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Walking experience in real and virtual environments: A comparative study

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ABSTRACT

Virtual reality (VR) offers new opportunities to promote active behaviors by enhancing engagement and allowing controlled modifications of urban environments. This study investigates whether virtual environments (VEs) can evoke affective responses comparable with real environments (REs), both psychologically and physiologically, by using an immersive VE combined with a walking simulator that replicates walking motion. Forty-nine healthy adults, Luxembourg residents or cross-border commuters, aged 18–65, including students, university staff, and the general public, walked two contrasting street segments, walking-friendly and car-friendly, in both RE and VE in a crossover design. Affective responses were assessed through questions on aesthetics, safety, enjoyment, comfort, relaxation, momentary stress, and real-time physiological data collected using E4 wristband.

Significant differences emerged between the RE and VE across all affective measurements, except for nonspecific skin conductance responses, with the RE consistently eliciting more positive affective responses. Nevertheless, similar affective trends were observed in both the RE and VE across the two segments. Moreover, environmental characteristics significantly influenced affective responses in both the RE and VE, with the walking-friendly segment yielding more positive affective ratings than the car-friendly one. The interactions between environment type (RE vs. VE) and segment type (car-friendly vs. walking-friendly) were not significant for most measurements, indicating that the effect of environment type on affective responses remained consistent across segments. These findings emphasize that VEs can mimic the overall patterns of affective responses observed in REs. This research highlights VR's potential in planning healthier cities, offering insights into its benefits and limitations for future research.

1. Introduction

Everyday environments, including built, natural, and social ones, significantly influence people's walking behavior and their affective responses to these environments (Birenboim, 2018; Koo et al., 2022). Identifying the environmental determinants of walking is a crucial prerequisite for developing effective interventions to promote active behaviors and lifestyles. Studies have investigated the effects of environmental attributes on walking, using various methodologies such as observational studies (e.g., questionnaires, interviews, tracking technologies such as GPS (Johansson et al., 2016)), and experimental studies (e.g., presenting still images (Birenboim, Dijst, Ettema, et al., 2019; Van Cauwenberg et al., 2016), videos (Kim & Lee, 2022), and immersive and non-immersive virtual environments (Birenboim et al., 2021; Li et al., 2022; Oselinsky et al., 2023)). While observational methods provide valuable insights into real-life behavior, experimental approaches allow for the controlled manipulation of specific environmental attributes, enabling causal inferences (Birenboim, Dijst, Ettema, et al., 2019; Ghanbari et al., 2024).

Among experimental research methods, immersive virtual environments (IVEs) — particularly those using head-mounted displays (HMDs) — are gaining importance due to their ability to expose participants to highly-controlled environments that are difficult to achieve in real-life experiments (Ghanbari et al., 2024; Oselinsky et al., 2023). They allow for the systematic evaluation of alternative urban design configurations (Joseph et al., 2020) and the recording of behavioral responses to these environments (Grübel, 2023), without the substantial monetary and time investments required to modify the real environment (Oselinsky et al., 2023). Additionally, IVEs provide near-complete sensory immersion ("embodied experience") within a safe, convenient, and

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realistic representation of potentially risky or difficult to manipulate in real-life experiments (Baran et al., 2018; Bhagavathula et al., 2018; Birenboim, Dijst, Ettema, et al., 2019; Ghanbari et al., 2024; Lee & Kim, 2021; Nazemi et al., 2021). HMDs, in particular, enhance this sense of realism by creating a strong sense of presence (Presti et al., 2022) — a perceptual and psychological state of deep involvement in a VE (Lombard & Ditton, 1997).

Previous research shows that IVEs can generate realistic affective and behavioral responses, enhance spatial perception, and evoke neurophysiological reactions similar to those in real environments (REs) (Llinares et al., 2023; Presti et al., 2022; Rivu et al., 2021). Despite the promising benefits of IVEs, evidence concerning the representativeness of IVEs compared with REs in outdoor environments, particularly regarding walking behavior, remains very limited. Most studies comparing REs and VEs have been conducted in indoor environments (Gao et al., 2025; Kalantari et al., 2021, 2024; Kuliga et al., 2015; Llinares et al., 2023; Pastel et al., 2022; Pizzi et al., 2019; Rivu et al., 2021; Xia et al., 2021), which limits the applicability of their findings to outdoor walking experiences. Among the few studies to explore outdoor environments, the majority have relied on a static VR setup, in which participants remain passive with no movement (Bhagavathula et al., 2018; Petukhov et al., 2024). These approaches fail to capture the dynamic and embodied nature of real-life walking experiences. Furthermore, although a handful of studies have demonstrated validity in provoking equivalent affective responses in REs and VEs (Llinares et al., 2023; Rivu et al., 2021), these were conducted indoors and using a static VR setup. Thus, there is a significant need for experimental research that compares virtual and real environments in outdoor environments using motion-based VR experiences, such as using locomotion devices (i.e., walking simulators) (Calogiuri et al., 2018) or in controlled lab-based spaces (Berton et al., 2020). To understand the full spectrum of walking behavior, it is crucial to address this gap by utilizing more ecologically valid VR setups that integrate movement to represent real-life walking experiences.

To date, few studies have assessed walking experiences using complete motion-based VR setups combining a headset, walking simulator, and IVE. Boletsis and Cedergren (2019) compared three motion-based VR methods: walking-in-place, controller/joystick, and teleportation. They found that walking-in-place yielded the greatest immersion and enjoyment, though it was also associated with increased fatigue and cybersickness, probably due to the fear of colliding with physical objects (Boletsis & Cedergren, 2019). Although the authors did not use an omni-directional treadmill, their results imply that physical movement enhances immersion and a sense of presence (Birenboim et al., 2021; Boletsis & Cedergren, 2019). Kreimeier et al. (2020) and Hooks et al. (2020) evaluated early omni-directional treadmills (Virtuix Omni and first-generation Cyberith Virtualizer) and found them to be more intuitive, safer, and more realistic than walking-in-place, though more physically demanding (Kreimeier et al., 2020). Users preferred the Omni for its safety and the Virtualizer for its intuitiveness (Kreimeier et al., 2020). Hooks et al. (2020) further assessed the usability and user acceptance of these two models. The bowl-based treadmill (Omni) was preferred over the flat-based one (Virtualizer) by users, based on overall preference, recommendation, and usefulness criteria (Hooks et al., 2020). The next generation of Cyberith (Virtualizer Elite 2) was assessed in two recent studies. Chakraborty et al. (2024) found participants tended to overestimate distances and showed diminished path integration performance compared with real-life walking (indoors). However, the difference in fidelity between natural and virtual walking was smaller than found in a previous study by Kang et al., 2023 using the Omni (Chakraborty et al., 2024; Kang et al., 2023). Homami et al. (2025) compared walk-in-place (using Kat VR mini), sliding (using Virtualizer Elite 2), and natural walking in a VR maze (indoors). They found that the Virtualizer Elite 2 offered the best balance between immersion and effort, while natural walking was fastest (Homami et al., 2025). All of these studies, whether using walk-in-place or natural walking, have been conducted indoors in labs. To the best of our knowledge, only one study (Calogiuri et al., 2018) has compared motion-based VR with real-life walking outdoors. However, that study used a pre-recorded 360-degree video played at a fixed pace, which may not have aligned with each participant's natural walking speed. By contrast, our study combined an omnidirectional treadmill with a computer-generated environment, allowing participants to control their walking pace and actively explore the VE, offering greater ecological validity.

Another pitfall is that among the above-mentioned studies comparing real and virtual environments, most have used only subjective (self-reported) (Bhagavathula et al., 2018; Kuliga et al., 2015; Petukhov et al., 2024; Pizzi et al., 2019; Rivu et al., 2021) or objective (physiological) affective measurements (Berton et al., 2020; Kalantari et al., 2021). Among the very few studies to simultaneously combine subjective and objective measurements of psychological and physiological affective responses to the environment (Calogiuri et al., 2018; Gao et al., 2025; Kalantari et al., 2024; Llinares et al., 2023; Xia et al., 2021), only one examined an outdoor environment using a motion-based VR setup (Calogiuri et al., 2018). This is particularly important, since subjective and objective affective measurements are interrelated but distinct, as each provides a unique perspective into how the environment influences behavior (Gaertner et al., 2023; Gardhouse & Anderson, 2013). Therefore, their integration is essential to achieve a comprehensive understanding of an individual's walking behaviors, perceptions, and affective responses (Gao et al., 2025; Ghanbari et al., 2024; Shoval et al., 2018). This highlights the need for further research to explore the effectiveness of VR in replicating real-life walking experiences, and its potential as a robust tool for leveraging both subjective and objective affective measurements to study human–environment interactions.

