding, which may later be used to retrieve memories. This is supported by evidence of a positive association between self-motion and memory of virtual environments (Ruddle et al., 2011; Plancher et al., 2013; Friedrich et al., 2021; Rädle et al., 2013). Studies also suggest that walking on an omni-directional treadmill may improve one’s cognitive map in virtual environments (Ruddle et al., 2011) and that self-motion is associated with improved spatial navigation in virtual environments (Friedrich et al., 2021; Rädle et al., 2013). However, beneficial effects of self-motion for cognition are not always found (Bampouni et al., 2024), possibly because the increased motor activity may place demands on the cognitive resources required for other processes (Jebara et al., 2014; Plancher et al., 2013). Walking can be automatic (Clark, 2015) but might be more cognitively demanding on a treadmill while wearing an HMD (Patelaki et al., 2023). Conflicting findings in this debate warrant the collection of further evidence.

There is currently little evidence of any impact of FoV restrictions on memory in VR. Some have suggested that a reduced FoV decreases cybersickness in VR (Wu & Rosenberg, 2022; Lin et al., 2002), this would leave the user more able to concentrate on their surroundings. However, it is likely that by reducing the visual information available to someone navigating a virtual environment, the user has fewer chances to perceive their surroundings and to form memories of it. In line with this, restricting the FoV in VR was found to impair spatial learning (Ni et al., 2006; Polys et al., 2007). However, an association of the use of vignettes with memory is not always confirmed, especially when measures of memory other than navigational ability are used (Adhanom et al., 2021), which leaves room for further investigation of memory in VR.

Finally, a fundamental factor and perhaps the most crucial concept in VR (Steuer, 1992) is the subjective perception of being in a virtual environment, commonly referred to as presence (Schuemie et al., 2001; Wilkinson et al., 2021). Presence has been found to positively correlate with VR-related nausea (Lin et al., 2002), but negative associations are also common (Weech et al., 2019; Salimi & Ferguson-Pell, 2021). Another positive association of presence is with memory of virtual environments (Makowski et al., 2017; Lin et al., 2002; Cadet & Chainay, 2020; Cadet et al., 2021). Furthermore, there is evidence of a positive association between active walking and presence in Virtual Reality (Lee et al., 2017) and a negative effect of FoV reductions on presence (Teixeira & Palmisano, 2021; Lin et al., 2002). Due to its numerous influential associations, presence may confound or mediate relationships of other VR-variables. This suggests that analysis of interrelationships of VR-variables who are known to be associated with presence should account for its effects.

The current study investigated the effects of self-motion and vignetting on healthy VR users' presence, cybersickness and memory. We hypothesized, that locomotion would increase presence scores while the vignette would diminish them. Furthermore, it was predicted that walking during a VR experience would increase cybersickness and that a vignette would reduce it. Finally, it was assumed that walking would benefit the VR user's memory of a virtual environment, and using a vignette would impair it. To test these hypotheses, we used a treadmill-VR setup with an HMD and let healthy adults walk through virtual environments with landmarks. The factor of self-motion was assessed by assigning each participant to two VR trials, during which they either stood or walked while completing a VR task. We assessed the factor of vignette between participants, by showing half of the sample a reduced FoV by implementing a blackened band around the edges of the VR display ("vignette on") and the other half of the sample a full FoV ("vignette off"). The two vignetting conditions are counterbalanced with the order of the self-motion conditions in the sample.

# Methods

## Participants

For this study, 37 healthy adults were recruited via SONA systems of Leiden University. Inclusion criteria were age between 18-65 years old, and no history of psychiatric or neurological disorders, and no past or current intake of psychotropic medication such as anti-depressants or anxiolytics. Of the 37 subjects invited to participate in the study, five participants were unable to finish the experiment due to technical issues: For two participants we had to quit the experiment prematurely due hardware issues (related to the handlebar) and for three participants we were unable to finish the experiment due to a software issue (unexpected 90° rotations in the virtual environment). The final sample consists of 32 adults ages 18 to 49 (M = 23.53, SD = 7.56; 23 female, 8 male, 1 non-binary; 30 right-handed, 2 left-handed). The majority of participants indicated they rarely play video games (78.1%).

For their participation, subjects were either compensated with 2 SONA credits or financial compensation of 7.50€. Each participant gave informed consent prior to participation. The study was approved by the Psychology Ethics Committee at the Faculty of Social and Behavioral Science at Leiden University, the Netherlands (approval code: 2023-09-24-J.Schomaker-V1-4988).

