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# Do light-based nudges influence pedestrian exit choice? A case study in a university building

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## ABSTRACT

Lighting is an integral element of every pedestrian environment, making it a promising tool for crowd management. However, limited knowledge exists on how different lighting conditions shape pedestrian choice behavior. This study systematically examines how both light intensity and light color influence pedestrian exit choice using data from a large field experiment in which varying light settings were applied to two building exits. Two multinomial logit (MNL) models, a light-intensity model and a light-color model, were estimated to quantify these effects. Findings indicate that only a limited subset of light-intensity and light-color conditions meaningfully influence pedestrian exit choice, with Off-Neutral, Bright-Neutral, White-Green, and Red-Green showing moderate, time-dependent effects. At the same time, contextual factors such as origin, local density, and time of day remain far stronger predictors of behavior. Moreover, learning effects emerge selectively and often counterintuitively, with pedestrians increasingly favoring the darker or red-lit exits in conditions where opposite directional responses are expected. The MNL models suggest that lighting can modestly influence pedestrian routing, provided it is applied with careful attention to contextual conditions and time of day.

## 1. Introduction

Managing pedestrian flows in crowded areas is a growing challenge for the managers of pedestrian spaces, such as transport hubs, event venues and urban spaces, as pedestrian demand continues to rise. Managers can redesign the spatial layout of their infrastructures to accommodate increasing crowd flows. Unfortunately, such drastic changes are often financially unfeasible. Next to expensive redesigns, environmental features can be adjusted to influence how pedestrians navigate. These changes should help to reduce congestion while improving safety and overall comfort of pedestrians. This approach, often referred to as 'nudging', focuses on influencing pedestrians' decision and behavior without limiting their freedom of choice.

Most common nudges are intrusive, such as ground personal directing the crowd, or signage explicitly pointing toward an exit through symbols or text. While these type of measures can be effective in guiding pedestrians (Duarte et al., 2014; Filippidis et al., 2021; Galea et al., 2014; Rousek and Hallbeck, 2011), they may also compromise pedestrian comfort levels and limit their autonomy.

A more subtle nudging approach is to use less intrusive cues to steer pedestrian movement. Lighting is a promising example of such an intervention. As an integral part of most pedestrian spaces, it is an ideal element of the environment to be used in crowd management. Light-based nudges can be characterized by means of two key features: intensity and color. Intensity refers to the brightness of the light source and can attract attention by illuminating specific routes, or alternatively, make a route less appealing

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by lowering the light intensity (e.g., in van Beek et al., 2024; Feliciani et al., 2024; Vilar et al., 2013). Color refers to the specific wavelength of the light and is often linked to psychological associations that may influence pedestrian choices (Bergum and Bergum, 1981). A more detailed overview of prior research regarding these light-based effects is provided in Section 2.

The objective of this study is to investigate whether ambient light can nudge pedestrians towards a specific direction. In particular, this research examines whether and to what extent variations in light intensity and color affect pedestrian choice behavior in a real-world environment. This work builds on the findings of van Beek et al. (2024), who demonstrated that pedestrian choice behavior was affected by light nudges in a virtual maze. They observed two distinct effects: pedestrians tended to follow brighter paths, and they were more likely to choose green-lit routes while avoiding red-lit ones. By extending this line of research to a real-world setting, this study investigates whether these effects persist under everyday conditions and, if so, to what extent. In particular, it quantifies both the magnitude and direction of the influence of variations in light intensity and color on pedestrian choice behavior in a single, context-specific scenario.

To achieve this objective, a field experiment is conducted in a real-world pedestrian infrastructure, applying different light conditions to observe the effect of ambient lighting on pedestrian decision-making regarding exit choice. Furthermore, a discrete choice model is employed to gain more comprehensive insights into how these light nudges influence pedestrian exit choice. As mentioned before, Section 2 reviews related research on the impact of light conditions on choice behavior. The methodology of this experiment is described in Section 3, including details on the physical layout of the environment, the experimental design, the lighting setup, the data collection procedures, and a general data overview. The discrete choice modeling approach used to analyze the experimental data is introduced in Section 4. Section 5 presents briefly the descriptive results, followed by the outcomes of the discrete choice models. These findings are subsequently discussed in Section 6. Finally, Section 7 ends the paper with a conclusion and implications for practice.

## 2. Related research on light nudging for pedestrian behavior

Previous research has investigated a wide range of factors that influence pedestrian choice behavior, including crowd management strategies, environmental features, and sociodemographic characteristics (van Beek et al., 2025). Within crowd management strategies, lighting stands out as an integral element in most pedestrian spaces and, therefore, a promising factor in influencing pedestrian movement. Reported effects in the literature can be categorized into two key features: intensity and color. Intensity refers to the concentration of light power emitted from a source in a specific direction, while color pertains to the wavelength of the light, often linked to psychological associations that may affect pedestrian decisions (Bergum and Bergum, 1981).

*Light intensity* has been shown to affect pedestrian path choice in both Virtual Reality studies (van Beek et al., 2024; Vilar et al., 2013) and a controlled experiment (Taylor and Socov, 1974). These studies found that pedestrians prefer to follow paths with brighter lighting. In particular, Taylor and Socov (1974) observed that the majority of pedestrians enter or leave a room through the exit with the brightest light. This study also found a relationship between the intensity ratio and the choice probability, indicating that pedestrians are more likely to follow the brighter path as the intensity ratio relative to the other path increases. The findings of van Beek et al. (2024) also indicated a slight preference for the brighter path when moving in a virtual maze. Similarly, Vilar et al. (2013) identified that pedestrians preferred the brighter path at both T-type and F-type intersections when trying to evacuate a virtual building. The common belief is that dimmed areas negatively affect pedestrian safety, yet the literature is inconsistent. Previous studies found that pedestrians felt less safe in dimly lit areas (Haans and De Kort, 2012; Kaplan and Chalfin, 2021; Painter, 1996). However, Ceccato et al. (2025) observed that a 30% reduction in light intensity did not lower safety perceptions in a metro station, suggesting the importance of context.

