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The role of the visual environment on characteristics of over-ground locomotion in natural and virtual environments

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ABSTRACT

Recent studies have suggested fundamental differences in the way that visual information is processed in virtual environments when compared to natural environments. To better understand these differences, we asked 20 young adults to walk in a real hallway featuring a mobile wall, which allowed three hallway width conditions: narrow (1.14 m), medium (1.31 m) and wide (1.48 m). A separate group of 21 young adults walked in a virtual hallway that closely replicated the real hallway. We were interested in determining (1) whether gait parameters and their variability would be similar between the natural and virtual environments, (2) whether visual information about the width of the hallway would affect gait performance in the two environments, and (3) whether the influence of hallway width would be similar in both environments. We hypothesized that because visual processing is fundamentally different in natural and virtual environments, spatiotemporal gait parameters would also be different in the two environments. Further, we hypothesized that gait and gait variability would be differentially affected by the manipulation of hallway width in the natural and virtual environments. Results indicated participants in the VR environment walked with decreased cadence, spent more time with both feet on the ground, and walked with more variability than participants in the natural environment. Further, several subtle but important differences were found regarding the effect of hallway width on gait in the two environments. In particular, the width of the hallway differentially affected cadence and normalized gait velocity between the real world and VR. These fundamental differences indicate more cautious gait in VR and could have significant implications when we consider how and when we use VR for rehabilitation, training and assessment.

1. Introduction

Virtual Reality (VR) is defined as "an immersive and interactive system that provides users with the illusion of entering a virtual world" (Heim, 2000). This technology can be used for the creation of environments that support entertainment, training, education, and rehabilitation/assessment applications (Slater et al., 2016). A major advantage of using VR for these purposes comes from the ability to provide complex stimuli, which are controlled, standardized, safe, and easily varied. In certain VR setups, the high-fidelity tracking and displays support "natural" sensorimotor control allowing the user to experience similar sensations and produce similar actions in VR and the natural environment (Hoppe et al., 2019). Furthermore, because this technology has the potential to measure rich information about a participant's actions and reactions to a variety of complex sensory stimuli, VR may also afford scientists of human movement a window into the planning and execution of complex actions at a level not possible in natural environments. This knowledge can be used to improve VR simulations, thus enhancing end applications, which is particularly important when considering purposes such as training, rehabilitation and motor skill assessment.

1.1. Clinical utility of virtual reality

To date, a large body of work surrounding the use of VR has been targeted at intervention, rehabilitation and training in older adults. In particular, VR and gaming technologies have been used to support

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sensorimotor rehabilitation using a variety of commercial and lab-based applications (see Rose et al., 2018 for a review). For example, VR has been explored as a tool to retrain faulty movement patterns resulting from neurological dysfunction and as an adjunct to rehabilitation after stroke (Zhang et al., 2021; de Rooij et al., 2021). Treadmill walking while viewing a VR display has also been utilized as an effective rehabilitation procedure resulting in meaningful improvements in gait characteristics after VR training (Winter et al., 2021).

While many VR applications deal with intervention and training after a person has been identified as having a motor deficit (e.g. after a fall or after stroke), there is a dearth of research focused on determining whether VR technology can play a role in fall prevention through early assessment and intervention. Motor skill assessment requires a clinician to measure the current state of motor skill performance exhibited by an individual. This allows the clinician to determine whether the patterns of behavior reflect underlying conditions that could lead to injury or disease, such as assessing an individual's risk of fall. Current clinical assessment techniques rely on self-report, paper and pencil interviews and clinical observation on contrived tasks that do not represent the breadth of common daily activities that can lead to injury. As a result, the specificity of these tools to discriminate between people with a high versus low probability of falling/injury is relatively weak (~29–54%) (Myers, 2003).

Virtual reality provides a tool for creating environmental constraints, cognitive demands, and assessment scenarios that are rich, customized, and easily varied that could potentially improve how we assess risk. An important caveat is that using VR for assessment necessitates a tight relationship between performance in VR and performance in the real-world (motor transfer) because the ultimate goal is to measure the current state of motor performance, not necessarily improve it at the time of assessment.

1.2. Motor transfer

Motor transfer is defined as the influence of previous experiences on performing a motor skill in a new context or on learning a new skill (see Magill, 2021 for a review). Transfer can be positive or negative depending on whether it improves or degrades performance in the new context or on the new task. The amount of positive transfer between two skill performances depends on the interplay between the movements that make up the skill and factors that are specific to the environment in which the skill is being performed. The identical elements theory of transfer, initially proposed by Thorndike and Edward (1921) suggests that when the individual movements that compose a skill are more similar, transfer between the two skills will be greater (Magill, 2021). Therefore, in practice, we would expect greater movement similarities (and greater transfer) when walking over-ground in the natural environment and walking over-ground in VR as compared to walking on a treadmill in VR. Research has indicated that locomotion on a treadmill is fundamentally different than over-ground locomotion (Hollman et al., 2016) and that over-ground walking in VR can improve a user's sense of immersion and facilitate more natural movements (Slater et al., 1995; Ruddle and Lessels, 2009; Peck et al., 2012).

The second component that can influence transfer between skills is the similarity of context components, such as the visual features of the environment. When the visual features are not similar between two environments, transfer between the two skills is generally smaller than when the visual features are similar (Magill, 2021). For example, motor skill assessments and rehabilitation are generally performed in sterile clinics. These clinics cannot reproduce the richness and variety of visual stimuli that are generally encountered when individuals perform skills in everyday life. Therefore, a limitation of current clinical assessment and rehabilitation is that performance improvements seen in the clinic may not fully transfer to activities of daily living. This limitation of current clinical assessments and rehabilitation protocols could be addressed by creating virtual environments that better simulate the movement components and visual features of real tasks performed in everyday life.