The current study aims to address these lacunas by comparing walking experiences in real and virtual environments as integrated, cohesive systems, using a walking simulator to replicate dynamic motion. Both the RE and VE setups included two contrasting street segments, hereafter referred to as the walking-friendly segment and the car-friendly segment. The study further measured psychological and physiological affective responses to the environment to evaluate the validity of IVEs in eliciting these responses, similar to those observed in REs. Through bridging these gaps, this study contributes to the growing body of empirical evidence concerning the application of motion-based VR in studying human–environment interactions and their potential implications for policy interventions.

Specifically, the study explores two hypotheses:

H1. Virtual environments (VEs) will produce similar affective responses (subjective and objective measurements) to those elicited by real environments (REs).

H2. Walking-friendly and car-friendly environments will elicit similar affective responses (subjective and objective measurements) across two environment types (RE vs. VE).

To test these hypotheses, an experimental design incorporating immersive VR was employed to compare affective responses in two contrasting urban segments, combining psychological and physiological measurements.

2. Methods

2.1. Environmental characteristics

The walking-friendly segment comprised a pedestrian zone featuring vegetation and buildings, while the car-friendly segment was a sidewalk along a trafficked four-way street with a green side strip. The total walking distance across both segments was approximately 350 m. The VE mimicked these two contrasting street segments.

To enhance realism, environmental sounds as well as the presence of pedestrians were simulated within the VE. Traffic and pedestrian intensity levels were adjusted to reflect the actual conditions of each street segment, based on peak hours and typical university student flow patterns. Fig. 1 presents a map of the case study, along with examples of the RE and VE and their respective segments.

2.2. Participant recruitment

The study was conducted at the Luxembourg Institute of Socio-Economic Research (LISER) and in its surroundings in Belval, Luxembourg. Data collection took place in April and May 2023 during daylight, from 9:30 to 17:30, under consistent weather conditions throughout the study period (M = 14.6 °C, SD = 5.03 °C), mainly on sunny or partly cloudy days. In total, 49 eligible participants were recruited to take part in the experiment. Eligibility criteria to participate were: a) ages between 18 and 65, b) fluent in English, c) Luxembourg residents or cross-border commuters, d) having moderate to excellent visual acuity, and e) having no motor or physical injuries. Pregnant women and people of over 120 kg body weight were excluded from the study due to walking simulator limitations.

The participants were mainly students and staff members from the University of Luxembourg and LISER. Each participant provided written informed consent before participating in the experiment, in accordance with ethical guidelines approved by the LISER Ethical Committee (reference number: LISER REC/2023/112.SURREAL/1). The participants' time and efforts were compensated with a 20 euro voucher.

2.3. Study design and procedures

Information about the experiment along with an online eligibility questionnaire was disseminated through posters and flyers distributed across the university's buildings, as well as via mailing lists managed by LISER and the university. Eligible participants were invited to attend their scheduled appointments individually at LISER's VR lab. All participants were sent a reminder the day before the experiment.

On arrival at the VR lab at the appointed times, the researcher explained the aims, experimental procedure, and potential risks (including cybersickness), after which the participants were asked to sign the informed consent form.

The pre-experiment stage started with participants wearing the Empatica 4 (E4) wristband on their non-dominant wrist and activating the sensor. Following this, they completed a short questionnaire on their perceived quality of life using the WHO Quality of Life-Brief questionnaire (WHOQOL) (The Whoqol Group, 1998) on a laptop, while seated. Participants were then randomly assigned to two experimental groups in a crossover design, experiencing both conditions (the RE and VE), to eliminate order effects. One group started with a walk in the RE, followed by a walk in the VE, while the other group started with a walk in the VE, followed by the RE. After each condition (RE or VE), participants immediately reported their affective responses in two segments. They also had a 5-min rest period in between conditions while seated.

In the RE, participants were accompanied by a researcher on a short walk, lasting approximately 3 min, from the lab to the starting point of the walking path. This initial walk served to mirror the habituation phase in the VE and to ensure participants were not directly exposed to the middle section of the path beforehand. At the starting point, Researcher 1 initiated the timing of the participant's walk and followed them at a distance of approximately 10 m to replicate the VE condition, in which participants walked alone. Researcher 1 recorded the time the participant reached the midpoint of the path — at the end of segment 1 (walking-friendly segment) — where they turned right to begin segment 2 (car-friendly segment). Researcher 2 was positioned at the end of segment 2 to hand over the affective responses questionnaire and to record the time at which the participant completed the walk.

In the VE, participants were first introduced to the experimental setup, including the HMD and the walking simulator. To familiarize them with the VE setting and movement, a habituation phase lasting 3–7 min was conducted in an industrial-like environment, adjusted based on the participant's readiness for the main task. The image from the habituation phase is available in the Appendix, Picture 1. Following the VE task, participants responded to questions regarding their level of presence (MEC_SPQ questionnaire (Vorderer et al., 2004)) in the VE and reported any cybersickness symptoms (CSQ questionnaire) (Kourtesis et al., 2023).

Having concluded the walking tasks, participants were instructed to self-complete a questionnaire on a laptop regarding their socio-demographics, familiarity with VR, physical activity habits, and perceived stress (PSS-10 questionnaire (Cohen et al., 1983)). The overall duration of the experiment was about 1 h and 15 min. The study design is shown in Fig. 2.

One day after the experiment, a follow-up email was sent to participants to inquire regarding their level of stress compared with other days and if they had experienced, or were still experiencing, any cybersickness or other side effects resulting from the experiment. Out of the 49 participants, 26 (53.1 %) responded. Of these, 25 reported no changes in their stress levels compared with usual, while one participant noted slightly elevated stress levels possibly related to the experiment.

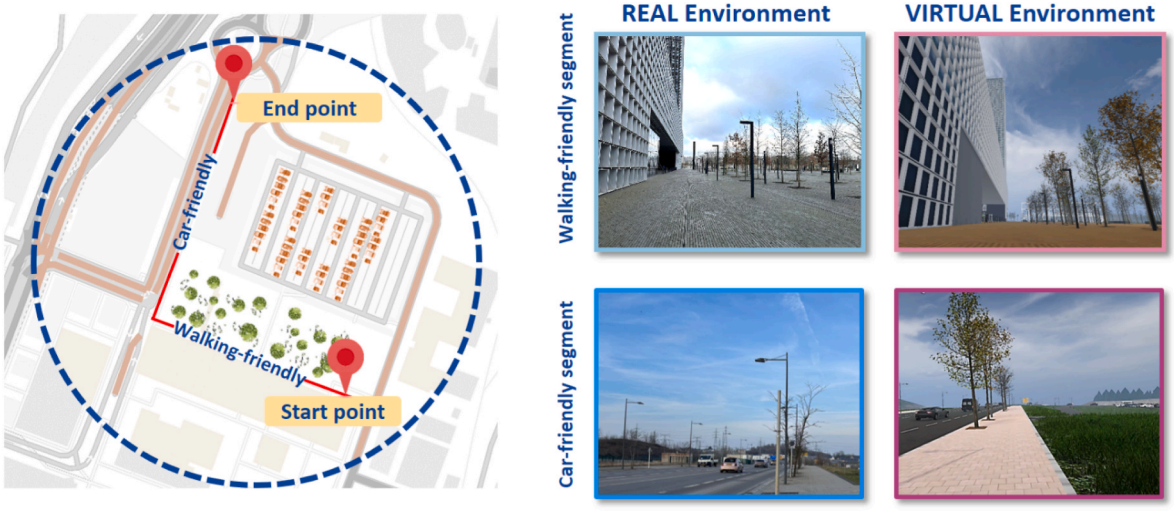


Fig. 1. Example view of the walking-friendly segment and car-friendly segment in the real and corresponding virtual environment.

