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ABSTRACT

Efficient crowd management is essential for optimizing the performance of pedestrian infrastructures, either in terms of crowd flow or pedestrian levels of safety and comfort. This study investigates the impact of one type of crowd management measure, namely lighting, on pedestrian behavior. Using Virtual Reality experiments, the impact of lighting, both the brightness level and the light color, on pedestrian route choice is studied. A virtual maze was designed, featuring 10 T-intersections, where the light conditions are varied at each T-intersection to study its impact on pedestrian route choice. Our study shows that pedestrian route choice is strongly influenced by the light color in a virtual environment. Pedestrians prefer to follow paths with green-colored lights and avoid paths with red-colored lights, irrespective of the light color on the other path. Moreover, pedestrians slightly prefer to use the path with a higher brightness level. Lastly, the results indicate that pedestrians do have a slight right-handed tendency on average, however, this effect cancels out almost completely when other guidance information is present in the scenario. Altogether, the findings suggest that lighting can impact pedestrian route choice behavior.

1. Introduction

Urban spaces are becoming more crowded due to the increased world population and an increase in the number of mass events for religious, sportive, or festive gatherings. As a consequence, the design capacity of urban spaces may not always be sufficient, leading to congestion, long(er) travel times, and reduced levels of comfort and safety. In the most extreme situations, the combination of high crowd density and low levels of safety and comfort can lead to disasters with many casualties (e.g., the Love Parade disaster in 2010, the Meron crowd rush in 2021, and the Astroworld Festival disaster in 2021) (Gado and Fishof, 2023; Helbing and Mukerji, 2012; Maurice, 2021).

To manage these dense crowd flows, both short-term and long-term crowd management interventions can be deployed. Examples of long-term interventions are the (re)design of the pedestrian infrastructure (e.g., demolishing buildings and relocating paths), and the use of automated barrier or gating systems. Unfortunately, a re-design is often very time-consuming and expensive. In contrast to the long-term interventions, the short-term interventions, such as dynamic fencing, signage, and lighting, can be implemented in the already existing environment without too many adaptations. The aim of short-term crowd management interventions is to enhance the efficiency of the infrastructures under crowded conditions by optimizing the pedestrians' behavior. For instance, by distributing them better over time and space, or homogenizing their walking speed.

State-of-the-art literature already provides insights into the effect of various crowd management measures on pedestrian behavior. For instance, the effect of obstacles (Bosina et al., 2016, 2020; Jia et al., 2020) and signage (Duarte et al., 2014; Galea et al., 2014; Rousek and Hallbeck, 2011) on pedestrian choice behavior and wayfinding performance has been subject to previous research. Other studies investigated the influence of lighting on pedestrian choice and movement behavior (Hidayetoglu et al., 2012; Taylor and Socov, 1974; Vilar et al., 2013).

When zooming in on the impact of lighting on pedestrian behavior, earlier research showed that both the brightness level (Dachner and Kinateder, 2016; Taylor and Socov, 1974; Wang et al., 2022) and the color of the light (Künzer et al., 2016; Olander et al., 2017) influence pedestrian route choice. Despite these studies, the literature does not offer sufficient findings to establish a more general understanding of the impact of lighting on pedestrian route choice, especially under non-emergency conditions. Consequently, crowd operators are not able to use lighting strategically to enhance the efficiency of crowded pedestrian infrastructures. In order to enhance the crowd management perspective on the matter, this study is solely focused on non-emergency conditions to study the normal behavior of behavior in a specific environment. As long as pedestrian behavior has not been scientifically proven to be similar in normal and emergency

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conditions, one cannot use findings from evacuations to manage crowds in day-to-day conditions.

The aim of the present study is to investigate the effect of lighting on one type of pedestrian choice behavior, being pedestrian route choice behavior. A virtual reality (VR) experiment is performed to quantify the effects, because of the methods' high levels of controllability, flexibility, and immersive nature in comparison with other experimental methods (i.e., field observations, controlled experiments, and surveys) (Feng et al., 2021a). In particular, this study aims to determine whether lighting conditions have an impact on pedestrian route choice in indoor environments under non-emergency conditions. Specifically, the impact of different levels of brightness and the color of the lighting on pedestrian route choice are analyzed. The brightness levels of this study vary from emergency lighting to sufficient lighting for an office, and the colors that will be considered are white, green, red, and blue.

The current study contributes to the body of research in two ways. Firstly, the findings deepen our understanding of the impact of different lighting conditions (both brightness and color) on pedestrian route choice. Our study is one of the first studies investigating the impact of static lighting on pedestrian route choice in non-emergency conditions. Secondly, the study provides crowd management teams with insights related to the impact of lighting. This allows them to manage crowds more effectively by, for example, guiding their route choice behavior.

This paper is structured as follows. The background discusses the findings of previous studies that have investigated the relationship between lighting and pedestrian choice behavior in Section 2. Section 3 presents the research methodology, featuring experimental design, equipment setup, experimental procedure, data collection, data analysis, and participants' characteristics. Accordingly, the results are presented and discussed in Section 4. Finally, Section 5 ends this paper with conclusions and suggestions for future research directions.

2. Background

Several studies in the literature investigated the effect of lighting on pedestrian behavior, especially during emergency conditions (Manav and Yener, 1999; Marples et al., 2020; Suzer et al., 2018). For instance, Lovreglio et al. (2016) conducted a survey study and found that emergency lights have a positive effect on the probability that an exit is chosen compared to emergency exits without emergency lights. Moreover, Wang et al. (2022) showed that natural lighting is an important environmental factor affecting emergency evacuation wayfinding behavior in an underground space, as most participants chose to follow natural lighting at intersections with conflicting direction information of evacuation signs and natural lighting.

Two perspectives of lighting have been investigated in the literature related to pedestrian choice behavior, namely the brightness level of the light and the color of the light. Regarding the brightness level, the literature features several experimental studies related to the impact of the brightness level on pedestrian route choice. In a study conducted by Taylor and Socov (1974), most participants preferred to follow the brighter path when there was a noticeable difference in brightness level between the two potential paths. This finding is in agreement with the virtual evacuation study of Vilar et al. (2013), which found that pedestrians prefer the brighter path in an indoor environment for both T-intersections and F-intersections. The VR experiment conducted by Dachner and Kinateder (2016) also indicated that pedestrians prefer the brightest path. However, their findings also showed that the impact of signage on pedestrian route choice is stronger than that of the light's brightness level. Moreover, the survey study of Hidayetoglu et al. (2012) showed that pedestrians perceive corridors with lower brightness levels more negatively than corridors with higher brightness levels.