However, the question remains as to whether VR simulations have to faithfully reproduce the real environment in order for movements performed in VR to transfer to the real environment. Gentile (1972) introduced the terms regulatory and non-regulatory variables to describe environmental information that individuals learn to identify and selectively attend to when performing skills. Regulatory variables describe aspects of the skill and environment that are directly relevant to the performance . For example, an obstacle on the ground that you must step over as you walk is considered a regulatory variable because the size and position of the obstacle directly influence the stepping movements you make. Your step must be high and long enough to clear the object. In contrast, non-regulatory variables are those aspects of the environment that are not specifically relevant to the performance but can indirectly influence performance simply due to their presence in the visual world (Gentile, 1972; Maraj et al., 1998). For example, the buildings lining the sidewalk that you are walking on are non-regulatory. You do not need to alter the steps you take because of the existence of the buildings, however, the fact that these visual features are present in the environment could indirectly influence your performance. The presence of non-regulatory variables may explain why scores on motor assessments and gains observed in clinical settings do not necessarily translate into improved performance in other environments (Kenyon and Blackinton, 2011) and why gait measured in a natural setting does not align with gait measured in a laboratory setting (Hillel et al., 2019). If the visual features, in the form of non-regulatory variables, are inconsistent between environments, performance may be differentially affected.

Hallway width is a characteristic of homes, assisted living facilities, clinics and hospitals that varies significantly. Although, the minimum hallway width is regulated by the international residential code (Section R311.6) at 36 inches (0.91 m) to allow for straight, unobstructed walking, the Americans with Disabilities Act suggests a minimum of 48 inches (1.22 m) to be considered a handicap-accessible hallway and at least 60 inches (1.52 m) for hallways that require passing space. This means that hallway width is a non-regulatory feature that could change between the clinic where an individual is assessed for fall risk and home where they spend the majority of their time walking. In the current study, our goal was to determine whether hallway width influenced standard gait measures in a straight-line over-ground walking task and whether the pattern of change is similar across natural and virtual environments. This preliminary work on the role of non-regulatory variables on performance allows us to begin to investigate whether VR can be a suitable tool for assessing motor skill.

1.3. Locomotion in virtual reality

One complex action that is of particular interest in VR implementations is locomotion (Nilsson et al. 2018). Locomotion within VR allows users to navigate and explore within the environment, performing realistic and engaging tasks (Bowman et al., 2004). In recent reviews, Nilsson et al., (2018) and Boletsis (2017) listed several methods that have been employed to facilitate gait or gait-like navigation in VR. These techniques range from using 3d controllers for joystick-based locomotion, and point-and-click teleportation, to walking-in-place/treadmill walking, and over-ground walking. While each of these techniques can be used effectively for specific purposes, when considering applications such as training, rehabilitation, and motor skill assessment, it is important to consider how well the locomotion technique addresses (rehabilitation, training) or matches (motor skill assessment) the desired real-world behavior.

Many VR experiences that include locomotion aim to create the same affordances as in the real-world while also being limited by the constraints of the surrounding environment, such as limited physical space. Many VR approaches have been used to try to enable "normal" or real-world walking despite these constraints. One approach is to utilize novel hardware, such as low friction surfaces (Kajita et al., 2004), treadmills (Stavar et al, 2011) or even robotic floors (Liu et al., 2018). While hardware-based approaches offer some advantages, such as increased safety and opportunities for continuous walking, these approaches are also limited in their ability to be implemented outside of a research environment due to their cost, size and required upkeep (firmware and hardware). A different approach is to attempt to solve this problem purely in software via approaches such as redirected walking (Nilsson et al., 2018) and blind walking (Renner et al., 2013; El and Marsh, 2019).

In blind walking, users are shown a target in a virtual world and then asked to walk to this location without visual feedback (i.e. blind). This technique is a common practice that is used to assess a user's perception of space (Gonzalez-Franco et al., 2019) and has been used in VR research as a means to assess perceived distances (Renner et al., 2013; El and Marsh, 2019). While this area of research also involves walking in an immersive setting, it is quite differently motivated than the current study, in that the walk occurs without any virtual feedback. This manipulation, therefore, provides a means of measuring a participant's perception of the spatial characteristics of the environment prior to removal of the visual information.

Redirected walking is a technique in which the virtual environment is subtly altered to create the illusion of straight-line walking while actually "tricking" the individual into walking in circles (Razzaque, 2005). Research on redirected walking often involves discerning the sensitivity of the redirected walking techniques (Steinicke et al., 2009) or the cognitive load on the participant (Bruder et al., 2015). While the work presented in this paper and research around redirected walking both involve walking in an immersive setting, the motivations between these research endeavors are incredibly different. Redirected walking aims to manipulate the user into perceiving the space as being larger than it physically is. The current work aims to create a one-to-one mapping of the physical and virtual spaces.

One of the advantages of one-to-one mapping is that it allows for quantification of ecologically valid gait parameters such as step extremity ratio (distance from the heel strike of one foot to the heel strike of the opposite foot divided by leg length), base of support (distance between the right and left footfalls during walking), cadence (number of steps per minute), double support time (duration of time spent with both feet in contact with the ground) and gait velocity. In walking studies, these measures are often analyzed to identify whether individuals are producing a conservative gait pattern due to instability (Horsak et al., 2021). Evidence has suggested that the parameters associated with instability are lower cadence, shorter SER, longer double support time, larger base of support, decreased velocity and increased step-to-step variability (Hollman, 2006; Horsak et al., 2021). These spatiotemporal measures in addition to their variability also allow for clinically relevant data to be gleaned via VR. For example, it has been well documented that variability of numerous gait measures increases in individuals with neurological conditions such as Parkinson disease and stroke and that this increase in variability is linked to an increased propensity for falls in individuals with PD, stroke and in typical aging.

In the VR literature, research most similar to the current study focuses on measuring these spatiotemporal parameters in an effort to understand the impact of VR environments on gait patterns during overground walking (Horsak et al., 2021). For example, researchers have studied the effect of isometric and non-isometric visual feedback by implementing translation gains as individuals walked across a gait mat (Janeh et al., 2017). The authors reported significant differences in walking velocity, step length and base of support between the real and virtual environments. Further, they showed that isometric (one-to-one) mappings provided a more natural match than non-isometric mappings. Of interest in Janeh et al. (2017) is that the visual conditions in the natural and virtual environment differed significantly. Individuals walked with visual feedback of the research lab in the natural environment, but were presented with a graphic representation of a hallway in VE. It remains unclear how these visual differences between the real and virtual environments may have influenced their results. More recently, Horsak et al. (2021) measured spatiotemporal gait parameters as individuals walked in natural and VR environments that were more visually congruent as well as VR spaces that were shorter or longer than the real lab. Their results indicated slower walking speed and increased variability when participants walked in VR compared to the real environment although they did not find significant differences between the same-sized, shorter and longer VR environments. In the current study, we extended Horsak et al. (2021) by manipulating the width of both the real and virtual environments.

