Real and Virtual Environment Mismatching Induces Arousal and Alters Movement Behavior

Christos Mousas* Purdue University West Lafayette, IN, U.S.A.
Dominic Kao† Purdue University West Lafayette, IN, U.S.A.
Alexandros Koilias‡ University of the Aegean Mytilene, Greece
Banafsheh Rekabdar§ Southern Illinois University Carbondale, IL, U.S.A.

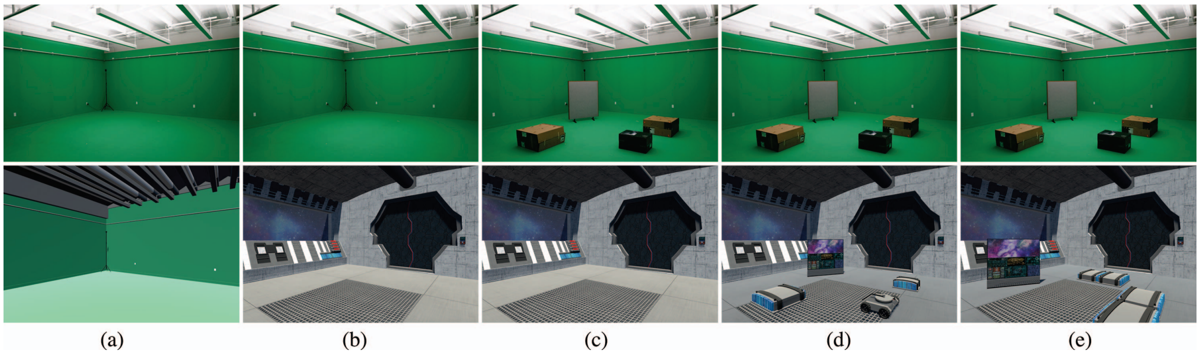


Figure 1: The five experimental conditions that were examined between the real (top) and virtual (bottom) environment. From left to right: (a) *Matched Appearance and No Constraints*, (b) *Mismatched Appearance and No Constraints*, (c) *Mismatched Appearance with Constraints*, (d) *Mismatched Appearance and Matched Constraints*, and (e) *Mismatched Appearance and Mismatched Constraints*.

Abstract

This paper examines a common problem found in a number of virtual reality setups—mismatches between real and virtual environments. Specifically, this paper investigates whether the mismatching between a real and a virtual environment in terms of appearance and physical constraints can affect the arousal (electrodermal activity) and movement behavior in the participants. For this study, one baseline condition and four mismatch conditions that examine different mismatching types were developed and tested in a between-group study design. The participants were immersed in a virtual environment and were asked to walk in a direction given to them along a provided path. During that time, electrodermal activity and the walking motion of participants were captured to assess potential alterations in their arousal and movement behavior respectively. Results obtained from this study indicate significant differences in the electrodermal activity and movement behavior of participants, especially when walking in a virtual environment that is mismatched both in appearance and physical constraints. Even though to a lesser degree, evidence was also found that correlates electrodermal activity with movement behavior. Limitations and future research directions are discussed.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

*e-mail: cmousas@purdue.edu
†e-mail: kaod@purdue.edu
‡e-mail: ctd17008@aegean.gr
§e-mail: brekabdar@cs.siu.edu

1 Introduction

Experiencing a virtual environment while being in a constrained, real environment (e.g., one's living room full of obstacles like couches, chairs, tables) might be problematic. Moving within that real environment while wearing a full-blind, head-mounted display may alter the psychological state of participants due to mistrust of the virtual environment. Generally, constrained real environments provide different challenges compared to virtual reality lab spaces. For example, in home or office virtual reality setups, the furniture constrains the walkable area, whereas virtual reality labs are typically large, empty rooms. Despite the fact that a number of mapping [70] and fitting [42] techniques have attempted to solve the mismatching problem; further experimentation is required in order to assess how deviations between virtual and real world may affect user psychology and movement behavior.

Most of the prior work on this topic has focused on locomotion within matched environments [13,36] or empty environments [60]. It has been found that the conflict between the provided visual stimuli of the virtual environment and the participant's knowledge of the real environment in which they are situated affects their navigational choices [66]. However, even though we do know that aesthetically mismatched real and virtual environments alter movement behavior in virtual reality users, less attention has been given to the user's psychological state. Therefore, more input is required on that exact type of mismatches which are responsible for affecting mental and physical behavior. In this paper, mental behavior is measured by capturing user physiological data, and, more specifically, electrodermal activity. It should be noted that based on Fowles [14] and Boucsein [6], electrodermal activity indicates physiological arousal [4, 33, 58] and can be used as a measuring medium for exploring one's emotional state.

Understanding the way alterations occur in arousal (electrodermal activity) and movement behavior when interacting within such environments can yield several beneficial applications which can prove useful for virtual reality developers. Thus, this paper investigates whether and what types of mismatches between a real and virtual environment (see Figure 1) might affect the electrodermal activity

2642-5254/20/$31.00 ©2020 IEEE
DOI 10.1109/VR46266.2020.00-19

(arousal) and movement behavior of virtual reality users. As a task, participants were asked to walk around the environment by simply following a provided path. Based on the collected data, this study aims at answering the following four research questions:

- **RQ1:** Are there differences in the electrodermal activity of participants across the five experimental conditions?
- **RQ2:** Are there differences in the movement behavior of participants across the five experimental conditions?
- **RQ3:** Are there differences in participants' behavior when interacting within completely mismatched environments compared to partially mismatched environments or identical environments?
- **RQ4:** Does arousal (psychological state) correlates with the movement behavior of participants when walking within mismatched real and virtual environments?

The remainder of this paper is organized as follows: related works are presented in Section 2, methodology and implementation details are given in Section 3, results are presented in Section 4 and are discussed in Section 5, and conclusions and potential future work are addressed in Section 6.

2 Related Work

Virtual reality is a powerful tool that can be used to conduct various experiments [39]. To date, it has been used to study movement behavior in sports [5], in tasks related to spatial cognition [41,49], in therapy and pain [25,26], phobia cases [15,57], and more. The advantage of virtual reality technology in studying human behavior, feelings, and perception is that it provides researchers the ability to control and manipulate the parameters of the stimuli, while the experimental conditions that participants are exposed to remain constant. Several studies have looked at the benefits and have evaluated the effects of virtual reality on human perception and behavior [40,61,63,75,76].

Mismatch between real and virtual environments and objects is an area within virtual reality that was introduced almost three decades ago [19] and has recently been revisited [66, 67]; yet, it remains an area that has not been examined thoroughly. So far, mismatching studies have examined the combination of visual and sensory feedback in studies related to neurology and perception [3, 43] and studies that have examined the combination of virtual environment substitution and movement behavior [66]. Hinckley et al. [19] mismatched a real object with a virtual one that could be considered similar but not identical; specifically, they used the head of a doll to control brain visualization. Barbagli et al. [3] explored the differentiation of forced direction of haptic feedback and how it influenced presented visual information. Matsuoka et al. [43] explored the tolerance for visual feedback distortions in a virtual environment and found that humans are not capable of reliably detecting inaccuracies during mismatched stimulus. Kwon et al. [37] investigated to what extent mismatching the shape and size of objects affected interaction usability and object presence. They found better results when both the size and the shape matched but found no significant results when size alone was altered. Finally, Simeone et al. [66] investigated whether aesthetical mismatch affected the movement behavior of participants. They found that indeed the aesthetic mismatch affected the movement of participants.

This paper has investigated the changes in user movement behavior when interacting within mismatched real and virtual environments. In general, walking and interacting within a virtual environment is an important feature that should be provided to users in a number of applications. Previous research has found that natural walking is the most realistic method for exploring virtual reality environments [73]. However, providing natural walking to virtual reality users in their home entertainment setup is quite challenging due to various issues, such as the potential size disparity between the real and virtual environments [60] and the existence of real objects located in the real environment that are not present in the virtual one [67]. To overcome this, a number of computational methods—the so-called locomotion interfaces that allow a user to navigate within a virtual reality environment—have been developed [60, 69, 71]. However, it is not always possible to use such methods in home setups or other locations which are not explicitly designed as a virtual reality lab. This is especially true when we bear in mind that in most cases the users must be seated or allowed to move only within small safe areas to mitigate the constraint problem.