Regarding the effects of *light color* on pedestrian choice behavior, the state of the art includes several studies that have examined its influence across different scenarios. For instance, pedestrian exit choice can be influenced with green flashing lights during evacuations of a road tunnel (Frantzych and Nilsson, 2004), a university building (Nilsson et al., 2005), and a movie theater (Nilsson et al., 2008). In particular, it was observed that emergency exits with green flashing lights were chosen more frequently than the ordinary emergency exits. Similarly, the findings of Künzer et al. (2020) indicated that participants preferred to follow green running lights in the intended direction at a metro station compared to the baseline without any lights. Moreover, a VR experiment featuring an indoor maze with consecutive choice tasks indicated that pedestrians tend to follow green-lit paths and to avoid red-lit paths (van Beek et al., 2024). However, most of these studies have examined evacuation contexts or were conducted in controlled laboratory or virtual environments. As a result, their findings cannot be readily generalized to everyday pedestrian choice behavior, where contextual factors such as directionality, convenience, and habitual routines may exert a stronger influence.

To the authors' knowledge, only two studies have examined light-based nudges in real-world settings. Feliciani et al. (2024) showed that pedestrians have a slight preference for the door with additional lighting, both when entering and leaving the building. The usage of a particular door changed by 2–10% when lighting was introduced, with the maximum effect of 10% exceeding the influence of other nudging strategies (i.e., a display with arrows, sound, and colored entrance mats). In an experiment at a light festival in Eindhoven, The Netherlands, the nudging effect of light intensity on pedestrian path choice was studied by Buikstra (2021). They observed mixed effects of lighting, yielding inconclusive findings on the application of light as a nudging method. These studies provide preliminary evidence that light can affect pedestrian choice behavior, but not in every scenario.

Even though the literature provided preliminary evidence that light conditions can nudge pedestrians towards a specific exit. Yet, the quantitative impact of light conditions is largely unknown. More systematic field studies are required to understand the extent to which light can be used to nudge pedestrians. In particular, what is the quantitative impact of light nudges on pedestrian choice behavior?

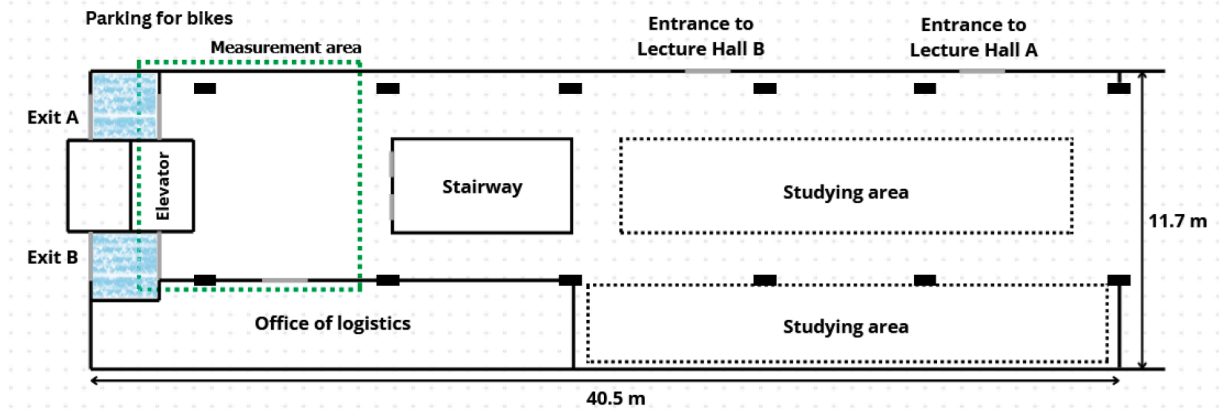


Fig. 1. Spatial layout of the first floor of the university building; the green dotted rectangle marks the measurement area, the light blue boxes indicate the zones where the lighting conditions were varied, and the black boxes indicate pillars. The gray lines represent the doors within the area.

### 3. Experimental methodology

To quantify the impact of light conditions on pedestrian choice behavior, a field experiment was performed in a university building. This section presents the research methodology of this field experiment. The experimental methodology of this study is separated into seven subsections. Firstly, [Section 3.1](#) presents the goal of the experiment. Secondly, [Section 3.2](#) describes the environment in which the field experiment was conducted. Thereafter, the experiment's timeline is discussed in [Section 3.3](#), including the different experimental phases. This is followed by the light condition design in [Section 3.4](#), the apparatus and data collection in [Section 3.5](#), and a brief overview of the participant sample in [Section 3.6](#). Lastly, a short overview of the dataset is presented in [Section 3.7](#).

#### 3.1. Experimental goal

The objective of this research is to quantify the impact of light nudges on pedestrian choice behavior in a real-world environment, taking an initial step toward understanding their effects across contexts and populations. This study aims to test three hypotheses derived from [van Beek et al. \(2024\)](#), who formulated these hypotheses based on findings from controlled experiments ([Taylor and Socov, 1974](#); [Vilar et al., 2013](#)) and established color associations ([Bergum and Bergum, 1981](#)). As their results supported these hypotheses, the present research investigates whether the same hypotheses hold in real-world contexts. The three hypotheses are:

- **H1:** Pedestrians are more likely to choose the route with the brightest light intensity,
- **H2:** Pedestrians are more likely to choose the route illuminated in **green**,
- **H3:** Pedestrians are more likely to avoid the route illuminated in **red**.

To address the hypotheses, a semi-controlled field study was set up to study the impact of light nudges on exit choice behavior in that particular context. This was done at a location that enabled observation of pedestrian behavior over an extended period, with a varying but relatively homogeneous population. This approach enabled a systematic analysis of the effects of light conditions while limiting the influence of learning effects and sociodemographic factors. Additionally, it allowed control over factors that can influence light perception (e.g. time of day).