Regarding the color of the light, most previous studies focused on pedestrian exit choice behavior during evacuations. In a VR experiment of Ronchi et al. (2016), it was observed that pedestrians prefer to use emergency exits equipped with either green-colored or white-colored flashing lights, as opposed to use exits with blue-colored flashing lights. Another survey conducted by Olander et al. (2017) showed that pedestrians prefer the presence of red-colored flashing lights in proximity to the emergency exits, since the flashing lights increase sensory affordance. Next to the effects of flashing lights, a survey study of Künzer et al. (2016) found that pedestrians have a higher tendency to follow the green-running lights in comparison to the red-running lights. They also showed that scenarios with red-running lights gave more guidance to pedestrians than scenarios without running lights. Furthermore, Cosma et al. (2016) showed that green lights installed on the floor can influence the movement trajectory of pedestrians during a smoke-filled evacuation, as they tend to walk closer to the lights.

This overview of studies shows that several research gaps exist in the state-of-the-art literature. Firstly, most studies that evaluated the impact of lighting on pedestrian choice behavior focused exclusively on emergency conditions. Only a few studies studied the impact of lighting on pedestrian behavior in non-emergency conditions. Earlier research already proved that pedestrian behavior can be different between normal and emergency conditions. For instance, (Vilar et al., 2014) found that the influence of signage is lower in emergency conditions compared to in non-emergency conditions. Moreover, a stated preference survey of Haghani and Sarvi (2016) showed that contributing factors (e.g., crowding around exit, and visibility of exit from pedestrian's perspective) on pedestrian exit choice behavior is significantly different between normal and emergency conditions. Though those studies are not related to the effect of lighting on pedestrian route choice, it indicates that one should not expect similar pedestrian choice behavior in normal and emergency conditions. For that reason, more research is required to understand the effect of lighting on pedestrian behavior in normal scenarios.

Secondly, research featuring the impact of light colors especially focused on dynamic lighting (e.g., running lights or flashing lights), while static colored LED lights have rarely been studied in previous studies.

3. Methodology

A VR study is adopted to perform this research. The following section presents the research methodology, including the research aim experimental design, the experimental setup, the experimental procedures, the data collection methodology, and the participants' characteristics of this study.

3.1. Research aim

The objective of this research is to study the impact of lighting, in terms of brightness level and light color, on pedestrian route choice under non-emergency conditions. Specifically, the main objective of this study regarding the light color is to study the effect of the colors with a specific meaning in the Western culture (i.e., green and red) on the pedestrian route choice. That means that the present study does not focus on the effect of the less conventional color (i.e., blue) on the pedestrian route choice, even though blue-colored lighting is part of the experimental design.

In order to complete the objective of the study, this research is going to test different hypotheses. The rationale behind each hypothesis is explained first and is followed by the hypothesis itself. Firstly, the literature shows that pedestrians are influenced by the brightness level (Taylor and Socov, 1974; Vilar et al., 2013). In particular, the brighter the scenario, the more likely that this route is adopted. Therefore, our first hypothesis tests whether similar behavior is found in our experiment.

H1 : Pedestrians prefer to follow the brighter path when they have to choose between two paths with different levels of light brightness.

In addition, several studies hint at the impact of the light color on pedestrian wayfinding and route choice behavior, especially in emergency conditions (Künzer et al., 2016; Ronchi et al., 2016). Yet, the choice conditions are essential, given that in some cases red is also interpreted as a guidance signal (Arias et al., 2019; Olander et al., 2017). One would suspect that red light correlates to avoidance behavior of pedestrians, as the color red is strongly associated to the concept "stop" (Bergum and Bergum, 1981). To better understand the impact of light color on pedestrian route choice, two additional hypotheses are developed, being:

H2 : Pedestrians prefer to follow green-colored paths, irrespective of the lighting color on the other path.

H3 : Pedestrians prefer to avoid red-colored paths, irrespective of the lighting color on the other path.

In the experiment, participants have the choice between a route on the left and on the right. The pedestrian literature shows that left–right route choices might also be influenced by a natural tendency toward either side (Duives and Mahmassani, 2012; Melton, 1935). To identify whether this effect also influences pedestrian route choice in this experiment, a fourth hypothesis is developed, which features the right-handed tendency of pedestrians during the VR experiment.

H4 : Pedestrians have a preference to follow the right path due to their right-handed tendency.

3.2. Experimental design

The experimental design of this study comprises two parts. A VR environment is designed to allow for the testing of the introduced hypotheses, and is presented in Section 3.1. Secondly, the experimental design is described in section Section 3.2.

3.2.1. Design of the virtual environment

Previous studies used a variety of experimental methods in their studies, predominantly featuring controlled lab experiments (Taylor and Socov, 1974; Vilar et al., 2013), and surveys (Hidayetoglu et al., 2012; Olander et al., 2017). Some studies adopted VR to study pedestrian behavior due to the benefits of VR (Cosma et al., 2016; Dachner and Kinateder, 2016; Ronchi et al., 2016). VR has an advantage compared to other experimental methods regarding its high controllability and flexibility (e.g., maintaining equal settings for all participants) (Feng et al., 2021a). On the other hand, the use of VR as a research tool to study pedestrian behavior raises concerns regarding its validity, especially due to the lack of direct comparisons between physical and identical virtual environments in the state-of-the-art literature. That said, the current study employed VR experiments to study the impact of lighting on pedestrian route choice, with the intention to provide the validation at a later stage.

A maze was designed to present participants with a task. The maze consisted of 10 T-intersections. Both sides of the intersections were identical in terms of structural appearance. In terms of visual appearance, the lighting conditions on both paths can be varied independently to ascertain participants' preferences in terms of lighting conditions. Besides variances in lighting conditions, the VR environment did not contain any other type of visual attraction (e.g., greenery, benches, and colored walls) to exclude their effect on pedestrian's route choice. The design of the VR environment was fairly straightforward, with a minimal amount of detail to reduce the number of factors influencing pedestrian route choice.