Various studies have investigated human movement behavior in either real [20, 23, 24] or virtual environments [8, 13, 64]; however, very little attention has been given to whether and what types of mismatches between a real and virtual environment actually affect human movement behavior. Most virtual reality research that focuses on human movement behavior has been dealing with the recurring issues of human-virtual character interaction [45, 52]; walking in virtual environments and obstacle avoidance [32, 56]; human-object interaction, such as object manipulation [12, 65]; and the impact of head-mounted displays on human movement behavior [31, 48]. Such studies investigate how humans change their movement behavior when they are asked to interact with the given task. Beyond the positive correlations that have been found when studying real and virtual kinematic and biomechanical metrics [28], there is insufficient research on how human movement is altered when immersed in a real environment [29].

In addition to human movement changes caused by virtual and real environment mismatches, the study is also examining how these changes may affect electrodermal activity in the participants. The aim is to confirm or not the hypothesis that the use of the full-blind, head-mounted display may be responsible for inducing in the participants a sense of disorientation and loss of direction. Based on written literature, feelings of lostness in real-life situations do induce arousal [11, 44, 74] just as aesthetic mismatches cause changes in human movement behavior [66].

Our research considers findings from prior studies [16, 68], which use physiological data in order to explore sensory mismatches, and we examine these by using three different directions. First, we investigate the arousal of participants when they interact with mismatched real and virtual environments in order to examine whether the missing knowledge of spatial constraints in real environments actually induces arousal. Second, apart from exploring a global representation of body movement (speed and trajectory deviation of root joint), we also assess local body movement (step length and step duration) of participants, which is important in understanding how participants regulate their movements in a more detailed manner. Third, beyond examining appearance mismatches we also assess mismatches related to spatial constraints to further understand how different mismatching types affect the arousal and movement behavior of participants. We believe this study functions predominantly as an extension to prior works, but it also introduces important data that should be considered when developing virtual reality applications for mismatched environments.

3 Materials and Methods

This section presents the details of the study which examine whether the mismatching between real and virtual environments has altered participants' electrodermal activity and movement behavior. The subsections describe the implementation details and the procedure that was followed.

3.1 Participants

The participants were recruited through posters placed on notice boards across campus, class announcements, and e-mails. The participant group was comprised of 100 healthy individuals (both students and faculty) that were divided into five groups of 20. All participants were volunteers and there was no type of compensation involved. Of the total participants, 31 were female ($M = 22.35$, $SD = 2.85$) and 69 were male ($M = 23.16$, $SD = 2.45$). Thirty-eight had no prior experience with virtual reality. Also, none of the participants experienced motion sickness during the experiment. Participants were provided written consent as dictated by the Institutional Review Board of our university.

3.2 Real and Virtual Environments

This study was performed at the motion capture studio of our department. The dimensions of the studio are 8 meters long, 8 meters wide, with the ceiling height at 4 meters. These dimensions were used to approximate the design of the virtual environments used in the study. We removed all furniture from the lab in order for it to be as empty as possible. For the purpose of this experiment, two different environments were designed. The first one was a replica of the motion capture studio that was used as our baseline environment. The second one was an imaginary environment that was designed to let us investigate the alteration of human electrodermal activity and movement behavior. Both the real and virtual environments used for this study are shown in Figure 1. Both the replica environment and the imaginary environment were designed in the Autodesk 3ds Max.

3.3 Conditions of the Experiment

For this experiment, we developed five experimental conditions in a way as to help us understand how and if participants' prior knowledge of spatial constraints in the real environment could alter their arousal and movement behavior when they were immersed in a virtual environment. The following five conditions (see also Figure 1 for visual illustration) were developed and examined in this paper:

- **Matched Appearance and No Constraints:** This is a baseline condition. The virtual environment is a replica of the real environment in which the experiment was conducted. This baseline condition was used in order to capture the way that participants move and respond in an unconstrained environment and conditions. No obstacles were in either the real or virtual environments during this condition.

- **Mismatched Appearance and No Constraints:** This condition presents an imaginary environment that matches the spatial constraints of the virtual environment. No obstacles were in either the real or virtual environments during this condition.

- **Mismatched Appearance with Constraints:** This condition uses the imaginary environment, and there is a mismatching of the appearance between the real and the virtual environments. Spatial constraints were added in the real environment by placing obstacles (carton boxes and a notice board). Obstacles do not show in the virtual environment. Note that participants were aware of the obstacles as the obstacles were placed there before the start of the experiment.

- **Mismatched Appearance and Matched Constraints:** This condition uses the imaginary environment, and the obstacles (carton boxes and a notice board) in the real environment are substituted with virtual objects in the virtual environment. The sizes of the objects in the virtual environment match the sizes of the obstacles in the real environment. As in the previous condition, the participants were aware of the obstacles placed in the real environment.

- **Mismatched Appearance and Mismatched Constraints:** This condition uses the imaginary environment, and there is a mismatching of both the appearance and the spatial constraints between the real and the virtual environments. The spatial constraints mismatching was achieved by placing obstacles (carton boxes and a notice board) in the real environment. Specifically, the position of obstacles in the virtual environment do not match the position of obstacles in the real environment. Note that participants were aware of the position of real obstacles as the obstacles were placed in the real environment before the start of the experiment.

The first condition was used as our baseline since it was considered to be the ideal condition in which a participant can experience walking within a virtual environment. The other four conditions can be considered as typical cases when experiencing virtual reality. Specifically, in most lab or home virtual reality setups, virtual reality users tend to interact with an imaginary virtual environment that does not match the lab or home appearance and layout.

3.4 Equipment and Virtual Reality Application

The devices used for this study were the MSI VR One backpack computer (Intel Core i7, NVIDIA GeForce GTX 1070, 16GB RAM) for running the virtual reality application, the HTC Vive Pro head-mounted display for projecting the virtual reality content, the Xsens motion capture system for transferring the motion of participants within the virtual environment and for capturing their motion, and finally the Shimmer3 GSR+[1] electrodermal activity sensor was used for capturing the physiological responses of participants. Note that a virtual reality backpack computer was used to avoid wiring all devices to a base station and to ensure that participants were able to walk properly and unobstructed in the virtual environment; therefore, by doing so, we ensured that movement alteration due to the presence of cables was eliminated and that the virtual reality content was transmitted at the proper frame rate. The application used for this study was developed in the Unity 3D game engine version 2019.1.4.

Even though we used a motion capture system, which means that the movements of the participants could be retargeted to a self-avatar within the virtual environment, we decided not to assign a self-avatar that would represent the participant within the virtual environment. This decision was made for two reasons. First, we know from a previous study that self-avatars alter the movement behavior of participants [53]. Second, most users who experience virtual reality use consumer-grade headsets that provide spatial navigation without the presence of motion capture systems; however, in order to represent a user in the virtual environment, a motion capture system is required. Therefore, since experiencing virtual reality with the use of a motion capture system from the comfort of our living room is highly uncommon, participants were not represented with a self-avatar. Nevertheless, possible limitations on user representation are discussed later.

