Collective Dynamics

Nudging Pedestrian Walking Dynamics Using Light Intensity and Color

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Crowd management attempts to efficiently and safely guide pedestrian crowds. 'Nudging' is one way to steer the crowd, gently coaxing people in the right direction. In this study, we study whether light can be used to 'nudge' pedestrians' operational walking dynamics. Specifically, we aim to determine the extent to which light intensity and light color influence the average walking speed of pedestrians. Six light conditions are tested in a VR experiment: regular white light (approx. 100 lux), dark (approx. 1 lux), bright (approx. 300 lux), blue, green, and red light. This study concludes that A) the average walking speed decreases in darker light (10.4%) conditions and increases in brighter light (7.7%) or colored (2.8%-8%) conditions. In addition, pedestrians decelerate more slowly and cautiously in dark light conditions, while the acceleration and deceleration profile do not significantly change for bright, blue, green, and red light conditions.

In addition, this study assessed whether a wireless HMD can be used to study pedestrians' average walking dynamics because a relatively new type of VR simulator was adopted. The validation analysis concludes that VR experiments featuring wireless HMD and open-plan movements overestimate step time (+7.5%) and step length (+12.8%) and underestimate the average walking speed (-22.8%). In addition, we find that relative trends regarding the impact of socio-demographic characteristics on the mean of the three analyzed metrics can, in most cases, be reproduced.

Keywords Pedestrians · walking speed · light conditions · Virtual Reality (VR) · laboratory experiment

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1 Introduction

Crowd management attempts to efficiently and safely guide pedestrian crowds. Static measures, such as fences, barricades, and gates, are often adopted to steer the crowd in the 'right' direction. The crowd has no choice but to follow the instructions in cases where these so-called hard paternalistic measures are applied. As a result, pedestrians are very aware of being guided. The lack of freedom limits visitors' experience when participating in large-scale events. For example, they experience annoyance and stress due to being forced to book a timeslot for their visit, meeting barricades along their path, being required to wait in long, dense queues, and being prompted by stewards in crowded corridors.

Another way to steer pedestrian movements is through 'nudging'. Similar to choices regarding health and life, the nudging of pedestrians aims to steer crowds towards the societal optimum, which is not necessarily the optimal solution for each individual in the crowd. In contrast to hard steering mechanisms, nudges are generally soft mechanisms that do not limit the availability of choices in the choice set of individuals but only change the preference for certain choices within the choice set. For instance, people can freely choose any route from A to B, but the route preferred by the city planners is slightly more attractive than the other routes from A to B.

Environmental elements, such as the appearance of the physical environment, light conditions, and the soundscape, are leveraged to nudge pedestrians. Several researchers have studied the efficacy of nudging measures on pedestrians' choice and movement behavior, although not all researchers identify their crowd management interventions as 'nudges' within their papers. For instance, the thorough literature review of [1] iterates many street design elements affecting pedestrian route choices, which could potentially be leveraged to steer their route choices proactively. Also, visual nudges, such as signage and visual cues (e.g., white lines), were found to influence traffic dynamics (a.o., [2], [3]). Another group of studies showed that light intensity and color can be used to steer the route choice of pedestrians in a maze (e.g., [4], [5]). Other researchers studied nudging measures that can be used to adjust pedestrians' gait and walking speed (e.g., [6], [7], and [5]). Lastly, soundscapes were also found to influence pedestrians' step frequency (e.g., [8], [9], and [10]).

This study delves into one type of nudging measure that has yet to be extensively explored: using light conditions to regulate pedestrians' operational walking dynamics. Specifically, we aim to examine the extent to which light intensity and light color influence the walking speed of pedestrians. To achieve this, we employ a Virtual Reality (VR) experiment, which allows for a high level of experimental control while immersing participants in realistic yet distinct scenarios within a short period. We focus on the efficacy of intensity (dark, bright light) and color (blue, green, and red light).

We will use one of the newest wireless head-mounted displays (HMDs) to allow participants to walk freely through space. Several researchers have already adopted wireless HMD to study pedestrians' choices (e.g., [11], [12], [13], [14]). However, a limited number of studies have attempted to perform a validation of pedestrians' walking behavior in VR featuring wireless HMD (e.g., [15], [16], [17])), which predominantly feature simplistic overground one-directional walking experiments. Consequently, it is still poorly understood whether these newest types of HMDs allow participants to adopt their natural walking motion, especially when assigned more complicated and longer walking assignments. To ensure we can use the newest wireless HMDs for the controlled light experiment, this study also validates wireless HMD as a research tool to study pedestrian walking dynamics. In particular, we investigate whether participants donning a wireless HMD and walking around in a VR environment adopt a similar average walking speed, step time, and step length as participants walking in a similar physical environment.

This paper continues as follows. First, section 2 provides an overview featuring the state-of-the-art concerning nudging measures on traffic in general and pedestrian movement and choice behavior in particular. Subsequently, section 3 presents the research methodology, which features the research procedures, experimental apparatus, setup of the VR environment, and the definitions of the metrics. Section 4 describes the participant sample and data. Section 5 presents the results of the experiments aimed at validating the wireless HMD setup for pedestrians' walking dynamics research. Accordingly, section 6 will analyze the impact of light conditions on walking dynamics and place them into the perspective of the existing literature. This paper finishes with conclusions and suggestions for future work in section 7.

2 State-of-the-art nudging pedestrian behavior

The concept of nudging originates from the work of [18], which studied how governments can influence people's decision-making without forcing them ([19]). Under the name 'Libertarian paternalism', [18] suggested a set of 'nudges' that aim to influence people's decisions while leaving their freedom of choice intact. Over the years, nudges have been proposed in a wide variety of topics, amongst other things, nutrition, physical exercise, and health (e.g., [20], [21], [22], [23]).

In the field of pedestrian research, nudges have also been introduced, which are, in this case, specifically aimed at guiding pedestrians' choice and movement behavior. In the early years, most of these nudges were aimed at optimizing the evacuation choices of pedestrians in indoor environments. Amongst other studies, [24] studied the impact of dynamic signage on optimizing pedestrian route choice. Along the same line, other studies researched the effect of the color of the exit signs ([25]), flashing exit signs ([26]), and various arrow types ([27]). Nudges have also been presented for regular crowding scenarios. For instance, [28] used role models to adjust the stair and escalator use. [29] adapted the light conditions in a city-center street to calm the crowd, increase alertness, and prevent aggression during night hours. [30] adopted various primers and color effects to stimulate individuals' moods and thereby increase people's desire to walk.

In recent years, two specific types of pedestrian choices have been the focal point of nudging experiments: their wayfinding & route choices and their operational walking dynamics (i.e., walking speed, step frequency, and step length). Here, predominantly light was adopted to improve pedestrians' decision-making. [31] determined whether the presence of light improved the wayfinding performance of pedestrians during evacuations and found that the evacuation time improved when ground lights were implemented. [32] established that most participants were drawn toward green running lights and avoided red running lights. A more in-depth route choice study by [5] featuring more light conditions established similar impacts. [33] studied the impact of light temperature and found that the number of hesitations along the route increased for light with a higher temperature (i.e., light temperature ranges from red(low) to white(medium) to blue(high)). Various researchers, amongst which [6], [34], [35], [7] and [36], studied the impact of the illumination level. All found that participants were likelier to choose the brighter path (i.e., the path with the highest light intensity).

To change the operational movement dynamics of pedestrians, predominantly aural (i.e., sound) and visual (i.e., light) stimuli have been tested. Most controlled experiments studied how pedestrians adjust their step frequency and step length when confronted with various types of sounds (e.g., [8], [9], [37], and [10]). Generally, pedestrians adopt a faster step frequency when the background music features a higher BPM (beats per minute) and/or is motivational. An interesting study by [38] furthermore showed that the fundamental diagram (i.e., the relationship between walking speed and crowd density) also changes due to the music type. Here, with background music, stop-and-go behavior was observed more frequently, and the stops were longer.

Lastly, four studies have studied the relationship between walking speed and light conditions. The study of [39] explored the impact of low light intensity on walking. They established that participants walked significantly slower under dimmed light conditions. [40] studied the effect of reduced light conditions on the gait of older adults with a high-level gait disorder and compared their responses to healthy elderly controls. Also, their study recorded that both groups slowed their gait when walking under near-darkness conditions. However, the results of [35] suggest that pedestrians walk faster over darker paths. The experiment setup (i.e., the lack of social safety on a darker path at night) partly explains the contrasting results. Lastly, [41] adopted visible running lights with various target speeds to nudge participants' walking dynamics. They established that the participants' speed was adjusted to the system's target speed.

In conclusion, previous research has predominantly focused on understanding nudges' impact on pedestrians' choice behavior. Concerning more operational behaviors, such as walking speed, acceleration, and collision avoidance, only preliminary studies have been performed. As a result, the impact of nudges on operational pedestrian behaviors is poorly understood, and more research is required to alleviate this issue.

3 Research methodology

This section presents the research methodology of the VR experiments. First, section 3.2 introduces the general workflow and the experimental procedures. Accordingly, the setup of the VR experiment is described in sections 3.3 and 3.4. The setup of the VR equipment is introduced in section 3.5. This section closes with a description of the data that has been collected in the two experiments (section 3.6) and mathematical definitions of the metrics used to describe pedestrians' operational walking dynamics (section 3.7 and 3.8).

3.1 Objective of the light experiments

The overall objective of this set of experiments is two-fold, namely, to validate the use of wireless VR to study pedestrian walking dynamics and to determine the impact of light conditions on walking speeds. Below, these two objectives are further detailed.

Validation experiment - Wireless VR has rarely been used for walking dynamics experiments. Therefore, we must first establish whether this research method will likely provide valid results. The validation experiment aims to establish to what extent wireless VR can be used to study pedestrians' operational walking dynamics. In particular, do pedestrians adopt similar walking dynamics when equipped with a wireless HMD and walking through a virtual reality environment using their own feet instead of a controller?

Light experiments - The light experiments target the main research question of this manuscript, namely, whether one can use varying light conditions to nudge pedestrians to alter their speed. Here, the choice set of the participant features all possible walking speeds that the pedestrian can adopt. The preferred choice is the pedestrian's free-flow walking speed. At any moment, the participant makes the (unconscious) choice to regulate their speed. The set of experiments will determine whether light conditions can nudge pedestrians to adopt a slightly higher or lower walking speed than their free-flow walking speed.

3.2 Experimental procedures

This VR experiment is part of a more comprehensive study into the impact of light conditions on pedestrians' choice and operational movement dynamics. The experiment took place for three weeks in May 2023. The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 2987). Participants took part in four short VR and real-life experiments within 60 minutes. In the following subsections, the comprehensive procedure is presented first. After this, a more detailed description of the real-life and VR validation experiments is provided.

3.2.1 Overview comprehensive procedure

The overview procedure of the comprehensive study is presented in Figure 1. The experimental procedure for each participant started with an intake, during which they were welcomed, asked to read and sign an informed consent form, and performed a basic color blindness test. The latter test was mainly adopted to determine whether all participants could distinguish the green, red, and blue colors used in two of the four VR experiments.