## Apparatus, Measures and Stimuli

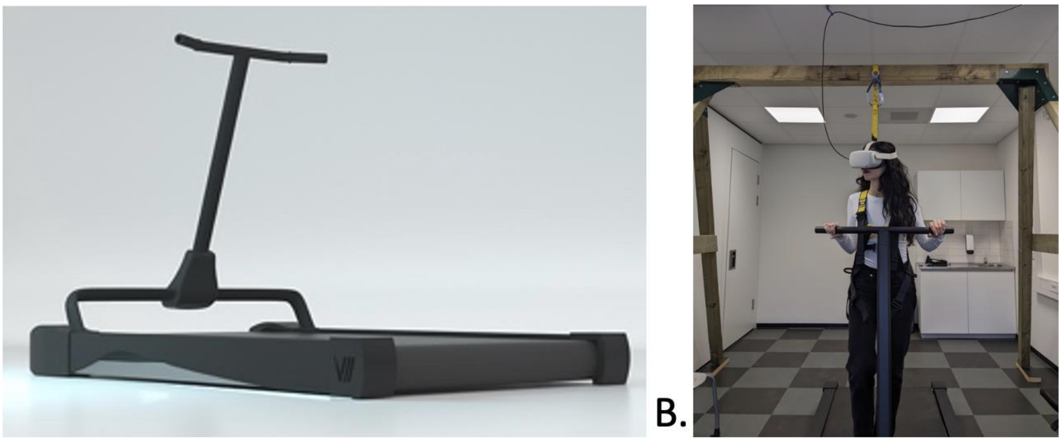
### *Apparatus*

The VirtuWalk treadmill – as depicted in Figure 1 - was used in this study. This treadmill is connected via its steel frame to a handlebar that registers forward push and activates the belt of the treadmill to move forward. The pressure applied on the handlebar is measured by 50kg load cells and translated via Unity commands into an activation signal for the treadmill's belt to start running. The belt of the treadmill runs with a maximum speed of 2m/s to which it accelerates in 10 seconds. To control the speed and torque of the treadmill's motor, an AC inverter drive is connected to the treadmill and stored in a small white closet which also contains other electrical components and a button to conveniently shut the belt of the treadmill on or off.

The VirtuWalk treadmill's handlebar also acts as an input device for a virtual environment (VE), in which users can move forward by pushing the handlebar forward, with a harder push resulting in a higher moving speed in the VE. Stopping was achieved by pulling the handlebar towards the user. Additionally, differential input on the handlebar's two sides was translated into a turn in the VE. For instance, if the handlebar was pushed harder on its left side, this resulted in a right-way turn in the virtual environment and vice versa.

To induce the immersive VR experience, we used a head-mounted display, the Oculus Meta Quest 2, connected via a USB cable to a computer operating on Microsoft 11 on which a virtual environment was run in Unity. To avoid participants entangling themselves in the cable, we guided it with hooks on the ceiling towards the computer. On the computer, all tests and questionnaires were presented to participants. As participants could not see their real surroundings while walking on the treadmill due to wearing the HMD, falling was a risk. To ensure our study's subjects' safety, we built a 2.5 m x 2.5 m large wooden frame above the treadmill (typically used for a swing set). Participants wore a body harness commonly used in industrial climbing, which was connected via a steel buckle to a short belt tied to the wooden frame to prevent serious falls (see Figure 1B).

The landmark recognition tests was programmed using OpenSesame (Mathot et al., 2012). The questionnaires (SSQ, IPQ and demographics) were presented using Qualtrics.



A. B.

**Figure 1. VirtuWalk-treadmill and experimental setup.** A) The VirtuWalk-treadmill used in the current study. This unidirectional treadmill can be used together with Virtual Reality. By exerting pressure to the handlebar, the participant could determine the walking speed and direction (both in the walking and standing condition). Harder pressure resulted in faster speed. Higher pressure on the left handle resulted in the agent moving to the right, while higher pressure on the right handle resulted in the agent walking to the left. In the walking condition, the treadmill would move in sync with the forward handlebar movement, requiring the participant to walk with the respective pace. In the standing condition the handlebar would be used in the same fashion, but the treadmill was turned off. B) The experimental set-up depicting a participant holding the handlebar, wearing a Virtual Reality headset and a safety harness attached to a wooden frame. Walking on this treadmill and using the handlebar to make turns causes a curved-walking illusion that was employed in the current experiment.

***Stimuli***

Two virtual environments were created in Unity 2022.2.2f1 (Unity Technologies, 2022). The two environments consisted of natural, forest environments with either a spring-theme and green color pattern or an autumn-theme and yellow/red color pattern. This thematic design was chosen to make the environments clearly distinguishable. A walking path spread out through both environments with atypical landmarks such as an oversized gun or large globe placed alongside the path. The landmarks differed between environments and were all taken from the Unity Asset Store. Both environments were matched in their number of turns, landmarks and total length. In the landmark recognition test, all landmarks from the VE's and lures that were not present in the VR experiences were presented in front of a grey background (for an overview of all landmarks and lures, see Appendix A).

For half the participants, a vignette was used. This vignette was created with the standard setting of the vignette function in the post-processing package 2.0 in Unity (Mode: Classic; Color: Black; Center, X: 0.5, Y: 0.5; Intensity: 0.45; Smoothness: 0.2; Roundness: 1). Figure 3 displays the differences between vignette conditions.

**Figure 2**. *Screenshot of one of the two virtual environments.* The same virtual environment under the vignetting off (left) and vignetting on (right) conditions.

***Measures***

Motivation was measured ("At this moment, I feel motivated", from 1 = fully disagree to 7 = fully agree) together with arousal ("What is your arousal state currently, from from 1=completely calm to 7=very agitated) after each of the two VR experiences. Mean motivation and mean arousal scores were computed as the average over the two trials.

To assess participants' cybersickness, we used the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993). The SSQ includes 4-point Likert scale questions, with none=0; slight=1; moderate=2; severe=3. We chose the cybersickness scale as a means of comparison.

To measure VR users' presence, we used the English version of the Igroup Presence Questionnaire (IPQ; Schubert et al., 2001). This questionnaire contains 14 items answered on a 7-point Likert scale with 1 as the minimal value. An average presence score was calculated based on the average of the 14 responses for each participant. Motivation and arousal were assessed by subjective ratings on 7-Point Likert scales. For the landmark memory test, corrected hit rate (CHR) was calculated as hits (proportion of correct "sure old"-responses for old items) minus the false alarms (proportion of incorrect "old"-responses for lures).