Consequently, this research studies whether lighting can influence pedestrian choice behavior in a single, context-specific scenarios with a relatively homogeneous crowd. Therefore, the findings cannot be generalized to other environments or populations. Nevertheless, this study represents one of the first field studies into the interaction between pedestrian choice behavior and light-based nudges.

#### 3.2. Field experiment description

This systematic field experiment was conducted at a building of Delft University of Technology, in particular the faculty building of Civil Engineering and Geosciences. The building has eight entrances, with the main entrance and the entrance opposite it being the most frequently used. This experiment was conducted at the entrance opposite the main entrance, which consisted of two doors that each open automatically outwards when a pedestrian approaches. These doors are separated by 3.6 m, with a storage room and an elevator shaft located between them. The separation is shown in [Fig. 1](#), which illustrates the building's spatial layout. It includes the entrances of two large lecture halls, the main bicycle parking, stairways, study areas, and both exits.

[Fig. 2](#) visualizes the entrance from both the outside and the inside. Pedestrians leaving the building can go in various directions. When using the main entrance as a reference, most campus buildings are situated to the right, and a few are located to the left. It is worth noting that the building's largest bicycle parking is on the right side of the entrance (see [Fig. 2a](#)). As most university students use bicycles to get around campus, most students exiting the building move towards this bicycle parking.



(a) Outside view.

(b) Inside view.

**Fig. 2.** The experimental environment from both (a) outside, and (b) inside perspective at the faculty building of Civil Engineering and Geosciences in Delft, the Netherlands.



**Fig. 3.** The timeline of the phases within the experiment, including the respective week numbers.

Each side of the facade features two doors arranged in sequence, with a small enclosed space between them that serves as a passage. Full control over the light system was granted within these passages. When a pedestrian chooses to leave through the enclosed passage to the right of the elevator, this is classified in the study as the pedestrian choosing exit A. Similarly, when a pedestrian exits through the enclosed passage to the left of the elevator, it is considered an exit from B. This classification is also shown in Fig. 1.

### 3.3. Experimental procedure

This experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 4621). The experiment consisted of five distinct phases, briefly described below and illustrated in Fig. 3. This figure presents the timeline of the various phases, providing an overview of the entire experiment and highlighting the corresponding week numbers of each phase.

1. *Baseline I*: The experiment started with one week in which the light panels were set to neutral lighting, which is white light with a brightness similar to the light level of the rest of the building. This phase is used to identify the “regular” choice behavior of pedestrians at the case study location.
2. *Experiment part A*: This phase studied the effect of light nudges on pedestrian exit choice. During this phase, the lights were changed systematically to compare the effects of different light conditions on exit preference. The design ensured that all light conditions were applied equally often across different days and times of day, allowing for a balanced comparison. The particular light conditions and detailed procedures are described in Section 3.4.
3. *Holiday*: During the experiment, there were two weeks of holidays in the academic year. The lights were set to neutral lighting during these weeks. However, these weeks are excluded from the data analysis due to the low occupancy of the building. Some days the building was fully closed, while on others only a few staff members occupied it.
4. *Experiment part B*: This phase was conducted as an extension of “Experiment part A” to ensure statistical validity for a select set of hypotheses. In the early mornings and the late afternoons, one exit was unlit while the other had neutral lighting. This setup allowed for examining whether pedestrians tend to avoid unlit paths as it becomes darker outside. During the rest of the day, the green and red colored lights are tested against each other. This combination is tested to assess whether their color effects are amplified when viewed simultaneously.
5. *Baseline II*: The experiment concluded with six weeks of neutral lights. This period was included to assess whether pedestrian exit choice behavior had systematically changed over the course of the experiment.

**Table 1**

An overview indicating how often each light setting has been applied across different weekdays and times of day. Here, TS1 is time slot 1 (opening time – 10:00), TS2 is time slot 2 (10:00 – 12:00), TS3 is time slot 3 (12:00 – 15:00), and TS4 is time slot 4 (15:00 – closing time). The numbers indicate the frequency in 'Experiment part A', while the numbers in parentheses indicate that in 'Experiment part B'.

Condition	Abbr.	TS1	TS2	TS3	TS4	Mo	Tu	We	Th	Fr
Neutral - Neutral	NN	7 (2)	7 (2)	7 (2)	7 (2)	7	5 (1)	7 (4)	4 (3)	5
Neutral - Off	NO	3 (3)	2	3	3 (3)	2 (2)	3 (1)	2 (1)	2 (1)	2 (1)
Neutral - Bright	NB	3	3	2	3	2	2	2	2	3
Off - Neutral	ON	3 (5)	2	3	3 (4)	2 (2)	2 (2)	2 (1)	2 (2)	3 (2)
Bright - Neutral	BN	3	3	2	3	2	2	3	2	2
White - Green	WG	3	3	3	3	2	3	2	3	2
White - Red	WR	2	4	3	2	2	2	2	3	2
Green - White	GW	3	2	3	3	2	2	2	3	2
Green - Red	GR	3	3 (4)	3 (4)	3	3 (3)	2 (1)	2 (1)	2 (2)	3 (1)
Red - White	RW	3	3	2	3	2	2	2	3	2
Red - Green	RG	2	3 (4)	4 (4)	2	2 (1)	3 (3)	2 (1)	2 (0)	2 (3)

### 3.4. Light condition design

Where the baseline phases are used as a reference, the phases 'Experiment part A' and 'Experiment part B' are used to study how both light intensity and light color influence pedestrian exit choice behavior. To study the effect of light intensity on pedestrians' decision-making when choosing an exit, three levels were implemented: the standard light level within the university building (N - Neutral), a very bright light (B - Bright), and lights off (O - Off). For light colors, three options were included: white (W), green (G), and red (R). White was selected because it represents the standard light color in the university building, while green and red were chosen based on observations from a prior VR experiment (van Beek et al., 2024). This VR experiment showed a strong preference for green-lit paths and clear avoidance of red-lit paths, while the impact of blue lights on pedestrian choice behavior was negligible. When these light condition pairs are mentioned in text, they are always structured with the light condition of exit A first, followed by the light condition at exit B. For example, green-white (GW) indicates that green lights were applied at exit A and white lights at exit B.