During the experiment, participants encountered multiple T-intersections subsequently, and they needed to find an exit of the maze. In the maze, participants always arrived at the subsequent intersection, irrespective of their choice on the prior T-intersection. Eventually, the participants found the exit of the maze after 10 T-intersections — no matter of the choices they made. The design of the maze is shown in Fig. 1. Participants began on the left and were tasked with navigating the maze to find the exit all the way on the right. The figure shows a funnel-shaped design is implemented between the fifth and sixth intersection participants encounter, featuring obstacles in the form of pillars. That area was implemented to create some variety within the maze in comparison to the repetitive T-intersections.

The virtual environment was constructed using Unreal Engine. The virtual maze contained more than 200 lights within the environment, leading to high computational powers and even to time lag. All the light sources emitted light into the environment from a rectangular plane. In order to reduce the computational power, the virtual lights were pre-baked, which means that the global lighting was already calculated before running the VR environment. The pre-calculation ensured that the computational power is reduced considerably. Moreover, the lights were only turned on when the participants were located within a 15-meter radius, which was the furthest distance that the participant could ever see in the virtual maze, except for in the funnel-shaped area. All of these measures led to a decrease in computational power, such that the participants could perform the virtual experiment without any time lag. The results of a few tests and our experience with the virtual environment indicated that the VR immersion was not affected by these measures.

3.2.2. Design of the experiment

In order to test our hypotheses, two route choice tasks are designed. First, participants needed to walk through the maze with variations in the brightness of the lights at the T-intersections. Second, they walked through the same maze featuring variations in the color of the lights. It should be noted that participants were told that they were placed in another maze during the second run in order to minimize the impact of learning. The first task featuring the brightness conditions was employed to test hypothesis H1. The second task featuring the light colors was used to test hypotheses H2 and H3. Hypothesis H4 related to the right-handed tendency is evaluated using the data from both experimental tasks.

Brightness experiment - This study included five different levels of brightness. These levels were labeled as 1 (very dark), 2 (dark), 3 (neutral), 4 (bright), and 5 (very bright). Here, brightness levels 1, 3, and 5 were an approximation of a corridor with only emergency lighting, a corridor with the recommended light level of 100 lux, and a well lighted working place, respectively. The approximation of brightness levels are derived from a pilot study conducted several weeks prior to the VR experiment in this study. This pilot study involved a comparison of human perception of lighting within an office space between real-life conditions and VR. The findings indicated what thresholds of the lighting in the VR environment were perceived equally bright to five specific brightness levels in the real-life conditions (i.e., 1 lux, 50 lux, 100 lux, 200 lux, and 300 lux). However, the pilot did not account for the high computational power of the VR experiment in this study. The virtual lights were pre-baked in order to reduce the computational power, which subsequently led to slight discrepancies in all the brightness levels. For that reason, the present study is only able to give an approximation for the different brightness levels.

To limit the number of scenarios, this study only focused on the intersections where the brightness levels between both paths in the T-intersection differed by a maximum of 2 levels (e.g., light level 1 and 4 are never enforced together). Consequently, 15 pairs of different brightness levels were created. Two of those pairs are illustrated in Figs. 2(a) and 2(b), which are chosen to emphasize the maximum difference in brightness level compared to the neutral level (i.e., brightness level 3).

In an ideal setup for the present study, a randomized order of pairs would be preferred. Nonetheless, due to the employed equipment in this study, implementing a randomized pair for every participant at each T-intersection was not feasible. The order of the pairs needed to

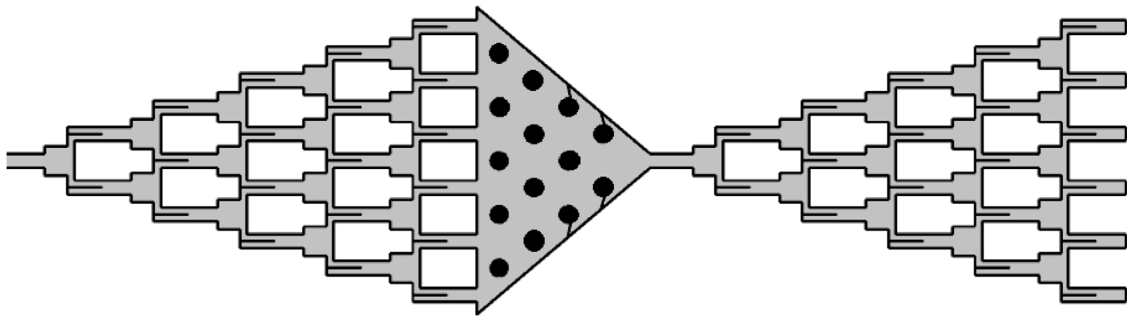


Fig. 1. The top view of the maze design, featuring many T-intersections and a funnel-shaped area. The gray region denote the navigable pathways for the participants in the VR environment, while the black circles represent obstacles in the form of pillars.

Table 1
All light conditions encountered by the participants at the T-intersections, separated by 4 groups for the brightness experiment (B1–B4) and 2 groups (C5–C6) for the color experiment. Here, the light levels are classified from 1 (very dark) to 5 (very bright), and the colors are indicated with w (white), g (green), r (red), and b (blue).

#	B1 (L/R)	B2 (L/R)	B3 (L/R)	B4 (L/R)	C5 (L/R)	C6 (L/R)
1	3/3	3/3	3/3	3/3	w/w	w/w
2	3/1	3/5	1/3	5/3	g/r	r/g
3	3/5	3/1	5/3	1/3	s/g	g/s
4	1/3	5/3	3/1	3/5	b/r	r/b
5	5/3	1/3	3/5	3/1	r/s	s/r
6	2/1	5/4	1/2	4/5	g/b	b/g
7	3/2	4/3	2/3	3/4	g/s	s/g
8	2/4	2/4	4/2	4/2	b/s	s/b
9	4/3	3/2	3/4	2/3	s/r	r/s
10	4/5	1/2	5/4	2/1	r/g	g/r

be predetermined before the VR experiment started. If the experiment only consisted of one specific order, the observed findings could be influenced by that specific order of the pairs. Pedestrians might perceive a specific light level differently based on its prior exposure. To avoid this issue, the present study introduces four different groups, each designed with their own order of pairs. Notably, this design offers the advantage that the data can be analyzed both between-group and within-group effects.