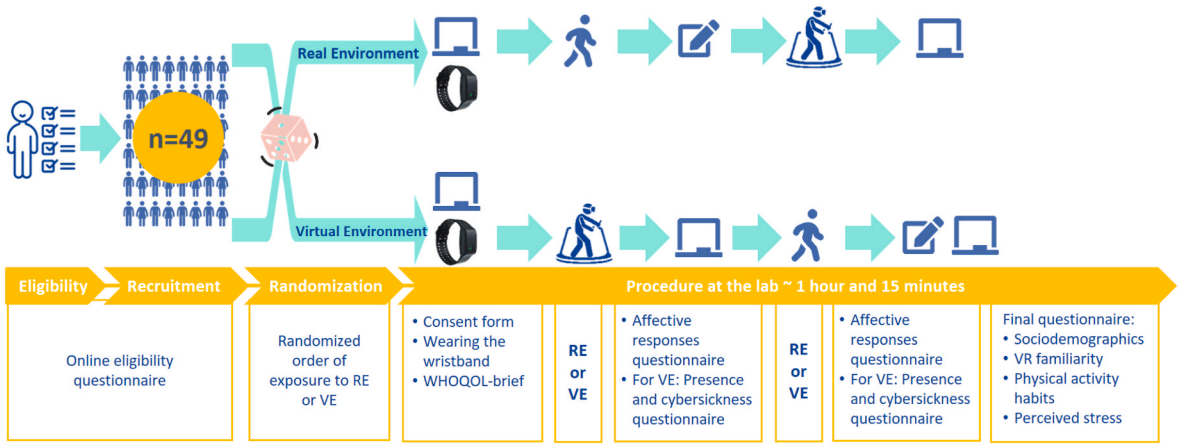


Fig. 2. Study design.

With regard to cybersickness, 19 participants reported no issues, while 7 experienced varying degrees of symptoms following the experiment. The reported symptoms included dizziness, nausea, light and noise sensitivity, and difficulty focusing on tasks. Most symptoms resolved within 30 min to a few hours after the experiment, and no symptoms were reported the following day. No severe or persistent side effects were noted.

2.4. Experimental apparatus

Fig. 3 presents the experimental setup, including the head-mounted display (HMD) and walking simulator. For the display, an HTC Vive Pro Eye HMD was used to create a highly immersive virtual reality environment, as it has a field of view of up to 110° (a resolution of 1440 x 1600 pixels per eye) for visualization of the VE.

A Cyberith Virtualizer ELITE 2 (Hager et al., 2019) was used to provide a natural locomotion experience in the IVE. This omnidirectional treadmill allows 360-degree rotation and is equipped with an adjustable harness system, as well as customizable inclination and height settings, enhancing user comfort.

Lastly, an E4 wristband, a noninvasive research device, was utilized to collect real-time physiological data (Birenboim, Dijst, Scheepers, et al., 2019). This device includes four sensors: a temperature sensor, an accelerometer, electrodermal activity (EDA), and photoplethysmography (PPG) sensors.

2.5. Measurements

2.5.1. Psychological affective responses

Participants' walking experiences in the RE and VE were assessed using a custom-built questionnaire, targeting their perceptions of the walking environment itself rather than the environment type. The questionnaire included items on aesthetics (Birenboim, Dijst, Ettema, et al., 2019), safety (Bhagavathula et al., 2018; Birenboim, Dijst, Ettema, et al., 2019; Zhao et al., 2022), comfort (Liao et al., 2022; Zhao et al., 2022), enjoyment (Birenboim, Dijst, Ettema, et al., 2019; Birenboim et al., 2021; Zhao et al., 2022), relaxation (Gao et al., 2025; Oselinsky et al., 2023), and momentary stress, using a 5-point Likert scale ranging from 1 (Very poor) to 5 (Very good). These affective dimensions were informed by restorative environment theories, particularly Kaplan and Kaplan's Attention Restoration Theory (ART) and Ulrich's Stress Reduction Theory (SRT), which emphasize how environments evoke affective and cognitive responses that influence behavior. According to the ART and SRT models, natural environments facilitate psychological restoration and stress recovery, while trafficked streets often provoke stress and physiological arousal (Kaplan & Kaplan, 1989; Roe & McCay, 2021; Ulrich et al., 1991).

This assessment was conducted immediately after the completion of each condition of walking (RE and VE). Cronbach's α was calculated to assess the internal consistency of the items measuring affective responses. Values were obtained between 0.87 and 0.91, indicating a high level of reliability.

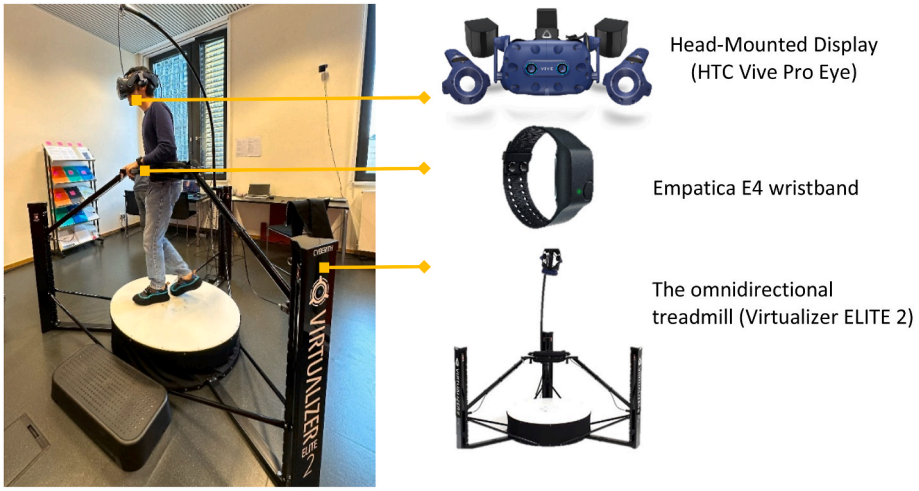


Fig. 3. The walking posture on an omni-directional treadmill (Virtualizer Elite 2), wearing HTC Vive Pro Eye HMD and Empatica E4 wristband.

2.5.2. Presence levels

Presence in VR is the perceptual and psychological state of deep involvement, engagement, and absorption in a VE, typically measured by subject self-reports (Lombard & Ditton, 1997).

The MEC (Measurement, Effects, Conditions) Spatial Presence Questionnaire (MEC_SPQ) (Vorderer et al., 2004) was used to assess the level of presence experienced in the VE exposure. We focused on five out of seven domains: Attention Allocation, Spatial Presence–Self Location (SPSL), Spatial Presence–Possible Actions (SPPA), Higher Cognitive Involvement, and Visual Spatial Imagery (VSI), using a 4-item scale. A 5-point Likert scale ranging from 1 (Strongly disagree) to 5 (Strongly agree) was employed. The only modification was in the Higher Cognitive Involvement domain, where for clarity, "I thought most about things having to do with the VE" was rephrased to "I found it easy to focus in the VE," based on feedback from the practice stage.

The average scores for the five independent domains were calculated, as was the Cronbach's α, (0.86), again indicating a high level of overall reliability (Appendix, Table 1).

2.5.3. Cybersickness

Cybersickness (or simulation sickness) is a VR-induced condition, characterized by symptoms such as headache, dizziness, disorientation, or nausea (Ramaseri Chandra et al., 2022). The Cybersickness in the VR Questionnaire (CSQ-VR) — derived from the VR Induced Symptoms and Effects (VRISE) section of the VR Neuroscience Questionnaire (VRNQ) — demonstrated that strong structural and construct validity was utilized (Kourtesis et al., 2023). The questionnaire evaluates symptoms across three categories — nausea, vestibular, and oculomotor — using a 7-point Likert scale (1 = Absence of feeling to 7 = Extreme feeling). Five out of six questions from this questionnaire were used, resulting in a high Cronbach's alpha of 0.85, again indicating strong reliability.