1.4. Purpose

This study was conducted to measure similarities and differences in gait performance when individuals walked over-ground in natural and virtual environments. In particular, we were interested in determining (1) whether spatiotemporal gait parameters and their variability are similar in over-ground walking in the natural environment and over-ground walking in a visually similar virtual environment, (2) whether manipulation of hallway width (a non-regulatory variable) affects movement in the natural and/or virtual environment, and (3) whether the influence of this non-regulatory variable is similar in both environments. These questions are of interest when considering the use of VR as a tool for the assessment of motor skill, where the pattern of behavior in VR should be representative of movement in the natural environment.

2. Methods

2.1. Participants

Forty-one healthy young adults (21 females, mean age=23.63 ± 3.0 years; range: 19-29 years) were recruited from the community using flyers and word of mouth. Participants were excluded if they had any self-reported neurological injury or pathology, or any orthopedic conditions which limited their function in the last 6 months. They were also excluded if they had experienced a fall in the previous year or did not have normal or corrected-to-normal vision. Informed consent was obtained before starting each session. This study was conducted in agreement with the Declaration of Helsinki and approved by the University of Wisconsin—Madison Institutional Review Board.

2.2. Apparatus

Twenty participants walked in the natural environment hallway (NEH) and 21 participants walked in a virtual environment hallway that closely replicated the natural environment (VEH). Different participants were recruited for the NEH and VEH conditions to minimize the possibility of learning. Specifically, we wanted to avoid the possibility that some participants may become aware of the hallway width manipulation in one environment and carry that knowledge forward to the other environment. For the NEH, an 8.13-meter-long hallway was constructed with one mobile wall and one fixed wall along the long axis of the hallway (Fig. 1). The mobile wall of the hallway could be manually adjusted to produce one of three predetermined hallway widths: narrow (1.14 m), medium (1.31 m), or wide (1.48 m) (Fig. 2). Participants entered the hallway through a functional door at one end. Four additional distractor doors were placed along the length of the hallway to improve ecological validity of the scene but were not used by the participant. One distractor door remained partially open to allow one experimenter to monitor and cue the participant at the start of each trial. A 1.2-meter-tall plant was placed at the end opposite the entrance door to make the scene more realistic. The plant was moved from the left to the right of the hallway every time the hallway width was modified. This was done to help conceal the change in hallway width. Throughout all walking trials, participants held an HTC Vive controller in each hand to

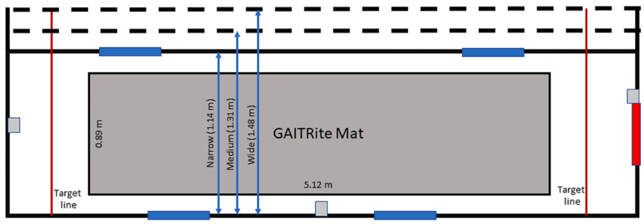

Fig. 1. Top-down diagram of the research hallway and the three width conditions. The dashed lines represent the location of the movable wall for the medium and wide conditions. The entrance to the hallway is noted as the red rectangle on the right of the diagram with the four distractor doors indicated by the blue rectangles on the top and bottom (i.e. right and left walls). The start lines are noted in red. The location of the lighthouses are shown by the gray squares.

replicate this feature of the VEH conditions.

To complete trials in the VEH conditions, participants donned an HTC Vive Pro head mounted display (HMD) and walked over-ground in the natural hallway. The HTC Vive Pro headset has a 110 degree field of view, refresh rate of 90 Hz and display resolution of 2880 × 1600 (1440 × 1600 resolution per eye). The HMD was adjusted for each participant's interpupillary distance (IPD) using measurements taken from a Huanyu Digial Pupilometer (LY-9C). An HTC Vive Wireless adapter was affixed to the headset to increase the participants' freedom of movement as they completed the walking trials. The headphones on the Vive headset were flipped up (i.e. not covering the ears) allowing participants to experience similar auditory information across the natural and virtual environment conditions (see Hoppe et al., 2019).To maximize the tracking space, three "Lighthouse" base stations were positioned in the hallway (Fig. 1). The virtual scenes displayed via the headset were a non-photorealistic match of the dimensions (length, height, and three widths), color and visual texture of the natural hallway (Fig. 3). To achieve this spatial match, the virtual scenes were based on pointcloud scans of the natural hallway, captured using a FARO LiDAR scanner. These virtual scenes were aligned to the natural hallway by matching tracked "Lighthouse" locations to their expected locations in the virtual scene, using a method similar to that in Peer and Ponto (2018). Participants held a Vive Pro controller in each hand throughout all trials and a graphical representation of the controllers was displayed in the virtual scene. The interactive virtual environment was created using the Unity game engine.

Spatiotemporal gait data were collected in both the NEH and VEH using a GAITRite (CIR Systems Inc., Clifton, NJ, USA) instrumented walkway system. The GAITRite system consists of a 5.12 m long, 0.89 m wide pressure-sensitive mat. A Logitech C922x Pro Stream webcam (Logitech International S.A., Lausanne, Switzerland) was positioned at one end of the hallway to record video of the participants walking along the mat. The video recording provided a visual reference of potential errors in the data resulting from participants stepping off the mat prematurely, or not following the protocol.

2.3. Experimental protocol

Before beginning the walking trials in both the NEH and VEH conditions, participants' leg lengths were measured by palpating for the greater trochanter of the femur and measuring to the lateral malleolus of the fibula. For the VEH conditions, interpupillary distance was recorded by having participants place their forehead against the bar on the pupilometer device and the bridge of their nose against the nose pads. The participant was asked to focus on a green target within the device. The examiner aligned the cross hairs of the pupilometer, which was set for infinite distance, with the participants' corneal reflections. IPD was then read directly from the device (range = 52-72 mm). This measurement was used to set the IPD within the HTC Vive Pro headset.