Accordingly, they were asked to perform several choice tasks in a maze while wearing a cable-based VIVE PRO EYE HMD device. During this experiment, participants moved through the VR simulator using a controller in combination with head movements. They could rotate around their axis, but were asked to physically stay approximately at one location. Subsequently, they completed a short survey related to the first experiment featuring a Simulation Sickness Questionnaire (SSQ) ([42]) and a Presence Questionnaire

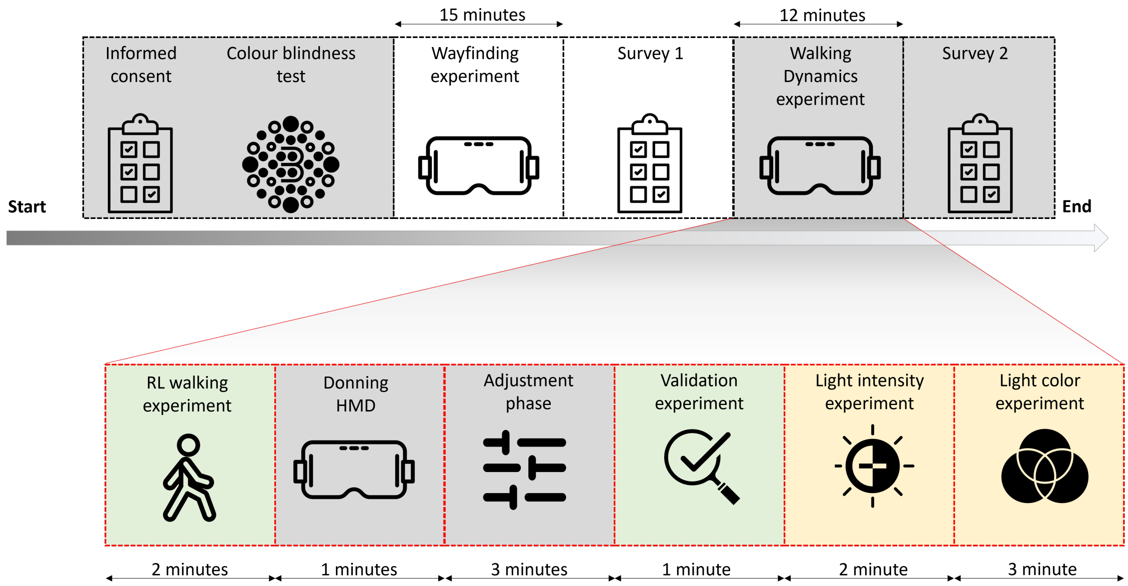


Figure 1 Experimental procedure for the comprehensive experiment

([43]). The instructor of the first experiment accordingly guided the participants to a second room.

Two other experiments took place in the second room, including a real-life walking experiment and a VR experiment (including both validation and light experiment), with a brief adjustment phase in between. After both walking experiments, the participants were asked to complete a second survey. This survey featured a second SSQ questionnaire, a PQ questionnaire, and some questions to record participant characteristics (e.g., age, gender, height, gaming experience).

3.2.2 Procedure real-life validation experiment

At the start of the real-life walking experiment, the participants were guided into an empty room with a circuit taped on the floor featuring several video cameras and HTC base stations. The instructor welcomed the participant to the second part of the experiment and provided short instructions. This instruction told the participants that they were part of a walking experiment, that they would first perform a real-life walking experiment, and that this experiment would accordingly be performed a second time in a VR environment. Stickers were stuck on the participant's legs. Afterward, the participants were led to the starting point of the circuit. Accordingly, they were instructed to trace the rectangular circuit until they had walked 4 complete laps using their 'regular' walking speed. When the participant passed the track's starting point for the 4th time, the instructor stopped the real-life walking experiment. The participant was asked to return to the starting point of the circuit.

3.2.3 Procedure VR experiment featuring walking dynamics

At the start of the VR experiment, the instructor recalibrated the HMD to avoid misalignment issues. Accordingly, the participants were instructed to don the HMD device while standing at the starting point of the circuit. Afterward, they were asked to look around and determine whether they could see the lines on the floor.

Most participants were unfamiliar with wireless HMD and were afraid to start walking because they felt afraid they would hit a wall. Therefore, at the start of the VR experiment, the instructor would stand in the next corner of the rectangular circuit and ask the participants to trace the line toward the instructor's voice to ensure the system was calibrated correctly. If calibrated correctly, the participants would automatically turn in front of the instructor, and the VR walking experiment would continue. The planning of the light conditions they would accordingly see is presented in Table 1.

After the calibration stage, participants were instructed to continue walking the track until the instructor told them to stop. They were also warned that they might see changes in the environment, but their only task was to continue walking on the circuit and trace the line. In reality, no changes occurred in the virtual environment during the first 4 minutes of the VR experiment. The first three minutes were used to acquaint the participants with the VR environment and the movement dynamics of a wireless HMD. During these first minutes, the participants were visibly relaxing and getting used to the virtual environment while they kept tracing the line. By the end of the adaptation phase, all participants were confidently walking and turning. The fourth minute of the 'normal' light conditions was used to collect the data for the *validation experiment*.

After the 4-minute mark, two different light-intensity conditions were shown to the participants. This part of the experiment, which we refer to as the *'light intensity experiment'*, aimed to test the participants' reaction to different light intensities. First, participants were exposed to a lower light intensity for 1 minute, which is experienced by participants as approximately 1 lux in an indoor environment (i.e., evacuation lighting only in an indoor environment). Second, the light conditions switched to a very bright indoor environment, with the feel of 300 lux. To ensure the participants were not overwhelmed by the sudden change in light conditions, the 'normal' white light conditions were briefly shown between the dark and bright conditions.

At minute 6, the participants were shown three different light color conditions. Hereafter, we coin this part of the experiment the *'light color experiment'*. First, the white light switched to green for 1 minute. Next, the green light conditions switched to blue. After another minute, the blue light conditions shifted to red light conditions. We hypothesized that green increases participants' walking speed, blue does not change their walking speed, and red decreases their walking speed. Therefore, the order of the colors is chosen so that the effects of the two conditions we want to most carefully study (i.e., the impact of green and red) are separated by a more 'neutral' condition.

After 9 minutes, the light conditions returned to normal. The instructor, who kept silent throughout the VR walking experiment during minutes 04:00 - 09:00, instructed the participants to stop, remove the HMD, and remove the stickers from their legs. The instructor then brought the participant back to the main room, where the participant was

Start time [min:sec]	End time [min:sec]	Intensity	Color [-]
00:00	03:00	Normal	White
03:00	04:00	Normal	White
04:00	04:55	Dark	White
04:55	05:05	Normal	White
05:05	06:05	Bright	White
06:05	06:20	Normal	White
06:20	07:20	Normal	Blue
07:20	08:20	Normal	Green
08:20	09:20	Normal	Red
09:20	12:00	Normal	White

Table 1 Planning of the light conditions in the VR experiment.

asked to complete the second survey.

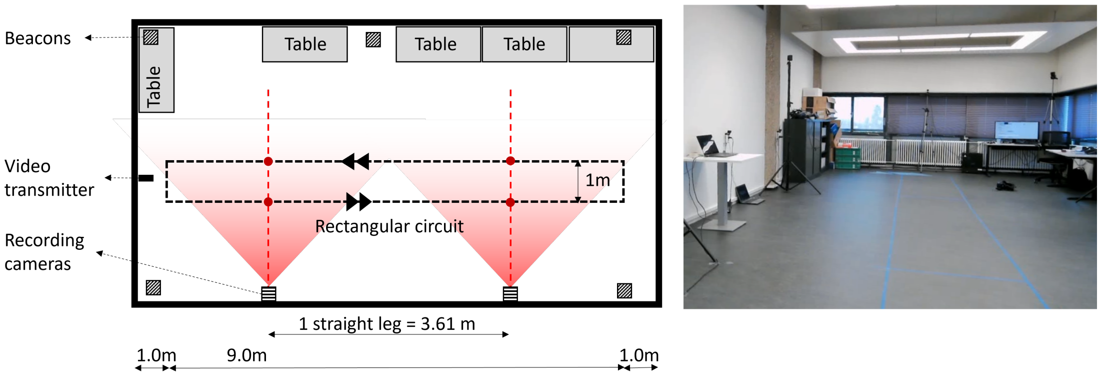
Please note that the order of the light conditions was the same for all participants to achieve statistical power. 30 participants are insufficient to carefully quantify the impact of the order of the light conditions. We acknowledge that the order of light conditions can potentially impact the results. For example, participants might become more confident throughout the experiment due to learning effects. Similarly, due to habit formation, participants might become less sensitive to the light conditions during the experiment. It is an exciting alley for future research to determine whether the order of the light conditions influences pedestrians' operational walking dynamics.

3.3 Setup real-life experiment

The laboratory and VR walking experiments took place in the VR laboratory of the Department of Transport & Planning of the Delft University of Technology (see Fig 2). The room is approximately 7m x 11m, with a continuous line of windows on the West and South sides of the room. A 5m x 11m free walking space was available for the VR experiment. The rectangular circuit was taped on the floor of the VR laboratory with blue-colored tape. This track was approximately 8.9 meters long and 1 meter wide. When the HMD was correctly calibrated, the taped track overlapped with the track the participants would see in the VR experiment.

3.4 Setup virtual environment

The virtual environment featured a relatively simple rectangular room. The VR room had slightly smaller dimensions than the real-life room (Fig. 3.a). That is, the length of the virtual room was 50 cm smaller and the width was 3 meters smaller, excluding the part of the room where tables were located. This ensured that participants could not walk into a table during both the immersive and the non-immersive experiments. When following the track, the participants would not touch the virtual or the physical walls. As a result of the difference in size, participants in the immersive experiment could potentially

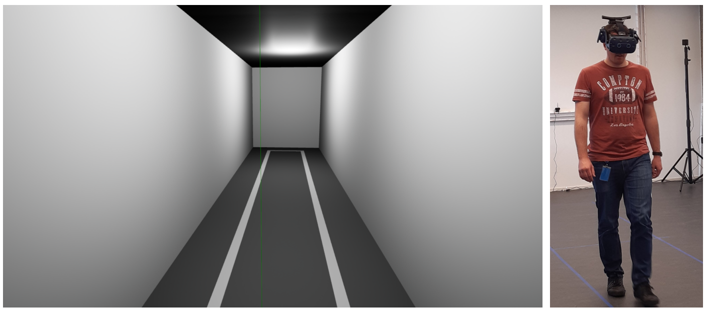


(a)

Figure 2 Overview of the VR walking experiment, where a. displays the room layout and b. is a photo taken in the laboratory during the VR experiment.

start their acceleration later, turn slower, and decelerate earlier than in the non-immersive experiment. To ensure this does not impact our findings, we only record the average walking speed on the track where the participants' walking speed has stabilized.

The walls of the virtual environment are painted white, and the floor is painted dark gray. The blue rectangular track in the real-life room is visualized in the VR environment in white, with precisely the same dimensions as the track in the real-life environment.



(a) (b)

Figure 3 Visualisation of (a) the VR environment and (b) a photo of an equipped participant.