The blueprint of the real environment layout is shown in Figure 2(a) and the predefined path the participants were asked to follow is shown in Figure 2(b). All participants were asked to follow the exact same path. The path course would appear progressively on the ground in the form of a rendered line that the participants would follow (see Figure 2(c)). In designing the predefined path, we considered the proxemics model [21, 22, 50]. The minimum distance between the points of the path and obstacles/walls was set at a distance of 23 cm (the diameter of the far phase of the intimate space is 46 cm). Therefore, we made sure that all participants had enough clearance to move relatively comfortably within the virtual space. It should be noted that the total distance participants had to cover was 150 meters. The rationale for choosing such a long walk was based on our assumption that even though participants were aware of the spatial constraints in the real environment, after walking through various positions within the virtual environment, they would expectedly become unaware of their spatial position with respect to the obstacles. This sense of disorientation (lostness) is what we

[1]https://www.shimmersensing.com/products/shimmer3-wireless-gsr-sensor

wanted to induce to our participants during this study to investigate possible alterations in their arousal and movement behavior.

We decided to have a line displayed on the ground, in front of the participant (see Figure 2(c)), which would indicate the path participants had to follow. Our intention was to examine how closely participants would adhere or how far they would deviate from the specified course. At this point it should be noted that a past study [66] has shown that placing obstacles on the boundaries of the real environment, while also giving abstract guidelines for reaching a position within the virtual environment, can cause participants to deviate from the optimal path (straight line between two waypoints) of direction when moving in mismatched real and virtual environment.

3.5 Measurements

Objective measurements (electrodermal activity and movement behavior) were collected to investigate possible variations in the participants' behavior during the experiment. The following sub-sections describe the measurements in detail.

3.5.1 Electrodermal Activity Features

To record electrodermal activity, we identified and calculated the number of peaks and their average amplitudes throughout the experiment. These procedures enabled us to examine both the frequency and the intensity of physiological arousal in the participants. Note that the electrodermal activity sensor cannot determine the valence of emotion; it can only ascertain increases in physiological arousal [30]. Such increases are defined as the necessary condition for the elicitation of an emotional state [6].

With regard to the recording procedure, we first captured baseline measurements of electrodermal activity in all our participants and then calibrated the measurements accordingly. Baseline measurement can indicate whether certain participants are likely to be hyper- or hypo-responders, independent of any effects of psychological manipulation. Following the recommendation of Braithwaite et al. [7], we implemented the necessary baseline measurements by directing the participants to walk within a real-world setting for two minutes without wearing the head-mounted display and without engaging in a virtual environment. A description of each calculated variable is given below:

- **Number of Peaks:** This variable refers to the total number of peaks found in the captured data. Ensuring an objective comparison of conditions necessitated the normalization of peaks in accordance with the duration of the trial. The number of peaks is considered the best direct indicator of arousal [30] (more peaks indicate higher arousal levels).

- **Amplitude of Peaks:** This variable pertains to the average amplitude of all peaks found in the capture data. The average amplitude of peaks determines the intensity of physiological arousal (a higher amplitude translates to a more intense experience). In this study, peak amplitude was measured in microsiemens (μS).

3.5.2 Movement Behavior Features

A motion capture system was used to record the movement behavior of participants under the assigned experimental conditions. Several different measurements based on the recordings can be extracted [8, 27, 69]. Our goal was to get both global and local input on how participants walked within the virtual environment. To obtain global input, we computed the average speed of the participants and the average deviation from the provided path (see Cirio et al. [8]). These measurements provided spatiotemporal information about the participants' movement behavior. To obtain local input, we computed step length and step duration (see Hollman et al. [27]). A description of each computed variable is given below:

- **Speed:** The average speed of the participants' motion when following the provided path. The speed was measured in meters per second.

- **Deviation:** The deviation was computed between the defined path and the one followed by the participant. For the deviation, the absolute value was computed in meters.

- **Step Length:** The length of each step (distance between two feet when both collide with the ground). The length was measured in meters. The step length was computed after segmenting the motion in single step segments [51].

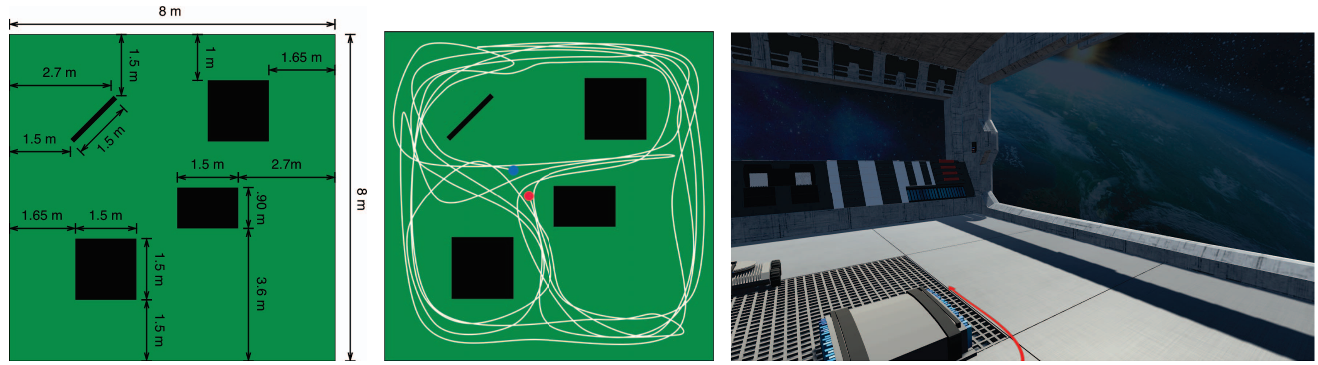
- **Step Duration:** The time that was used by each participant to perform a single step. The step duration was computed in seconds. The duration for each step was estimated after segmenting the motion in single step segments [51].

3.6 Procedure

The experiment was conducted in the motion capture studio of our department. Once the participants arrived at the studio, the experimenter briefed all participants on the project and the equipment they would have to wear. Before the commencement of the experiment, participants were asked to sign the provided consent form and complete a demographics questionnaire, both provided in paper-based format. Then, the experimenter helped the participants put on the necessary equipment. First, the motion capture system was attached to the participants' body and then followed the calibration process. Next, the participants were asked to wear the backpack computer and were provided assistance when necessary. When the computer was set, the experimenter helped each participant attach the Shimmer sensor using a wrist strap on the wrist of the non-dominant hand. The electrodes of the electrodermal activity sensor were placed on the index and middle finger of each participant. At this point, participants were asked to take a short walk in the real environment (motion capture studio) to ensure that they were able to move comfortably when wearing all the required equipment and devices. Next, the experimenter assisted the participants with the head-mounted display.

After the participants were familiarized with the virtual reality equipment, the experimenter asked them to move toward a location in the middle of the real environment indicated with a marked area on the ground. Participants were told that once the application began, they would be placed in a virtual environment and that a line would appear in front of them indicating the course of the path that should follow (see Figure 2(c)). Participants were instructed that the only task they had to perform was to follow the path that would appear and that the path would progressively unfold as they moved. No other description about the environment was shared. Participants were also told that an on-screen cue would inform them once the experiment process was done.

The virtual reality condition to which each participant would be exposed was not mentioned. Note that the participants participated only in one of the five experimental conditions. Participants saw the virtual environment only when the experiment had begun. It should also be noted that participants were able to observe the structure of the real environment and the obstacles located within it during the corresponding conditions. Participants were informed that if they felt tired or uncomfortable and wanted to stop the experiment, they had full permission to do so at any time without consequences. Once the walking task of the experiment was completed, the participants were asked to remove the head-mounted display and all attached equipment with the help of the experimenter. They were thanked for their participation and then they were finally informed by the experimenter about the objectives of the study. Participants were also allowed to ask any questions upon completion of the study. The total duration of the experiment including the calibration process of the motion capture system did not exceed 45 minutes.



(a) (b) (c)

Figure 2: (a) The blueprint of the real environment. (b) The path participants were asked to follow. The red dot indicates the starting point and the blue dot indicates the destination (final) point. (c) The red line indicates the progressive display of the path which participants had to follow as they were moving along within the virtual environment.