This study did not adopt a full factorial experimental design, as doing so would have increased the number of required lighting combinations and observation periods, rendering the setup infeasible for a long-running field experiment in an operational building. For this reason, light intensity and light color were examined separately. Although interactions between light intensity and light color are an interesting direction for future research, too little is currently known about the isolated effects of these cues to justify testing their combinations.

When testing light intensity, the lights remained white, consistent with those in the rest of the building. Conversely, when studying light color, the lights were always set to the standard neutral intensity. For clarity, the reference lighting is called neutral when discussing light intensity and white when discussing light color. In practice, neutral and white represent the same condition, so NN is equivalent to WW.

For intensity, this study compared exit choice behavior under neutral lighting with both the lights off condition and the bright one (i.e., light conditions: NO, ON, NB, and BN). However, the bright condition was never applied simultaneously with the lights off. For color, all three colors were tested against each other (i.e., light conditions: WG, WR, GW, GR, RW, and RG). Settings with identical light colors on both exits were excluded, except for the neutral condition (i.e., light condition: WW). This neutral condition served as the baseline for both the intensity and color light conditions.

A systematic approach was adopted to study the effect of light nudges on pedestrian exit choice behavior. The light settings are changed three times a day, Monday through Friday, at 10.00, 12.00, and 15.00. These switching times were scheduled during the middle of lecture hours to avoid the most crowded periods at the faculty building exits, coinciding with light condition changes. This is illustrated in Fig. 4, which shows the cumulative pedestrian flow as a function of time of day (i.e., pedestrian flow at both exits across the entire experiment). The figure shows peaks in the number of pedestrians at the start and end of lecture hours, while the three switching times occur during the valleys in between the peaks.

To maintain a balanced experimental design, the light settings were applied equally often across all days and time slots. Table 1 shows the frequency of all light settings for each day and time slot in 'Experiment part A' and 'Experiment part B'. Here, the time slots are classified as time slot 1 (opening time - 10:00), time slot 2 (10:00 - 12:00), time slot 3 (12:00 - 15:00), and time slot 4 (15:00 - closing time). Due to the timing of light condition switches, the light condition pair applied in time slot 4 on a given day is the same as that in time slot 1 of the following day. Table 1 shows that the neutral-neutral (NN) condition is applied more often than the other conditions. This is due to the experimental design, which included one day of neutral setting per week to mitigate potential learning effects among pedestrians to some extent.

Fig. 5 presents four different lighting conditions within the pedestrian space, providing visual context for the experimental conditions. In all cases, the light variation was applied at exit A (the passage on the right from the inside perspective), while exit B

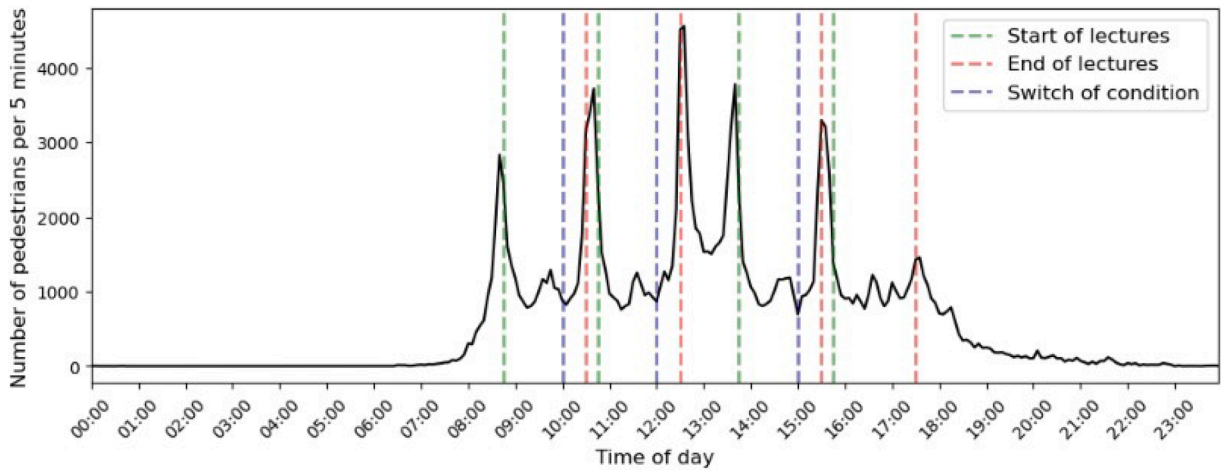
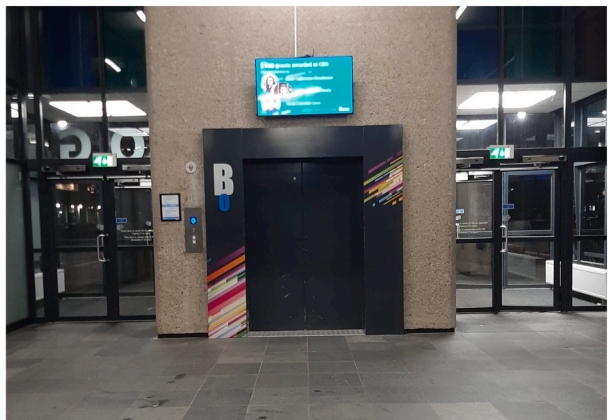


Fig. 4. The number of pedestrians entering and exiting via exit A and B per 5-min interval, accumulated over the duration of the full experimental period. Lecture start and end times are shown in green and red, respectively. The switching moments for light conditions are visualized in blue.