***Procedure***

Upon arrival, participants provided informed consent and were explained how to use the treadmill, handlebar and HMD. Prior to starting the actual experiment, participants put on the security harness and got hooked into the larger wooden frame positioned above the treadmill, which is seen above the treadmill. Then, each participant could practice walking on the treadmill for around 15 seconds without the HMD to get used to the reactivity of the handlebar and the movement of the belt. Subsequently, the HMD was put on and participants stood still on the treadmill waiting for the experiment leader to start up the task and read scripted verbal instructions. Participants were instructed on how to use the handlebar to move forward and to make turns and they were asked to move along the path following arrows indicating the route. The experiment consisted of two trials, during which participants navigated through two different VEs. In each VE there was a single path with slight bends, but no turns or intersections. Participants were instructed to walk until the end of the virtual path appearing in front of them, to stay close to its middle and pay attention to their surroundings. Additionally, they were told whether the treadmill belt would be moving (i.e. walking condition) or not (i.e. standing condition) while they were moving through the VE. Completing one virtual path took roughly 4-7 minutes (total time spent in the two VEs: 8-14 minutes). After reaching the path's end, subjects took off the HMD and were unhooked from the security frame. Then they sat in front of the lab computer and performed the landmark recognition test. During this test, the twenty landmarks from the previous VE were shown, interspersed with fifteen new landmarks (i.e., lures). Participants indicated for each landmark whether it was old (press "X") or new (press "N"; also see Schomaker et al., 2022). In case they indicated the landmark was "old", they were asked to also indicate whether they were sure that they had seen it ("sure old"; "press X"), had probably seen it ("probably old"; press "N"), or whether they guessed ("guess"; press "M"). This task was completed in 2-3 minutes. Only after the first trail, they filled in a demographics questionnaire, including questions regarding age in years, handedness (right; left; ambidextrous), experience with video games (I play: never; rarely; regularly; daily), and gender identity (male; female; non-binary; other; prefer not to say). Afterward they rated their current levels of motivation and arousal. Finally, they were filled in the IPQ (Schubert et al., 2001) and SSQ (Kennedy et al., 1993). Filling in the questionnaires took about 4-7 minutes. The total experimental procedure took about 45 minutes. Afterwards participants were debriefed about the purpose of the study (verbally and/or on paper depending on the participant's preference. When participants could not finish the task due to technological issues, they still received compensation and were offered a debriefing.

### *Statistical Analysis*

For all analyses in this study, IBM SPSS Statistics 27.0.0.0 was used. Corrected hit rate (i.e., hits minus false alarms on the landmark test), cybersickness (total SSQ score), and presence (total IPQ score) were calculated for each participant.

As primary analyses, we ran separate mixed ANOVAs for the outcome variables cybersickness, memory and presence, with the within-subjects factor self-motion (walking vs. standing) and vignetting (on; off) as a between-subjects factor. Missing data for the cybersickness data was handled by deleting cases listwise because total SSQ scores could not be calculated.

Correlations were calculated between presence (IPQ), cybersickness (SSQ), motivation, arousal, and landmark memory. For these analyses we used the mean scores over trial 1 and 2. As we expected that presence and cybersickness would potentially change over the duration of the experiment, we also computed correlations between IPQ and SSQ scores for trial 1 and 2 separately.

An a priori power analysis suggested a sample size of 48 to attain power of 80% to detect a medium sized effect in a mixed measure ANOVA with a 2x2 design (G*Power2). We set the alpha-threshold to .05 for all analyses.

## Results

### Correlational analyses

We first computed correlations between presence (IPQ), cybersickness (SSQ), landmark memory (CHR), motivation and arousal. Table 1 shows descriptive behavioral data (mean and standard deviation) and contains all correlations between the variables.

**Table 1**

*Means, SDs and correlations for presence, cybersickness, memory and motivation scores*

| Variable | M | SD | IPQ | SSQ | CHR | Arousal | Motivation |
|---|---|---|---|---|---|---|---|
| IPQ | 3.0 | 0.5 | - | | | | |
| SSQ | 20.4 | 21.7 | -.167 | - | | | |
| CHR | 0.6 | 0.2 | .033 | -.064 | - | | |
| Arousal | 3.3 | 1.4 | .220 | .072 | .138 | - | |
| Motivation | 5.2 | 1.2 | .464** | -.305 | .256 | .162 | - |

*Note*. This table contains Pearson Correlations (for $n$ = 32) between presence (IPQ Total), cybersickness (SSQ Total), landmark memory (CHR), arousal (7-point Likert), and motivation (7-point Likert). ** $p < .01$

A medium-sized positive correlation between presence and motivation was found, with higher presence associated with higher motivation, $r(32) = .46$, $p < .01$. No other correlations between presence, nausea, landmark memory, arousal and motivation were found (all $p$s > .101).

As we expected cybersickness and presence to be associated we also calculated correlations between the IPQ and SSQ scores per trial (1; 2) separately. For trial 1, we observed a statistical trend effect, $r(30) = -.315$, $p = .089$, with higher presence associated with lower cybersickness scores. For trial 2, no correlation was observed, $r(30) = -.057$, $p$ = .756.