Every group started the experiment with the pair without a difference in brightness level, i.e., brightness level 3 on both sides of the T-intersection. That pair was followed by the four conditions comparing the extreme values of the brightness level (i.e., brightness level 1 and 5) to the neutral level (i.e., brightness level 3). The order of these four pairs were varied between groups. Ten different pairs regarding the brightness conditions remained after that, these pairs were separated into two sets of five pairs. Groups 1 and 3 encountered one of the sets of pairs, and groups 2 and 4 encountered the other set. The order of the conditions was varied between the groups with the same set of five pairs. The order of the pairs regarding the brightness conditions for each group is shown in Table 1. The table shows that each group only encountered 10 of the 15 pairs regarding the brightness conditions. The limited number of pairs was a conscious design choice in order to reduce the VR exposure time of the participants. Participants can experience negative physical effects (e.g., physical discomfort, fatigue and eye strains) during their VR immersion. These effects tend to strengthen with an increase in the VR exposure time of the participant. Hence, the limited number of pairs for each group.

Color experiment - Four different colors were chosen to be used in the VR experiment, namely white, green, red, and blue. Firstly, the white lights were chosen as they are the most widely used light color in indoor environments. The white lights were also used as the color for the brightness experiment of this study. Moreover, the green and red lights were chosen due to their widely recognized associations. Green is associated with 'safe' and 'go', and red is associated with 'danger' and 'stop' (Bergum and Bergum, 1981; Or and Wang, 2014). This paper investigates whether this can be generalized to a preference to follow green-colored paths and to avoid red-colored paths in route choice behavior. Finally, this study considered one color that does not have a cultural meaning in the Netherlands, or at least no meaning to the best of the authors' knowledge, which is the color blue.

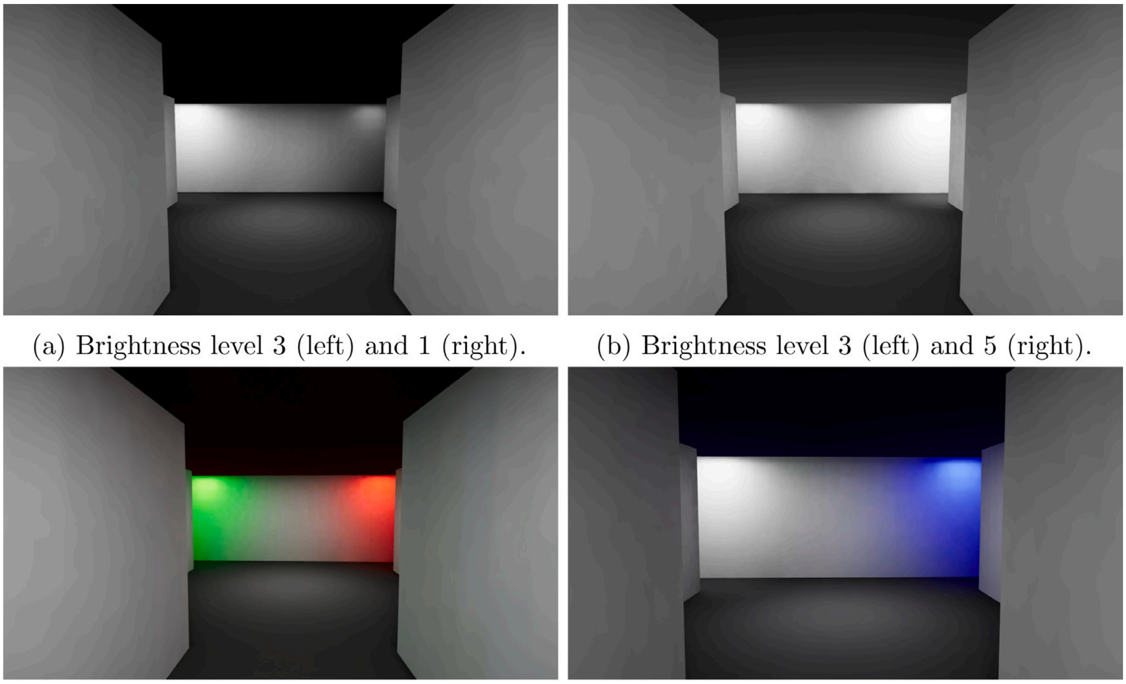
In total, the experiment consisted of 13 different pairs featuring light colors. Two conditions of the light color experiment are illustrated in Fig. 2 to visualize all colors of the experiment. The experiment is especially focused on the impact of green and red lights, such that hypotheses H2 and H3 can be tested. That is, the study is less focused on the impact of the blue lights, leading to a fewer amount of pairs containing blue lights.

In order to analyze the data of all 13 pairs regarding light color conditions, the participants were separated into two groups. Just as for the brightness experiment, the groups only encounter 10 of the 13 pairs regarding light color to reduce the VR exposure time of the participants. Both groups started their experiment with the pair of white-colored light on both sides of the T-intersection, followed by 9 other pairs. Within these 9 pairs, both groups encountered all 6 pairs related to the comparison of white, green, and red lights. The order of these pairs is varied between the two groups, as the pairs of group 2 are the mirror image of group 1. The last three pairs of each group were related to the blue-colored lights. Each group encountered blue light once together with white light, once with green light, and once with red light. Again, the pairs of group 2 are the mirror image of group 1. The exact order of the pairs regarding light color for both groups is introduced in Table 1. Note that all colors were enforced with brightness level 3, such that the brightness of the lights did not influence the results in the color experiment.

3.3. Equipment setup

The participants were immersed in the virtual environment by means of a HTC Vive Pro Eye VR system. The system consists of a head-mounted display (HMD) with headphones, two laser-based base stations, and one hand controller. This VR system enables 360-degree head tracking and a 110-degree view with a combined resolution of 2880 × 1600 pixels and 615 PPI. Unreal Engine 5 and SteamVR were used to run the different VR environments. The game engine and the VR software ran on an AMD Ryzen 7 2700X with 3.7 GHz CPU, and an NVIDIA GeForce RTX2080 graphics card.

Here, base stations were used to track the exact location of the HMD and the hand controller within the observed area. A hand controller was used by the participants to control their movement in the VR environment. Each time the participants touched the home pad of the controller with their thumb, they took one step forward in the VR environment. They were also able to press the home pad continuously. The maximum walking speed in the VR environment was calibrated to 1.4 m/s, which is similar to free-flow walking for young adults under normal conditions (Bosina and Weidmann, 2017). An example of a participant using the VR system is depicted in Fig. 3.



(a) Brightness level 3 (left) and 1 (right). (b) Brightness level 3 (left) and 5 (right).

(c) Light colors green (left) and red (right). (d) Light colors white (left) and blue (right).