(a) Light setting: ON



(b) Light setting: BN

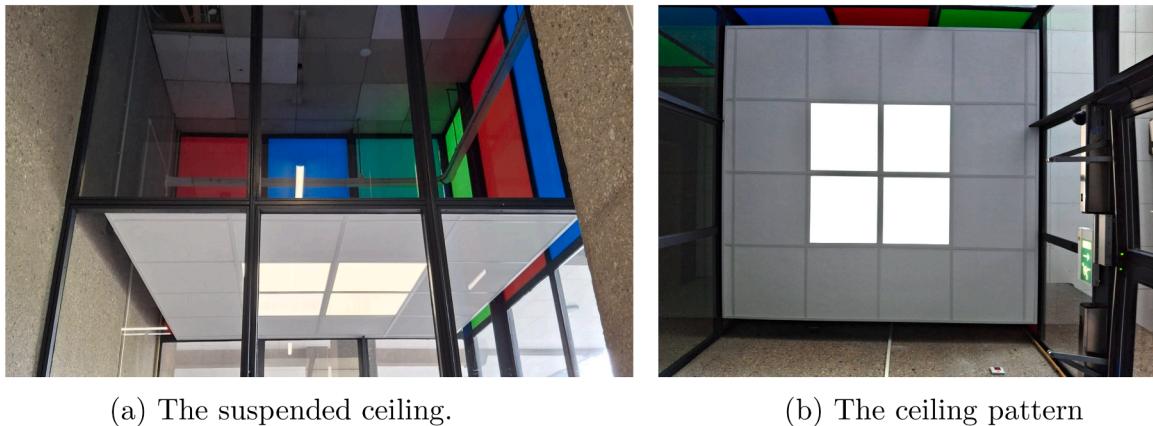


(c) Light setting: GW



(d) Light setting: RW

Fig. 5. The experimental setup has been applied with different light settings: (a) no light - neutral, (b) bright - neutral, (c) green - white, and (d) red - white. In all cases, the light variation was applied at exit A (the passage on the right from the elevator).



(a) The suspended ceiling.

(b) The ceiling pattern

**Fig. 6.** Perspective of the experimental setup with respect to the lighting arrangement, showing the ambient lights (a) integrated into a suspended ceiling and (b) positioned in a specific pattern.

was applied with neutral white lights. Accordingly, the lights off condition is shown in Fig. 5a, bright lights in Fig. 5b, green lights in Fig. 5c, and red lights in Fig. 5d.

### 3.5. Apparatus and data collection

New lights were installed in the enclosed passages at exits A and B. Each enclosed passage was provided with a suspended ceiling consisting of 12 ceiling plates and 4 LED panels measuring 60 x 60 cm each. The LED panels were arranged in a square pattern in the middle of the ceiling plates (see Fig. 6a and b). The lights used were Purpl 30W LED RGB + CCT panels. Both light intensity and color could be adjusted manually in the Tuya Smart smartphone application. The lights were connected to a Mobile Wi-Fi network installed on the ceiling in front of the elevator.

Two Xovis sensors, type PC2R-L-O, were used to record the pedestrian movements in front of the exits. The sensors count the number of people crossing predefined lines and track pedestrian trajectories within the measurement area at 10 Hz. The sensors were installed at a height of 6 m, resulting in a measurement area of approximately 8 x 10 m. This covers a large part of the area between the exits and the next pedestrian decision point. The trajectory data included pedestrian IDs, 2D coordinates of each moving object, and timestamps. Due to privacy regulations, no images or videos were recorded. The measurement area is shown in Fig. 7, which features the trajectory data of a single day.

Fig. 7a shows all recorded trajectories, whereas Fig. 7b presents the dataset after applying the cleaning procedure. First, pedestrians entering the building were excluded because they likely did not observe the light conditions at both exits, and their origins are unknown, preventing an accurate analysis of their choice behavior. Thereafter, pedestrians leaving the building from the elevator and logistics were removed for the same reason. Therefore, only pedestrians leaving the building were considered, as they had the opportunity to (sub)consciously observe the light conditions at both exits. Additionally, pedestrians who saw the light condition change were excluded. In particular, pedestrians who entered within two minutes of the switching time were excluded from the dataset.