2.5.4. Psychological stress measurements (perceived stress scale)

The Perceived Stress Scale (PSS-10) was used to evaluate general stress levels. The PSS is a widely recognized tool for measuring the perception of chronic stress, and was originally developed by Cohen and Mermelstein (1983) (Cohen et al., 1983). It assesses individuals' feelings and thoughts over the past month and offers adequate cross-cultural reliability (Benita & Tunçer, 2019). It employs a 5-point Likert scale (0 = Never to 4 = Very often), with total scores ranging from 0 to 40. Higher scores indicate greater levels of perceived stress.

2.5.5. Physiological stress measurements/affective responses

To track individuals' physiological responses, E4 wristband was utilized. Previous studies have successfully used the EDA data from E4 to assess human stress levels in a lab-based context (Stuyck et al., 2022), or VE (Bastiaansen et al., 2022; Birenboim et al., 2021) and RE (Birenboim, Dijst, Scheepers, et al., 2019; Campanella et al., 2023; Chrisinger & King, 2018; Winz et al., 2022). In this study, we considered EDA with a sampling rate of 4 Hz, and heart rate (HR) with a sampling rate of 1 Hz.

2.5.5.1. Electrodermal activity. Electrodermal activity (EDA) — also known as galvanic skin response (GSR) — refers to variations in the electrical properties of the skin due to sweat secretion. It is considered one of the most sensitive and valid markers of physiological arousal and stress activation (Benedek & Kaernbach, 2010; Benita & Tunçer, 2019; Kyriakou et al., 2019; Llinares et al., 2023). EDA is characterized by two types of responses: long-term tonic level (skin conductance level, SCL) and stimulus-related phasic response (skin conductance response, SCR). While SCL represents the baseline level of a recording without external stimulus, SCR represents the body's reaction to a stimulus.

For pre-processing, we employed the algorithm proposed by Kyriakou et al. (2019), which detects moments of stress (MOS) with an accuracy of 84 %, validated through both laboratory experiments and real-world urban environments. We took a number of pre-processing steps. First, in order to remove high-frequency signal noise from the EDA (induced by pressure on the device, body movement, irregular respiration, or device-internal technical causes), we applied a first-order Butterworth low-pass filter with a cut-off frequency of 5 Hz. We then applied a first-order Butterworth high-pass filter with a cut-off frequency of 0.05 Hz to separate the SCR and the SCL in the EDA signal. To calculate the average EDA, an additional processing step was included. This was in line with the first stage of the four-step method proposed by Kleckner et al. (2018), which provides a simple, transparent, and flexible approach to identify corrupted EDA data and conduct automatic quality assessments (Kleckner et al., 2018; Posada-Quintero et al., 2018). In this step, the acceptable EDA range was set to 0.05–60 μS, and data from two participants were removed as their EDA values fell outside this range. This exclusion was only applied for EDA data and did not affect the rest of the analyses.

Afterwards, two EDA-related indicators were created: average skin conductance level (SCL) and nonspecific skin conductance responses (NSSCR). For the calculation of SCL, a Continuous Decomposition Analysis (CDA) was performed in MATLAB using the freeware LEDALAB V3.4.4 (www.ledalab.de) (Benedek & Kaernbach, 2010). High SCL values (μS) indicate high levels of physiological arousal, whereas low SCL values represent lower levels.

Lastly, the frequency of NSSCRs (referring to skin conductance responses occurring without a specific eliciting stimulus) was measured using a specified amplitude threshold of 0.05 μS (Lim et al., 2024; Posada-Quintero et al., 2018). As reported in previous studies, NSSCR levels rise alongside those of physiological arousal and can serve as a potentially valid indicator of stress (Lim et al., 2024).

2.5.5.2. Heart rate. Heart rate (HR) is widely used as a physiological indicator for monitoring changes in mental state. Increased HR is associated with stress and emotions such as anger, anxiety, and joy, while lower HR is linked to serenity, sadness, and contentment (Birenboim, Dijst, Scheepers, et al., 2019). Average HR values were derived from a session's blood volume pulse (BVP) analysis, calculated as the average heart rate over 10-s intervals with a sampling rate of 1 Hz.

2.6. Analysis

The current research adopted a within-subject design to compare participants' subjective affective responses and physiological reactions in two types of environments: virtual and real. These comparisons were further analyzed in the context of two distinct segments: walking-friendly and car-friendly. The analysis was structured to first examine differences between the environments, followed by segment-specific comparisons. All the analyses were carried out using R Studio.

First, descriptive statistics were calculated for the total sample to provide an overview of the participants' self-reported responses. Second, to address H1, focusing on inter-group differences between the VE and RE, a Shapiro-Wilk test was performed to assess the normality of the data. As the data was not normally distributed, a Wilcoxon Signed-Rank Test was conducted to reveal possible differences in walking experiences in the RE and VE. Third, to address H2, investigating segment-specific comparisons, normality was again assessed using a Shapiro-Wilk test. Since the data was again not normally distributed, a Friedman test was employed, followed by post-hoc pairwise Wilcoxon tests with Bonferroni correction. In all Wilcoxon tests, effect sizes were measured using the standardized effect size r, calculated as $r = |z|/\sqrt{n}$, where z represents the z-score associated with the two-tailed p-value of the test, and n denotes the number of paired observations.

Lastly, a mixed linear model (MLM) was employed using R (via the "lme4" and "lmerTest" packages) to assess the associations between environment type (VE vs. RE), segment type (walking-friendly vs. car-friendly), and their interactions, while accounting for potential confounders. All the models included a random intercept for participants, to

account for repeated observations within individuals. For psychological affective responses, the six items were combined into a composite mean score per environment and segment, with the "stressful" item reverse-coded so that higher values consistently reflect more-positive effects. The models were fitted to psychological and physiological affective responses using a three-step approach: Model 1 incorporates the environment type and confounders including age, gender, education, employment, previous VR experience, chronic stress levels, and quality of life; Model 2 adds the segment type; and Model 3 includes the interaction between the environment and segment type. As a sensitivity analysis, the same modeling structure was applied to each psychological affective item separately. The results are reported in the Appendix, Table 3. Furthermore, type III F-tests were computed for all models, and partial eta-squared and omega-squared were derived as effect size indices. These are reported in the Appendix, Tables 4 and 5.

3. Results

3.1. Sample characteristics

In total, 49 adults participated in the experiment; however, data from two participants was excluded due to technical issues (computer overheating) and cybersickness, leaving 47 participants for analysis. The overall characteristics of the sample are summarized in Table 1. Most participants were aged 25–34 years (55 %) and 57.5 % were female. A significant proportion held a master's degree or equivalent (68.1 %), with the majority being students (57.5 %), followed by salaried employees (27.7 %). Additionally, 93.5 % were residents of Luxembourg, and an equal percentage reported having no children under 16 living with them. The majority of participants (89.4 %) were familiar with the case study environment (Belval). With regard to experience of VR, 38.3 % had no prior experience, 57.4 % had limited experience, and 4.3 % identified as experienced users.

For physical activity levels, 34 % of participants engaged in 30–90 min of moderate or vigorous exercise per week, 28 % engaged in 90–150 min, and 23 % reported more than 300 min. Chronic stress levels indicated that 59.6 % of participants experienced moderate to high levels of stress, while 40.4 % reported low levels.

3.2. Descriptive analysis

Participants reported a moderate to high sense of presence in the VE, as measured by the MEC-SPQ, with the highest ratings for Attention Allocation (M = 4.38, SD = 0.75). Cybersickness symptoms, assessed using the CSQ, indicated relatively low discomfort: nausea (M = 1.85, SD = 1.15); vestibular symptoms (M = 2.25, SD = 1.34); oculomotor symptoms (M = 1.56, SD = 0.92).

Participants, on average, reported relatively high scores for physical quality of life (M = 79.86, SD = 10.33) and psychological quality of life (M = 71.1, SD = 12.57). Furthermore, bodily pain scores showed that all participants reported being either "not limited at all" or "a little limited" in daily activities, with an average score of 23.15 (SD = 1.20), indicating minimal to no limitations (Table 2).