Fig. 2. Several T-intersections of the VR maze that the participants encountered featuring the (a)–(b) brightness experiment, and (c)–(d) color experiment.

3.4. Experimental procedure

This VR experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 2987). The recruitment consisted of different methods, e.g., forwarding emails, social media, and flyers on the university campus. All participants joined the experiment voluntarily, and received a 10 euro gift card for their participation, irrespective of the outcome. The experimental procedure consisted of three parts, namely the introduction, the wayfinding experiment in VR, and the post-experiment questionnaire.

1. *Introduction.* The experimental procedure was communicated to the participants by means of a written statement. They were instructed to find the exit in the two mazes. After reading the written statement, the participant needed to sign a consent form in order to perform the experiment. Finally, they were required to complete a color blindness test, where they had to identify six different colors and three pseudoisochromatic plates. Participants were not allowed to participate in the experiment if they were not able to complete the color blindness test successfully.
2. *Wayfinding experiment.* Participants were equipped with the VR system, including the VR headset and the hand controller. Initially, participants were placed into a simple VR test environment, allowing them to familiarize themselves with the movement in VR. As soon as they indicated that they were ready for the formal experiment, they were placed in the VR maze, and were asked to find the exit of the first maze (i.e., the maze featuring different brightness conditions). The only instruction for participants finding the exit was that they should never turn 180 degrees. When participants found the exit, they had a break of 1-minute to rest their eyes before starting their second task (i.e., the maze featuring different light color conditions). At that time, the participants were informed that they were placed in another maze.
3. *Post-experiment questionnaire.* After finishing the experiment, participants were instructed to fill in a digital post-experiment questionnaire, which consisted of five parts. The first part of the questionnaire featured questions related to personal characteristics (e.g., age, gender, and VR experience) and their association with different colors. Thereafter, the questionnaire contained a few questions related to their wayfinding strategies in the second part. Also, the simulator sickness questionnaire (Kennedy et al., 1993), the presence questionnaire (Witmer et al., 2005), and the system usability scale questionnaire (Brooke, 1996) were provided to the participants in the third, fourth, and fifth part. After completing the questionnaire, the entire experiment was finished and the participants were rewarded with the gift card. All participants completed the experiment.

3.5. Data collection

Two types of data were collected during the VR experiment in the present study. Quantitative data was collected via the HTC Vive Pro Eye VR system and the Unreal Engine. It included the participant's trajectory (i.e., x and y coordinates) and head rotation (i.e., pitch, yaw, and roll) at every time step of $\Delta t = 0.1$ s. Qualitative data were collected through the post-experiment questionnaire. It included participant's responses to questions regarding their personal characteristics, their wayfinding strategy, their simulation sickness, their feeling of presence within the virtual environment, and the usability of the VR system.

3.6. Data analysis

The participants' choice to go left or right at the T-intersection was determined based on their trajectory data. Their y-coordinate is used to locate them in one of the 11 areas of the maze (i.e., 10 areas related to the T-intersections and 1 area representing the funnel-shaped region in the middle). The areas including the intersections are defined from one main corridor to the other, and one of these areas is visualized with the orange rectangle in Fig. 4. For each intersection-related area, the x-coordinate of the participants of the last time step within that area is subtracted from that of the first time step to determine their choice of left or right path.

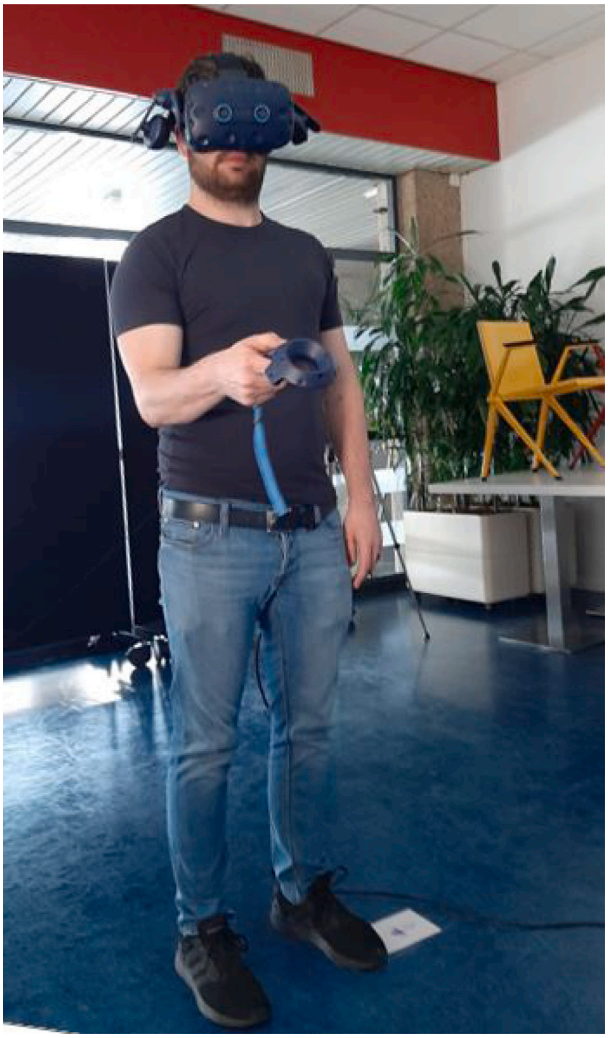


Fig. 3. One participant using the HTC Vive Pro Eye VR system in the experiment, including the HMD and the hand controller.

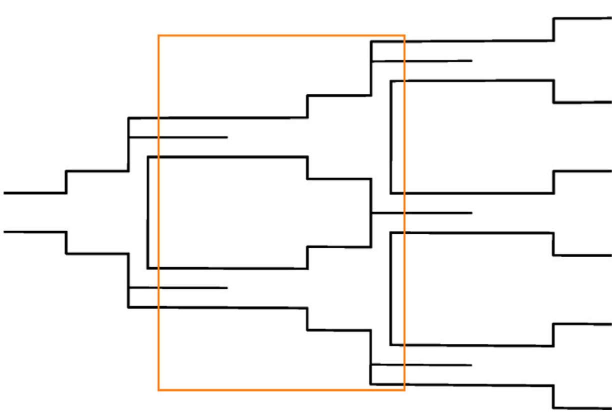


Fig. 4. The floor configuration of a part of the maze, with one of the areas indicated with the orange rectangle. Here, the participant's walking direction is from the left to the right.