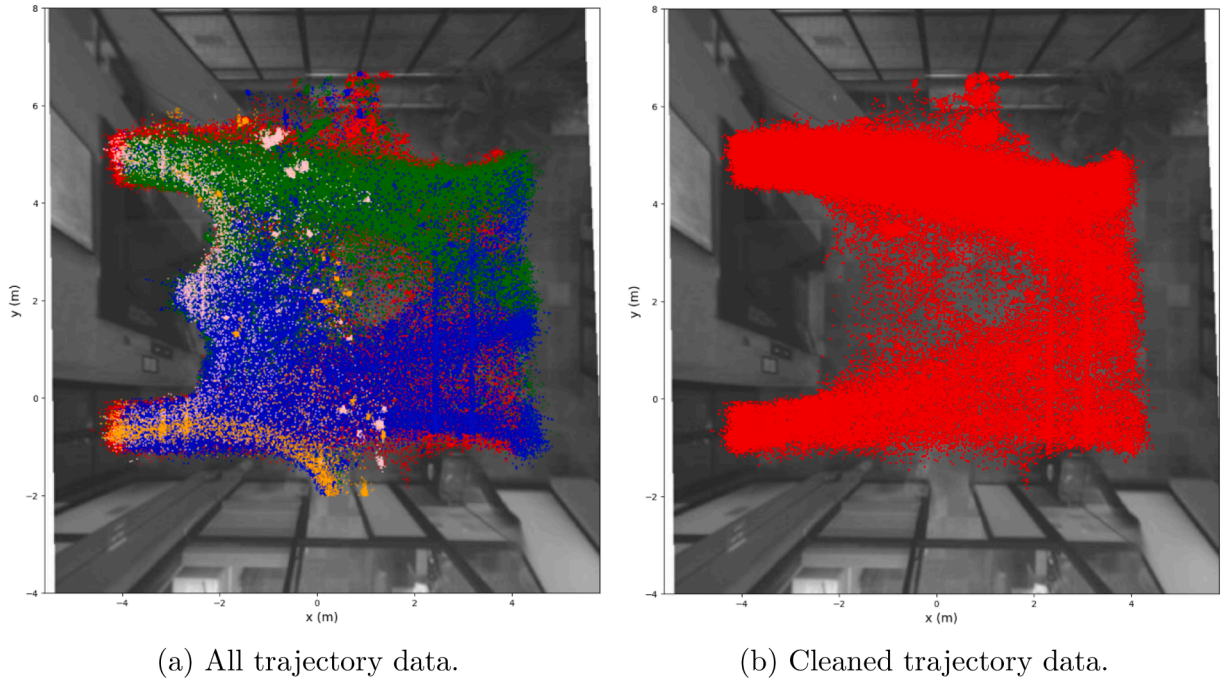
### 3.6. Description of participants

Pedestrians are not re-identifiable from the collected data, as only their trajectories were stored. The data excluded any specifics regarding the pedestrians' characteristics. As the experiment took place on the first floor of a university building with multiple large lecture halls (with a capacity of approximately 325 people each), the data included students, staff members, and visitors to the university. Although it cannot be inferred from the collected data, it is reasonable to assume that most individuals visited the building regularly. This might result in habitual routing, exit choice, and operational movement behavior.

### 3.7. Data description

This study features a total of 67,737 pedestrian trajectories, including 5001 in 'Baseline I', 31,963 in 'Experiment part A' and 'Experiment part B' combined, and 30,773 in 'Baseline II'. All trajectories reflect pedestrians leaving the building.

Table 2 presents the distribution of pedestrian trajectories across the different light settings used in the experiment. For each setting, the table shows the number of pedestrians who left the building while that setting was in effect. That number is further disaggregated by pedestrian origin, where origin 1 corresponds to individuals entering the measurement area from the right side of the corridor, origin 2 from the center, and origin 3 from the left side. The table indicates that more pedestrian trajectories are recorded for the NN, NO, ON, GR, and RG light settings. The higher number for the NN setting arises from the design choice to include one additional day



**Fig. 7.** Visualization of trajectory within the measurement area for (a) all trajectories, and (b) the cleaned trajectories. Colors correspond to pedestrian origins: exit A (green), exit B (blue), elevator (pink), logistics (orange), and inside the building (red).

**Table 2**

Descriptive statistics of the experiment, where  $N_{\text{total}}$  represents the total number of pedestrian trajectories per light condition, and  $N_{\text{origin}_1}$ ,  $N_{\text{origin}_2}$ ,  $N_{\text{origin}_3}$  respectively the number of pedestrian trajectories per light condition at origins 1 (right), 2 (middle) and 3 (left).

Light Condition	$N_{\text{total}}$	$N_{\text{origin}_1}$	$N_{\text{origin}_2}$	$N_{\text{origin}_3}$
Baseline I (NN)	5,001	2,301	1,814	886
NN	6,226	2,497	2,490	1,239
NO	2,878	1,075	1,212	591
NB	1,875	807	707	361
ON	3,590	1,351	1,488	751
BN	2,196	884	876	436
WG	2,332	964	933	435
WR	1,832	771	746	315
GW	2,388	934	922	532
GR	3,434	1,347	1,401	686
RW	2,134	786	941	407
RG	3,078	1,218	1,238	622
Baseline II (NN)	30,773	14,123	11,420	5,230

per week with a neutral setting, to mitigate potential learning effects. The higher number of trajectories captured in the other four settings results from the fact that these settings were included in *Experiment Part B*, whereas the remaining settings were only applied in *Experiment Part A*.

#### 4. Model description

A discrete choice modeling approach was adopted to analyze the dataset. In particular, a MultiNomial Logit (MNL) model was chosen as an initial modeling framework, as it is widely used as a starting point in discrete choice modeling due to its strong theoretical foundation, low computational power, and interpretability. Additionally, the dataset lacks panel data or detailed sociodemographic information that would support the estimation of more complex models, such as mixed logit or latent class models. Therefore, the MNL model was considered the best choice for this study. The theoretical specification of the MNL model is detailed in [Section 4.1](#). [Section 4.2](#) discusses the variables included in the model, whereas the model estimation procedure is discussed in [Section 4.3](#). Finally, the dataset presented in the last section is balanced for the model, as mentioned in [Section 4.4](#)

#### 4.1. Model specification

Given the MNL model, the utility function is given by

$$V_i = \sum_{n=1}^N \beta_{i,n} X_{i,n} + \sum_{n,m=1}^N \beta_{i,n,m} X_{i,n} X_{i,m} \quad (4.1)$$

where  $i$  indicates the alternative,  $n$  and  $m$  are indices for the variables,  $V_i$  is the systematic utility of alternative  $i$ ,  $\beta_{i,n}$  is the coefficient associated with variable  $n$  for alternative  $i$ ,  $\beta_{i,n,m}$  is the coefficient associated with the interaction between variables  $n$  and  $m$  for alternative  $i$ ,  $X_{i,n}$  is the value of variable  $n$  for alternative  $i$ , and  $N$  is the number of variables. The  $\beta$ -coefficients represent the impact of independent variables on the likelihood of a particular outcome, while the specific variables are detailed in Section 4.2. The probability for a particular choice is determined by

$$P_i = \frac{\exp(V_i)}{\sum_I \exp(V_j)}, \quad (4.2)$$

with choice probability  $P_i$  for alternative  $i$ , and  $I$  is the number of alternatives. In particular, the model describes the probability that a pedestrian exiting the building chooses exit A or exit B.

#### 4.2. Variable specification

The MNL model includes six variables; their definitions are listed in Table 3. These variables can be divided into three groups: light condition variables, crowd behavior-related variables, and contextual variables.