3.3. Psychological affective responses

3.3.1. Differences in walking experiences between the real and virtual environments

The differences in walking experiences between the RE and VE, across six affective responses, are presented in Table 3. The results reveal significant differences across all affective responses. Overall, participants rated the RE significantly higher than the VE for "Aesthetics," "Comfortable," "Safe," "Relaxing," and "Enjoyment." By contrast, participants reported significantly higher "Stressful" feelings in the VE condition. Fig. 4 visualizes these comparisons. At the same time, analysis of total walking time and average walking speed between VE and RE conditions reveals no statistically significant differences (Appendix, Table 2).

Table 1
Sample characteristics.

Feature	Category	Frequency/ sample (47)	%
Age	18–24	11	23.4 %
	25–34	**26**	**55.3 %**
	35–44	9	19.2 %
	45–54	1	2.1 %
Gender	Female	**27**	57.5 %
	Male	20	42.5 %
Educational level	Upper-secondary education	4	8.5 %
	Bachelor's level or equivalent	5	10.6 %
	Master's level or equivalent	**32**	**68.1 %**
	Doctoral degree or equivalent	6	12.8 %
Employment status	Employed (salaried employee)	13	27.7 %
	Student	27	**57.5 %**
	Unemployed	1	2.1 %
	Employed and student	6	12.7 %
Residency	A resident of Luxembourg	**44**	**93.5 %**
	A cross-border commuter (i.e., living outside Luxembourg and commuting to work or school in Luxembourg on a regular basis)	4	8.5 %
Number of children below 16 (living with them)	0	**44**	**93.6 %**
	2	3	6.4 %
Belval familiarity	Yes	**42**	**89.4 %**
	No	5	10.6 %
VR experience	No experience (Never used)	18	38.3 %
	Limited experience (once or twice or several times in a year)	**27**	**57.4 %**
	Experienced (once or twice in a month and several times in a week)	2	4.3 %
Moderate and vigorous physical activities in a typical week (Only include activities that lasted at least 10 min at a time.)	Less than 30 min per week	4	9 %
	30–90 min per week	16	34 %
	90–150 min per week	13	28 %
	150–300 min per week	3	6 %
	More than 300 min per week	11	23 %
Perceived scale stress (PSS)	Low stress	19	40.4 %
	Moderate to high stress	**28**	**59.6 %**

3.3.2. Differences in walking experiences between the walking-friendly and car-friendly segments

Table 4 presents the differences between the walking-friendly and car-friendly segments, with affective responses analyzed separately for the RE and VE. As expected, significant differences are observed, with walking-friendly segments consistently eliciting higher ratings than car-friendly segments in both the RE and VE across all affective responses. Fig. 5 visualizes these comparisons.

Table 2
Descriptive analysis.

Feature	Domain	Mean	SD
Presence levels (MEC-SPQ)	Attention Allocation	4.38	0.75
	Spatial Presence–Self Location (SPSL),	3.50	1.07
	Spatial Presence–Possible Actions (SPPA)	3.58	1.07
	Higher Cognitive Involvement	3.53	1.09
	Visual Spatial Imagery (VSI)	3.98	0.82
Cybersickness (CSQ)	Nausea	1.85	1.15
	Vestibular	2.25	1.34
	Oculomotor	1.56	0.92
Quality of life (WHOQOL) (Scale: 0–100)	Physical	79.86	10.33
	Psychological	71.10	12.57
SF-36: Activities you might do on a typical day	Domain 3: Bodily pain (scores from 0 to 24)	23.15	1.20

Table 3
Differences in walking experiences between the RE and VE.

Affective responses	VE M(SD)	RE M(SD)	Diff (VE_RE)	P_value	Effect size
Aesthetics	3.04 (1.13)	3.40 (1.13)	−0.36	**<0.01**	0.2
Comfortable	3.46 (1.07)	4.09 (0.95)	−0.63	**<0.001**	0.4
Enjoyment	3.10 (1.10)	3.37 (1.16)	−0.28	**0.03**	0.2
Safe	3.59 (1.12)	3.93 (1.02)	−0.34	**0.01**	0.2
Relaxing	3.02 (1.14)	3.41 (1.26)	−0.39	**<0.01**	0.2
Stressful	2.02 (0.97)	1.63 (0.79)	0.39	**<0.001**	0.3

3.3.3. Mixed linear models (MLM) results for psychological affective responses

The MLM analysis reveals significant associations between the environment type (VE vs. RE) and segment type (car-friendly vs. walking-friendly) for psychological affective responses across all models. As shown in Table 5, the VE elicited lower affective responses compared with the RE, and the car-friendly segments received lower ratings than the walking-friendly ones.

The interaction between the environment and segment type was examined in Model 3. The results show this is not statistically significant, with an estimated explained variance by the interaction term equal to the null ($\omega^2 = 0.00$, $\eta p^2 = 0.01$; see the Appendix, Table 4), suggesting that the impact of the VE on affective responses is consistent across the segment types. Sensitivity analyses based on separate MLMs for each of the six affective items show consistent results (Appendix, Table 3). Further, type III F-tests reported in the Appendix, Table 4, support the significance of the main effects identified in the mixed models.

3.4. Physiological responses

3.4.1. Differences in walking experiences between the RE and VE environment, and walking-friendly and car-friendly segments

To investigate differences in physiological responses between the RE and VE, four physiological indices (HR, EDA, SCL, and NSSCR) were analyzed (Table 6).

3.4.1.1. HR. Participants exhibited significantly higher HR in the RE than the VE, as shown in Table 6. However, no significant differences are observed when comparing walking-friendly vs. car-friendly segments within each environment. This trend remains consistent across both environments.

3.4.1.2. EDA. EDA analysis reveals significantly higher EDA in the VE than the RE, indicating more physiological arousal in the virtual environment. Within the VE, the car-friendly segment elicits significantly higher EDA than the walking-friendly segment. However, within the RE, the difference between segments is not statistically significant.

3.4.1.3. SCL. Comparing SCL between the RE and VE reveals significant differences, with the VE inducing greater arousal than the RE. In the VE, SCL is also substantially higher in the car-friendly segment than the walking-friendly one. Nevertheless, SCL does not vary significantly

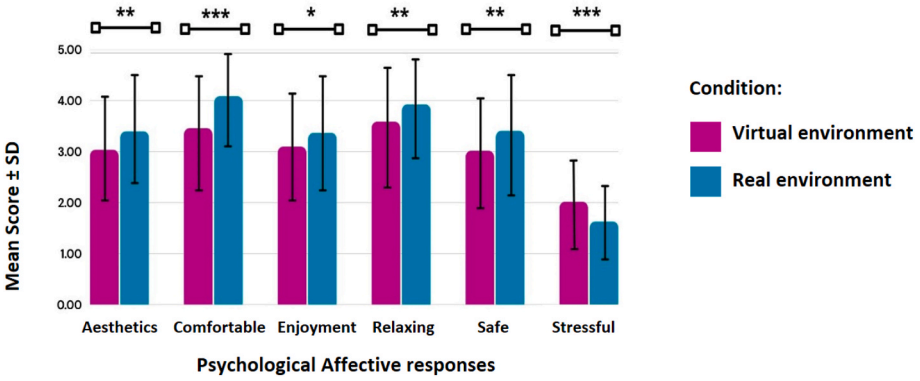


Fig. 4. Differences in walking experiences between the RE and VE.

Table 4
Differences in walking experiences between walking-friendly and car-friendly segments.