The intensity and color of the lights inside the virtual environment were controlled using area lights placed on the ceiling. Ambient lighting was explicitly not added to the virtual environment to ensure that a very dark environment would indeed be perceived as very dark. The area lights provided directional lighting from a specific rectangular source of 60x60cm and were positioned approximately 5 meters apart on the ceiling.

The intensity of the virtual lights was calibrated to mimic the appearance of a Philips Hue Surimu lamp on the ceiling, emitting an average of 1 lux, 100 lux, or 300 lux towards the floor in a real-life environment. Please note that the identified lux levels (i.e., 1, 100, 300 lux) are a rough approximation based on the various researchers' perceptions regarding the similarity of the light intensity in a natural environment featuring a Philips

Hue lamp and a virtual environment featuring an area light.

For the color setup, the light intensity settings of the Normal white light condition (approx. 100 lux) were adopted, and only the color appearance of the light was changed from white (RGB:255,255,255) to blue (RGB: 0,0,255), green (RGB: 0,255,0), or red (RGB: 255,0,0). As this study aims to study the difference in impact between various distinct colors (i.e., red vs. blue) and not shades of the same color (i.e., light red vs. dark red), we have adopted very basic color profiles in this study. This resulted in 6 distinct light conditions, which are visualized in Figure 4. Even though the light intensity was kept the same in all three colored light conditions, some participants noted after the experiment that they experienced the red and blue light conditions to be darker than the green light conditions. Thus, slight differences in intensity occur due to pedestrians' varying experience of colored light.

3.5 Equipment setup

An HTC VIVE Pro Eye was adopted to visualize the VR environment, with a wireless adaptor attached to the back of the participants' heads (Fig. 5). This adaptor is not visible in the virtual environment. The battery of the HMD device is attached to the back of the participant's pants to ensure that the participant's hands do not collide with the battery while moving.

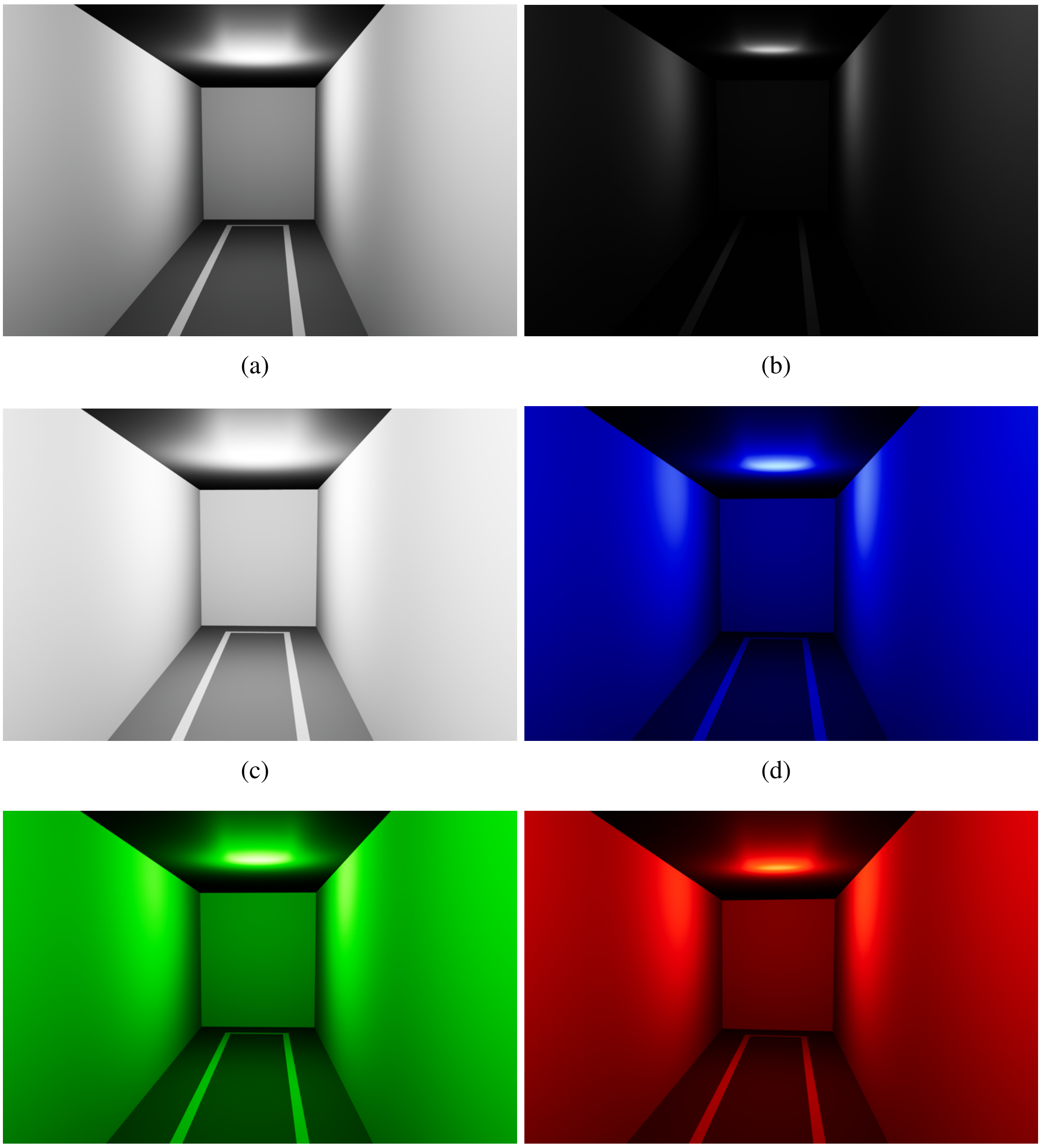
An HTC Vive Pro Eye VR system comprises an HMD with headphones, five lighthouse beacons, and a video transmitter. This VR system features a 110-degree view with a combined resolution of 2880 × 1600 pixels and 615 pixels per inch. In addition, the VR system enables 360-degree head tracking. Unreal Engine 5 and SteamVR were used to run the different VR environments on a computer with an AMD Ryzen 7 2700X with a 3.7 GHz CPU and an NVIDIA GeForce RTX2080 graphics card.

Lighthouse beacons were positioned facing each other at the four corners of the VR laboratory at a height of 2.2 meters. A fifth lighthouse sensor was located in the center of the long wall facing the center of the experimental space to ensure full coverage at the center of the experimental space. The wireless link box (i.e., video transmitter) was located at the short end of the room on the centerline of the track, just out of reach of the participants' movement area.

The participant's movements in the physical space control the positioning of the participant in the virtual environment. An example of a participant using the VR system is depicted in Figure 5. The height of the participants' vantage point in the virtual environment is calibrated to the height of each participant, thus allowing each participant to experience the VR environment in the same way as they would experience a real-life environment.

3.6 Data collection

A multitude of metrics can describe the operational walking dynamics of pedestrians (e.g., [44], [45], [46], [47]). Generally, three distinct metrics are adopted to describe the operational walking dynamics and gait of pedestrians: the average walking speed, the step



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

Figure 4 Visualization of the VR environment under (a) Normal/Regular, (b) Dark, (c) Bright, (d) Blue, (e) Green, and (f) Red light conditions.

Figure 5 One of the participants of the experiment walking through the VR environment.

frequency, and the step length. This study will also use these three metrics to validate the wireless HMD as a tool to perform research into pedestrians' operational walking dynamics. The average walking speed is also adopted to determine light conditions' efficacy in steering pedestrians' operational walking dynamics. Due to the difference in the nature between the validation experiment and the two light experiments, two separate data collection strategies are adopted: a visual data collection strategy that is better suited for the validation experiment and a digital data collection strategy that more effectively captures the relevant data for the light experiments. Below, both will be briefly described.

3.6.1 Visual data collection strategy

In the validation experiment, a vision-based data collection strategy is adopted to limit systematic errors in the comparison due to the partially manual encoding and partially automated coding of the pedestrian's coordinates. As the participants walk the same physical circuit in the real-life and VR experiments, the same data recording equipment and setup are used in the real-life and VR validation experiments. In particular, the participants' stepping motion and average walking speed were recorded using the two cameras on the wall of the experimental room. The two cameras were placed at hip height (approx 1.2 m), 3.61 meters apart to record the participants' movements, and were directed at a straight angle with the long stretch of the circuit.

To compute the average walking speed, two things were recorded:

- the **time** at which a participant crossed one of the two recording lines ($t_{\text{begin}}(p,c,l,i)$ and $t_{\text{end}}(p,c,l,i)$)
- the **walking direction** for each moment at which a participant crossed one of the two recording lines (back, and forth)

Here, we annotated the time at which participants crossed one of the two camera lines when the middle of the participant's leg crossed the centerline of the video image. For this purpose, each participant was equipped with two white stickers with a blue dot on both sides of their legs. The stickers were placed as high as possible on the legs without running the risk of the participants' hands blocking our view of the stickers. In the real-life experiment, we recorded the participants' walking speed during four consecutive laps (eight straight stretches). In the VR experiment, we first allowed them to adjust to the virtual environment. After four minutes, the participants' average walking speed was recorded for 60 seconds.

The step frequency and length were also recorded using a visual recording strategy. Here, we especially studied the participants' gait while in the field of view of the two cameras. Here, four types of data were recorded to characterize their gait:

- the **timestep** that the bottom of the shoe is completely in contact with the floor ($t_{\text{begin}}(p,c,s)$ and $t_{\text{end}}(p,c,s)$)
- the **pixel-coordinates** where the front tip of their shoe is located at the timestep that the bottom of the shoe is completely in contact with the floor ($x_{\text{begin}}(p,c,s)$, $x_{\text{end}}(p,c,s)$)
- the **walking direction** of the participant for each time step at which the participant's shoe touches the floor.
- the **camera identifier** for each time step at which the participant's shoe touches the floor (for orthorectification purposes)

For each participant, the following data was collected during the validation experiment:

- Walking time for 7-8 straight legs in a physical environment
- Walking time for 6-8 straight legs in a VR environment
- Step time and step length for a minimum of 53 steps in a physical environment
- Step time and step length for a minimum of 66 steps in a VR environment

The number of data points differs per participant and varies between the physical and VR validation experiments. There are two reasons for this. First, for some participants, the last leg of the real-world experiment was compromised due to participants preemptively stopping the experiment due to miscounting. Only straight legs that were finished without interruptions are accounted for in the dataset. Second, the number of steps depends on the number of steps the participants make in the field of view of the cameras and, thus, their step length. We only take into account stepping movements in which both the start of the step (i.e., the bottom of shoe 1 touches the floor entirely) and the end of the step (i.e., the bottom of shoe 2 touches the floor entirely) are recorded by the same camera to avoid synchronization errors between the cameras. When the step length decreases, the number of participant's steps performed inside the field of view increases.

3.6.2 Digital data collection strategy

A digital data collection strategy was adopted for the two light experiments. In particular, the coordinates (i.e., X and Y) and rotations (i.e., yaw, roll, pitch) of the HMD were recorded, representing the participants' movement dynamics. Even though there might be slight differences between the movements of a participant's head (the HMD) and the rest of the participant's body, we expect average walking dynamics to be limited in the case of regular walking motion where pedestrians are standing up straight. There is no need to interact with other individuals. One additional benefit of the HMD's positioning system is that the positioning of the HMD is automatically logged at a very high frequency (10 Hz), thus allowing for a very granular recording of the participant's movement dynamics.