##### Light condition variables

The key variable in this study captures the light settings at both exits, as the main objective is to study how light nudges affect exit choice. All *light settings* were encoded as Boolean variables and compared with the benchmark condition, the neutral-neutral condition (NN), which represents the lighting used in the rest of the building. The light settings (i.e., the combination of the light conditions at both exits) are treated as a single condition to capture their overall effect.

##### Crowd behavior variables

The model accounts for several variables that describe the behavior of the surrounding crowd dynamics at the moment that a pedestrian makes a choice. The model evaluated several density-related variables: global density, local density, and the outflow. The *global density* is defined as the total number of pedestrians present in the measurement area when a pedestrian enters. In contrast, the *local density* captures the distribution of pedestrians by dividing them into two groups based on which exit they are closest to. The *outflow* is the number of pedestrians heading towards that specific exit. Because these three variables were highly correlated, the model retained only one to avoid redundancy. Each variable was therefore tested individually in the MNL model, and the one that yielded the lowest Akaike Information Criterion (AIC) was selected. Consequently, the *outflow* was selected out of the three variables related to crowd dynamics. This approach is consistent with the model estimation procedure in Section 4.3.

##### Environmental and contextual variables

The environmental variables describe the infrastructure layout, weather, and the outdoor light levels at the moment a pedestrian makes an exit choice. Several variables were designed to describe these factors.

First, the *pedestrian's origin* within the building was considered. The origin was divided into three segments based on the entry point into the measurement area: the right side of the stairway (origin 1), the stairway (origin 2), or the left side (origin 3). Although the measurement area does not include the stairway, pedestrians are assumed not to change origin in the unmeasured section. Origin 2 was used as the benchmark condition.

Second, since the lights are located in two glass hallways, outdoor light conditions are expected to influence how pedestrians perceive light at both exits. The outdoor lighting conditions are represented by the variable *global radiation*, measured at a weather station in Rotterdam (approximately 10 km from the experimental setup). In particular, the perceived intensity of the hallway lights may change when outdoor light levels decrease due to clouds, rain, or sunset, as the relative difference in light intensity increases during low global radiation conditions. Please note that the actual light intensity of the lights is always one of three standardized values.

In addition, participants might react differently at different times of day due to habitual behaviors and increasing tiredness. To account for these systematic effects, the variable *daytime* was included. Time of day was evaluated in three ways: as a continuous variable, as Boolean variables dividing morning (07:00-12:00), afternoon (12:00-18:00) and evening (18:00-22:00), and as a Boolean variable capturing the afternoon dip in alertness (15:00-18:00). All three model specifications were tested, featuring an ASC and one of the potential time of day variables. The continuous time of day variable was selected because it yielded the lowest AIC when added individually to the model.

Moreover, due to the experiment's duration, its repetitive nature, and the lack of consequences when choosing an exit with a certain intensity or color, it is expected that pedestrians learn over time that the light settings have no meaning. To account for a potential learning effect with respect to the light cues, the variable '*experiment duration*' was included. The square root of the experiment duration was used to capture the potentially diminishing effect over the course of the experiments, reflecting that the learning effect is stronger at the beginning and gradually decreases over time.

**Table 3**

An overview of the independent variables used in the multinomial logit models to determine exit choice probabilities of both exits.

Category	Type	Variable	Range	Details
Light condition	Boolean	NN	0-1	Exit A: Neutral, exit B: Neutral; benchmark variable
		NO	0-1	A: Neutral, B: Lights off
		NB	0-1	A: Neutral, B: Bright
		ON	0-1	A: Lights off, B: Neutral
		BN	0-1	A: Bright, B: Neutral
		WG	0-1	A: White, B: Green
		WR	0-1	A: White, B: Red
		GW	0-1	A: Green, B: White
		GR	0-1	A: Green, B: Red
		RW	0-1	A: Red, B: White
		RG	0-1	A: Red, B: Green
Global density	Continuous	$N_{global}$	0–27	Total number of pedestrians in front of exits A and B
Local density	Continuous	$N_{local,A}$	0–16	Number of pedestrians in front of exit A ( $y_i < 2$ ) when entering the measurements area
		$N_{local,B}$	0–11	Number of pedestrians in front of exit B ( $y_i > 2$ ) when entering the measurements area
Outflow	Continuous	$N_{out,A}$	0 – 22	Number of pedestrians in front of exit A ( $y_i < 2$ ) and walking towards the exit
		$N_{out,B}$	0 – 14	Number of pedestrians are in front of exit B ( $y_i > 2$ ) and walking towards the exit
Origin	Boolean	Origin 1	0–1	Pedestrian $i$ starts from the right side of the measurement area ( $y_i > 3.5$ )
		Origin 2	0–1	Pedestrian $i$ starts from the middle of the measurement area ( $0.25 < y_i < 3.5$ ); benchmark category
		Origin 3	0–1	Pedestrian $i$ starts from the left side of the measurement area ( $y_i < 0.25$ )
Time of day	Continuous	Daytime	0–23	Hour of the day at which pedestrian $i$ enters the measurement area
Global radiation	Continuous	Radiation	0 – 1040	Average global radiation $J/cm^2$
	Boolean	Sun 1	0–1	1 if global radiation is $0 J/cm^2$
		Sun 2	0–1	1 if global radiation between 0 and $120 J/cm^2$
		Sun 3	0–1	1 if global radiation above $120 J/cm^2$ ; benchmark category
Experiment duration	Continuous	Learning	1–9	Experiment day on which pedestrian $i$ enters; transformed using the square root of the day

### 4.3. Model estimation procedure

This study separated the effects of light intensity and light color on pedestrian exit choice. Accordingly, the effects of both features were analyzed using their respective model and datasets. Both datasets were analyzed using the same modeling procedure, which is detailed below.