For both the NEH and VEH trials, participants were told to walk at a comfortable pace across the length of the hallway while staying centered on the gait mat. A target line was taped 1.46 m past each end of the mat (see Fig. 1). Participants were asked to step off the mat and walk past the target line, turn around, face the mat, and wait to be cued to start the next trial. Participants followed this protocol for 10 consecutive trials within a single hallway width condition (narrow, medium, or wide). The

Fig. 3. View of the virtual hallway when standing at the edge of the GAITRite mat looking at the entrance door.

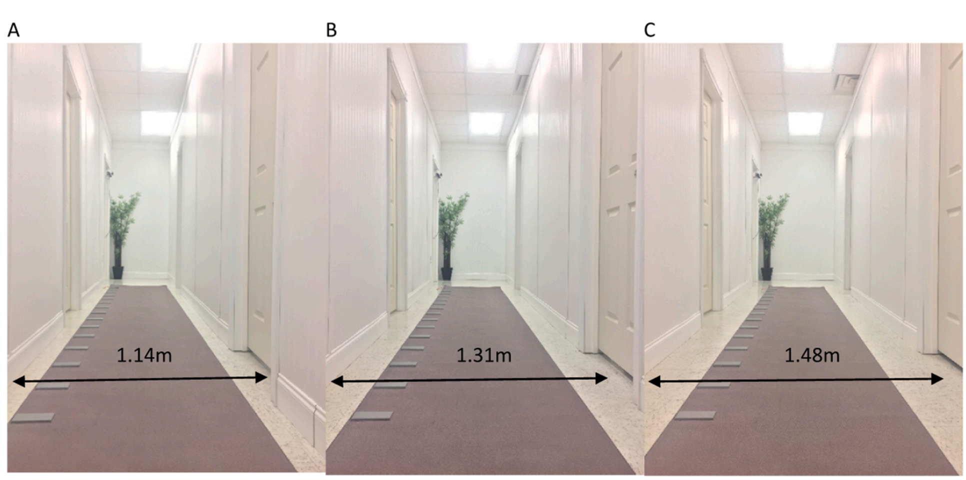

Fig. 2. Views of the hallway when standing at the entrance door. The right wall was moved between blocks of 10 trials so that the distance between the two walls was A) 1.14 m (narrow), B) 1.31 m (medium), C) 1.48 m (wide). The GAITRite mat was repositioned for each condition to maintain a centralized position.

block of 10 trials concluded with the participant being asked to leave the hallway through the functional door and to walk to an adjacent research room. Once in the adjacent room, participants were asked to complete a survey. During this time the hallway width was manually adjusted to the next width condition for the NEH trials.By asking participants to move to another room while the hallway width was adjusted, we minimized the participant's awareness that the hallway width was being changed between blocks. For the VEH trials, the next hallway width condition was loaded into the headset while the participant was in the separate room and calibration of the environment was checked. Three blocks of 10 trials were completed, for a total of 30 trials. Each block featured a different hallway width: narrow (1.14 m), medium (1.31 m), or wide (1.48 m). Participants were not made aware of the hallway width manipulation and conditions were counterbalanced across participants using a Latin Square design. Between-block surveys consisted of the Edinburgh Handedness Inventory (Oldfield, 1971) after block 1 and the Waterloo Footedness Questionnaire (Elias et al., 1998) after block 2. Upon completion of the last block of trials, participants were debriefed and compensated for their time.

2.4. Data processing

The GAITRite system allows for the quantification of several spatiotemporal gait parameters. The primary outcome measures used to describe gait performance were cadence, step extremity ratio (SER), normalized base of support (BOS), percent of gait cycle spent in double support (%DS), and normalized stride velocity (SVel). GAITRite data were first examined for footfall errors and half steps. Footfalls that were not completely on the walkway were considered a miss-step and the step was removed from further analysis. Only trials with at least 4 consecutive valid footfalls were included in the data analysis. Cadence was defined as the number of steps taken per minute. SER was determined by dividing the step length by leg length and averaging both the left and right ratios. Base of support in cm was defined as the distance perpendicular to length of the mat that would connect the center of both heels during two consecutive footfalls. The average base of support was divided by the individual's full body height and the result was multiplied by 100 to produce a height-normalized value. The percent of the gait cycle spent in double support was defined as the duration of the walk trial the participant spent with both feet in contact with the ground divided by the total time of the walk trial, multiplied by 100. Velocity in cm/s was calculated by dividing the distance between the initial and final footfall recorded by the gait mat and dividing by the total time of the trial. Velocity was also normalized to each individual's leg length. Finally, the standard deviations of the gait variables were used as metrics of gait variability.

2.5. Statistical analysis

Data were first assessed for normality using the Shapiro-Wilke test and by visually inspecting the histograms and Q-Q plots (see Supplementary Data 1). When results of the Shapiro-Wilke and visual inspection indicated non-normality, data were transformed using the Log10 or reciprocal methods, as described in (Howell, 2013) prior to further analysis.[1] Homogeneity of variance was assessed using Levene's test. All data were found to meet the homogeneity of variance assumption ($p > 0.05$). Sphericity was assessed using Mauchly's W test. When violations of sphericity occurred, degrees of freedom were adjusted using the Greenhouse-Geisser correction. Repeated measures ANOVAs with 2 Environments (NEH, VEH) as the between-subjects factor and 3 Hallway Widths (Narrow, Medium, Wide) as the within-subjects factor were conducted to detect differences in spatiotemporal gait measures and their variability. An a priori value of $p<0.05$ was chosen to determine significance. Significant Hallway Width X Environment interactions were further explored via simple main effects, to compared performance between the two environments at each hallway width. Data analysis was completed in SPSS v. 25 (IBM, Armonk, NY, USA).