## Presence

In addition, the presence data was subjected to a mixed ANOVA with the factors self-motion (walking vs. standing) and vignetting (on vs. off). Figure 3 depicts the boxplots and individual datapoints for the IPQ presence ratings in the walking and standing conditions when vignetting was on and off. A positive main effect of self-motion on presence ratings was observed, $F(1,30) = 13.45$, $p$ = < .001, $\eta^2 = .310$, with higher presence ratings in the walking condition (M = 3.13; SD = 0.49) than in the standing condition (M = 2.81; SD = 0.54). Post-Hoc evaluation revealed that this analysis was high-powered to find this effect at 94,61% (G*Power 2). Vignetting did not affect the IPQ scores, $F(1,30) = 0.03$, $p = .871$, and no interaction effect was observed, $F(1,30) = 0.57$, $p = .457$.

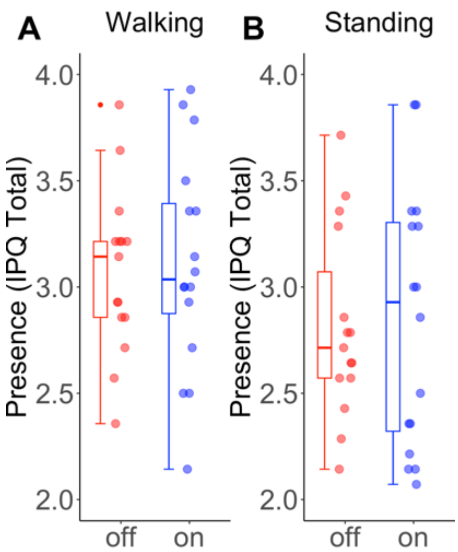



**Figure 3**. *Presence ratings in the walking and vignetting conditions*. Boxplots of presence ratings for the combinations of the two factors self-motion (walking vs. standing) and vignette (vignette on vs. vignette off). Center line = median; box limits = upper and lower quartiles, whiskers = minimum and maximum within 1.5x interquartile range, points = individual data.

## Motivation and arousal

Motivation and arousal were investigated with the same mixed ANOVA as presence. No main effect of walking condition was found for motivation, $F(1,30) = .054$, $p = .818$, $\eta^2 = .002$, nor an interaction between walking and vignetting, $F(1,30) = 0.859$, $p = .362$, $\eta^2 = .028$. However, vignetting negatively impacted motivation, with lower motivation ratings in the *vignetting on*

(M = 4.65; SD = 1.50) than in the *vignetting off* condition (M = 5.79, SD = 1.02), $F(1,30) = 9.39$, $p = .005$, $\eta^2 = .238$. For arousal no effect of walking condition was found, $F(1,30) = 2.32$, $p = .138$, $\eta^2 = .072$, and no main effect of vignetting were observed, $F(1,30) = .061$, $p = .806$, $\eta^2 = .002$. Nor did walking and vignetting interact, $F(1,30) = 0.37$, $p = .547$, $\eta^2 = .012$.

**Landmark memory**

We subjected the landmark memory data (CHR) to the same mixed ANOVA as the cybersickness scores. Figure 4 shows the boxplots and individual data points for memory performance on the landmark task for the walking and standing conditions with and without vignetting.

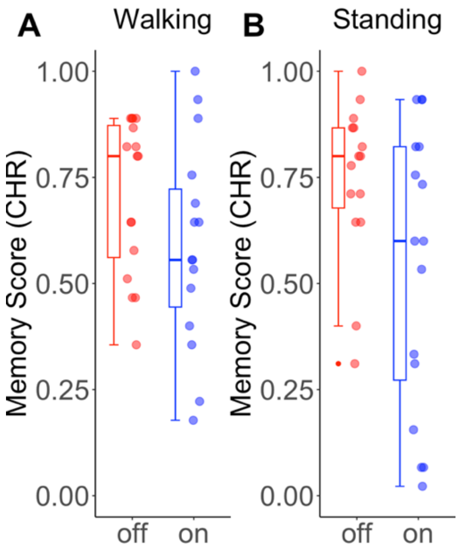



**Figure 4**. *Landmark memory in the walking and vignetting conditions*. Boxplots of memory performance. Corrected hit rate (CHR) was calculated as follows: Proportion “Sure old” hits minus proportion “old” false alarms.

for each possible combination of the factors self-motion (walking vs. standing) and vignette (on vs. off). Center line = median; box limits = upper and lower quartiles, whiskers = minimum and maximum within 1.5x interquartile range, points = individual data.

Vignetting negative affected landmark memory, $F(1,30) = 4.92$, $p = .034$, $\eta^2 = .141$, with a lowe CHR in the *vignetting on* (M = 0.54; SD = 0.24) than in the *vignetting off* condition (M = 0.70; SD = 0.17). No main effect of self-motion, $F(1,30) = 0.01$, $p = .943$. Nor was an interaction effect observed, $F(1,30) = 0.02$, $p = .895$.

**Cybersickness**

See Figure 5 for boxplots and individual data points of the cybersickness scores (SSQ) in the walking and standing conditions with vignetting on and off. As the assumptions of equality of covariances and of homogeneity of variances were violated, we used a square root transformation on the data, which resolved these issues. We ran the mixed ANOVA on the transformed cybersickness data, with the factor self-motion (walking vs. standing) as a within-subjects factor, and vignetting (on; off) as a between-subjects factor. No main effect of self-motion, $F(1,28) = 2.69$, $p = .112$ or vignetting, $F(1,28) = 3.16$, $p = .087$, was found. Nor did self-motion and vignetting interact, $F(1,28) = 0.274$, $p = .605$.