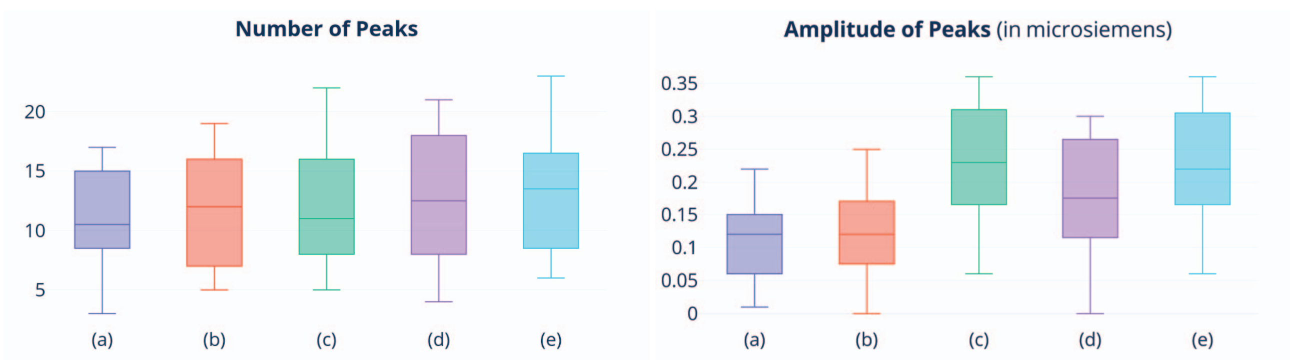


Figure 3: The electrodermal activity measurements for all examined conditions: (a) *Matched Appearance and No Constraints*, (b) *Mismatched Appearance and No Constraints*, (c) *Mismatched Appearance with Constraints*, (d) *Mismatched Appearance and Matched Constraints*, and (e) *Mismatched Appearance and Mismatched Constraints*.

4 Results

This section presents the results obtained from the study. All the analyses were performed using the IBM SPSS v. 23.0 [54] software. A one-way analysis of variance (ANOVA) was used to analyze the data, using the five conditions as independent variables and the collected data (electrodermal activity and movement behavior) as dependent variables. The normality assumption of the measurements was evaluated graphically using Q-Q plots of the residuals [18]. The Q-Q plots indicated that the obtained data had fulfilled the normality assumption. The homogeneity variance assumption was also evaluated via the residual plots; which exhibited no indication of heteroscedasticity. The individual differences were assessed using a post-hoc Bonferroni test if the ANOVA was statistically significant. A $p < .05$ value was judged as statistically significant. All collected data were screened for correlations using the Pearson product-moment correlation coefficient. Lastly, in order to test participant homogeneity, we defined the five conditions as independent variables and the height of the participants as dependent variables. A one-way ANOVA revealed no significant results [$F(4,95) = .791$, $p = .534$].

4.1 Electrodermal Activity Data

We compared the obtained electrodermal activity data (number of peaks and amplitude of peaks) across the five experimental conditions to examine whether the mismatched environments altered the levels of arousal in our participants. The results for the electrodermal activity are illustrated in Figure 3, and descriptive statistics are provided as supplementary material.

No significant results were found at the $p < .05$ level with respect to the **number of peaks** [$F(4,95) = .484$, $p = .747$]. However, we did find significant results in the participants' **amplitude of peaks** across the five experimental conditions [$F(4,95) = 9.480$, $p < .001$]. Pairwise comparisons show that the mean amplitude of peaks during the *Matched Appearance and No Constraints* condition was significantly lower than that for the *Mismatched Appearance with Constraints* condition at the $p < .001$ level and the *Mismatched Appearance and Mismatched Constraints* condition at the $p < .001$ level. Moreover, the mean amplitude of peaks during the *Mismatched Appearance and No Constraints* condition was significantly lower than that for the *Mismatched Appearance with Constraints* condition at the $p < .001$ level and the *Mismatched Appearance and Mismatched Constraints* condition at the $p < .001$ level.

4.2 Movement Behavior

We compared the obtained global and local movement behavior features (speed, deviation, step length, step duration) across the five experimental conditions to examine whether the mismatch between real and virtual environments altered participants' movement behaviors. The results for the movement behavior features are illustrated in Figure 4, and descriptive statistics are provided as supplementary material. Finally, for visualization purposes, the averaged captured trajectories for each examined condition are shown in Figure 5.

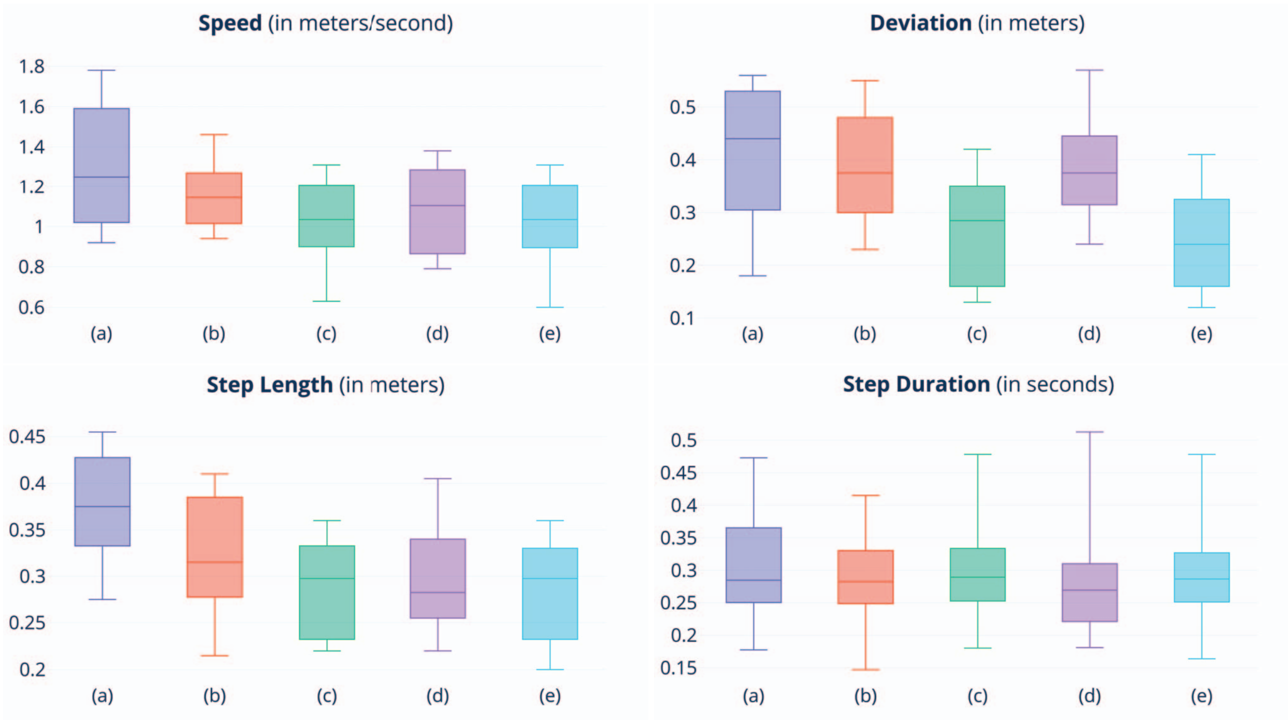


Figure 4: The movement behavior features measurements for all examined conditions: (a) *Matched Appearance and No Constraints*, (b) *Mismatched Appearance and No Constraints*, (c) *Mismatched Appearance with Constraints*, (d) *Mismatched Appearance and Matched Constraints*, and (e) *Mismatched Appearance and Mismatched Constraints*.