The hypotheses are tested based on the average tendency of participants toward a certain path. The tendency is indicated with a numerical value between 0 and 1 for every participant. Various different tendencies are determined in order to test all four hypotheses, namely the tendency to follow the brighter path, the tendency to follow the green-colored path, the tendency to follow the red-colored path, and the tendency to choose the path on the right. For the tendency related to the brightness conditions, 0 means that a participant always followed the path with the lowest brightness level (i.e., the darker path), and 1 means that they always followed the path with the highest brightness level (i.e., the brighter path). The average tendency for every participant is calculated by dividing the number of times they followed the path with the higher brightness level over the total number of choices with different brightness conditions during the experiment. This is irrespective of whether the left or right path was enforced with a higher brightness level. Each participant had 9 choices with different brightness condition in total.

For the tendencies related to the colored paths, all participants encountered five choices featuring green-colored lights on either path, and five choices that feature red-colored lights on either path. The tendency of a participant toward the path of interest (i.e., the green-colored or the red-colored path) is equal to 0 when the participant avoided the path consistently, and equal to 1 when the participant always followed that path of interest. Lastly, for the participants' tendency to follow the path on the right, the tendency is equal to 1 when the participant chose the right path in all their choice, and equal to 0 when they chose the left path in all their choices (i.e., 20 choices in total over both tasks).

3.7. Participants' characteristics

The required sample size was estimated with the priori power analysis using G*Power 3.1.9.7 (Faul et al., 2009). The result of the t-test comparing one group to a constant indicated that 25 participants are required to recognize large effects with 95% power. Here, the adopted large effect size is set to 0.69, as established in Paes et al. (2021). In total, the VR experiment was conducted with a convenience sample of 64 participants, of which 37 were males and 27 were females. The age range was limited to adults between 18 and 35 years old, since the age of pedestrians is known to affect their walking speed (Pinna and Murrau, 2018; Subaih et al., 2020) and route choice behavior (Bernhoft and Carstensen, 2008; Hill, 1982). As a result, the participants' age ranged from 19 to 35 years old, with an average of 26.3 years (SD = 3.6 years). Most were highly educated (62.5% holds a Master's degree), had limited experience with VR, and were relatively familiar with computer gaming in general. The participants' characteristics are summarized in Table 2.

The participant's perception of the virtual environment is determined with respect to the Simulator Sickness Questionnaire (SSQ), the Presence Questionnaire (PQ), and the System Usability Scale (SUS) questionnaire. The SSQ assesses the discomfort that participants experience when using simulated environments. The discomfort is expressed with a variety of symptoms in the SSQ, and these symptoms are scored based on a 4-point Likert scale ranging from 0 (none) to 3 (severe) by the participants. Three subscales can be calculated based on the scoring of the symptoms, namely nausea, oculomotor disturbance, and disorientation. Thereafter, the total symptom score can be determined by summing all three subscale scores and subsequently multiplying it by 3.74 (Kennedy et al., 1992), with a maximum score of 236 (Kennedy et al., 2003). In our study, the lowest subscale score is nausea (M = 7.34, SD = 8.56), followed by oculomotor disturbance (M = 13.64, SD = 16.31), and disorientation (M = 17.99, SD = 22.78). These three scores led to a total score of 14.44 (SD = 15.74) for the SSQ. The total score is similar to those in Kinateder et al. (2014), Feng et al. (2022), and relatively lower than (Dominic and Robb, 2020; Feng et al., 2021a).

The PQ evaluates the participant's sense of presence within the virtual environment by asking 29 questions on a 7-point scale (Witmer et al., 2005). The total score of the PQ is determined by summing all the reported scores of the 29 questions. In this study, the average total score of the PQ is 130.68 (SD = 18.21), which indicates that the participants have a good sense of presence in our virtual environment. The PQ score

Table 2
Description featuring the participants' characteristics and levels of familiarity with gaming and VR. Here, the Dutch education level is indicated between brackets.

Descriptive information	Category	Number (percentage)
Gender	Male	37 (57.8%)
	Female	27 (42.2%)
Highest education level	High school or equivalent	5 (7.8%)
	Associate's degree or equivalent (MBO)	0 (0%)
	Bachelor's degree or equivalent (HBO or WO)	19 (29.7%)
	Master's degree or equivalent (WO)	35 (54.7%)
	Doctoral degree (PhD) or equivalent	5 (7.8%)
Previous experience VR	Very often	0 (0%)
	Often	4 (6.3%)
	Neutral	5 (7.8%)
	Barely	29 (45.3%)
	Never	26 (40.6%)
Familiarity with computer gaming	Strongly agree	19 (29.7%)
	Agree	18 (28.1%)
	Neutral	13 (20.3%)
	Disagree	11 (17.2%)
	Strongly disagree	3 (4.7%)

of this study is slightly lower than Feng et al. (2021a), Zhu et al. (2020), but much higher than Deb et al. (2017), Feng et al. (2021b).

Lastly, the SUS questionnaire establishes the usability of a product, i.e., the usability of a simulator system in this study (Brooke, 1996). The SUS questionnaire exists of 10 questions, each of them can be scored on a 5-point scale. The total score of the SUS questionnaire is determined by summing all the reported scores and subsequently multiplying by 2.5, with a maximum of 100. The average total SUS score of this study is 77.31 (SD = 9.55), which indicates that our virtual environment has a 'good' usability according to the scoring interpretation system of Bangor et al. (2009). The SUS score is slightly lower than in Deb et al. (2017), Feng et al. (2022), but much higher than in Feng et al. (2021b), Stigall and Sharma (2019).

Overall, the usability of the VR environment of this study is established by the high level of presence and system usability, as well as by the low values for the SSQ indices. The participants barely felt any discomfort in their VR experience.

4. Results

This section presents our findings regarding the impact of lighting on pedestrian route choice behavior. First, the impact of the brightness is discussed and hypothesis H1 is answered in Section 4.1. Accordingly, the two hypotheses related to the color of the lights are answered in Sections 4.2 and 4.3. Finally, the hypothesis related to the right-handed tendency is answered in Section 4.4.

4.1. Impact of brightness

On average, the participants have a tendency of 0.545 to follow the path with the brighter light level across all groups. That is, the participants move to the brighter path of a T-intersection in 54.5% of their choices. In order to understand whether the preference for the brighter path is significantly different from a random choice between left and right (i.e., 50%), a one-sample t-test is carried out. The test showed that the participants' average preference is significantly different from the random choice value (see Table 3). That is, participants exhibited a significant tendency to follow the brighter path.