Affective responses	VE segments					RE segments				
	Walking-friendly M (SD)	Car-friendly M (SD)	Diff [a]	p-value	Effect size	Walking-friendly M (SD)	Car-friendly M (SD)	Diff [a]	p-value	Effect size
Aesthetics	3.32 (1.04)	2.77 (1.15)	−0.55	**<0.01**	0.3	3.87 (0.92)	2.94 (1.13)	−0.94	**<0.001**	0.5
Comfortable	3.77 (1.05)	3.15 (1.02)	−0.62	**<0.001**	0.4	4.38 (0.90)	3.79 (0.91)	−0.60	**<0.001**	0.4
Enjoyment	3.43 (1.04)	2.77 (1.07)	−0.66	**<0.001**	0.4	3.87 (0.92)	2.87 (1.17)	−1.00	**<0.001**	0.4
Safe	4.04 (1.04)	3.13 (1.01)	−0.91	**<0.001**	0.4	4.49 (0.72)	3.36 (0.97)	−1.13	**<0.001**	0.5
Relaxing	3.34 (1.17)	2.70 (1.02)	−0.64	**<0.001**	0.4	3.94 (1.05)	2.89 (1.24)	−1.04	**<0.001**	0.4
Stressful	1.77 (0.91)	2.28 (0.97)	0.51	**<0.001**	0.4	1.38 (0.68)	1.87 (0.82)	0.49	**<0.01**	0.3

[a] Diff= (Car-friendly) – (Walking-friendly).

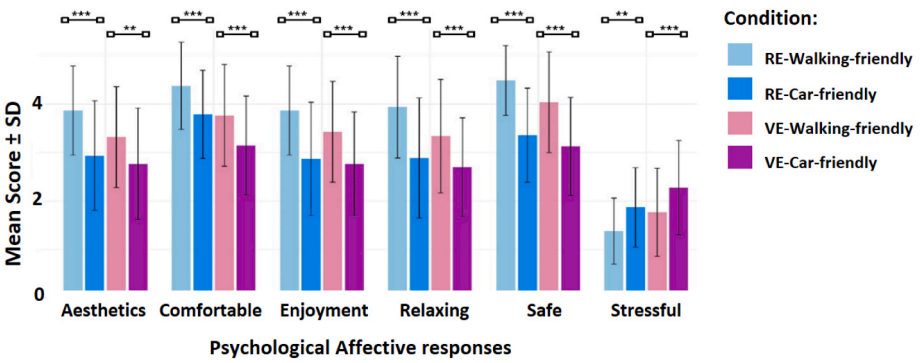


Fig. 5. Differences in walking experiences between walking-friendly and car-friendly segments in the RE and VE.

Table 5
MLM results for psychological affective responses.

Model	Predictor	β (Estimate)	Std. Error	P-value	t-value	95 % CI
Model 1	Virtual Environment (vs. RE)	−0.40	0.12	**<0.001**	−3.44	[−0.63, −0.17]
Model 2	Virtual Environment (vs. RE)	−0.40	0.10	**<0.001**	−4.11	[−0.59, −0.21]
	Car-friendly segment (vs. walking-friendly)	−0.76	0.10	**<0.001**	−7.80	[−0.95, −0.57]
Model 3	Virtual Environment (vs. RE)	−0.51	0.14	**<0.001**	−3.71	[−0.77, −0.24]
	Car-friendly segment (vs. walking-friendly)	−0.87	0.14	**<0.001**	−6.33	[−1.13, −0.60]
	Environment × Segment Interaction	0.22	0.19	0.26	1.12	[−0.16, 0.60]

Model 1: Environment type + Confounders including age, gender, education, employment, previous VR experience, chronic stress levels, and quality of life.
Model 2: Model 1+ Segment type.
Model 3: Model 2+ Environment segment Interaction.

across the different RE segments.

3.4.1.4. NSSCR. The analysis of NSSCR shows no significant difference between the RE and VE. Similarly, different segments (walking-friendly vs. car-friendly) within both RE and VE show no significant differences. It is important to note that for eight participants, NSSCR was not recorded in either the RE or VE.

3.4.2. Mixed linear models (MLM) results for physiological affective responses

The MLM analysis was also conducted for each physiological outcome separately, as presented in Table 7. Type III F-tests, reported in the Appendix, Table 5, support the significance of the main effects identified in the mixed models.

For HR, the results reveal significant associations between the environment and segment type. HR is consistently significantly lower in the VE across all models, and the car-friendly segment is associated with a significant increase in HR compared with the walking-friendly segment. However, the interactions between the environment and segment type are not statistically significant, with an estimated explained variance by the interaction term equal to the null ($\omega^2 = 0.00$, $\eta p^2 = 0.00$, see Appendix, Table 5), indicating a consistent effect of the VE on HR across both segment types.

The analysis of EDA indicates that the VE is consistently associated with higher EDA levels than the RE across all models, and the car-friendly segment is associated with higher EDA compared with the walking-friendly one. Notably, the interaction between environment and segment type is statistically significant, with a stronger effect in the car-friendly segment. However, the estimated explained variance by the interaction term is negligible ($\omega^2 = 0.00$, $\eta p^2 = 0.00$; see Appendix, Table 5), suggesting that, although detectable, the moderating effect of the segment type on the VE–RE difference in EDA is very small in magnitude.

The results of the SCL analysis also show a similar pattern, indicating significant associations between the environment and segment type in the first two models. SCL levels are consistently higher in the VE and the car-friendly segment. However, in Model 3, the impact of the segment type is no longer statistically significant, and the interaction between the environment and segment type is also not statistically significant, with an estimated explained variance by the interaction term equal to the null ($\omega^2 = 0.00$, $\eta p^2 = 0.00$, see Appendix, Table 5). This suggests that the impact of the VE on SCL remains consistent across both segments.

Lastly, for NSSCR, while Model 1 indicates that the VE significantly increases NSSCR, this effect disappears in Models 2 and 3. Nevertheless, the car-friendly segment is associated with significantly higher NSSCR levels, suggesting that the segment type plays a more crucial role in driving NSSCR responses than the environment type. Additionally, the interaction between the VE and segment type is not significant, with an estimated explained variance by the interaction term equal to null ($\omega^2 = 0.00$, $\eta p^2 = 0.00$, see Appendix, Table 5).

Table 6
Physiological responses.

Indexes	VE vs. RE (overall)				VE segments			RE segments		
	VE M(SD)	RE M(SD	P-Value	Effect size	Walking-friendly M (SD)	Car-friendly M (SD)	P-Value	Walking-friendly M (SD)	Car-friendly M (SD)	P-Value
HR (avg)	88.31 (9.13)	104.71 (9.75)	**<0.001**	28.9	85.89 (7.23)	90.71 (5.15)	0.25	103.57 (7.44)	105.90 (5.36)	0.77
EDA (avg)	5.33 (5.22)	1.82 (2.00)	**<0.001**	0.8	4.72 (4.95)	5.89 (5.39)	**<0.001**	1.61 (1.77)	1.96 (2.15)	0.06
SCL (avg)	6.46 (9.56)	1.99 (2.78)	**<0.001**	0.7	5.76 (8.60)	7.11 (10.31)	**<0.001**	1.85 (2.80)	2.11 (2.76)	0.14
NSSCR (avg)	2.80 (1.94)	2.68 (1.73)	0.87	0.03	2.80 (1.89)	2.80 (1.99)	0.55	2.45 (1.62)	2.89 (1.81)	0.16

Table 7
MLM results for physiological affective responses.