Regarding the movement behavior features that describe the global motion of participants, we found a significant effect on the participants' **speed** across all five experimental conditions [$F(4,95) = 5.982$, $p < .001$]. Pairwise comparisons show that the mean score for the *Matched Appearance and No Constraints* condition was significantly higher than that for the *Mismatched Appearance with Constraints* condition at the $p < .001$ level, the *Mismatched Appearance and Matched Constraints* condition at the $p < .05$, and the *Mismatched Appearance and Mismatched Constraints* condition at the $p < .001$ level. We also found a significant effect on the participants' **deviation** from the provided path across the five experimental conditions [$F(4,95) = 9.653$, $p < .001$]. Pairwise comparisons show that the mean score for the *Mismatched Appearance with Constraints* condition was significantly lower than that for the *Matched Appearance and No Constraints* condition at the $p < .001$ level, the *Mismatched Appearance and No Constraints* condition at the $p < .01$ level, and the *Mismatched Appearance and Matched Constraints* condition at the $p < .01$ level. Moreover, the pairwise comparisons show that the mean score for the *Mismatched Appearance and Mismatched Constraints* condition was significantly lower than that for the *Matched Appearance and No Constraints* condition at the $p < .001$ level, the *Mismatched Appearance and No Constraints* condition at the $p < .01$ level, and the *Mismatched Appearance and Matched Constraints* condition at the $p < .01$ level.

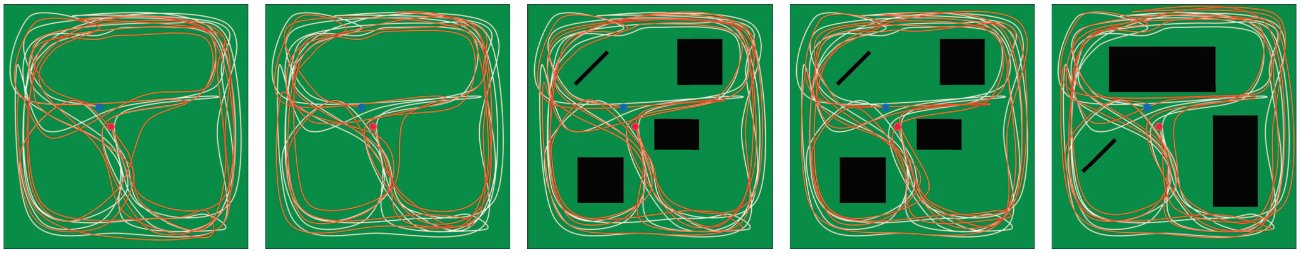
Regarding the movement behavior features that describe the local motion of participants, we found a significant effect on the participants' **step length** across all five experimental conditions [$F(4,95) = 9.226$, $p < .001$]. Pairwise comparisons show that the mean score for the *Matched Appearance and No Constraints* condition was significantly higher than that for the *Mismatched Appearance and No Constraints* condition at the $p < .05$ level, the *Mismatched Appearance with Constraints* condition at the $p < .001$ level, the *Mismatched Appearance and Matched Constraints* condition at the $p < .001$ level, and the *Mismatched Appearance and Mismatched Constraints* condition at the $p < .001$ level. No significant results were found at the $p < .05$ level with respect to the **step duration** of the participants' motion [$F(4,95) = .170$, $p = .616$].

4.3 Correlation Between Data

We conducted a correlation analysis to investigate possible correlations between the collected datasets (electrodermal activity and movement behavior). The Pearson product-moment correlation coefficient was used for screening the data. Based on the conducted correlation analyses, we were able to identify a negative weak downhill linear correlation between **peaks amplitude** and **step length** [$r = -.280$, $n = 100$, $p = .005$], between **peaks amplitude** and **deviation** [$r = -.238$, $n = 100$, $p = .017$], and between **number of peaks** and **step length** [$r = -.276$, $n = 100$, $p = .007$].

5 Discussion

For this study, five experimental conditions were developed to examine the effects of mismatches between a real environment and a virtual environment on participants' electrodermal activity (arousal) and movement behavior. The obtained results from the electrodermal activity measurements (**RQ1**) showed that there were alterations in participants' arousal in the group that experienced the *Mismatched Appearance with Constraints* and the *Mismatched Appearance and Mismatched Constraints* conditions. Although we were not able to find a difference in the number of peaks, the amplitude difference is quite important and indicates that the intensity, which the participant group experienced the *Mismatched Appearance with Constraints* and the *Mismatched Appearance and Mismatched Constraints* conditions, was higher than the two conditions in which no obstacle were present in the real environment. Since no significant difference was found between the conditions *Mismatched Appearance with Constraints* and *Mismatched Appearance and Mismatched Constraints*,



(a) (b) (c) (d) (e)

Figure 5: Visualization of the average trajectories (red) of all participants for each of the examined conditions ((a) *Matched Appearance and No Constraints*, (b) *Mismatched Appearance and No Constraints*, (c) *Mismatched Appearance with Constraints*, (d) *Mismatched Appearance and Matched Constraints*, and (e) *Mismatched Appearance and Mismatched Constraints*) and the defined path (white).

it can be said that the participants exhibit similar physiological states when placed in a constrained real-world environment and instructed to walk in a virtual environment in which virtual obstacles are either missing or mismatched. This phenomenon indicates that regardless of whether participants are exposed to *Constraints* or *Mismatched Constrains* situations, their prior knowledge of real-world obstacles exerts similar effects on participants' physiological responses.

According to previous studies [17, 34, 46, 72], the appearance of the virtual environment itself can be a factor in altering arousal levels in participants. In this study, the intentionally produced constraint-related mismatches is what triggered changes in the participants' behavior. Even though past studies on peak measurement have produced mixed results [1, 35], and therefore, rendering this method somewhat uncertain when assessing arousal, based on the statistically significant differences we found in the amplitude of the peaks we can safely say (**RQ3**) that when participants are immersed in a virtual environment that mismatches the real one in terms of appearance and spatial constraints, participant arousal (intensity levels) is indeed triggered. This is an indication that such environments challenge participants and induce psychological tension.

When participants were asked to comment on their experiences, a few mentioned that once they lost awareness of the real environment, they became worried and even afraid of colliding with obstacles. This finding seems to be in line with previous studies that have indicated a correlation between fear and arousal [2, 9, 10, 55]. Thus, it can be inferred that there is some evidence which implies that arousal might be triggered or affected due to the fear of colliding with real-world obstacles.

The results from the motion-features measurements (**RQ2**) indicate the following. From a global point of view, participants tended to move slower in the virtual environment when obstacles were located within the real environment compared to the conditions in which no obstacles were present. This is an interesting result that expands on a previous study indicating that aesthetically mismatched real and virtual environments alter the movement behavior in participants. Specifically, our findings come in a partial agreement with Simeone et al. [66], which have also detected that the presence of obstacles (and walls) has a similar effect. Contrary to our study, in Simeone et al. [66] deviation levels seem to increase rather than decrease. We interpret this as follows. In our study, the obstacles were located in the middle of the environment and not on the edges (boundaries). Moreover, we provided the participants with a specific path to follow instead of providing them with an abstract guideline on how to reach specified waypoints. It can be argued that due to the fear of colliding with real-world obstacles, participants tended to comply better with the provided path; therefore, the deviation levels decreased. It should also be noted that participants exposed in the *Mismatched Appearance and Mismatched Constraints* condition told us that even though they were trying to follow the provided path as closely as possible, they were still cautious since they felt the need to avoid colliding with objects and walls, which implies that participants felt unsafe.

From a local point of view, we found that when participants were placed in mismatched conditions, the step length decreased. This decrease in the step length is another interesting finding. It shows from a local point of view how participants tended to regulate their stepping motion. For us, it looks like participants did not feel safe enough to perform long steps but rather short ones in order to move to an area closer to their current position. We believe that participants made this decision in an attempt to maintain their balance in a way that would allow them to be in full control in the event of an unexpected situation. Although we found significant results in speed, deviation, and step length, no such differences were found in the step duration across the five experimental conditions. Based on the statistically significant differences, it can be said (**RQ3**) that the participants regulated their movement behavior differently when interacting within the three mismatched conditions that include spatial constraints compared to the matched in appearance with no constraints condition. In other words, when participants are immersed in imaginary environments while knowing that there is no matching in terms of spatial constraints, they tend to be more cautious with their movement behavior compared to when they are immersed within an identical virtual environment.