To verify whether extreme brightness levels have a stronger effect on the pedestrian route choice, an analysis of the participants' route choices involving paths featuring either brightness level 1 or 5 is performed. These findings showed that the participants had a tendency of 0.573 to follow the brighter path when the other path was enforced with brightness level 1, and a tendency of 0.521 to follow the brighter path when the brighter path was enforced with brightness level 5. The tendencies are irrespective of the light level on the other path, and irrespective of the location of the brighter path (i.e., the left or right path). Table 3 showed that the results related to level 1 are marginally significant, and that those related to level 5 are not statistically significant. The findings do suggest that the darkest brightness level influenced the pedestrian route choice more than the brightest level, however, the statement is not statistically significant.

Our findings reveal that participants preferred to follow the path with the brighter light level, confirming hypothesis H1 stating that pedestrians prefer to follow the brighter path. This finding aligns with earlier findings in the literature. For instance, Taylor and Socov (1974) found that pedestrians strongly preferred to enter the room through the brighter path. Also, Vilar et al. (2013) showed that participants' choice favored the brighter corridors at both T-intersections and F-intersections in emergency conditions. The agreement between the findings of this study and the existing literature suggests a consistent preference for the brighter path for different scenarios (e.g., emergency and non-emergency scenarios).

It is worth highlighting that the observed preference of participants for the brighter path is much lower in this study (M = 0.545) compared to the study of Vilar et al. (2013) (M = 0.872). A possible explanation for the difference is the different scenario of both studies, i.e., the emergency versus non-emergency conditions. Another explanation is that the level of immersion in the VR environment experienced by our participants was lower compared to the physical experiment. In the physical experiment of Vilar et al. (2013), participants experience conditions as they would in a real-life scenario, leading to a realistic level of safety and comfort. However, participants in the current study might not experience the same decrease in level of safety for darker paths because of the stylized scenario they were immersed in, possibly leading to changes in their route choice behavior. In a way, participants probably perceive a higher level of safety in the VR environment compared to real-life scenarios, resulting in participants being more likely to follow the darker path in the VR environment over the physical experiments like (Vilar et al., 2013).

4.2. Impact of green-colored lights

The results showed that participants have a tendency of 0.716 to follow the green-colored lights, irrespective of the side of the green-colored lights and the light color on the other path. A one-sample t-test showed that the preference for the green-colored path is statistically significant, as shown in Table 3. The preference for green-colored lights can be explained by the color-concept association shown in, amongst others, Bergum and Bergum (1981) and Or and Wang (2014). Both studies found a strong correlation between the concept of "Go" and the color green. This might suggest that pedestrians are likely to consider green-colored paths as paths they can use.

Table 3
Results of the one-sample t-test for all findings regarding the hypotheses.

Hypothesis	Pedestrians following ...	p-value	Significance
H1	The brighter path	0.025	Yes*
	Brightness level 1	0.066	Yes**
	Brightness level 5	0.551	No
H2	The green lights	< 0.001	Yes*
H3	The red lights	< 0.001	Yes*
H4	The path on the right	0.08	Yes**

* The significance is indicated with a confidence level of 95%.
** The significance is indicated with a confidence level of 90%.

To study the effect of other light colors (i.e., white, red, and blue) on pedestrian route choice in combination with the green-colored lights, the tendency toward the green-colored path was compared to each light color individually. Please note, that the tendency is still computed irrespective of the location of the green-colored path, i.e., it does not matter whether the green lights are enforced on the left or the right path. The tendency to choose a green-colored path is calculated by dividing the number of times participants chose the green-colored path by the total number of times the two light colors were enforced together. Participants were most likely to follow the green-colored path when the other path is colored white (M = 0.742), followed by the red-colored (M = 0.734) and blue-colored paths (M = 0.625). The chi-squared test for independence indicated that there was not enough evidence to reject the null hypothesis (p = 0.20). That is, there is no statistical difference in participants following the green light between the three light color on the other path (i.e., white, red, and blue). This finding suggests that pedestrians always prefer the green-colored path irrespective of the color of the other path, though there seem to be differences in the compliance. In particular, the compliance is lowest when blue lights are depicted on the other path. This seems to indicate that colors without cultural meaning reduce the attractive impact of the green-color lights on the pedestrian route choice.

The results of statistical and descriptive analysis indicate that the green-colored path is always preferred, irrespective of the other path's color. These findings are in line with the literature. Also, Künzer et al. (2016) showed that pedestrians prefer to follow green-colored running lights in a train station compared to a standard scenario and a scenario featuring red-colored running lights. Moreover, pedestrians preferred to use emergency exits that contain either green-colored or white-colored flashing lights compared to blue-colored ones (Ronchi et al., 2016). Furthermore, Kinateder et al. (2019) showed that pedestrians most often evacuate through the door with green-colored exit signs. Jointly, our findings, and the findings from the literature, seem to indicate that pedestrians have a preference for paths with green lights in general, irrespective of the circumstances (i.e., emergency or non-emergency conditions) and the light source type (e.g., running lights, flashing lights, and static lights). The findings of this study confirm hypothesis H2, indicating that participants have a strong preference to follow the green-colored paths in a virtual environment

4.3. Impact of red-colored lights

The results showed that participants have a tendency of 0.303 to follow the red-colored paths, irrespective of the side of the red-colored path and the lighting color on the other path. The one-sample t-test identified that the tendency is significantly different compared to the random choice value (see Table 3).

Similarly to the green-colored lights, the tendency to avoid the red-colored path is also analyzed in comparison to each individual light color. This analysis showed that participants are most likely to avoid the red-colored path when the other path is colored green (M = 0.266), followed by the blue-colored paths (M = 0.281), and white-colored paths (M = 0.352). The results indicated that participants always tend to avoid the red-colored path, despite the color of the other path and the side where the red path is enforced. The percentage suggests that the tendency depends on the light color on the other path (i.e., participants avoid red-colored paths more when the other path is more attractive to them). However, a chi-squared test for independence did not find statistical differences in participants following the red lights between the three light color (i.e., white, green, and blue) on the other path (p = 0.30).