To determine the average walking speed, the X- and Y-coordinates of the HMD are recorded. In addition, to compute the average walking speed on the straight and corner legs of the track, two additional things are recorded, namely the time at which a person's head crosses one of the two recording lines (i.e., $t_{\text{begin}}(p,c,l,i)$ and $t_{\text{end}}(p,c,l,i)$). The latter two variables are used to compute the average speed on the four parts of the rectangular circuit: two straight legs and two corner legs.

3.7 Computation metrics of interest using vision-based data

The three metrics are computed using the vision-based data: the average walking speed, the step time, and the step length. Below, the mathematical definitions are presented for all three metrics.

3.7.1 Computing the average walking speed

The average walking speed along a straight stretch is computed using equations 1 - 3 in both the VR and the real-life experiment. First, the time-interval $T_{\text{leg}}(p,l,i)$ determines the time it takes participant p to walk the i-th straight leg of the circuit (see equation 1).

$$T_{\text{leg}}(p,c,l,i) = t_{\text{end}}(p,c,l,i) - t_{\text{begin}}(p,c,l,i). \tag{1}$$

Here, $t_{\text{begin}}(p,c,l,i)$ and $t_{\text{end}}(p,c,l,i)$ are the respective moment in time t in seconds that participant p in light condition c passes the two subsequent recording lines that demarcate the start and end of the straight legs of the rectangular circuit. Accordingly, the average effective walking speed $v_{leg}(p,n)$ of participant p during the i-th straight stretch is computed using:

$$v_{\text{leg}}(p,c,l,i) = \frac{d_l}{T_{\text{leg}}(p,c,l,i)}, \tag{2}$$

where N_{leg} represents the number of recorded stretches for participant p and d_l the length in meters of leg l. In this case, only the straight legs, which are 3.61 m long, are considered. Please note that we use the effective speed in the direction of the goal instead of an average of the instantaneous walking speed. This allows for a better comparison with the gait analysis literature, which generally uses this construct.

Lastly, the average walking speed $\bar{v}_{\text{leg}}(p,c)$ in m/s of a participant p in light condition c for a specific leg type l across all straight stretches is computed as the arithmetic mean of all speed record $v_{\text{leg}}(p,c,l,i)$ for participant p. This average walking speed of a participant is given by

$$\bar{v}_{\text{leg}}(p,c,l) = \frac{\sum_i v_{\text{leg}}(p,c,l,i)}{N_i(p,c)}. \tag{3}$$

where $N_i(p,c)$ is the number of recorded legs of a certain type for participant p in a certain light condition.

3.7.2 Computing the step time

The step frequency is computed using equations 4 and 5 in both the VR and the real-life experiment. Here, first, the time interval $T_p(m)$ between two respective shoes touching the floor is (see Figure 6) computed using :

$$T_{\text{step}}(p,c,s) = t_{\text{end}}(p,c,s) - t_{\text{begin}}(p,c,s). \tag{4}$$

In equation 4, $T_{\text{step}}(p,s)$ represents the time when the bottom of the shoe of participant p in light condition c touches the floor entirely for the s-th time in the field of view of the recording of one of the two video cameras. Please note, that for some steps $t_{\text{begin}}(p,c,s) = t_{\text{begin}}(p,c,s+1)$. Accordingly, the average step time of participant p in light condition c is computed as the arithmetic mean of all step time values and is determined with

$$\overline{T}_{\text{step}}(p,c) = \frac{\sum_s T_{\text{step}}(p,c,s)}{N_s(p,c)}. \tag{5}$$

Here, s represents the s-th step for which the same camera records both the step's start and end times. $N_s(p,c)$ represents the total number of steps recorded for participant p in light condition c.

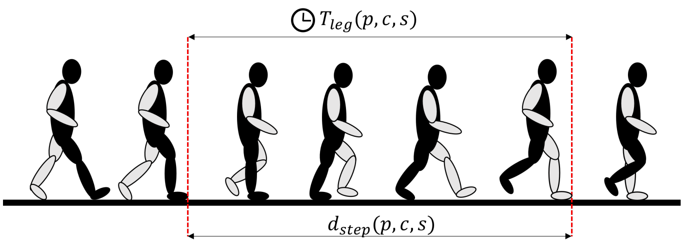


Figure 6 Visualisation of the step length metric

3.7.3 Computing the step length

The step distance is computed utilizing equations 6, 7 and 8. First, the pixel coordinates must be orthorectified to compute the step length. In this process, the pixel coordinates are translated into real-world coordinates. In this study, we only take steps to orthorectify the x-coordinates from pixels to meters, as the y-coordinates are not used in any of the three metrics.

During the offline calibration of the two cameras, for each pixel in both video images, a ratio α_y has been determined that identifies the pixel/meters ratio for a particular pixel in the picture. This ratio relates to the distance in pixels between the tip of the shoe and the center line of the video image x_{center} to the distance between the tip of the shoe and the center line of the video image in meters. The ratio α_y depends on the pixel y-coordinate in the video image. Accordingly, the distance between the shoe tip and the video image's center line in meters is translated using simple linear regression into

$$x'_{\text{begin}}(p,c,s) = \alpha_y * (x_{\text{begin}}(p,c,s) - x_{center}). \tag{6}$$

Here, $x_{\text{begin}}(p,c,s)$ represents the x-coordinate of the tip of the shoe in pixels when the bottom of the shoe touches the floor for the s-th time in light condition c, and $x'_{\text{begin}}(p,c,s)$ represents the orthorectified location of the tip of the shoe of participant p in meters. $x'_{\text{end}}(p,c,s)$ is computed using the same algorithm.

Our step length calculation relies on the orthorectified x-coordinates, which are the x-coordinates of the shoe tip in meters when two consecutive shoes touch the floor. The step length $d(p,m)$ of one step of participant p in meters is then determined by taking the difference between these orthorectified x-coordinates and is given by

$$d_{\text{step}}(p,c,s) = |x'_{\text{end}}(p,c,s) - x'_{\text{begin}}(p,c,s)|, \tag{7}$$

where s represents the s-th step of participant p during light condition c in meters in the camera's field of view. Accordingly, the average step length of participant p is determined as the arithmetic mean of all recorded step lengths for participant p.

$$\overline{d_{\text{step}}}(p,c) = \frac{\sum_s d_{\text{step}}(p,c,s)}{N_s(p,c)} \tag{8}$$

3.8 Computing metric of interest using digital trajectory data

We are predominantly interested in pedestrians' average walking speed in the light experiment. Equation 1 is adopted to determine the time period $T_{\text{leg}}(p,c,l,i)$ required by participant p during light condition c to cover the i-th leg of leg type l. Yet, in this case, $t_{\text{begin}}(p,c,l,i)$ and $t_{\text{begin}}(p,c,l,i)$ represent the moment in time that the head of the participant crosses one of the two recording lines. Accordingly, the distance $d_{\text{leg}}(p,c,l,i)$ traveled by the pedestrian during time period $T_{\text{leg}}(p,c,l,i)$ is determined using eq. 9, where $\vec{x}_p(t)$ represents the position coordinates of participant p at time t.

$$d_{\text{leg}}(p,c,l,i) = \sum_{t=t_{\text{begin}}(p,c,l,i)}^{t_{\text{end}}(p,c,l,i)} |\vec{x}_p(t+\Delta t) - \vec{x}_p(t)| \tag{9}$$

The average speed of participant p during light condition c on the i-th leg of leg type l is computed by dividing the cumulative distance $d_{\text{leg}}(p,c,l,i)$ traveled by the pedestrian by the time period Δt spent doing so (eq. 10).

$$\overline{v}(p,c,l,i) = \frac{d_{\text{leg}}(p,c,l,i)}{T_{\text{leg}}(p,c,l,i)} \tag{10}$$

This speed definition is similar to the velocity definition of Edie [48]. Please note, As a result of this definition, lateral movements are also considered, which can slightly overestimate very low speeds ($< 0.4m/s$). This computation method does, however, ensure that the walking speed can be computed more effectively during the corner turns, where the distance traveled can differ heavily between participants depending on their corner-taking strategy. Lastly, the average walking speed $\overline{v}(p,c,l)$ of participant p during light condition c per leg type l is determined as the arithmetic mean of the set of walking speed records $\overline{v}(p,c,l,i)$ for a particular type of leg l, where $N_i(p,c)$ represents the number of walking speed records for participant p in light condition c and leg type l.

$$\overline{v}(p,c,l) = \frac{\sum_i \overline{v}(p,c,l,i)}{N_i(p,c)} \tag{11}$$

4 Description participant sample

The literature describes a negative impact of age on the average walking speed of pedestrians (e.g., [49]). Thus, this study explicitly selected young participants to limit the impact of this effect on the distribution of our measurements in the walking experiments. Moreover, only healthy individuals without physical impairments that would hamper their walking abilities were selected. As a result, only people between 18 and 35 years old and those without walking disabilities could participate in the experiments. In addition, the light experiments also featured a color-based experiment. Therefore, only individuals who could identify the difference between white, green, red, and blue were allowed to participate in the experiment.

The participants were recruited via flyers, social media messages, and posters distributed at the university. As a result, most of them were Bachelor, Master, and PhD students. Some of the participants were working in our department. Yet, steps were taken to prevent them from obtaining pre-emptive knowledge of the objective and content of the experiments. During recruitment, the interested individuals were only told that they would partake in a set of VR experiments aimed at studying pedestrian behavior.

In total, 37 healthy participants with good eyesight participated in the VR experiment, featuring 12 females and 25 males. We did not record their country of origin. Yet, the instructors noted that most participants were European, particularly Dutch citizens. The participants had an average height of 175.5 centimeters and a standard deviation of 9.7 centimeters. This reasonably represents the average height of the Dutch population ([50]). The participants' ages ranged from 20 to 35, with an average of 26.8 years and a standard deviation of 3.6 years. The experiment population is, on average, very young and not representative of the general population. Yet, this age distribution is expected based on our selection criteria.

Due to some instabilities in the connection with the wireless HMD, the light experiment was cut short for some participants. All participants finished the validation experiment. Participants were only included in the light and color impact analyses dataset if a complete trajectory without glitches was available. This selection process ensured that 37 participants were accounted for in the light-intensity analysis and 27 in the light-color analysis. Despite the exclusion of 10 participants, the distribution of their characteristics remained largely unchanged, with the percentage of women only dropping from 32% to 29%, and their average age decreasing by a mere 0.2 years.

The data has been deposited in the 4TU ResearchData repository and can be found under the DOI:10.4121/9b30a3cc-df03-4c06-8ba7-8df4648b2d80.