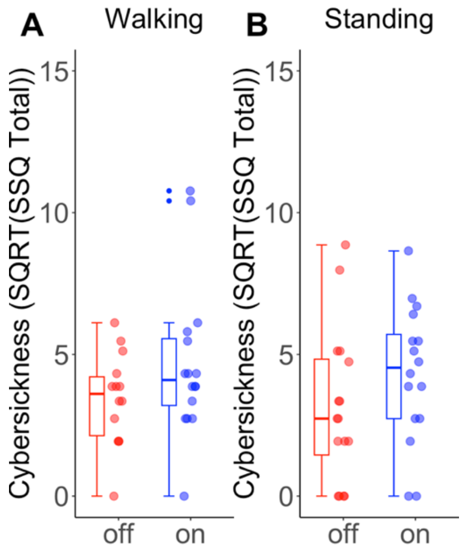



**Figure 5** *Cybersickness ratings in the walking and vignetting conditions*. Boxplots of transformed cybersickness ratings (square root of SSQ Total) for the different combinations of the two factors, self-motion (walking/ standing), and vignette (on/ off). Center line = median; box limits = upper and lower quartiles, whiskers = minimum and maximum within 1.5x interquartile range, points = individual data.

## Discussion

This study aimed to examine the effects of self-motion and vignetting on presence, cybersickness and memory in healthy adults interacting with a virtual environment. Participants followed a predetermined route in two virtual environments (VE 1 and VE 2; order counterbalanced between participants), in a standing and walking condition (order also counterbalanced between participants). After each round, participants filled in a presence and a cybersickness questionnaire and indicated their motivation and arousal. In addition, their memory of the environment was tested after each round with old/new judgments in a landmark memory test in which landmarks and lures were presented.

Interestingly, presence was positively correlated with motivation, suggesting that individuals who felt more present, also felt more motivated. A link between motivation and presence is in line with previous findings (Liu et al., 2019). Presence could have an effect on motivation by increasing enjoyment of the virtual experience increasing intrinsic motivation (Meldrum et al., 2015), as motivation and enjoyment are closely linked (Raedeke, 2007). Understanding how to impact motivation can be key to therapy success (Tang et al., 2022; Lemmens et al., 2023), but both motivation and presence are self-report measures - not under experimental control - it therefore remains unclear what the causality of this relationship is. It is possible that higher motivation led to higher subjective presence but it could also be that feeling present made participants more motivated. Future studies could aim to manipulate presence experimentally – e.g., through the use of different types of immersive systems associated either with lower or higher presence. Typically, more immersive systems lead to higher presence. Alternatively, to further determine the nature of the relationship between motivation and presence, motivation could be experimentally manipulated, via task instructions (emphasizing one task over another), or by introducing reward motivation.

Not only were presence and motivation associated, presence was also higher in the walking compared to the standing condition. Our findings confirm a presence-enhancing effect of using a walking interaction with a VR system compared to a standing interaction, thereby confirming prior evidence (Lee et al., 2017; Usoh et al., 1999; Slater et al., 1995). This effect was likely driven by an increased overlap of proprioceptive and sensory information compared to the standing condition (Steuer et al., 1992; Slater et al., 1995). Additionally, moving one's legs rather than using only upper body movement in the interaction with the VR system (Lee et al., 2017), and tactile cues on the feet during the walking motion on the treadmill belt may have contributed to increased presence (Cooper et al., 2016).

In contrast, presence was not affected by vignetting. This conflicts with previous findings (Lin et al., 2002; Oh & Son, 2022). Presence-reducing effects of vignettes may only appear if they cross a perceptual threshold (Lin et al., 2002; Oh & Son, 2022), which may not have been reached by the vignette in our study. Since vignettes that reduce VR-related nausea often simultaneously inhibit presence (Lin et al., 2002), the lack of effect of the vignette on cybersickness in this study further supports the theory that our vignette was simply too weak to elicit effects on the outcome variables. Our findings are in line with another study that reported no association between FoV restriction in VR and presence ratings (Lin et al., 2020).

Vignetting negatively impacted motivation and memory performance, with participants recognizing fewer landmarks when a vignette was present rather than absent. This finding is in line with previous findings that restricting the FoV in VR impairs spatial learning by restricting the necessary information available to the user (Ni et al., 2006; Polys et al., 2007). Our finding, however, contrasts with the findings of Adhanom et al. (2021), who found that vignetting did not reduce memory of VR users exploring a naturalistic virtual environment. Two key differences may explain the discrepancy in findings. First, Adhanom et al. (2021) used an adaptive vignette only appearing during angular head movement, so that their participants had a full view of the environment while stationary, whereas our participants were presented with a constant, non-adaptive vignette. Second, participants in the Adhanom et al. (2021) study moved around freely at 360 degrees without a predetermined route, allowing them to inspect the environment freely. In our study, subjects were restricted to forward movement on a path with landmarks placed on its side, which gave participants less room for the visual inspection of the landmarks covered by our vignette. Alternatively, it is possible that the motivation reducing effect of vignetting underlies the negative memory effect, but this explanation cannot be addressed with the current data, as motivation was a self-report measure.