Outcome	Model	Predictor	β (Estimate)	Std. Error	P-value	t-value	95 % CI
HR	Model 1	Virtual Environment (vs. RE)	−17.84	0.63	**<0.001**	−28.27	[−19.08, −16.61]
	Model 2	Virtual Environment (vs. RE)	−18.35	0.65	**<0.001**	−28.16	[−19.63, −17.07]
		Car-friendly segment (vs. walking-friendly)	1.97	0.65	**<0.01**	3.01	[0.69, 3.25]
	Model 3	Virtual Environment (vs. RE)	−17.98	1.04	**<0.001**	−17.35	[−20.02, −15.95]
		Car-friendly segment (vs. walking-friendly)	2.33	1.02	**0.02**	2.28	[0.33, 4.33]
		Environment × Segment Interaction	−0.61	1.33	0.65	−0.46	[−3.21, 2.00]
EDA	Model 1	Virtual Environment (vs. RE)	3.24	0.09	**<0.001**	34.26	[3.05, 3.42]
	Model 2	Virtual Environment (vs. RE)	3.10	0.10	**<0.001**	31.99	[2.91, 3.29]
		Car-friendly segment (vs. walking-friendly)	0.55	0.10	**<0.001**	5.75	[0.36, 0.74]
	Model 3	Virtual Environment (vs. RE)	2.81	0.15	**<0.001**	18.40	[2.51, 3.11]
		Car-friendly segment (vs. walking-friendly)	0.28	0.15	**0.05**	1.92	[−0.01, 0.57]
		Environment × Segment Interaction (VE, seg2)	0.47	0.19	**0.02**	2.43	[0.09, 0.85]
SCL	Model 1	Virtual Environment (vs. RE)	4.75	0.22	**<0.001**	21.80	[4.33, 5.18]
	Model 2	Virtual Environment (vs. RE)	4.62	0.23	**<0.001**	20.48	[4.17, 5.06]
		Car-friendly segment (vs. walking-friendly)	0.53	0.23	**0.02**	2.35	[0.09, 0.98]
	Model 3	Virtual Environment (vs. RE)	4.25	0.36	**<0.001**	11.87	[3.55, 4.96]
		Car-friendly segment (vs. walking-friendly)	0.18	0.35	0.61	0.51	[−0.51, 0.87]
		Environment × Segment Interaction (VE, seg2)	0.60	0.46	0.19	1.30	[−0.30, 1.50]
NSSCR	Model 1	Virtual Environment (vs. RE)	0.13	0.06	**0.03**	2.14	[0.01 to 0.26]
	Model 2	Virtual Environment (vs. RE)	0.05	0.06	0.47	0.73	[−0.08, 0.17]
		Car-friendly segment (vs. walking-friendly)	0.33	0.06	**<0.001**	5.22	[0.21, 0.46]
	Model 3	Virtual Environment (vs. RE)	0.08	0.10	0.44	0.77	[−0.12, 0.28]
		Car-friendly segment (vs. walking-friendly)	0.36	0.10	**<0.001**	3.75	[0.17, 0.55]
		Environment × Segment Interaction (VE, seg2)	−0.05	0.13	0.69	−0.40	[−0.30, 0.20]

Model 1: Environment type + Confounders, including age, gender, education, employment, previous VR experience, chronic stress levels, and quality of life.
Model 2: Model 1+ Segment type.
Model 3: Model 2+ Environment segment Interaction.

4. Discussion

This study aimed to investigate whether a virtual environment setup could produce similar affective responses to those elicited by a real environment setup, both psychologically and physiologically, while walking using an IVE and a walking simulator that mimicked dynamic motion. Additionally, it explored whether the influence of walking in different environmental contexts (walking-friendly and car-friendly segments) on affective responses would be consistent across the VE and RE. Findings from 47 participants revealed significant differences between the RE and VE across all psychological and physiological affective measurements, except for NSSCR. However, no interaction effects concerning the segment type and RE-VE differences were found, except for EDA. Furthermore, similar affective trends were identified in both the RE and VE across two segments — walking-friendly and car-friendly environments.

In the following, we discuss the two main hypotheses: H1) VEs can elicit similar affective responses, both subjective and objective, as REs; and H2) environmental characteristics do not moderate affective responses between two environment types (REs and VEs). Following this, we delve into the strengths and limitations of using VR in the context of walking behavior studies. Lastly, we conclude with recommendations for future research into utilizing VR for policy interventions and interpreting findings.

4.1. Psychological and physiological affective responses while walking: differences between REs and VEs (H1)

Our findings revealed significant differences between a RE and VE across nearly all psychological and physiological affective measurements, except for NSSCR. The RE consistently scored higher than the VE on both psychological and physiological affective responses, indicating more positive affective experiences in the RE.

Existing studies using RE–VE comparisons can be categorized into three distinct groups. The first group has found no significant differences between real and virtual environments, suggesting that under certain conditions, VEs can elicit equivalent psychological and physiological responses to REs (Llinares et al., 2023; Pastel et al., 2022). Llinares et al. (2023) found similar psychological and physiological responses among adults in both RE and VE classrooms (Llinares et al., 2023). Furthermore, Pastel et al. (2022) reported no differences in spatial orientation accuracy (Pastel et al., 2022). However, the second group has noted partial differences between REs and VEs, with some behavioral or affective measures diverging but others remaining similar (Berton et al., 2020; Bhagavathula et al., 2018; Calogiuri et al., 2018). Bhagavathula et al. (2018) found that pedestrian crossing behavior was largely consistent across real and virtual environments, yet approaching vehicle speed estimation was significantly less accurate in VR (Bhagavathula et al., 2018). Similarly, Calogiuri et al. (2018) provided particularly relevant insights, as their study was the only one to use motion-based VR for walking behavior and measured both subjective and objective responses to the environment. While perceived restorativeness was comparable in the RE and the treadmill-VE condition, enjoyment, tranquility, and perceived exertion were significantly lower in VR, further supporting our results (Calogiuri et al., 2018). Berton et al. (2020) also demonstrated that eye-gaze behavior while walking in crowds was similar in REs and VEs, but VR users exhibited longer fixations and narrower gaze distributions, probably due to tunnel vision effects induced by the limited field of view in HMDs (Berton et al., 2020).

Lastly, the third group aligns closely with our findings, reporting significant differences between REs and VEs across multiple psychological and physiological measurements (Kalantari et al., 2024; Petukhov et al., 2024). Kalantari et al. (2024) found that wayfinding performance was consistently less efficient and more mentally taxing in VR, with participants taking longer routes, making more mistakes, and experiencing higher cognitive load and uncertainty compared with a real environment. In their study, the lack of full bodily engagement due to teleportation-based movement was cited as a possible reason (Kalantari et al., 2024), although this is not relevant for the current study. Likewise, Petukhov et al. (2024) reported that distance perception in VR was significantly less accurate than a real environment, with errors increasing as distances increased (Petukhov et al., 2024).

While our findings do not support our first hypothesis, despite having controlled for many of the key factors previously cited as reasons for RE–VE differences (i.e., high-fidelity IVR, full bodily engagement in movement, a high level of presence, and low incidence of

cybersickness), it is important to note that the trends observed in the VE were notably similar to those in the RE. Given the observed differences, absolute validity cannot be claimed; however, the consistent direction of effects across environments (RE vs. VE) and segments (car-friendly vs. walking-friendly) supports the relative validity of the VE setup. This underscores the potential of VR to reproduce overall patterns of psychological and physiological affective responses comparable with those experienced in a real environment. In practice, this suggest that motion-based VR setups can be used to study comparative effects of urban design attributes and to test scenarios relevant for urban planning interventions, provided that researchers and practitioners interpret absolute effect magnitudes with caution. One possible hypothesis for the observed differences lies in certain technology-oriented limitations of VR experiments. For instance, treadmill-based walking may not fully replicate natural walking, and the relatively low field-of-view of HMDs can restrict immersion. Additionally, although participants provided positive feedback on the realism of the VE, fully realistic simulations remain a challenge. Ongoing advancements in graphics rendering and hardware are expected to further bridge the experiential gap between VEs and REs.

4.2. Impact of environmental characteristics on affective responses in REs and VEs

Our findings confirm the second hypothesis, indicating that environmental characteristics significantly influenced affective responses in both the RE and VE, but did not moderate the overall differences between them. In both environments, the walking-friendly segment consistently elicited more positive affective ratings for aesthetics, comfort, enjoyment, safety, and relaxation, whereas the car-friendly segment was associated with higher stress levels. Similarly, physiological responses showed elevated stress markers in car-friendly segments, with higher HR, EDA, and SCL compared with walking-friendly areas in both the RE and VE. This pattern is in line with Kaplan and Kaplan's ART and Ulrich's SRT models, which suggest that calm, walkable, and more-natural environments, similar to our walking-friendly segment, facilitate restoration and enhance positive affective states, while trafficked streets, similar to our car-friendly segment, induce stress and physiological arousal. This consistency supports the absolute validity of VR as an effective tool for assessing psychological and physiological responses to various urban environments.

Additionally, the interaction between the environment type (RE vs. VE) and segment type (car-friendly vs. walking-friendly) was not significant for most measurements, including subjective affective responses, HR, SCL, and NSSCR. The variance explained by the interaction terms was also negligible, indicating that any moderating effect of the segment type on RE–VE differences was minimal. This suggests that the effect of environment type on affective responses remained consistent across both segments.