Apart from the differences across the examined conditions, we also explored possible correlations among the different forms of data that were collected. Although only weak correlations were found, the results indicate that changes in the participants' movement correlate with electrodermal activity (**RQ4**). There are various findings that correlate electrodermal activity and subjective self-reported ratings [35, 62]. However, in this study, the finding that correlates the movement behavior with the electrodermal activity is quite intriguing and unexpected.

Our findings indicate that when arousal increases, step length and deviation from the provided path decrease. Based on discussions we had with participants, this is due to participants being unaware of the real environment. Participants felt fear induced by the possibility of colliding with the real-environment obstacles and therefore decided to manipulate their movements with caution. Although there is a previous study which has correlated physiological activity with motor control [47], we cannot adamantly support that electrodermal activity could function as an index for human movement behavior due to the weak correlations. Such correlations demand further investigation in order to conclude whether a walking task with matching and mismatching conditions could be used as a method to determine human behavior. Thus, more in depth and focused studies should be conducted in order to obtain more reliable and conclusive results with respect to this finding.

5.1 Limitations

Besides the promising findings that our study has yielded, there are a few limitations that should be addressed. The first is related to electrodermal activity. We are aware that if we wish to accurately measure degrees of arousal alterations, electrodermal activity should be captured within a 1-to-5-second post-stimulus window in order to determine whether there is an association between electrodermal activity and specific events happening within a virtual environment [30]. We are also aware that while electrodermal activity data provide alteration measurements in arousal, according to Lazzaro [38], the captured data can also be affected by muscle activity, such as limb movement, which is quite important for virtual reality interaction. Due to the nature of the task that our participants were asked to perform, both limb movements and head turns were continuous. In addition, instead of capturing event-related electrodermal activity, we performed our analysis on a continuous captured signal.

Although we have found significant results in the amplitude of peaks, as well as some weak evidence on electrodermal activity and participant movement behavior correlations, we are not sure whether such a finding can be considered as a regular occurrence. Due to the targeted scope of the experiment in which participants are instructed to perform a walking task, there is a likelihood that the locomotion of participants introduced noise and subsequently interfered with the captured signal. Therefore, there is a chance that the significant effects that were found when examining the results of the electrodermal activity might be random instead of regular. At this point, we would like to note that we had somewhat suspected that such an occurrence would have happened prior to the commencement of the experiment. However, since we were aware that such noise effect would be included in the data captured from all participants alike, we assumed that the effect from noise would be similar for all and therefore deemed that this would not cause problems with our findings.

The second limitation is related to the way participants were depicted within the virtual environment. Our conscious choice to omit including virtual presence for the participants' body might have caused them to move differently since they had no feedback in respect to their exact position and size of their body and also in respect to the obstacles and other spatial constraints within the virtual environment. Therefore, it is assumed that additional experimentation in which participants are represented with a self-avatar might provide interesting and quite possibly varying results. However, in an attempt to accurately simulate real-life virtual reality users, in this study we decided not to assign participants a self-avatar since in most cases people who use virtual reality in home setups do not use a motion capture system that transfers their motion to a self-avatar. Therefore, the benefit of not using a self-avatar is that the outcome findings represent a greater percentage of the population of virtual reality users.

A third limitation is that for the purposes of this experiment we examined just five conditions even though we could have added more (e.g., the Matched Appearance and Matched Constraints condition). However, in our case, we decided to limit our study to the five conditions since in real life it is more common to have users experience a virtual environment that is different from their real home environment, in terms of appearance and constraints. Moreover, it is also quite common for users to experience a virtual environment in the presence or real-world obstacles. However, to further understand the effects that appearance and constraint mismatches between real and virtual environments may have on arousal and movement behavior, further studies that investigate additional interaction scenarios, such as Matched/Mismatched Appearance versus Matched/Mismatched Constraints and Matched/Mismatched Appearance versus Constraints/No Constraints, seem imperative. In addition, among the five experimental conditions, four were set as mismatched appearances. Including more conditions of *Matched Appearance* as a comparison against those reflecting *Mismatched Appearance* might generate valuable results. Moreover, a factorial design with appearance and physical constraints as two independent variables may render results easier to interpret.

Our intention was to capture the emotional experience of participants as they walk within virtual environments that do not necessarily match the appearance and constraints of a real environment. Unfortunately, the electrodermal activity sensor can provide only data concerning the arousal levels of participants. Thus, the last limitation we wish to acknowledge is the omission of a questionnaire. That is, because an emotional experience is characterized by its valence and arousal level, additional self-reported emotion ratings are necessary to explore other emotional dimensions, such as stress and confidence. The reason we decided at first not to use one was based on past studies [59] which have indicated that self-reported responses are highly subjective and do not always correspond to the actual experience of the participant. However, upon completion of the experiment and after having several discussions with our participants we realized the fear of colliding with real objects was an additional factor which affected movement behavior. Therefore, it seems critical that our future studies should include questionnaires as they have proven to be quite useful in extracting important feedback.

Concluding the limitation section, we note that the fear of colliding with real-world obstacles might have also induced mistrust in our participants when they were asked to walk within the virtual environment. In general, mistrust can be caused by either false-positive experiences, in which an obstacle appears in a virtual environment but is missing in the real one, or false-negative experiences, wherein an obstacle is present in the real environment but not in the virtual one. Although we probed into false-positives, the experimentation characterized by false-negative conditions seems to be critical in the derivation of valuable information regarding the mistrust of participants and their fear of collision with real and virtual obstacles.

5.2 Design Considerations

We believe that the data extracted from examining human behavior within mismatched real and virtual environments should be documented for future consideration when developing virtual reality applications. Thus, we would like to reflect on how our conclusions can aid the design of virtual environments. Considering that mismatches in terms of appearance and constraints affected both the arousal and the movement behavior of participants, it is necessary for techniques that map virtual to real [70] or real to virtual environments [42] not to be limited to a 1-to-1 mapping process but to also take into account additional clearance area that will need to be provided to users. Moreover, including visual feedback (e.g., a line of the path 'or other visuals indicating the clearance area) could be a solution in a design that would enhance user spatial awareness since this study shown that, when exposed to a constrained environment, users are then likely to be more precise in following a visual path (visual guidance).

6 Conclusions and Future Work

Understanding the way a virtual reality participant's behavior changes when interacting within virtual environments, which do not match the appearance and constraints of the real ones, might help developers build virtual reality experiences, including navigation and interaction within such environments, that can be considered more precise and thus more efficient. As a result, user engagement and immersion would also improve. In this paper, we studied the impact that real and virtual environment mismatching had on participants' arousal and movement behavior. Our results indicate a number of different effects which go beyond previous findings. The obtained findings indicate that the mismatching between real and virtual environments indeed affects the electrodermal activity (arousal) and movement behavior of our participants; however, this was more obvious when there were both appearance and constraints mismatches between the real and the virtual environments. Finally, we found some weak evidence that correlates electrodermal activity with movement behavior.

Apart from the mentioned limitations that need further exploration, we would like to expand our work to different domains that are related to trust and comfort in mismatched real and virtual environments. We are planning to continue using motion capture and electrodermal activity to better understand human behavior; however, we are planning to enhance the collected data by taking into account the gaze of participants. It is highly hypothesized that the use of a head-mounted display with embedded eye-tracking functionality would provide useful insights into the distribution and duration of gaze fixations, which will help us understand how participants locate their ongoing and forthcoming walking steps within a virtual environment. Finally, the unexpected correlation that was found between electrodermal activity and human movement will function for us as a stimulant to further explore this direction with all its implications in the near future.

References

[1] J. Bakker, M. Pechenizkiy, and N. Sidorova. What's your current stress level? detection of stress patterns from gsr sensor data. In *2011 IEEE 11th international conference on data mining workshops*, pp. 573–580. IEEE, 2011.