Landmark memory was comparable in the walking and standing conditions, while previous work has suggested a positive link between memory and self-motion (Plancher et al., 2013; Jebara et al., 2014; Brooks, 1999; Friedrich et al., 2021; Rädle et al., 2013). One explanation for this discrepancy may be that the memory-enhancing effect of increased motion may only occur if the movement is guided by the user's decisions in contrast to a more passive condition, i.e., the effect of self-motion on memory may be the result of volition (Plancher et al., 2013; Jebara et al., 2014; Brooks, 1999). In our study, volition was similar in the walking and standing conditions, as movements were self-initiated, but also restricted to the same extent in both conditions. In line with our findings, another study did not observe effects of self-motion on memory in VR, possibly due to different operationalizations of low and high self-motion (e.g., walking freely using locomotion or a joystick, versus watching someone else's movements, or being anchored in front of a stationary screen; e.g., Plancher et al., 2013; Bampouni et al., 2024). Another difference between our studies and previous ones is that usually memory is tested for spatial- or navigation-related aspects (Friedrich et al., 2021; Rädle et al., 2013), while we tested memory for isolated landmarks, outside of their spatial environment.

In contrast with previous studies, we did not observe a link between cybersickness and landmark memory (Stanney et al., 2002; Kim et al., 2005), possibly due to the symptoms being mild in our sample (Bos et al., 2005). A reason for this may be that we tested a relatively young population, and it is possible that cybersickness symptoms would be more common in other populations (Kim et al., 2021; Garrido et al., 2022). The effect of cybersickness on memory thus needs further investigation, to address this potential unwanted side-effect of cybersickness.

In turn, walking condition did not influence cybersickness. While this is in line with some previous work (e.g., Sousa et al., 2022), however, several other studies have observed a negative link between self-motion and cybersickness, with self-motion associated with fewer cybersickness symptoms (Lee et al., 2017; Ng et al., 2020; Chance et al., 1998). Such findings have been explained in terms of an alignment between real and virtual motion that reduces sensory mismatch and increases immersion (Lee et al., 2017; Ng et al., 2020; Chance et al., 1998). One explanation for the discrepant findings may be that the operationalization of self-motion varies between studies, ranging from normal walking in a room (Chance et al., 1998), or walking in place (Lee et al., 2017), to turning in synchrony with a virtual rollercoaster experience (Ng et al., 2020). In our study we used a treadmill in which acceleration of 2m/s could be induced, which makes the experience distinctly different from self-initiated, natural walking. In our set-up both the walking and standing condition could thus have resulted in a sensory mismatch between virtual, perceived and real motion, potentially obscuring differences in cybersickness between the two conditions. Furthermore, the walking and standing conditions were quite similar in terms of self-motion, as also in the standing condition, participants could determine heading direction and speed via use of the handlebar. Future studies aimed at investigating the role of self-motion on cybersickness could consider using conditions that differ more in terms of self-initiated motion, e.g., including an additional passive exposure condition may help tease apart the role of self-initiated movement and walking. Another potential limitation is that walking condition is a within-subjects factor, and potentially effects of cybersickness could have built up over the two trials (Zielasko, Rehling, Clement, Domes, 2024). However, we counterbalanced the order of the walking conditions (walking-standing; standing-walking) across participants, such that potential order effects would be canceled out. Another potential limitation is that walking condition was a within-subjects factor, and potentially effects of cybersickness could have built up over the two trials (Zielasko, Rehling, Clement, Domes, 2024). However, we counterbalanced the order of the walking conditions (walking-standing; standing-walking) across participants, such that potential order effects would be canceled out.

In our experiment, we did not observe a correlation between presence and cybersickness across the two trials. However, for the first trial we observed a statistical trend effect in line with previous work, suggesting that higher presence is associated with less cybersickness symptoms (Cooper et al., 2016; Salimi & Ferguson-Pell, 2021; Weech et al., 2019). Previous studies suggested that this link could be explained by higher presence being associated with more attention towards the virtual experience rather than towards cybersickness symptoms (Cooper et al., 2016; Salimi & Ferguson-Pell, 2021; Weech et al., 2019). In contrast, some others have suggested that vection (illusory self-motion) in VR is associated positively with higher presence and cybersickness (Keshavarz et al., 2015). The precise link between cybersickness and presence thus remains unclear (Weech et al., 2019).

We found no effect of vignetting on cybersickness. This finding is inconsistent with some previous studies that observed such a link (Lin et al., 2002; Budhiraja et al., 2017; Oh & Son, 2022). One key difference between these studies and ours, however, is the restrictive effects of the vignettes used. Lin et al. (2002) found reduced total SSQ scores for those presented with a FoV restricted to 100° and to 60° but not for the reduction to 140°. Even more extreme in the study of Oh & Son (2022), only a reduction to 30° was sufficient to reduce SSQ scores. Our vignetting condition reduced the FoV by less than half (equivalent to 90°), showing that it is weaker than most nausea-reducing vignettes in other investigations (Lin et al. 2002; Oh & Son 2022). Another distinguishing feature is based on the finding that vignettes seem to be more effective in severe cases of cybersickness (Budhiraja et al., 2017). Those who did find nausea-decreasing effects of vignettes sometimes designed their studies to be nausea-provocative by either involving 4 Hz oscillations (Lin et al., 2002) or fast and sudden movements (Budhiraja et al., 2017). We experienced low overall cybersickness in our study as reflected by cybersickness scores around half the size of another investigation (Budhiraja et al., 2017). Low levels of cybersickness in our study could potentially be explained by the low mean age of our sample, as young populations are less susceptible to cybersickness (Oh & Son, 2022), and short VR exposures (<15 minutes), which are linked to lower levels of nausea (Da Silva Manrinho et al., 2022). These findings suggest that the efficacy of vignettes depend on the strength of cybersickness symptoms. Future research could aim to compare conditions that induce varying or higher levels of cybersickness to begin with (e.g., using longer tasks, as cybersickness symptoms tend to build up; Zielasko, Rehling, Clement, Domes, 2024).