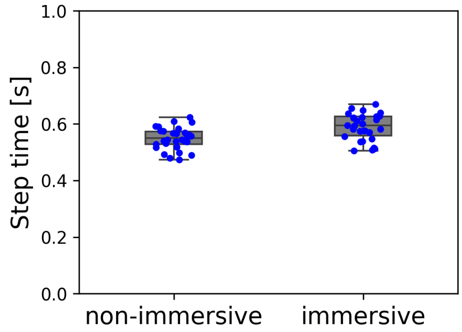


Figure 7 Probability density function (PDF) of step time $\overline{T}_p$ in the real-life experiment (Real-life) and VR experiment (VR).

5 Pedestrian walking dynamics in real-life and VR

Before presenting the results of the light experiments in section 6, this section first discusses the results of the real-life and VR experiments. These results are compared with the existing literature in section (5.2).

5.1 Results VR validation experiment

In this section, we validate the use of the wireless HMD for three metrics of pedestrian walking dynamics: step time, step length, and average walking speed. In addition, we determine whether wireless HMDs can be used to study the impact of participants' characteristics on their operational walking dynamics.

Figure 7 displays the probability density function of the participants' *step time* $\overline{T}_{\text{step}}(p)$ in the real-life and VR experiments. The mean step time in the real-life experiment is 0.55 s with a standard deviation of 0.04 s. The mean step time in the VR experiment is 0.59 s with a standard deviation of 0.05 s. A Shapiro-Wilk test indicates that both probability density functions are normally distributed ($p = 0.78$ & $p = 0.24$). A paired t-test is adopted to determine whether the two probability density functions are similar. This test compares the means of two measurements taken from the same individual (i.e., $H_0 : \mu_1 = \mu_2$). The paired t-test results identify a significant difference in step time of 0.04 seconds between the step time of the participants in the real-life and VR experiments ($t = 7.49$, $p =< 0.001$). The difference in the mean corresponds with a 7.5 % increase in step time in the VR experiment and a 0.08 m/s increase in walking speed for a pedestrian with a step length of 0.73 m/s. This suggests that participants walk slightly slower through a virtual environment while wearing wireless HMD. At the same time, the 0.04-second difference in step time has a fairly small impact on the walking speed. When considering the well-established effects of age(-6.25% children vs. adults - [51]), and gender($+8.04\%$ -[52]),

Figure 8 displays the probability density function of *step length* in the real-life and VR validation experiment. The mean step length in the physical experiment is 0.73 m,

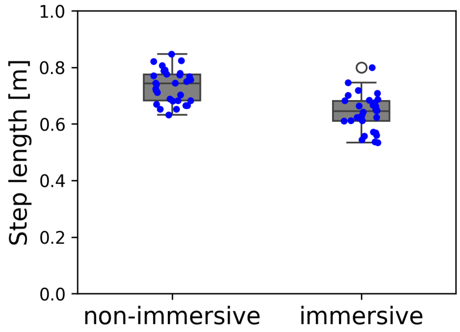


Figure 8 Probability density function (PDF) of step length $\overline{d}_p$ in the real-life experiment (Real-life) and VR experiment (VR).

with a standard deviation of 0.06 m. The mean step length in the VR experiment is 0.64 m, with a standard deviation of 0.06 m. Similar to the distributions of the step time, these two probability density functions are normally distributed (i.e., Shapiro-Wilk test, $p = 0.46$ & $p = 0.65$). The paired t-test results indicate that the step length is significantly shorter in the VR experiment than in the real-life experiment (i.e., $t = -77.5$, $p =< 0.001$). This corresponds with an average 12.8% shorter step length while navigating the VR environment. This result indicates that participants take smaller steps while walking through a virtual environment wearing a wireless HMD.

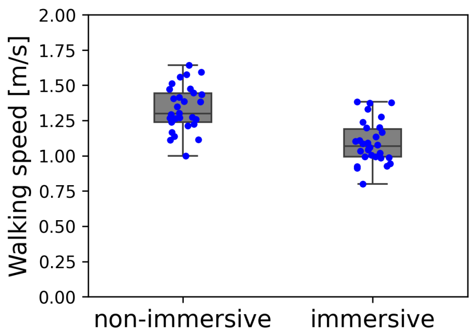


Figure 9 Probability density function (PDF) of average walking speed $\overline{v}_p$ in the real-life experiment (Real-life) and VR experiment (VR).

Figure 9 displays the probability density function of the *average effective walking speed* in real-life and VR experiments. The Shapiro-Wilk test results identify that the two distributions are normally distributed (i.e., $p = 0.85$ & $p = 0.20$). Accordingly, a paired t-test identifies that the difference between the means (μ) is significantly different (i.e., $t = -10.83$, $p =< 0.001$). On average, the average walking speed of participants is 22.8% lower in the VR environment than in the real-life environment. This result corresponds with the two previous results featuring the step time and step length, as the speed results from multiplying the step length and the step frequency (i.e., the inverse of the step time).

Thus, if the step length decreases, the step time increases, the step frequency decreases, and the average effective walking speed decreases.

5.2 Discussion of the VR validation experiment's results

To the authors' knowledge, seven studies have been comparing real-life locomotion (i.e., walking overground) in a real-life environment and a VR environment, though under different conditions. The first three studies studied the walking behavior of their participants using a treadmill. Here, [53] registers an increased step time and the number of steps. Similarly, [54] found that the stride length (i.e., one step with one leg), cadence, and speed (i.e., the inverse of step time) during the VR experiments significantly differed between treadmill walking in reality in comparison to over-ground walking and treadmill walking in VR. Shorter stride lengths and a lower cadence were observed in the VR scenario. Similarly, [55] also identifies that the preferred walking speed of pedestrians in VR environments is lower than in a physical environment. In our study, similar effects were found. This implies that the difference in step length, step time, and walking speed recorded by [53], [54], and [55] is partly the result of walking in a virtual environment and not solely the result of participants' adjustments to walking on a treadmill.

Four other studies did adopt overground walking while moving through a VR environment, all of which recorded a respective decrease in walking velocity of 14%, 6%, 7%, and 17% ([15], [16], [56], and [17]). In addition, [16] established a decreased step length. Our results are in line with these four studies. In the VR validation experiment, participants have a shorter step length, a longer step time, and a lower average effective walking speed. Yet, our study's relative decrease in the average effective walking speed is higher than in previous studies. Potentially, the experience level of the participants, who had never experienced a wireless HMD before, partly explains the larger difference in walking speed. In addition, the more complicated assignment with the sharp turns could also have limited the walking speed in the VR environment.

Significant differences in the average step time (0.04 s), step length (0.07 m), and walking speed (0.24 m/s) were found. The effect size of all three differences is large (step time) or considerable (step length and walking velocity) when testing them using Cohen's d formula (i.e., 0.799, 1.499, 1.519). Yet, what does this mean for VR studies featuring HMD devices? To answer that question, we must put these impacts into perspective. In Table 2, we recorded the impacts of age, gender, height, and weight on step time, step length, and walking time identified by [57], a cross-sectional study under healthy adults. A comparison of the differences between our results and those recorded by [57] shows that the difference in step time that we find is relatively big. The difference in step length is much smaller than the differences of gender and height in step length recorded by [57]. The difference in walking speed we find is similar to the impacts of age and gender on walking speed found by [57]. Thus, even though the values are relatively small, the impact of the wireless HMD on the participants' walking behavior is the same size (or larger than) known other impacts of socio-demographic factors on walking behavior.

Our study concludes that while the wireless HMD setup may introduce small but significant differences in the average step time, step length, and walking speed, it can still be a valid tool for studying pedestrian walking behavior. Understanding and accounting for the systematic under- and overestimation caused by the wireless HMD is crucial. This knowledge can guide researchers in effectively using wireless HMDs in their VR studies despite the potential for slight inaccuracies.

Socio-demographic characteristic	Step time (s)	Step length (m)	Walking speed (m/s)
age (male, 30 or 50 years)	0.00	0.04	0.02
gender (30 years, male or female)	0.03	-0.31	-0.09
height (male, 1.70m or 1.90m)	0.03	0.15	0.10
weight	0	0.02	0.02

Table 2 Impacts on step time, step length and walking speed recorded by [57]

6 Pedestrian walking dynamics for varying light conditions

The VR light experiments lasted approximately 560 seconds for each participant, and their movement trajectories were recorded with a frequency of approximately 10 Hz. This resulted in a set of trajectory files, one for each participant. Figure 10 depicts one of these trajectories. In total, 186,989 data points were collected, with an average of 5,053 data points per participant.

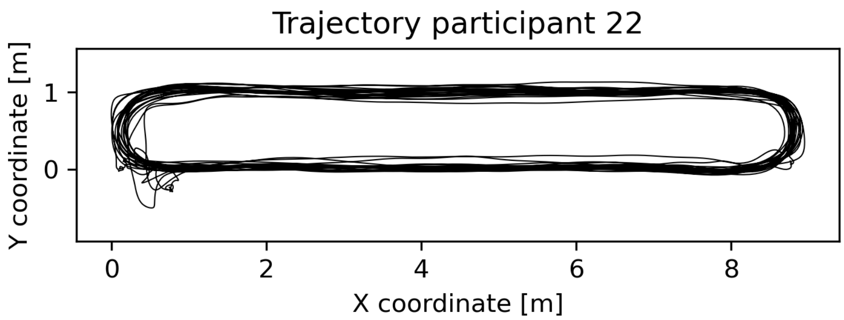


Figure 10 Trajectory of participant 22, as recorded by the HMD.

Below, the impact of both light characteristics (intensity and color) will be studied in separate subsections using the participants' trajectory data. First, the effect of light intensity is examined in section 6.2. Accordingly, section 6.3 presents the results on the impact of the color of the light on pedestrians' walking speed. Yet, before doing so, section 6.1 first presents an overview of the operational walking dynamics in the VR experiment under regular light conditions.

6.1 Walking dynamics of pedestrians in VR environments

We adopt the Normal White light condition as a benchmark during the analyses in the following sections. Therefore, we first present the general walking dynamics of the participants for this particular light condition.

Under Normal White light conditions, the participants' walking speed in the VR environment varies depending on their location on the circuit. Figure 11 depicts the average walking speed profile of the participants concerning their location on the trajectory, where (a) represents their movements along the straight leg from the windows to the wall (starting at x=0m and moving towards x=8), and (b) their movements from the wall to the windows (starting at x=8m and moving towards x=0m). Figure 11 shows that, on average, the participants' walking speed decreases when turning on one of the corner legs of the circuit. After the turn, the participants accelerate again along the first part of the straight legs of the circuit. The acceleration phase lasts slightly longer than the deceleration phase. Participants adopted a relatively stable walking speed two meters after each turn again. The participants adopt their free-flow speed between 2 and 6 meters from each corner.

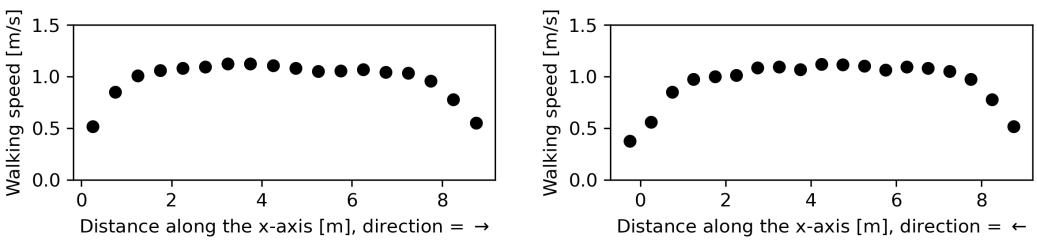


Figure 11 Probability density function of mean walking speed on the straight and corner stretches in the validation experiment.