[2] O. Bălan, G. Moise, A. Moldoveanu, M. Leordeanu, and F. Moldoveanu. Fear level classification based on emotional dimensions and machine learning techniques. *Sensors*, 19(7):1738, 2019.

[3] F. Barbagli, K. Salisbury, C. Ho, C. Spence, and H. Z. Tan. Haptic discrimination of force direction and the influence of visual information. *ACM Transactions on Applied Perception (TAP)*, 3(2):125–135, 2006.

[4] D. E. Berlyne. *Conflict, arousal, and curiosity.* McGraw-Hill Book Company, 1960.

[5] B. Bideau, R. Kulpa, N. Vignais, S. Brault, F. Multon, and C. Craig. Using virtual reality to analyze sports performance. *IEEE Computer Graphics and Applications*, 30(2):14–21, 2009.

[6] W. Boucsein. *Electrodermal activity*. Springer Science & Business Media, 2012.

[7] J. J. Braithwaite, D. G. Watson, R. Jones, and M. Rowe. A guide for analysing electrodermal activity (eda) & skin conductance responses (scrs) for psychological experiments. *Psychophysiology*, 49(1):1017–1034, 2013.

[8] G. Cirio, A.-H. Olivier, M. Marchal, and J. Pettre. Kinematic evaluation of virtual walking trajectories. *IEEE transactions on visualization and computer graphics*, 19(4):671–680, 2013.

[9] J. Diemer, G. W. Alpers, H. M. Peperkorn, Y. Shiban, and A. Mühlberger. The impact of perception and presence on emotional reactions: a review of research in virtual reality. *Frontiers in psychology*, 6:26, 2015.

[10] J. Diemer, N. Lohkamp, A. Mühlberger, and P. Zwanzger. Fear and physiological arousal during a virtual height challenge—effects in patients with acrophobia and healthy controls. *Journal of anxiety disorders*, 37:30–39, 2016.

[11] S. Dolnicar et al. Fear segments in tourism. *CAUTHE 2005: Sharing Tourism Knowledge*, p. 196, 2005.

[12] L. Dominjon, A. Lécuyer, J.-M. Burkhardt, P. Richard, and S. Richir. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 19–25. IEEE, 2005.

[13] P. W. Fink, P. S. Foo, and W. H. Warren. Obstacle avoidance during walking in real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, 4(1):2, 2007.

[14] D. C. Fowles. The three arousal model: Implications of gray's two-factor learning theory for heart rate, electrodermal activity, and psychopathy. *Psychophysiology*, 17(2):87–104, 1980.

[15] A. Garcia-Palacios, H. Hoffman, A. Carlin, T. Furness Iii, and C. Botella. Virtual reality in the treatment of spider phobia: a controlled study. *Behaviour research and therapy*, 40(9):983–993, 2002.

[16] L. Gehrke, S. Akman, P. Lopes, A. Chen, A. K. Singh, H.-T. Chen, C.-T. Lin, and K. Gramann. Detecting visuo-haptic mismatches in virtual reality using the prediction error negativity of event-related brain potentials. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, p. 427. ACM, 2019.

[17] M. Geiser and P. Walla. Objective measures of emotion during virtual walks through urban environments. *Applied Sciences*, 1(1):1–11, 2011.

[18] A. Ghasemi and S. Zahediasl. Normality tests for statistical analysis: a guide for non-statisticians. *International journal of endocrinology and metabolism*, 10(2):486, 2012.

[19] J. C. Goble, K. Hinckley, N. F. Kassell, and R. Pausch. Passive real-world interface props for neurosurgical. In *CHI Conference on Human Factors in Computing Systems*, pp. 452–458, 1994.

[20] M. M. Gross, E. A. Crane, and B. L. Fredrickson. Effort-shape and kinematic assessment of bodily expression of emotion during gait. *Human movement science*, 31(1):202–221, 2012.

[21] E. T. Hall. A system for the notation of proxemic behavior 1. *American anthropologist*, 65(5):1003–1026, 1963.

[22] E. T. Hall. *The hidden dimension*, vol. 609. Garden City, NY: Doubleday, 1966.

[23] J. M. Hausdorff, C. Peng, Z. Ladin, J. Y. Wei, and A. L. Goldberger. Is walking a random walk? evidence for long-range correlations in stride interval of human gait. *Journal of Applied Physiology*, 78(1):349–358, 1995.

[24] J. M. Hausdorff, P. L. Purdon, C. Peng, Z. Ladin, J. Y. Wei, and A. L. Goldberger. Fractal dynamics of human gait: stability of long-range correlations in stride interval fluctuations. *Journal of applied physiology*, 80(5):1448–1457, 1996.

[25] H. G. Hoffman, D. R. Patterson, and G. J. Carrougher. Use of virtual reality for adjunctive treatment of adult burn pain during physical therapy: a controlled study. *The Clinical journal of pain*, 16(3):244–250, 2000.

[26] H. G. Hoffman, D. R. Patterson, G. J. Carrougher, and S. R. Sharar. Effectiveness of virtual reality–based pain control with multiple treatments. *The Clinical journal of pain*, 17(3):229–235, 2001.

[27] J. H. Hollman, R. H. Brey, R. A. Robb, T. J. Bang, and K. R. Kaufman. Spatiotemporal gait deviations in a virtual reality environment. *Gait & posture*, 23(4):441–444, 2006.

[28] B. Hu, L. Ma, W. Zhang, G. Salvendy, D. Chablat, and F. Bennis. Predicting real-world ergonomic measurements by simulation in a virtual environment. *International Journal of Industrial Ergonomics*, 41(1):64–71, 2011.

[29] M. Huber, Y.-H. Su, M. Krüger, K. Faschian, S. Glasauer, and J. Hermsdörfer. Adjustments of speed and path when avoiding collisions with another pedestrian. *PloS one*, 9(2):e89589, 2014.

[30] Imotions. Galvanic skin response: The complete pocket guide, 2016.

[31] Y. Jiang, E. E. O'Neal, L. Franzen, J. P. Yon, J. M. Plumert, and J. K. Kearney. The influence of stereoscopic image display on pedestrian road crossing in a large-screen virtual environment. In *Proceedings of the ACM Symposium on Applied Perception*, p. 6. ACM, 2017.

[32] Y. Jiang, E. E. O'Neal, P. Rahimian, J. P. Yon, J. M. Plumert, and J. K. Kearney. Joint action in a virtual environment: Crossing roads with risky vs. safe human and agent partners. *IEEE transactions on visualization and computer graphics*, 2018.

[33] B. E. Jones. Arousal systems. *Front Biosci*, 8(5):438–51, 2003.

[34] K. Kim, M. Z. Rosenthal, D. J. Zielinski, and R. Brady. Effects of virtual environment platforms on emotional responses. *Computer methods and programs in biomedicine*, 113(3):882–893, 2014.

[35] C. Krogmeier, C. Mousas, and D. Whittinghill. Human–virtual character interaction: Toward understanding the influence of haptic feedback. *Computer Animation and Virtual Worlds*, p. e1883, 2019.

[36] S. F. Kuliga, T. Thrash, R. C. Dalton, and C. Hölscher. Virtual reality as an empirical research tool—exploring user experience in a real building and a corresponding virtual model. *Computers, Environment and Urban Systems*, 54:363–375, 2015.

[37] E. Kwon, G. J. Kim, and S. Lee. Effects of sizes and shapes of props in tangible augmented reality. In *2009 8th IEEE International Symposium on Mixed and Augmented Reality*, pp. 201–202. IEEE, 2009.

[38] M. Lazzaro. Game usability: advice from the experts for advancing the player experience. *Morgan Kaufmann*, pp. 315–345, 2008.