[1] As a check, we analyzed both transformed and untransformed data. Statistical results were the same in both data sets with the following two exceptions. A significant Hallway Width X Environment interaction for SER variability failed to reach significance in the transformed dataset (p=0.06) despite being significant in untransformed dataset (p=0.045). The main effect of Hallway Width was significant in the transformed dataset for Normalized Velocity Variability despite not being significant in the untransformed data set. Given the differences in these two results across datasets, we advise caution in their interpretation.

3. Results

3.1. Participant feedback

During the debriefing, the majority of participants (38 of 41) were unaware of the hallway width manipulation. When asked specifically about the visual aspects of the hallway, one participant in the natural environment commented on the stark white color of the hallway and another participant commented on the plant. Three participants in the VR environment reported that something about the hallway changed between blocks. Two participants indicated that they thought the hallway was narrower in certain blocks while one participant indicated that they knew something had changed, but could not put a finger on what it was

3.2. Statistical comparisons

Main effects of Environment were found in two spatiotemporal measures (cadence and %DS) and in all variability measures (Cadence, SER, Vel, %DS and BoS) (see Tables 1 and 2). Cadence was lower and individuals spent a greater proportion of the gait cycle with both feet on the ground when walking in the virtual environment than when walking in the natural environment (see Fig. 4A and C). Variability of cadence, SER, percent time spent in double support, normalized velocity and base of support were larger in the virtual environment than in the natural environment (see Fig. 5).

Table 1
Main effects and interactions for spatiotemporal gait measures.

Variable	Hallway Width (Narrow, Medium, Wide)	Environment (Natural, Virtual)	Hallway Width X Environment
Cadence	$F_{2,78}$=0.963, p = 0.386	$F_{1,39}$=6.745, p == 0.013*	$F_{2,78}$=3.193, p == 0.046*
Step Extremity Ratio (step length/leg length)	$F_{2,78}$=1.653, p == 0.198	$F_{1,39}$=0.880, p == 0.354	$F_{2,78}$=0.871, p == 0.423
Double Support (% of gait cycle)	$F_{1.1,78}$=0.07, p == 0.824	$F_{1,39}$=5.824, p == 0.021*	$F_{1.1,78}$=0.873, p == 0.369
Normalized velocity	$F_{1.42,78}$=0.341, p == 0.639	$F_{1,39}$=2.814, p == 0.101	$F_{1.4,78}$=5.122, p == 0.017*
Base of Support	$F_{1.6,78}$=0.027, p == 0.974	$F_{1,39}$=0.084, p == 0.774	$F_{1.6,78}$=0.121, p == 0.840

* denotes significances at the $p < 0.05$ level

The main effect of Environment on cadence must, however, be interpreted in light of a significant interaction between Environment and Hallway Width for that spatiotemporal measure. Although there was a significant difference in cadence between the two environments for the medium and wide hallway conditions, cadence was not different between the natural and virtual hallways at the narrow width (see Fig. 4A).

An interaction between Hallway Width and Environment was also found for normalized velocity (see Table 1). NVel was significantly larger in the natural environment for the wide hallway width only. Velocity was similar between the two Environments for both the narrow and medium widths (see Fig. 4D).

4. Discussion

This study compared locomotor performance in a real environment and a visually similar immersive virtual environment. Hallway width was manipulated to better understand the influence of a non-regulatory visual feature on gait performance. Our study was designed to address three specific questions. First, we were interested in determining whether spatiotemporal gait parameters and their variability are similar in over-ground walking in the natural environment and over-ground walking in a visually similar virtual environment. Second, we wanted to determine whether the non-regulatory variable, hallway width, affects movement in both the natural and virtual environment. Finally, if hallway width influences behavior, we wanted to determine whether the pattern of influence was similar in both environments. Overall, main effects of Environment were found for several spatiotemporal measures and their variabilities indicating that locomotor performance is not the same in real and virtual environments. Further, interactions between Environment and Hallway Width were found for Cadence and Normalized Velocity. As discussed in greater detail below, these fundamental differences in responses to the manipulation of a non-regulatory variable between the two environments could have significant implications when we consider how and when we use VR in clinical applications such as motor skill assessment.

4.1. Performance differences between real and virtual environments

Cadence was approximately 7 steps/minute lower, the percent of time spent in double support was 2% longer, and all measures of variability were larger in VR than in the natural environment. These results support recent findings by Horsak et al. (2021), Martelli et al. (2019) and Janeh et al. (2017) who also reported differences in spatiotemporal gait measures when individuals walked overground in VR compared to real environments. Longer double-support time (and resulting lower cadence) indicates more cautious gait behavior since it decreases the amount of time spent balancing on one leg (Maki, 1997; Ko et al., 2018; Springer et al., 2006). Further, increased gait variability has been associated with increased gait instability, increased fall risk, and increased cognitive load (see Hausdorff, 2005 for a review). Hollman et al. (2006, 2007) found similar results when individuals walked in VR on a treadmill. They concluded that participants adopted a more conservative gait strategy to overcome an optic-flow induced threat to stability as a result of the visual stimuli presented in the VR environment. As recently noted by Horsak et al. (2021), these differences between performance in VR and the real environment persist despite technological improvements in HMDs such as increased resolution and wider fields of view available in newer headsets. These persistent differences despite improvements in VR software and hardware support a recent hypothesis by Harris et al. (2019) that skills performed in VR use a different mode of visual control than the same skills performed in the natural environment.

Table 2
Main effects and interactions for variability of gait measures.