When comparing the distributions of the average walking speed on the straight legs and the corner legs in the regular VR experiment scenario, a decrease in the average walking speed is recorded (see Fig. 12). On the straight legs (i.e., $2.00m \leq y \leq 6.90m$), the average walking speed is 1.09 m/s, with a standard deviation of 0.16 m/s. On the corner legs (i.e., $y < 2.00m \mid y > 6.90m$), an average walking speed of 0.80 m/s is recorded, with a standard deviation of 0.19 m/s. When comparing the participants' walking speed between the real-life and VR environments, we find an average walking speed decrease of 18.1%. Please note, in this computation, we use the *average walking speed* instead of the average *effective walking speed*, resulting in a smaller decrease in the average walking speed.

6.2 Impact of light intensity

To determine the impact of light intensity, the average walking speed of pedestrians under normal, dark, and bright conditions were compared. Table 3 provides an overview of the statistical comparison between the probability density functions of the average walking

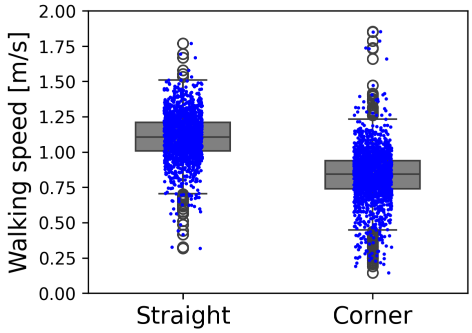


Figure 12 Probability density function (PDF) of mean walking speed on the straight and corner stretches.

speed for both leg types (i.e., straight and corner). In addition, Figure 13 presents the boxplots of the 6 distinct distributions. The table and figure indicate that the participants slow down under dark conditions and speed up under bright conditions. On straight legs and in the dark, the average walking speed decreases by 10.4%. At the same time, in very bright conditions, the average walking speed on the straight legs increases by 5.8%.

The impact of the light in bright conditions is slightly more substantial on the corner legs of the circuit. In this case, the walking speed decreases by 8.6% in dark conditions but increases by 7.7% in bright light conditions. We hypothesize that the visual cues in the environment, such as the shading of the walls and corners, are better visible in bright conditions, thus allowing pedestrians to speed up.

Leg type	Condition	Mean [m/s]	Std. [m/s]	Normal dist.
Straight	Dark	0.93	0.12	Yes
Straight	Normal	1.04	0.13	Yes
Straight	Bright	1.09	0.12	Yes
Corner	Dark	0.52	0.13	Yes
Corner	Normal	0.65	0.11	Yes
Corner	Bright	0.70	0.09	Yes

Table 3 Mean and standard deviation of the walking speed various light color conditions and the Shapiro-Wilk test results.

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A Shapiro-Wilk test, which tests whether a distribution is distributed normally, identifies that all six walking speed distributions for the six light intensity conditions are normally distributed (i.e., none of the normality hypotheses were rejected). Consequently, a paired t-test can be adopted to determine whether the means of the walking speed distributions are significantly different. In particular, all sets of two walking speed distributions featuring two different light conditions of the same leg type were compared. Table 4 presents the test results. To check for significance, we adopted a significance level threshold of $\alpha = 0.017$, corresponding with the regular significance level of $\alpha = 0.05$ with a Bonferroni correction for sets of three hypothesis tests. As one can see, the means of all

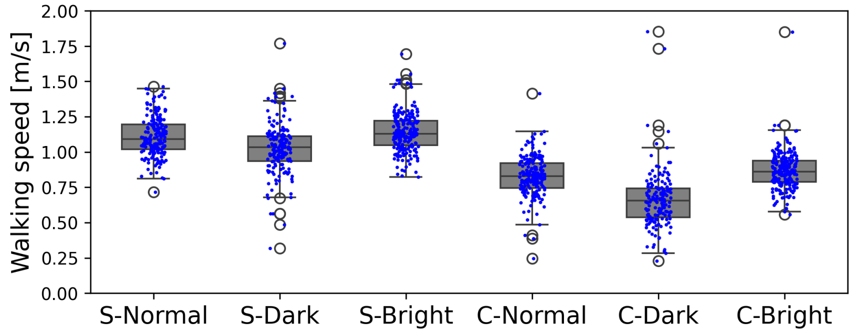

Figure 13 Probability Density Function (PDF) of the average walking speed during regular (approx. 100 lux), dark (approx. 1 lux), and bright (approx. 300 lux) light conditions.

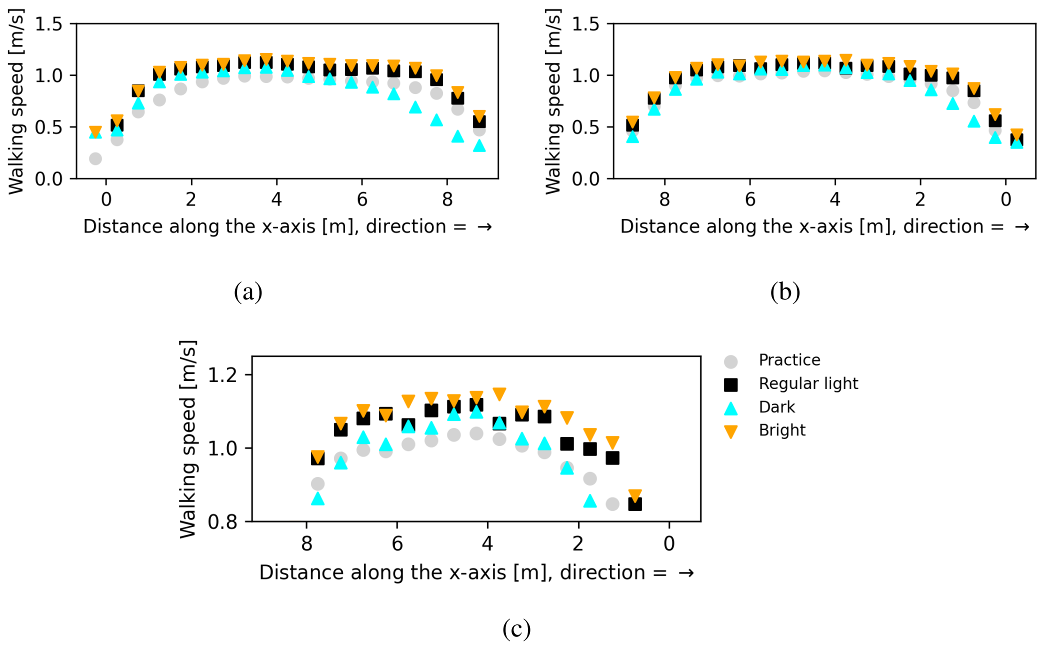

Figure 14 Visualization of the walking speed under various light intensity conditions, where a) and b) visualize the walking speed on the two straight legs, and c) depicts a zoomed version of Figure 14.b.

six distributions are significantly different. These statistical test results indicate that light intensity substantially influences pedestrians' walking speed.

Leg type	Condition 1	Condition 2	t-stat	p-value	Sign.
Straight	Normal	Dark	6.97	< 0.01	Yes
Straight	Normal	Bright	-6.60	< 0.01	Yes
Straight	Dark	Bright	-12.25	< 0.01	Yes
Corner	Normal	Dark	-15.50	< 0.01	Yes
Corner	Normal	Bright	-25.15	< 0.01	Yes
Corner	Dark	Bright	-22.08	< 0.01	Yes

Table 4 The paired t-test results for the average walking speed during various light intensity conditions
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When studying the profile of the walking speed across the length of the track (see Fig. 14), we see a similar pattern. The average walking speed is highest across the board in bright conditions and lowest during dark conditions. During the practice rounds, participants walk slower than during the regular conditions, most likely due to their unfamiliarity with the wireless HMD. Yet, the acceleration and deceleration gradient is also quite similar during the practice rounds to the acceleration and deceleration gradient during regular walking conditions. Interestingly, during dark light conditions, also the shape of the deceleration curve (i.e., Fig. 14.a $y < 2$ and Fig. 14.b $y > 6.8$) changes. Participants start slowing down earlier, more gradually, and adopt a lower walking speed when moving through the corner. The instructors also noted that participants started using their feet and hands to feel for physical cues in the corners, which were slightly darker than in the middle of the track. This happened while the physical walls in the VR laboratory were nowhere near the participants when they were standing in the corners of the circuit in the VR environment. The decreased clear visual cues most likely urged the participants to move more cautiously and use more senses to acquire the necessary information.

6.3 Impact of light color

Table 5 provides an overview of the mean and standard deviation of the eight distinct walking speed distributions regarding the four light colors for both leg types. Figure 15 presents the probability density functions for all eight distributions. The three color conditions are generally perceived to be slightly darker than the Normal light intensity conditions. Therefore, we expected pedestrians to decrease their walking speed slightly. Yet, contrary to our expectation, the average walking speed of the participants increases by 2.8 % to 8 % in all the colored light conditions (i.e., blue, green, red). Yet, the difference in the mean of the average walking speed of participants between the three different colored light conditions is minor. At the same time, the standard deviation of the average walking speed is relatively large, considering the difference between the three means.

Similar to the impact of the light intensity, in the color experiment, the average walking speed on the corner legs is approximately 6% lower than on the straight legs. This is a

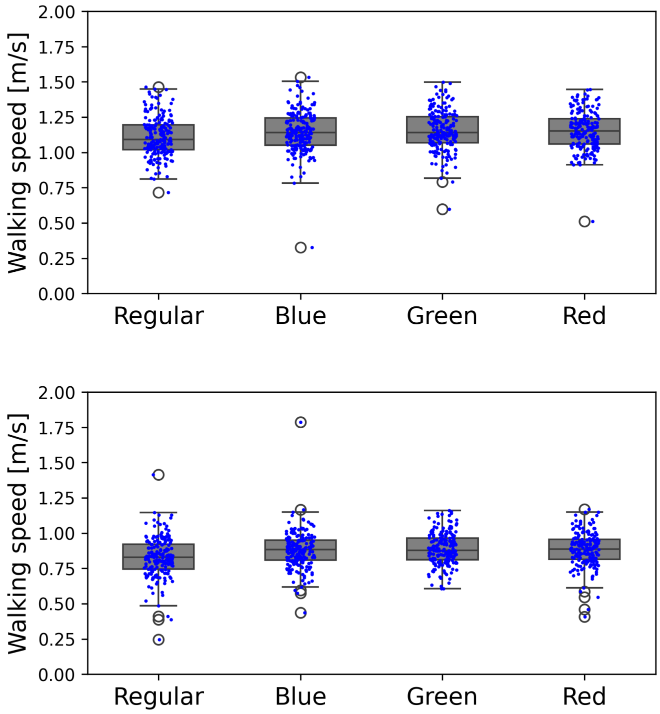


Figure 15 Probability Density Function (PDF) of the average walking speed during regular (white), blue, green, and red light conditions on the straight (top) and corner (bottom) legs..

systematic trend also identified in the validation experiment (see section 4). Yet, also on the corner legs, the colored light conditions increase the average walking speed.