[39] J. M. Loomis, J. J. Blascovich, and A. C. Beall. Immersive virtual environment technology as a basic research tool in psychology. *Behavior research methods, instruments, & computers*, 31(4):557–564, 1999.
[40] J. M. Loomis, J. M. Knapp, et al. Visual perception of egocentric distance in real and virtual environments. *Virtual and adaptive environments*, 11:21–46, 2003.
[41] H. A. Mallot, S. Gillner, H. A. van Veen, and H. H. Bülthoff. Behavioral experiments in spatial cognition using virtual reality. In *Spatial cognition*, pp. 447–467. Springer, 1998.
[42] S. Marwecki and P. Baudisch. Scenograph: Fitting real-walking vr experiences into various tracking volumes. In *The 31st Annual ACM Symposium on User Interface Software and Technology*, pp. 511–520. ACM, 2018.
[43] Y. Matsuoka, S. J. Allin, and R. L. Klatzky. The tolerance for visual feedback distortions in a virtual environment. *Physiology & behavior*, 77(4-5):651–655, 2002.
[44] A. Maurer. What children fear. *The Journal of Genetic Psychology*, 106(2):265–277, 1965.
[45] L. Meerhoff, J. Bruneau, A. Vu, A.-H. Olivier, and J. Pettré. Guided by gaze: Prioritization strategy when navigating through a virtual crowd can be assessed through gaze activity. *Acta psychologica*, 190:248–257, 2018.
[46] B. Mehler, B. Reimer, J. F. Coughlin, and J. A. Dusek. Impact of incremental increases in cognitive workload on physiological arousal and performance in young adult drivers. *Transportation Research Record*, 2138(1):6–12, 2009.
[47] A. H. Memar and E. T. Esfahani. Eeg correlates of motor control difficulty in physical human-robot interaction: A frequency domain analysis. In *2018 IEEE Haptics Symposium (HAPTICS)*, pp. 229–234. IEEE, 2018.
[48] B. J. Mohler, J. L. Campos, M. B. Weyel, and H. H. Bülthoff. Gait parameters while walking in a head-mounted display virtual environment and the real world. In *EGVE (Short Papers & Posters)*, 2007.
[49] B. J. Mohler, S. H. Creem-Regehr, and W. B. Thompson. The influence of feedback on egocentric distance judgments in real and virtual environments. In *Proceedings of the 3rd symposium on Applied perception in graphics and visualization*, pp. 9–14. ACM, 2006.
[50] N.-J. Moore, M. Hickson, and D. W. Stacks. *Nonverbal communication: Studies and applications*. Oxford University Press, 2014.
[51] C. Mousas. Full-body locomotion reconstruction of virtual characters using a single inertial measurement unit. *Sensors*, 17(11):2589, 2017.
[52] C. Mousas, D. Anastasiou, and O. Spantidi. The effects of appearance and motion of virtual characters on emotional reactivity. *Computers in Human Behavior*, 86:99–108, 2018.
[53] C. Mousas, A. Koilias, D. Anastasiou, B. Rekabdar, and C.-N. Anagnostopoulos. Effects of self-avatar and gaze on avoidance movement behavior. In *IEEE Conference on Virtual Reality and 3D User Interfaces*, pp. 726–734, 2019.
[54] N. H. Nie, D. H. Bent, and C. H. Hull. *SPSS: Statistical package for the social sciences*, vol. 227. McGraw-Hill New York, 1975.
[55] S. D. Norrholm, E. M. Glover, J. S. Stevens, N. Fani, I. R. Galatzer-Levy, B. Bradley, K. J. Ressler, and T. Jovanovic. Fear load: the psychophysiological over-expression of fear as an intermediate phenotype associated with trauma reactions. *International Journal of Psychophysiology*, 98(2):270–275, 2015.
[56] E. E. O'Neal, Y. Jiang, K. Brown, J. K. Kearney, and J. M. Plumert. How does crossing roads with friends impact risk taking in young adolescents and adults? *Journal of pediatric psychology*, 44(6):726–735, 2019.
[57] T. D. Parsons and A. A. Rizzo. Affective outcomes of virtual reality exposure therapy for anxiety and specific phobias: A meta-analysis. *Journal of behavior therapy and experimental psychiatry*, 39(3):250–261, 2008.
[58] D. W. Pfaff. *Brain arousal and information theory*. Harvard University Press, 2006.
[59] T. Razavi. Self-report measures: An overview of concerns and limitations of questionnaire use in occupational stress research. Discussion Papers in Accounting and Management Science, University of Southampton, 2001.
[60] S. Razzaque, Z. Kohn, and M. C. Whitton. *Redirected walking*. Citeseer, 2005.
[61] R. S. Renner, B. M. Velichkovsky, and J. R. Helmert. The perception of egocentric distances in virtual environments-a review. *ACM Computing Surveys (CSUR)*, 46(2):23, 2013.
[62] H. A. Ries. Gsr and breathing amplitude related to emotional reactions to music. *Psychonomic Science*, 14(2):62–62, 1969.
[63] R. A. Ruddle, E. Volkova, and H. H. Bülthoff. Learning to walk in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 10(2):11, 2013.
[64] F. A. Sanz, A.-H. Olivier, G. Bruder, J. Pettré, and A. Lécuyer. Virtual proxemics: Locomotion in the presence of obstacles in large immersive projection environments. In *2015 IEEE Virtual Reality (VR)*, pp. 75–80. IEEE, 2015.
[65] K. Seo, J.-k. Kim, D. H. Oh, H. Ryu, and H. Choi. Virtual daily living test to screen for mild cognitive impairment using kinematic movement analysis. *PloS one*, 12(7):e0181883, 2017.
[66] A. L. Simeone, I. Mavridou, and W. Powell. Altering user movement behaviour in virtual environments. *IEEE transactions on visualization and computer graphics*, 23(4):1312–1321, 2017.
[67] A. L. Simeone, E. Velloso, and H. Gellersen. Substitutional reality: Using the physical environment to design virtual reality experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp. 3307–3316. ACM, 2015.
[68] A. K. Singh, H.-T. Chen, Y.-F. Cheng, J.-T. King, L.-W. Ko, K. Gramann, and C.-T. Lin. Visual appearance modulates prediction error in virtual reality. *IEEE Access*, 6:24617–24624, 2018.
[69] J. L. Souman, P. R. Giordano, M. Schwaiger, I. Frissen, T. Thümmel, H. Ulbrich, A. D. Luca, H. H. Bülthoff, and M. O. Ernst. Cyberwalk: Enabling unconstrained omnidirectional walking through virtual environments. *ACM Transactions on Applied Perception (TAP)*, 8(4):25, 2011.
[70] Q. Sun, L.-Y. Wei, and A. Kaufman. Mapping virtual and physical reality. *ACM Transactions on Graphics (TOG)*, 35(4):64, 2016.
[71] J. N. Templeman, P. S. Denbrook, and L. E. Sibert. Virtual locomotion: Walking in place through virtual environments. *Presence*, 8(6):598–617, 1999.
[72] A. Toet, M. van Welie, and J. Houtkamp. Is a dark virtual environment scary? *CyberPsychology & Behavior*, 12(4):363–371, 2009.
[73] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr. Walking> walking-in-place> flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pp. 359–364. ACM Press/Addison-Wesley Publishing Co., 1999.
[74] D. M. Wegner and T. Giuliano. Arousal-induced attention to self. *Journal of Personality and Social Psychology*, 38(5):719, 1980.
[75] P. Willemsen, M. B. Colton, S. H. Creem-Regehr, and W. B. Thompson. The effects of head-mounted display mechanics on distance judgments in virtual environments. In *Proceedings of the 1st Symposium on Applied perception in graphics and visualization*, pp. 35–38. ACM, 2004.
[76] C. A. Zanbaka, B. C. Lok, S. V. Babu, A. C. Ulinski, and L. F. Hodges. Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. *IEEE Transactions on Visualization and Computer Graphics*, 11(6):694–705, 2005.