## Conclusion

We found that walking promoted presence, and presence and motivation were positively associated. This finding is particularly relevant in the context of physical rehabilitation, where immersive and engaging interventions can help motivate individuals to exercise. Future studies should address the causality of the correlation between presence and motivation, and the applicability of these findings in clinical populations to further assess the technology's potential in therapeutic settings should be addressed. Additionally, our results indicate that vignettes may not reduce cybersickness and could negatively impact memory and motivation in virtual environments, suggesting that the use of vignettes is not recommended when learning and memory are relevant. Determining the optimal conditions to promote presence and to reduce cybersickness are adamant for the adoption of treadmill-VR. Our study provides the first indication that treadmill-VR is a promising, low-cost technology that enhances presence without increasing cybersickness.

## Competing interests

The authors declare there are no competing interests.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## Author contribution

Immanuel Stoltenhoff: Conceptualization, Methodology, Data Curation, Formal Analysis, Software Development, Validation, and Writing – Review & Editing, Project Administration, Writing – Original Draft Preparation, Review & Editing.
Ineke van der Ham: Conceptualization and Review & Editing.
Anne Cuperus: Conceptualization and Review & Editing.
Judith Schomaker: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft Preparation, Review & Editing, Supervision and Visualization.

All authors have read and approved the final manuscript.

## Data availability statement

Pseudonymized data will be made available after publication on DataVerseNL and on the Open Science Framework. This includes data from the questionnaires (e.g., IPQ and SSQ), landmark memory results per participant and condition.

## Research involving humans and/or animals

This study involved adult, healthy human participants.

## Informed consent

Non-ambiguous informed consent was obtained from all participants before participation. The study was evaluated and approved by the local ethics committee, the Psychology Research Committee, at the Faculty of Social and Behavioural Sciences at Leiden University, the Netherlands.


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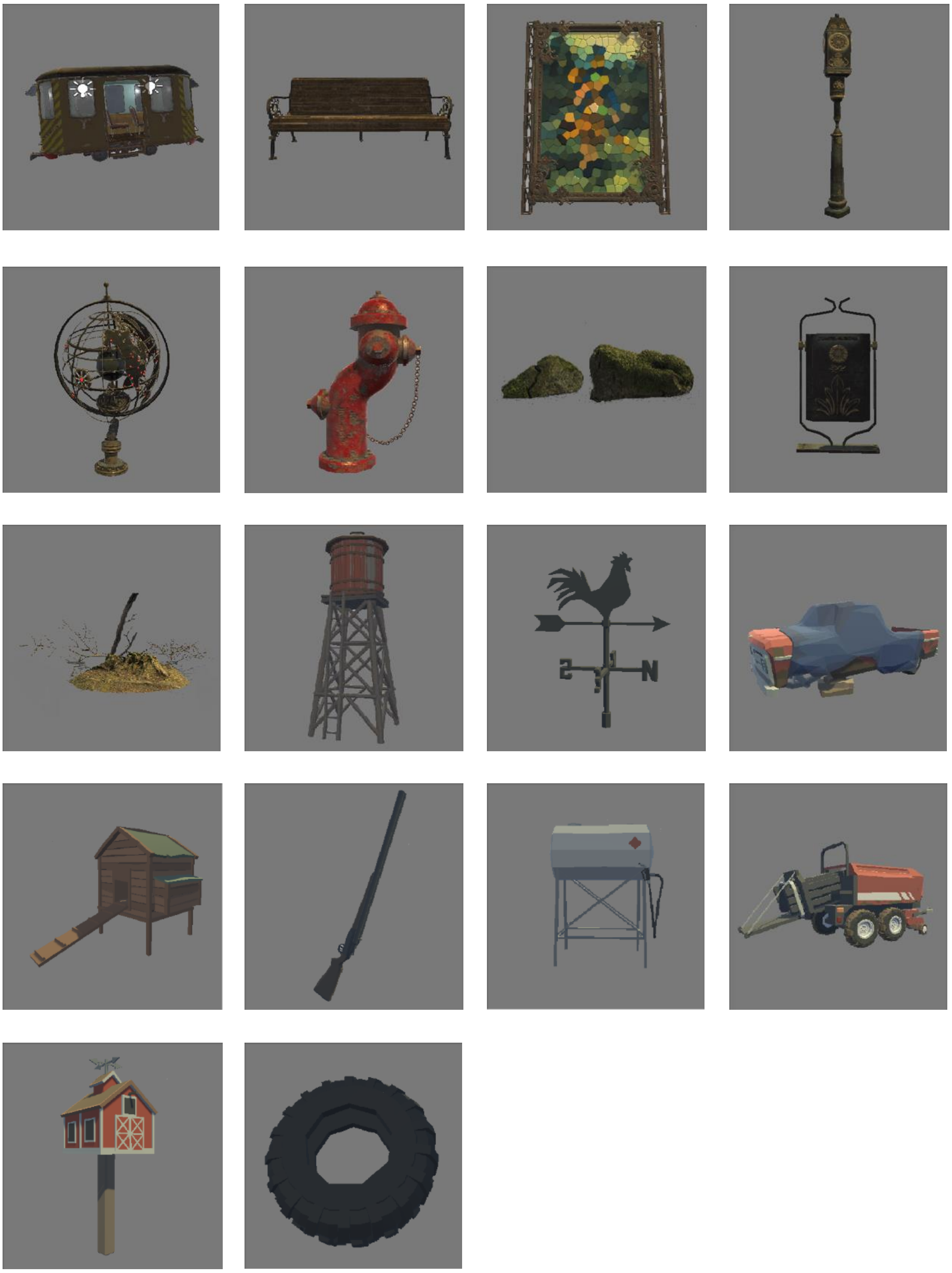
## Appendix A