Leg type	Light color	Mean [m/s]	Std. [m/s]	Normal dist.
Straight	Regular	1.09	0.13	Yes
Straight	Blue	1.13	0.12	Yes
Straight	Green	1.13	0.14	Yes
Straight	Red	1.12	0.14	Yes
Corner	Regular	0.96	0.19	Yes
Corner	Blue	1.03	0.16	Yes
Corner	Green	1.04	0.16	Yes
Corner	Red	1.03	0.17	Yes

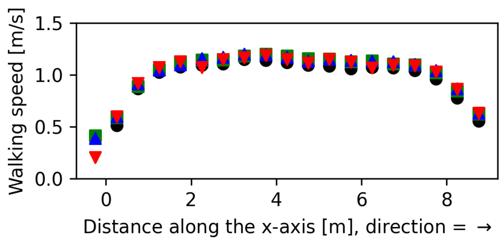
Table 5 Mean, standard deviation, and Shapiro-Wilk test results for pedestrians' walking speed during various light color conditions.

Also, for the distributions of the average walking speed featuring the color light experiment, a Shapiro-Wilk test was performed to determine whether the PDF had a normal distribution, which was true for all eight distributions. Consequently, a set of paired t-tests was performed. Here, the significance level was adjusted using a Bonferroni correction for a set of six hypothesis tests (i.e., $\alpha = \frac{0.5}{6} = 0.008$). The results of these tests are depicted in Table 6. As a result, the differences between the blue, the green, and the red light conditions do not significantly influence the participants' average walking speed. Yet, the difference between the regular and colored conditions is significant on the straight and the corner legs. This suggests that the use of light color does significantly influence pedestrian walking speed.

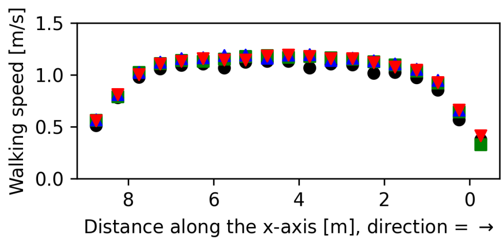
Leg type	Condition 1	Condition 2	t-stat	p-value	Sign.
Straight	Regular	Blue	-6.21	< 0.001	Yes
Straight	Regular	Green	-5.62	< 0.001	Yes
Straight	Regular	Red	-3.41	0.002	Yes
Straight	Blue	Green	-0.61	0.549	No
Straight	Blue	Red	1.55	0.133	No
Straight	Green	Red	2.35	0.026	No
Corner	Regular	Blue	-7.19	< 0.001	Yes
Corner	Regular	Green	-7.45	< 0.001	Yes
Corner	Regular	Red	-5.39	< 0.001	Yes
Corner	Blue	Green	-2.08	0.047	No
Corner	Blue	Red	-0.49	0.625	No
Corner	Green	Red	0.77	0.451	No

Table 6 Paired t-test results for pedestrians' average walking speed during various light color conditions.

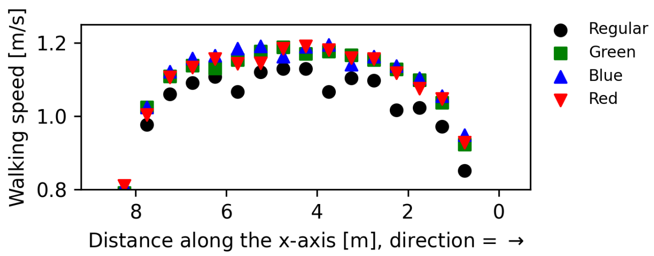
When studying the profile of the walking speed across the length of the track (see Fig. 16), we see very little difference between the three light conditions. They all follow a



(a)



(b)



(c)

Figure 16 Visualization of the walking speed under various light intensity conditions, where a) and b) visualize the walking speed on the two straight legs, and c) depicts a zoomed version of Figure 16.b.

relatively similar pattern. The zoomed graph (Fig.16.c) shows that, across the board, the average walking speed of the participants is lowest during regular light conditions. Participants' average walking speed varies slightly between light conditions, but no apparent differences between the three color conditions can be established. In conclusion, the light conditions do not seem to severely change the acceleration and deceleration behavior of the participants during the blue, green, and red color conditions.

6.4 Discussion of the VR light experiment's results

Four previous studies presented results on the relationship between walking speed and light conditions. Three studies mentioned changes in walking speed due to the changing light conditions. Their findings suggest that participants indeed walk significantly slower under dimmed light conditions. [40] found a decrease of 14.36% in the average walking speed. [39] recorded a far smaller decrease in walking speed of 1.5% - 3% for various dimmed light conditions. [35] mentioned a decrease in walking speed but did not specify an exact percentage. Our findings suggest a walking speed decrease under dark conditions of 10.4% on the corner legs and 5.8% on the straight legs. These values are most in line with the results of [40].

The impact of color and brighter light conditions (i.e., more lux) has not been studied. Even though some anecdotal stories of crowd managers in the field of event safety point in the same direction as our findings, no formal studies can be used to validate our results. Therefore, it would be wonderful if one or more other experimental field studies could replicate the findings of our experiment.

One must remember that this study is the first preliminary study researching the impact of light conditions on participants' walking speed. A relatively small, homogeneous participant sample was adopted. Moreover, to achieve statistical significance, the light conditions were not randomized. Consequently, some of the effects established in this research can be due to waning participant interest, learning effects, participant selection, and differences in the spatial layout between the virtual and physical space. Even though the results regarding the impact of light intensity follow a similar pattern as the previous studies on this topic, the results of this study need to be corroborated by a more comprehensive study featuring a larger heterogeneous population and a randomized research setup.

7 Conclusions and future works

This study determined to what extent light conditions can be used to steer the walking dynamics of pedestrians. A unique Virtual Reality experiment featuring wireless HMD has been adopted to determine the impact of light conditions on the average walking speed of pedestrians. In particular, this study investigated the difference in the average walking speed as a result of regular (i.e., white lights of approximately 100 lux), dark (i.e., white lights of approximately 1 lux), bright (i.e., white light of approximately 300 lux), blue, green, and red light conditions.

This study concludes that:

- participants' average walking speed decreases in darker light conditions and increases in brighter light conditions,
- the participants' deceleration profile changes under dark light conditions as participants decelerate more slowly and cautiously,
- participants' average walking speed increases slightly under colored light conditions,
- participants' average walking speed increases irrespective of the exact color adopted,
- participants' acceleration and deceleration profile does not change with respect to regular light conditions for colored light conditions.

These results suggest that light conditions can alter pedestrians' walking speed. As the impact of light intensity on the average walking speed is most pronounced, using light intensity to steer pedestrian speeds seems more effective. Thus, light might be a very interesting non-evasive crowd management measure that can be used for traffic-calming and capacity control when used to adjust the walking speed of large crowds.

This study has attempted to validate a wireless HMD to study pedestrians' operational walking dynamics. The results of the validation experiment allow us to conclude that:

- step time is overestimated when using a wireless HMD,
- step length is underestimated when using a wireless HMD and

- the effective walking speed on straight legs is underestimated when using a wireless HMD.

The validation experiment results imply that participants immersed in a virtual world using a wireless HMD are more restricted in their movements and adopt a slightly lower walking speed than when performing the same actions in non-immersed settings. Most likely, participants move more carefully in a VR experiment featuring overground walking to avoid potential collisions. Even though the effects concerning step time and step length are small, their compound impact on the average walking speed is relatively large. Especially in the case of evacuation studies, these behavioral differences between real-life and VR experiments could lead to an overestimation of, for instance, the building evacuation time.

This VR study represents a first step towards the more extensive usage of VR experiments to study pedestrians' operational walking dynamics. This study attempted to validate a wireless HMD-VR setup to study pedestrians' operational walking dynamics. It provided preliminary answers regarding the validity of VR simulations to study operational walking dynamics. Yet, more research is required to allow VR experiments to become a mainstream tool in a researcher's toolbox. Amongst other things, more extensive experiments with more participants, randomized trials, and more sophisticated gait analysis equipment are required to further substantiate this study's findings. Also, the impact of the virtual and real-world environment design on the walking dynamics of pedestrians requires further study. Besides that, the impact of perception differences between the spatial layouts, light conditions, and soundscapes in the virtual and the real world needs to be better understood to allow researchers to design more realistic virtual copies of the physical space.

Next to research into the impact of the wireless HMD, more extensive research is required into the impact of nudging through light. For instance, this preliminary study did not randomize the order of the colors. Randomized experiments with a larger heterogeneous participant sample are required to corroborate the impacts of the light conditions established in this study. In addition, the light experiments unraveled the effect of light in a scenario featuring only one participant. Yet, several studies have shown that pedestrians adapt their walking speed to their peers and the crowd (e.g., [52], [45], [58]). Future experiments should identify whether the established effects hold when the social interactions between pedestrians with distinct free-flow velocities come into play.

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Ethics Statement The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 2987). All participants were informed in advance regarding the nature of the experiment, our data retention and distribution policies, and asked to sign an Informed Consent form. Stringent mental and physical health and safety procedures were in place. The participants were aware that they could stop the experiment at any time without repercussions. All participants agreed that their data could be distributed in an anonymized format. In addition, 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.

Author Contributions **Dorine C. Duives**: Conceptualization, Methodology, Formal analysis, Data curation, Writing - Original Draft, Writing - Review & Editing, Funding Acquisition, Supervision. **Arco van Beek**: Conceptualization, Methodology, Formal Analysis, Investigation, Data curation, Visualization, Writing - Review & Editing. **Yan Feng**: Writing - Review & Editing.