For EDA, the interaction between the environment and segment type was statistically significant. However, the proportion of variance explained by the interaction remained very small, indicating that although a moderating effect was statistically detectable, its magnitude was limited. This is particularly surprising, given that other physiological measurements were in the expected directions. One possible explanation for EDA responding differently could be its heightened sensitivity to external factors, such as temperature variations.

4.3. Strengths

This study is among the few that have compared REs and VEs using an embodied motion experience, while integrating both psychological and physiological measurements. By using Empatica 4 — which incorporates multiple physiological indicators, including HR, EDA, SCL, and NSSCR — the current study provides a more comprehensive understanding of walking experiences. This approach offers a holistic assessment compared with studies that only rely on self-reported measurements.

The use of an omnidirectional walking simulator allowed for natural locomotion in comparison with teleportation or joystick navigation methods, which do not fully replicate the sensation of walking. This enhanced the study's ecological validity and contributed to a more immersive and realistic VR walking experience.

Additionally, the study involved extensive efforts to ensure environmental consistency across the RE and VE by maintaining controlled levels of crowdedness, traffic intensity, and temperature. This helped minimize potential confounding variables that could have influenced affective responses. To further reduce bias and mitigate order effects, we randomized the exposure sequence between the RE and VE, ensuring that participants did not consistently experience one condition first.

More importantly, we incorporated two contrasting urban segments, walking-friendly and car-friendly, which enriched our findings by providing a stronger basis for understanding how urban characteristics influence walking behavior and affective responses.

To minimize cybersickness, we implemented several practical precautions, as suggested by previous studies (Ghanbari et al., 2024; Ramaseri Chandra et al., 2022) and our own trial-and-error experience. These precautions included limiting exposure time to less than 10 min (including habituation), providing an eye-rest period by ensuring participants removed the headset between habituation and the main experiment, ensuring proper ventilation by keeping a window open to prevent overheating, and offering water and sweets. Additionally, the high sense of presence reported by participants may have contributed to the low incidence of cybersickness in this study, as previous research has shown that a lower sense of presence is a significant predictor of cybersickness (Jasper et al., 2023).

Lastly, we took several steps to reduce the novelty effects of VR, as a VE itself can be a factor in altering behavioral measures, as demonstrated in previous studies (Mousas et al., 2020). We incorporated a habituation phase before the main experiment in order to control for the effects of first exposure to VR.

4.4. Limitations

Despite these strengths and the feasibility of using VR in walking behavior studies, some limitations should be acknowledged.

First, while VR allows for controlled environmental attributes, certain aspects, such as weather variations and specific sensory cues (e.g., temperature and wind speed), remain beyond full experimental control, as noted in previous studies (Calogiuri et al., 2018; Ghanbari et al., 2024). We attempted to maintain indoor temperatures similar to the outdoor conditions (the RE) during data collection in Luxembourg (ranging from 4 to 24 °C) by keeping a window open; however, the participants' body temperatures were consistently lower in the RE. This may have influenced other physiological responses, including EDA. Furthermore, wind speed, which ranged from 5 to 24 km/h in the RE, could not be replicated in VR and may have also affected the physiological data.

Second, one of the main technology-oriented limitations of VR experiments is cybersickness. In this study, only one participant experienced severe cybersickness, causing us to stop the experiment. Among the rest, four participants reported mild symptoms, with one resolving immediately after removing the headset and the others fading between 30 min and 3 h, as confirmed via follow-up emails. We mitigated cybersickness risks through several measures as mentioned in the "Strengths" section, but its potential impact cannot be entirely ruled out. One potential hypothesis based on previous literature is that low display resolution and a restricted field-of-view can contribute to cybersickness (Ghanbari et al., 2024).

Third, while an omnidirectional walking simulator aims to offers a walking experience that is as realistic as possible, there is still room for improvement in terms of ergonomics to enhance the user experience.

Similar concerns have been noted in previous studies using different simulator brands (Birenboim et al., 2021; Kang et al., 2023). We observed that six participants had difficulties adjusting to the walking mechanism and the VE, highlighting a key takeaway from this study: the necessity of implementing a walking habituation phase without wearing a headset. We have further elaborated on this point in the "Future Directions" section.

Fourth, the relatively low number of participants and the use of a convenience sampling method in this study limit the generalizability of the findings to the general population.

Lastly, while we randomized the exposure to environments (the RE and VE), the sequence of segments (walking-friendly and car-friendly) was not randomized. This may have introduced order effects, such as adaptation effects or physiological carryover, which in turn may have influenced the participants' responses. Since the car-friendly environment was systematically experienced after the walking-friendly segment, we cannot rule out that the increased EDA and SCL in the virtual car-friendly segment (Table 6) partly reflect physical exertion while walking in the VE, rather than solely the expected stress-inducing characteristics of the car-friendly environment. Nonetheless, HR and NSSCR did not vary by segment type, and no differences by segment type were observed for the physiological responses in the RE. The psychological affective response model showed a systematically lower affective appraisal of the car-friendly segment than of the walking-friendly segment, independently of environment type (the VE or RE), suggesting a potential adaptation effect. Therefore, although the results are consistent with our second hypothesis, the associations between environment type and both physiological and psychological responses should be interpreted with caution. Replication studies with a randomization component for the segment type (car-friendly vs. walking-friendly) are warranted to fully disentangle the effects of environment type, segment type, and experimental design.

4.5. Future directions

Future research should build on the strengths of this study while addressing its limitations, to enhance the validity and applicability of VR-based walking studies.

One key aspect, as discussed in the "Limitations" section, is the necessity of implementing a habituation phase without a headset to help participants adapt more effectively to the walking simulator. Since almost all participants were unfamiliar with the device, wearing a VR headset from the beginning may have made it challenging for them to simultaneously adapt to both the VE and the walking mechanism. This may have introduced unintended cognitive load and stress, potentially influencing affective responses. Therefore, we recommend an initial habituation stage without wearing a headset, allowing participants to become comfortable with the walking simulator, followed by a subsequent stage with the headset. While this additional step may appear time-consuming, it is likely to improve participant comfort, reduce unnecessary stress, and enhance data reliability. Additionally, perceived exertion associated with the walking simulator should be considered as a potential confounding factor, as it may influence both physiological and affective responses in motion-based VR studies.

Furthermore, future studies should systematically investigate how variations in the field of view and the use of higher-resolution displays contribute to the sense of presence, incidence of cybersickness, and emotional engagement in immersive VR experiments.

Beyond methodological aspects, future research should also incorporate a larger and more diverse sample to enhance the generalizability of the findings. Given the significant differences we observed between real and virtual environments, replicating this study with a larger sample size would help quantify the magnitude of the differences. This would be crucial in validating VR as a tool for urban planning, ensuring that its application mimics real-world environments.

Furthermore, gait dynamics, such as changes in walking speed and step length, should be included in future studies, as they may have influenced participants' walking experiences.

5. Conclusion

Our findings indicate that while the VE consistently received lower affective ratings than the RE, the overall trends in psychological and physiological responses were closely mirrored. Furthermore, the significant differences across segment types, with car-friendly segments consistently associated with higher arousal and lower affective ratings in both the RE and VE, reinforce the validity of VR as a tool for assessing urban environmental influences. This study provides valuable insights into the feasibility and reliability of using VR to assess affective responses to urban environments.

Our research also contributes to the growing body of empirical evidence on how emerging technologies can inform policy interventions, particularly for policies stimulating healthier cities. By demonstrating both the potential benefits and limitations of VR-based studies, these findings reinforce the importance of refining VR methodologies to enhance realism and ecological validity, and account for individual variability in future research.

CRediT authorship contribution statement

Marzieh Ghanbari: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Dijst:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Reza Aghanejad:** Formal analysis, Data curation. **Sébastien Claramunt:** Software, Formal analysis. **Camille Perchoux:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of the use of AI

During the preparation of this work, the authors used Grammarly and ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chbr.2026.100950.

Data availability

The authors can provide further information about the data upon reasonable request, subject to any necessary approvals and agreements.

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