Our findings showed that pedestrians tend to avoid the red-colored path in the virtual environment, irrespective of the light color on the other path. Thus, hypothesis H3, stating that pedestrians prefer to avoid paths with red-colored lights, is proven. This finding is in line with the strong color-concept association that correlates red with the concept of "Stop" and "Danger" (Bergum and Bergum, 1981; Or and Wang, 2014). Interestingly, our findings contrast with the previous studies on the impact of red lights in emergency conditions. Previous studies showed that red flashing lights next to exit signs are preferred by pedestrians during an evacuation, as it increases the sensory affordance (Olander et al., 2017; Arias et al., 2019). Moreover, Künzer et al. (2016) found that red-running lights gave pedestrians more guidance than no lights at all during evacuations, though it also led to more indecisive route choices. The differences between our results and literature highlight that the influence of red lights needs to be studied for both normal and emergency situations.

4.4. Impact of right-handed tendency

An analysis of the participants' very first choice is performed in order to diminish the impact of other factors (e.g., light conditions and spatial knowledge) on the route choice. The very first choice of the participants was their choice at the first T-intersection that they encountered in the maze with the brightness conditions. At that moment in time, the participants had no bias related to lighting conditions, no effect of prior choices, and no spatial knowledge about the pattern of the maze. Consequently, participants were most likely to act on instinct alone in that first choice. The result showed that 45 out of 64 participants (70%) chose the right path in their very first choice in the entire experiment, including the brightness and color experiment.

The question is to what extent this effect was also observed throughout the rest of the experiment, as participants gradually acquired more information about the environment in their perception (i.e., the learning effect). For instance, they might have associated a certain light condition with the path they have to follow, since their prior choice with that lighting condition let them to the next T-intersection. The global analysis showed that the participant's average tendency to go right is 0.530. The one-sample t-test showed that the result is marginally significant compared to the random choice. That is, the participants had a slight preference for choosing the path on the right-hand side. Yet, the observed effect for the global tendency is far less than for the instinctive first choice. Also, the effect is much smaller than originally observed in the literature (Taylor, 1986; Serrell, 1998; Scharine and McBeath, 2002). For instance, Melton (1935) found that 70% to 80% of pedestrians turned right as they entered galleries of a large art museum.

An explanation for the difference is presented by Bitgood (1995), who stated that the right-handed tendency only occurs when factors (e.g., goal-oriented directions or landmarks) are not present in the scenario. Based on our findings, the lighting stimuli seem to be one of the factors dampening the right-handed tendency, since the average tendency for very first choice is much lower than the average tendency of the entire experiment (i.e., the experiment including both mazes).

An additional analysis is performed to study whether the opposite is also the case, i.e., to study whether the right-handed tendency is also influencing the steering mechanism of this study. The analysis was performed with participants with an instinctive right-handed tendency (i.e., participants that chose the right path in the very first choice). If the right-handed tendency and the most preferred light condition were aligned, people were more likely to follow that path (M = 0.673). Here, the most preferred light condition is decided for each pair derived from hypotheses H1, H2, H3. If the right-handed tendency and the most preferred light condition were not aligned (i.e., stimuli on the left path), the average tendency to follow the path of the preferred light condition was smaller (M = 0.568). The Wilcoxon signed-rank test found that the difference between the two is significant ($p < 0.01$). That is, the effect of the preferred light condition was 10% higher when the preferred light condition was aligned with the right-handed tendency. Thus, the effect of the preferred light condition is indeed dampened by the right-handed tendency.

The same analysis was performed for the participants with an instinctive left-handed tendency (i.e., participants that chose the right path in the very first choice). An alignment of the left-handed tendency and the applied stimuli led to a tendency of 0.634 to follow that path. If the applied stimuli were not aligned with the left-handed tendency, the participants had a tendency of 0.600 to follow the applied stimuli. The Wilcoxon signed-rank test stated that there are no significant differences between the two possibilities ($p = 0.57$). That is, the alignment of the instinctive left-handed tendency and the stimuli did not impact the choice behavior.

Our findings confirm hypothesis H4 related to the right-handed tendency with a confidence level of 90%, as participants followed the right path 53% across all groups and choices in the experiment. Here, the confidence level is calculated with the one-sample t-test. Moreover, it is found that the right-handed tendency of participants does play a role in our experiment and that one would expect a dampened effect of the applied lighting stimuli when the stimuli are enforced on the left path.

5. Conclusion & future research

This study aims to study the effect of lighting on the pedestrian route choice in indoor environments. A VR experiment was designed and conducted in order to understand the impact of the lighting's brightness level and color on pedestrian route choice. Our study shows that pedestrians have a slight preference to follow the brighter path at a T-intersection, and that their preference is strongly influenced by the light color. Pedestrians prefer to follow green-colored paths and to avoid the paths with red lights, irrespective of the light color on the other path. For that reason, we conclude that the color of lighting systems is an interesting new intervention mechanism that crowd operators can consider to manage pedestrian infrastructures. In particular, green-colored and red-colored lights should be employed to attract and repel pedestrians from specific areas. Moreover, the study shows that pedestrians do have a right-handed tendency, but that the tendency is limited by other external factors (e.g., light conditions, prior choices, and spatial knowledge).

The present study uses VR because of the high controllability of the experiment, such that a limited amount of factors can influence the pedestrian route choice. The missing validation will be subject to future research. The next step is to perform a field experiment in order to validate the findings of this VR experiment. The tendency toward colored paths is strongly observed within the virtual indoor environment, which is a good start in order to understand the correlation between pedestrian path choice and the lighting of the environment. However, it might not be representative for physical pedestrian infrastructures. These types of infrastructures contain more external factors strongly impacting the pedestrian route choice, e.g., follow-the-leader behavior, goal-oriented pedestrians, and asymmetrical path choices (i.e., one path is visually more attractive than the other). For that reason, a field experiment needs to verify to what extent the observed tendencies are valid at the crowded pedestrian infrastructures.

Another subject for further research is to study the data of the present experiment into more detail. The data will be analyzed with more sophisticated choice models (e.g., a binomial logit models, or a latent class choice model) in order to get a better understanding of our findings. For instance, the impact of individual brightness levels can be studied to validate our preliminary finding that the darker brightness levels have a stronger influence on pedestrian route choice compared to the brighter ones.

CRediT authorship contribution statement

Arco van Beek: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yan Feng:** Writing – review & editing, Supervision. **Dorine C. Duives:** Writing – review & editing, Supervision, Funding acquisition. **Serge P. Hoogendoorn:** Supervision.

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.

Data availability

Data will be made available on request.

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