**Figure A1**

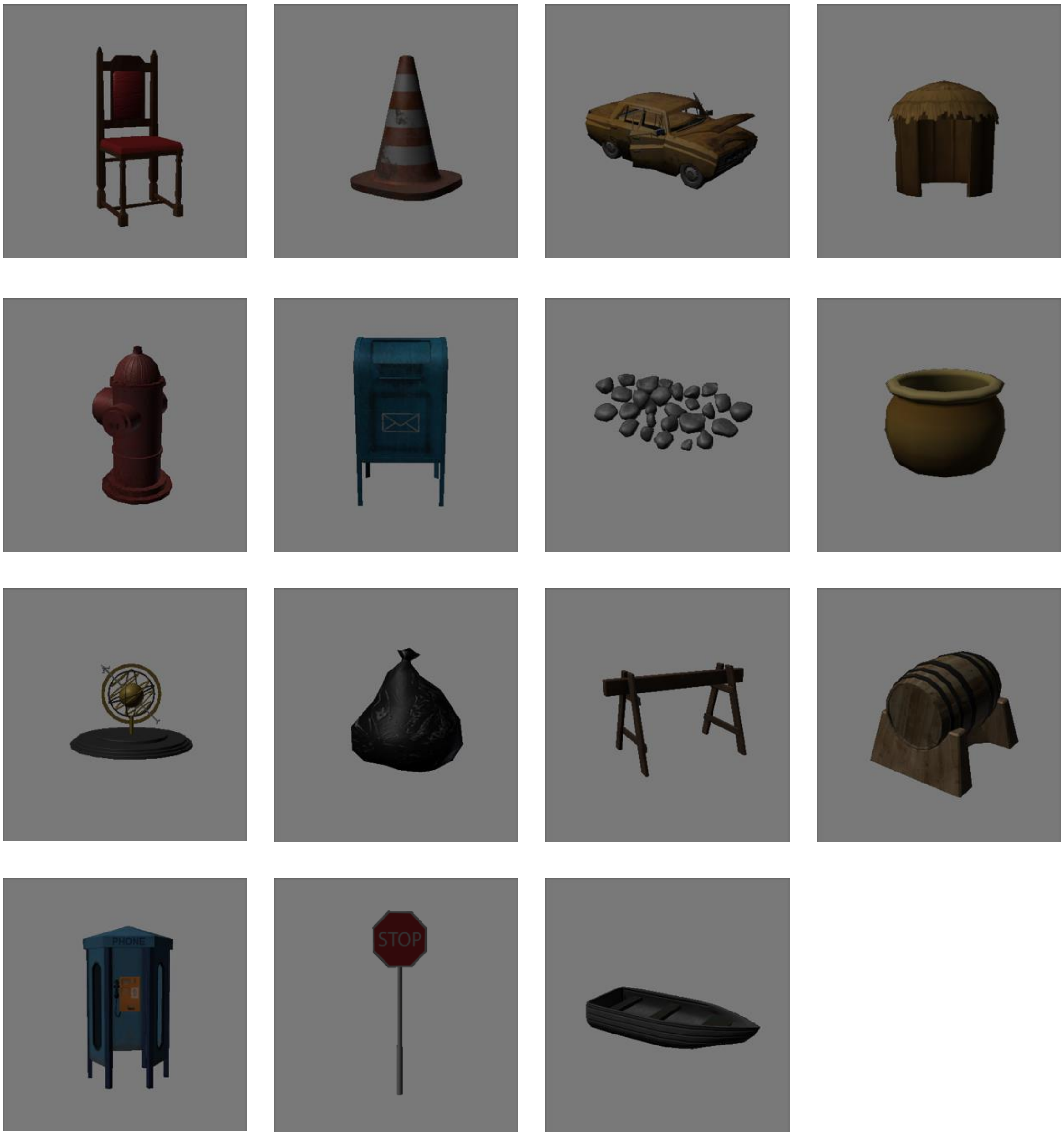
*Virtual Landmarks*



*Note*. These are all landmarks used in the two virtual environments of the experiment. These landmarks were positioned next to the walking path in the virtual environments and used in the landmark recognition test. Landmarks are presented here as they were seen in the test, on a grey background.

**Figure A2**

*Lures for the Landmark Recognition Test*




*Note*. These images display the lures used in the landmark recognition test administered to participants after each time they underwent a VR experience. Lures are depicted as they were seen in the questionnaire on a grey background.