Variable	Hallway width		
(Narrow, Medium, Wide)	Environment		
(Natural, Virtual)	Hallway Width X Environment		
Cadence	$F_{2,78}$=2.648, *p* == 0.077	$F_{1,39}$=14.601, *P* < 0.001**	$F_{2,78}$=0.120, *p* == 0.887
Step Extremity Ratio Variability (step length/leg length)	$F_{2,78}$=0.784, *p* == 0.460	$F_{1,39}$=14.656, *P* < 0.001**	$F_{2,78}$=2.926, *p* == 0.06
Double Support Variability (percent of gait cycle)	$F_{1.7,78}$=2.272, *p* == 0.081	$F_{1,39}$=19.914, *P* < 0.001**	$F_{2,78}$=3.25, *p* == 0.053
Normalized velocity Variability (leg lengths/second)	$F_{2,78}$=3.516, *p* == 0.035*	$F_{1,39}$=18.952, *P* < 0.001**	$F_{2,78}$=0.618, *p* == 0.530
Base of Support Variability	$F_{2,78}$=0.380, *p* == 0.685	$F_{1,39}$=62.64, *P* < 0.001**	$F_{2,78}$=1.336, *p* == 0.269

* denotes significances at the $P < 0.05$ level, ** denotes significance at the $P <= 0.01$ level

Harris et al (2019) suggested that the graphic information present in immersive VR may activate the sensory processing system differently than the visual information that is available in our natural environment due to the presentation of varying depth objects on a fixed depth screen (Eadie et al., 2000). Specifically, findings from several studies have indicated impaired distance estimations and an overall “flatter” appearance in virtual environments, which suggests that the use of binocular cues may be impaired (see Harris et al., 2019 for a review). The use of monocular distance cues in VR primarily activates the ventral visual pathway, which is normally responsible for perception and recognition of stimuli, rather than activating the dorsal visual pathway, which is primarily activated by binocular information and is responsible for visual control of action (Mon-Williams et al., 2001). The overall result is that visually guided motor skills can be performed in VR using ventral control, but this results in a fundamentally different mode of movement control than is present in the real-world. With this fundamental difference in visual processing across the two environments, it may be impractical or impossible for individuals to produce the movements in the same way in VR as in the real environment given current display technology. This could have significant implications for how we use VR in applied settings without further technological advancements.

4.2. Role of non-regulatory variables on performance

Our results also indicated several subtle but important differences in how the non-regulatory variable of hallway width influenced gait in both the natural and virtual environments. In particular, the width of the hallway differentially affected cadence and normalized gait velocity between the two environments. Although cadence and velocity were similar in the virtual and natural environments for the narrow hallway width, for the wide hallway width cadence and velocity were significantly lower in VR than in the natural environment. The interaction effects between Environment and Hallway Width suggest that not only does performance in VR not match performance in the real world, but also that the pattern of differences between the two environments can be moderated by a non-regulatory variable. This further complicates the use of VR technologies for applications that require a tight match between performance in the two environments. The interaction effects suggest that simply scaling performance values between the two environments cannot account for the differences. Instead, skills for which a tight match between the performance in VR and the natural environment is desired (e.g. assessment), will require a thorough understanding of similarities and differences across conditions before performance in VR can be reliably associated with performance in the real world. This means that it may be challenging (although not impossible) to use VR for assessment applications.

What may explain the differential effect of hallway width in the real and VR environments? The width of the environment in which a participant performs a motor task has been studied in real-world gait and cycling paradigms (Toepfer et al. 2020; Vansteenkiste et al., 2013). In a recent study from our lab, we reported on the effects of hallway width on gait performance in a population of older adults (Toepfer et al., 2020). We found that base of support and step velocity were influenced by hallway width, with a trend toward a wider base of support and slower velocities in narrower hallways than in wider hallways. Similarly, Vansteenkiste et al. (2013) showed that riders decrease their