References

[1] Basu, N., Haque, M.M., King, M., Kamruzzaman, M., Oviedo-Trespalacios, O.: A systematic review of the factors associated with pedestrian route choice. Transport reviews **42**(5), 672–694 (2022)

[2] Kovaceva, J., Wallgren, P., Dozza, M.: On the evaluation of visual nudges to promote safe cycling: Can we encourage lower speeds at intersections? Traffic injury prevention **23**(7), 428–433 (2022)

[3] Rubaltelli, E., Manicardi, D., Orsini, F., Mulatti, C., Rossi, R., Lotto, L.: How to nudge drivers to reduce speed: The case of the left-digit effect. Transportation Research - Part F: Traffic psychology and behaviour **78**, 259–266 (2021)

[4] Marples, D., Gledhill, D., Carter, P.: The effect of lighting, landmarks and auditory cues on human performance in navigating a virtual maze. In: Symposium on Interactive 3D Graphics and Games, pp. 1–9 (2020)

[5] van Beek, A., Feng, Y., Duives, D.C., Hoogendoorn, S.P.: Studying the impact of lighting on the pedestrian route choice using virtual reality. Safety Science **174**, 106467 (2024)

[6] Taylor, L.H., Socov, E.W.: The movement of people toward lights. Journal of the Illuminating Engineering Society **3**(3), 237–241 (1974)

[7] Vilar, E., Rebelo, F., Noriega, P., Teles, J., Mayhorn, C.: The influence of environmental features on route selection in an emergency situation. Applied ergonomics **44**(4), 618–627 (2013)

[8] Styns, F., van Noorden, L., Moelants, D., Leman, M.: Walking on music. Human movement science **26**(5), 769–785 (2007)

[9] Yanagisawa, D., Tomoeda, A., Nishinari, K.: Improvement of pedestrian flow by slow rhythm. Physical Review E **85**(1), 016111 (2012)

[10] Ikeda, S., Nozawa, T., Yokoyama, R., Miyazaki, A., Sasaki, Y., Sakaki, K., Kawashima, R.: Steady beat sound facilitates both coordinated group walking and inter-subject neural synchrony. Frontiers in human neuroscience **11**, 147 (2017)

[11] He, F.: A high-fidelity vr simulation study: Do external warnings really improve pedestrian safe crossing behavior? Master's thesis, University of Waterloo (2021)

[12] Kinateder, M., Comunale, B., Warren, W.H.: Exit choice in an emergency evacuation scenario is influenced by exit familiarity and neighbor behavior. Safety science **106**, 170–175 (2018)

[13] Camara, F., Dickinson, P., Merat, N., Fox, C.: Examining pedestrian-autonomous vehicle interactions in virtual reality. In: Proceedings of 8th Transport Research Arena TRA 2020. Transport Research Arena (2019)

[14] Gremmelmaier, H., Töttel, L., Pavlitskaya, S., Orf, S., Zofka, M., Zöllner, J.M.: Getting ready for all types of users: A virtual reality training center for automated vehicles. In: 2022 IEEE Symposium Series on Computational Intelligence (SSCI), pp. 77–85. IEEE (2022)

[15] Mohler, B., Campos, J., Weyel, M., Bülthoff, H.H.: Gait parameters while walking in a head-mounted display virtual environment and the real world. In: 13th Eurographics Symposium on Virtual Environments and 10th Immersive Projection Technology Workshop (IPT-EGVE 2007), pp. 85–88. Eurographics Association (2007)

[16] Janeh, O., Langbehn, E., Steinicke, F., Bruder, G., Gulberti, A., Poetter-Nerger, M.: Walking in virtual reality: Effects of manipulated visual self-motion on walking biomechanics. ACM Transactions on Applied Perception (TAP) **14**(2), 1–15 (2017)

[17] de Schot, L., Nilsson, D., Lovreglio, R., Cunningham, T., Till, S.: Exploring single-line walking in immersive virtual reality. Fire Safety Journal **140**, 103882 (2023)

[18] Sunstein, C.R., Thaler, R.: Libertarian paternalism. American Economic Review (2003)

[19] Barton, A., Grüne-Yanoff, T.: From libertarian paternalism to nudging—and beyond. Review of Philosophy and psychology **6**, 341–359 (2015)

[20] Kwan, Y., Cheng, T., Yoon, S., Ho, L., Huang, C., Chew, E., Thumboo, J., Østbye, T., Low, L.: A systematic review of nudge theories and strategies used to influence adult health behaviour and outcome in diabetes management. Diabetes & metabolism **46**(6), 450–460 (2020)

[21] Oullier, O., Cialdini, R., Thaler, R.H., Mullainathan, S.: Improving public health prevention with a nudge. Economic Perspectives **6**(2), 117–36 (2010)

[22] Forberger, S., Reisch, L., Kampfmann, T., Zeeb, H.: Nudging to move: a scoping review of the use of choice architecture interventions to promote physical activity in the general population. International Journal of Behavioral Nutrition and Physical Activity **16**, 1–14 (2019)

[23] Kremers, S.P., Eves, F., Andersen, R., et al.: Environmental changes to promote physical activity and healthy dietary behavior (2012)

[24] Galea, E.R., Xie, H., Lawrence, P.J.: Experimental and survey studies on the effectiveness of dynamic signage systems. Fire Safety Science **11**, 1129–1143 (2014)

[25] Kinateder, M., Warren, W.H., Schloss, K.B.: What color are emergency exit signs? egress behavior differs from verbal report. Applied ergonomics **75**, 155–160 (2019)

[26] Ronchi, E., Nilsson, D., Kojić, S., Eriksson, J., Lovreglio, R., Modig, H., Walter, A.L.: A virtual reality experiment on flashing lights at emergency exit portals for road tunnel evacuation. Fire technology **52**, 623–647 (2016)

[27] Corbetta, A., Kroneman, W., Donners, M., Haans, A., Ross, P., Trouwborst, M., Van de Wijdeven, S., Hultermans, M., Sekulovski, D., Van Der Heijden, F., Mentink, S., Toschi, F.: A large-scale real-life crowd steering experiment via arrow-like stimuli. Collective Dynamics **5**, 61–68 (2020)

[28] Krisam, M., Korenke, R., Maier, M., Korenke, J.: Nudges can both raise and lower physical activity levels: The effects of role models on stair and escalator use–a pilot study. Physical Activity and Health **4**, 86–94 (2020)

[29] Haans, A., De Kort, Y.: Reducing social aggression with dynamic lighting: the de-escalate project in eindhoven. Justitiele Verkenningen **40**(4), 54 (2014)

[30] Chen, J., Lehto, X., Lehto, M., Day, J.: Can colored sidewalk nudge city tourists to walk? an experimental study of the effect of nudges. Tourism Management **95**, 104683 (2023)

[31] Cosma, G., Ronchi, E., Nilsson, D.: Way-finding lighting systems for rail tunnel evacuation: A virtual reality experiment with oculus rift®. Journal of Transportation Safety & Security **8**, 101–117 (2016)

[32] Künzer, L., Hofinger, G., Zinke, R.: The influence of colored running lights on route choice–dynamic guidance and affordance. In: Proceedings of the 8th International Conference on Pedestrian and Evacuation Dynamics: PED, vol. 2016, pp. 167–172 (2016)

[33] Suzer, O.K., Olgunturk, N., Guvenc, D.: The effects of correlated colour temperature on wayfinding: A study in a virtual airport environment. Displays **51**, 9–19 (2018)

[34] Dachner, G.C., Kinateder, M.: Effects of visual information on decision making during way-finding in emergency and non-emergency situations. Collective dynamics **1**, 185 (2016)

[35] van Beek, A.H.N.: Influence of light settings on pedestrian dynamics. Tech. rep., Technical University of Eindhoven (2020)

[36] Buikstra, N.J.: Off the beaten track: The effectiveness of illuminance difference-based nudges on route choices of pedestrians in a crowd. Tech. rep., Technical University of Eindhoven (2021)

[37] Franěk, M., van Noorden, L., Režnỳ, L.: Tempo and walking speed with music in the urban context. Frontiers in psychology **5**, 1361 (2014)

[38] Zeng, G., Schadschneider, A., Zhang, J., Wei, S., Song, W., Ba, R.: Experimental study on the effect of background music on pedestrian movement at high density. Physics Letters A **383**(10), 1011–1018 (2019)

[39] Pedersen, E., Johansson, M.: Dynamic pedestrian lighting: Effects on walking speed, legibility and environmental perception. Lighting Research & Technology **50**(4), 522–536 (2018)

[40] Kesler, A., Leibovich, G., Herman, T., Gruendlinger, L., Giladi, N., Hausdorff, J.M.: Shedding light on walking in the dark: the effects of reduced lighting on the gait of older adults with a higher-level gait disorder and controls. Journal of NeuroEngineering and Rehabilitation **2**(1), 1–8 (2005)

[41] Huang, L., Zhuang, J., Zhang, Y.X.: A method of speed control during over-ground walking: Using a digital light-emitting diode light strip. Advanced Materials Research **718**, 1371–1376 (2013)

[42] Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G.: Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The international journal of aviation psychology **3**(3), 203–220 (1993)

[43] Witmer, B.G., Jerome, C.J., Singer, M.J.: The factor structure of the presence questionnaire. Presence: Teleoperators & Virtual Environments **14**(3), 298–312 (2005)

[44] Wang, J., Boltes, M., Seyfried, A., Tordeux, A., Zhang, J., Weng, W.: Experimental study on age and gender differences in microscopic movement characteristics of students. Chinese Physics B **30**(9), 098902 (2021)

[45] Duives, D., Daamen, W., Hoogendoorn, S.: Influence of group size and group composition on the adhered distance headway. Transportation Research Procedia **2**, 183–188 (2014)

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

[47] Hoogendoorn, S.P., Daamen, W.: Pedestrian behavior at bottlenecks. Transportation science **39**(2), 147–159 (2005)

[48] van Wageningen-Kessels, F., Hoogendoorn, S.P., Daamen, W.: Extension of edie's definitions for pedestrian dynamics. Transportation Research Procedia **2**, 507–512 (2014)

[49] Himann, J.E., Cunningham, D.A., Rechnitzer, P.A., Paterson, D.H.: Age-related changes in speed of walking. Medicine and science in sports and exercise **20**(2), 161–166 (1988)

[50] Centraal Bureau voor de Statistiek: Nederlanders korter, maar nog steeds lang (2021). URL https://www.cbs.nl/nl-nl/nieuws/2021/37/nederlanders-korter-maar-nog-steeds-lang

[51] Pinna, F., Murrau, R.: Age factor and pedestrian speed on sidewalks. Sustainability **10**(11), 4084 (2018)

[52] Wagnild, J., Wall-Scheffler, C.M.: Energetic consequences of human sociality: walking speed choices among friendly dyads. PloS one **8**(10), e76576 (2013)

[53] Renaux, A., Muhla, F., Clanché, F., Meyer, P., Maïaux, S., Colnat-Coulbois, S., Gauchard, G.: Effects of using immersive virtual reality on time and steps during a locomotor task in young adults. Plos one **17**(10), e0275876 (2022)

[54] Sheik-Nainar, M.A., Kaber, D.B.: The utility of a virtual reality locomotion interface for studying gait behavior. Human factors **49**(4), 696–709 (2007)

[55] Wodarski, P., Jurkojć, J., Polechoński, J., Bieniek, A., Chrzan, M., Michnik, R., Gzik, M.: Assessment of gait stability and preferred walking speed in virtual reality. Acta of bioengineering and biomechanics **22**(1), 127–134 (2020)

[56] Horsak, B., Simonlehner, M., Schöffer, L., Dumphart, B., Jalaeefar, A., Husinsky, M.: Overground walking in a fully immersive virtual reality: A comprehensive study on the effects on full-body walking biomechanics. Frontiers in bioengineering and biotechnology **9**, 780314 (2021)

[57] Samson, M.M., Crowe, A., De Vreede, P., Dessens, J.A., Duursma, S.A., Verhaar, H.J.: Differences in gait parameters at a preferred walking speed in healthy subjects due to age, height and body weight. Aging clinical and experimental research **13**, 16–21 (2001)

[58] Tunçgenç, B., Travers, E., Fairhurst, M.T.: Leadership and tempo perturbation affect coordination in medium-sized groups. Scientific reports **11**(1), 4940 (2021)