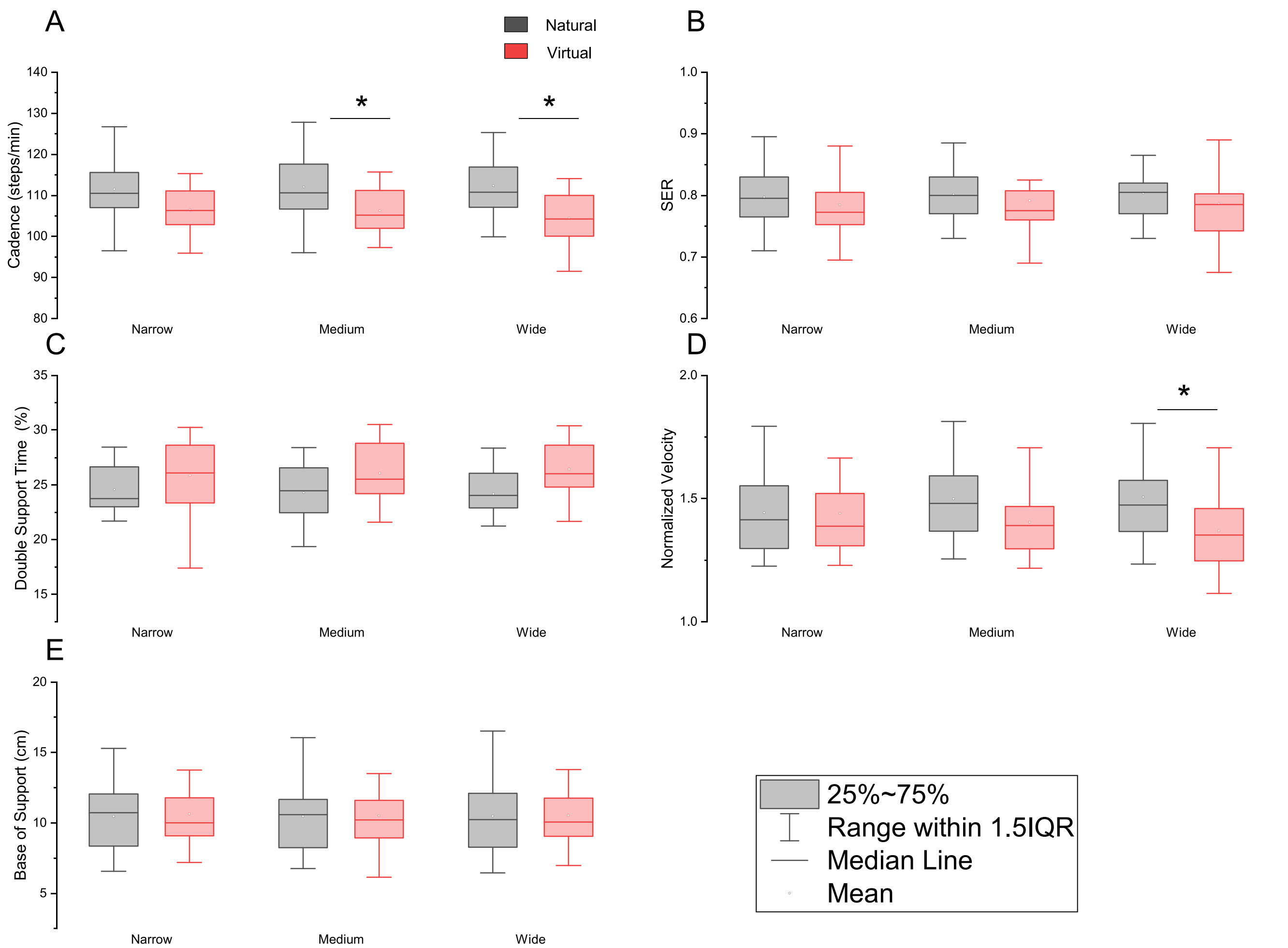

Fig. 4. Box plots showing means, medians, and range for spatiotemporal gait parameters A) Cadence, B) SER, C) Double Support Time, D) Normalized Velocity and E) Base of Support. For ease of interpretation, untransformed data are shown. Main effects of Environment were found for Cadence and %DS. Cadence was larger and %DS was longer in VR than in the natural environment. Interactions between Environment and Hallway Width were found for Cadence and NVEL. * represents significant differences between the two environments at the Bonferroni corrected *p* value. 4A shows that although cadence was similar in the natural and virtual environments at the narrow hallway width, cadence was significantly lower in VR when participants walked in the medium and wide hallways. As shown in 4D, for normalized velocity, differences between the natural and virtual environment were found for the wide Hallway Width.

cycling speeds with narrower lane widths. This effect has been explained using the speed-steering workload tradeoff model and was first examined in car driving. Essentially this effect suggests that high speeds and narrow lanes both require higher mental effort (Godley et al., 2004). Reductions in speed thus have the desirable effect of keeping mental workload down. Similar results were found in the natural environment in the current study. Inspection of Fig. 3 shows that in our natural environment walking task there is a trend toward higher walking speeds as hallway width increases.

In contrast, results from our VR condition show that walking speed decreases with hallway width (see Fig. 3). Interestingly, these later results replicate those of Gade et al. (2013), who showed that cycling speed decreased when the path width increased in both young and elderly participants in a virtual cycling task. Gade et al. (2013) suggested that changes in optic flow across the lane widths may explain the different behavior when cycling in VR compared to the real world.

It has been hypothesized that visual control of locomotion (and cycling) is partially achieved using the focus of expansion (FOE) of optic flow (Gibson, 2014) which is then integrated with proprioceptive and vestibular information (Campos and Bulthof, 2012). When we travel on a straight path, a radial pattern of image motion (optic flow) is produced that specifies the current direction and speed of locomotion. Several reports have suggested that participants underestimate optic flow speed (or overestimate self-motion) in VR when compared to the natural environment (Banton et al., 2005; Powell et al. 2011; Kassler et al. 2010; Caramenti et al., 2018; but see Perrin et al., 2019). Disrupted perceptual judgment has also been shown to result in altered speed of self-motion (De Smet et al. 2009). In the current study, one key optic flow cue available to the participant as they walked within the hallway was the bearing angle from the eyes to the right and left walls (Li and Chen, 2010). As the hallway width increased, the bearing angle also increased. Perhaps the differences in bearing angle across the hallway widths lead to increased judgment errors with respect to self-motion speed. This may have caused participants to overestimate their walking velocity and as a result slow down to reduce mental workload.

Since we only used three hallway widths in the current study, this hypothesis requires replication and further testing. To systematically test this effect, we suggest conducting a follow-up study using a larger number of systematically increasing hallway widths. Future studies investigating the effect of hallway/room width on gait performance should also consider incorporating measures of workload, either via dual-task paradigms or via physiological measures such as heart or respiratory rate (Miller, 2001). Similarly, the abstract nature of the virtual scene may have contributed to an inaccurate spatial sense. Some work has explored the effect of scene composition and complexity of spatial judgments, with conflicting results. Thompson et al. (2004)

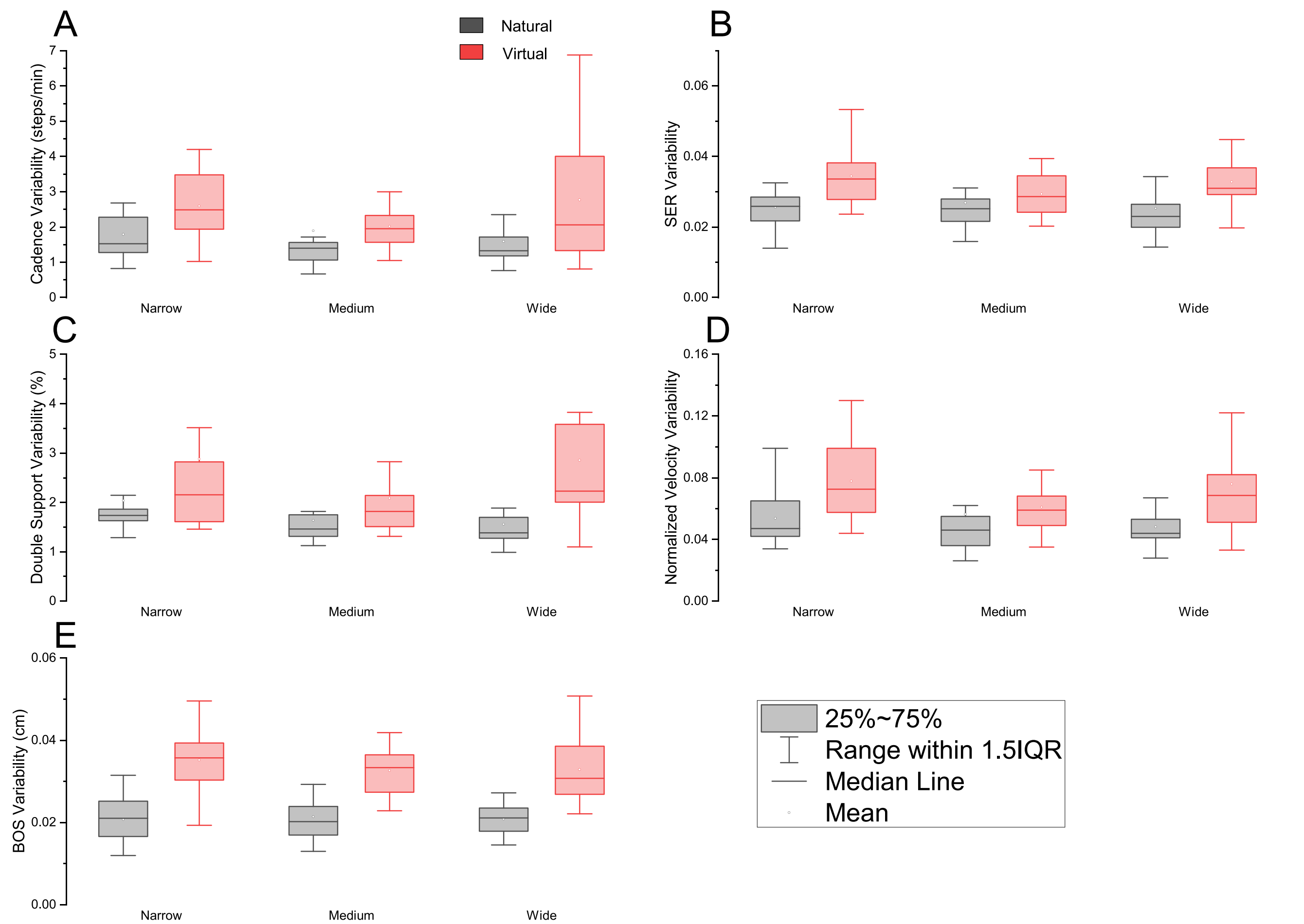

Fig. 5. Box plots showing means, medians, and range for spatiotemporal gait variability measures A) Cadence Variability, B) SER Variability, C) Double Support Time Variability, D) Normalized Velocity Variability and E) Base of Support Variability. For ease of interpretation, untransformed data are shown. Main effects of Environment were found for all variability measures revealing that variability was higher in the virtual environment than the natural environment for all measures.

found no difference in spatial judgements made using photorealistic stereo panoramas, abstract textures, or a wireframe. In contrast, Phillips et al. (2009) did find photorealistic and wireframe environments to elicit different spatial judgments. Exploring the influence of different levels of visual fidelity might be a viable course for follow-up work.

4.3. Limitations

Several limitations of this study must be considered when interpreting our results. First, the virtual hallway was an abstract representation of the real environment. This limits our ability to isolate hallway width as the only visual non-regulatory factor influencing performance. While it would be ideal to simulate the visuals to perfect fidelity in the virtual and real conditions, the current state of technology makes this challenging. Techniques such as light field reconstructions are both difficult to capture and redisplay (Overbeck et al., 2018). While applying photorealistic textures to planar surfaces such as walls could add to the realism, “simulations that approach reality may prompt an Uncanny Valley effect, thereby encumbering cognitive resources and worsening learning outcomes” (Howard, 2017). Beyond this, showing an environment that has roughly equivalent geometry has been shown to elucidate the same sense of scale with that of a photorealistic reconstruction (Willemsen and Gooch, 2002). Finally, in the current experiment, by ensuring that all other potential visual non-regulatory variables remained constant within the VR environment while hallway width was manipulated, we attempted to control for this confound. A second limitation is that given current HMD technology, the weight of the headset and limited field of view could have impacted performance in the VR condition. The normal field of view for a human is approximately 200° (Klymenko and Rash, 1995) but the HTC Vive Pro offers only a 110° field of view. Research has indicated that a reduced field of view is associated with decreased walking speed (Turano et al., 2004). Therefore, it is likely that some of the differences in gait measures between the virtual and natural environment can be attributed to the HMD technology itself. Third, the characteristics of the sample, healthy young adults, limits our ability to extrapolate the results to other populations. Fourth, because we employed a between subjects design, our power to detect differences in our data was decreased. We made the decision to employ this experimental design in order to avoid the potential that participants would become consciously aware of the changing hallway width (particularly in the physical hallway), however, follow-up work using a within-subjects design would result in more power to detect differences in the environmental conditions. Second, the abstract composition of the virtual hallway may limit the generalizability of the results to contexts using similarly abstract stimuli. Finally, the number and magnitude of hallway widths available to test was limited by the physical hallway employed. The use of narrower and wider hallway widths would allow us to better understand the pattern of differences exhibited both with this non-regulatory variable as well as between natural and virtual environments.

5. Conclusions and applications

Overall, our results suggest that walking in a virtual versus natural environment results in different spatiotemporal gait performance and increased variability. Further, non-regulatory variables not only influence performance in both natural and virtual settings, the effect of those variables may be dependent on the setting in which the performance is measured. This could have significant implications when we consider motor transfer between the two environments. While it may be reasonable to conclude that movements measured in the narrow hallway environment are representative of performance in the natural environment, those same movements performed in VR in the wide hallway may no longer be representative of performance in the natural environment. Therefore, if we hope to use performance in VR as a means of training or assessing an individual's skill, our measures may not be representative of their true performance. Ultimately, it is essential that we continue to investigate the similarities and differences in motor skill performance in both natural and virtual environments to better understand when VR can be used as an effective assessment and/or training tool and when the differences could impair transfer between the two environments.

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CRediT authorship contribution statement

Andrea H. Mason: Conceptualization, Methodology, Writing – original draft, Visualization, Supervision, Funding acquisition. **Alejandra S. Padilla:** Data curation, Formal analysis, Writing – review & editing. **Alex Peer:** Software, Writing – review & editing. **Max Toepfer:** Data curation, Formal analysis, Writing – review & editing. **Kevin Ponto:** Conceptualization, Methodology, Software, Writing – review & editing, Funding acquisition, Supervision. **Kristen A. Pickett:** Conceptualization, Methodology, Writing – original draft, Visualization, Supervision, Funding acquisition.

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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Supplementary materials

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