A step-based modeling approach was adopted to determine the MNL models, estimated using Biogeme (Bierlaire, 2023). The process began with a baseline model including only the alternative-specific constant (ASC). This baseline was then compared with a series of more extensive models, each adding one set of independent variables to the baseline. Model comparisons were conducted using the chi-squared test. Among the models that significantly outperform the baseline, the extended model with the lowest Akaike Information Criterion (AIC) was selected as the new reference model. This procedure was repeated iteratively until the extension of the reference model by any additional independent variable no longer led to a significant improvement in the model's performance.

Thereafter, the model was checked for multicollinearity. When strong correlations were detected between variables, the weaker-performing variable was removed to improve model stability. This applied, among others, to the ASC, which was excluded because it showed high collinearity with the variable daytime.

Subsequently, interaction terms between the light settings and several variables were tested using the same step-based modeling approach. In particular, interaction effects between the local density, global radiation (i.e., Sun 1, Sun 2, and Sun 3), time of day, and experiment duration were tested. Please note that only interactions involving the light conditions were emphasized due to their direct relevance to the study's main objective. Finally, any interaction term that was not statistically significant was removed from the model.

### 4.4. Dataset balancing for model

An MNL model estimates coefficients using the entire sample. As a result, groups that are overrepresented in the dataset can disproportionately affect the results, potentially leading to biased predictions. In this study, the dataset was poorly balanced across two important features: pedestrian origin and light conditions. Initial modeling showed that pedestrian origin was the most influential

**Table 4**

Descriptive statistics of the experiment, showing exit choice probabilities per light setting ( $P_A$  and  $P_B$ ), and the mean probabilities over 15-min intervals ( $\bar{P}_A$  and  $\bar{P}_B$ ).

Light Setting	$P_A$	$P_B$	$\bar{P}_A$	$\bar{P}_B$	$\sigma_{A,B}$
Baseline I (NN)	0.71	0.29	0.65	0.35	0.15
NN	0.68	0.32	0.68	0.32	0.13
NO	0.72	0.28	0.71	0.29	0.13
NB	0.69	0.31	0.68	0.32	0.17
ON	0.69	0.31	0.68	0.32	0.13
BN	0.69	0.31	0.69	0.31	0.15
WG	0.67	0.33	0.64	0.36	0.17
WR	0.70	0.30	0.71	0.29	0.15
GW	0.68	0.32	0.64	0.36	0.16
GR	0.70	0.30	0.68	0.32	0.15
RW	0.71	0.29	0.69	0.31	0.12
RG	0.67	0.33	0.66	0.34	0.15
Baseline II (NN)	0.72	0.28	0.72	0.28	0.14

variable in determining exit choice, and light settings are the main focus of this study. These initial findings showed that pedestrians tend to walk toward the exit directly in front of them: those coming from origin 1 mostly use exit A, while those from origin 3 prefer exit B.

To reduce bias, the dataset was resampled across both features such that all groups were adjusted toward a common target size.

As mentioned in Section 4.3, this study evaluated two separate MNL models, one focusing on light intensity and the other on light color. Accordingly, the dataset was split up into two subsets. The light intensity subset included the light settings NN, NO, NB, ON, and BN, while the light color subset included WW, WG, WR, GW, GR, RW, and RG.

Table 2 shows that the number of observations substantially varies across groups. For the light intensity subset, group sizes range from 361 (NB, origin 3) to 2497 (NN, origin 1). The group sizes range from 315 (WR, origin 3) to 2497 (WW, origin 1) for the light color subset.

To address this imbalance, a target group size of 630 observations was defined as the maximum of twice the size of the smallest group of either subset. This target was applied consistently across both subsets. A combination of random over-sampling and under-sampling was then used to achieve this target size. These are two naive data-balancing methods often used in machine learning. Groups with fewer than 630 observations were over-sampled, while groups exceeding this threshold were under-sampled. This procedure resulted in two subsets with equal-sized groups: one with 9450 trajectories for the light intensity subset and one with 13,230 trajectories for the light color subset.

During the under-sampling process, all observations with a pedestrian above 4 were included by default (3.2% of the data) to preserve medium- to high-density scenarios, as density is also included as an explanatory variable in the models. As a result, the sampling procedure is constrained rather than purely random.

## 5. Results

This section presents the results of the field experiment and the corresponding discrete choice models. Descriptive findings regarding pedestrian exit choice are first emphasized in Section 5.1. Thereafter, the modeling results are shown: the light intensity model in Section 5.2, and the light color model in Section 5.3.

### 5.1. Descriptive results

To provide an initial understanding regarding the effect of light nudges on pedestrian exit choice, the analysis starts with the exit choice probability, which is defined as the proportion of pedestrians using exit A or exit B. Table 4 presents these probabilities across all light settings and throughout the full duration of the experiment, including the phases 'Baseline I', 'Experiment Part A', 'Experiment Part B' and 'Baseline II'. The exit-choice probability during the first baseline week reflected pedestrians' overall tendency to use exit A when leaving the university building ( $P_A = 0.71$ ).

The table also shows that the exit choice probabilities were relatively similar across all light settings, with a maximum variation of 5% ( $P_A = [0.67, 0.72]$ ). Although slight differences can be observed compared with the baseline week, these variations are too small to draw meaningful conclusions about the effect of light nudges. To enable statistical testing, the exit choice probability was therefore determined for 15-min intervals, resulting in a distribution of exit probabilities for each light setting. These distributions are visualized in Fig. 8. To avoid unreliable estimates from low-density time intervals, only intervals with more than 20 pedestrians were used. The mean ( $\bar{P}_A$  and  $\bar{P}_B$ ) and standard deviation ( $\sigma_{A,B}$ ) of these distributions are presented in Table 4.

The Shapiro-Wilk test indicated that most distributions deviated from normality ( $p < 0.05$ ). Therefore, a nonparametric Kruskal-Wallis test was conducted to determine whether the distributions of exit-choice probabilities differ across light settings. This test

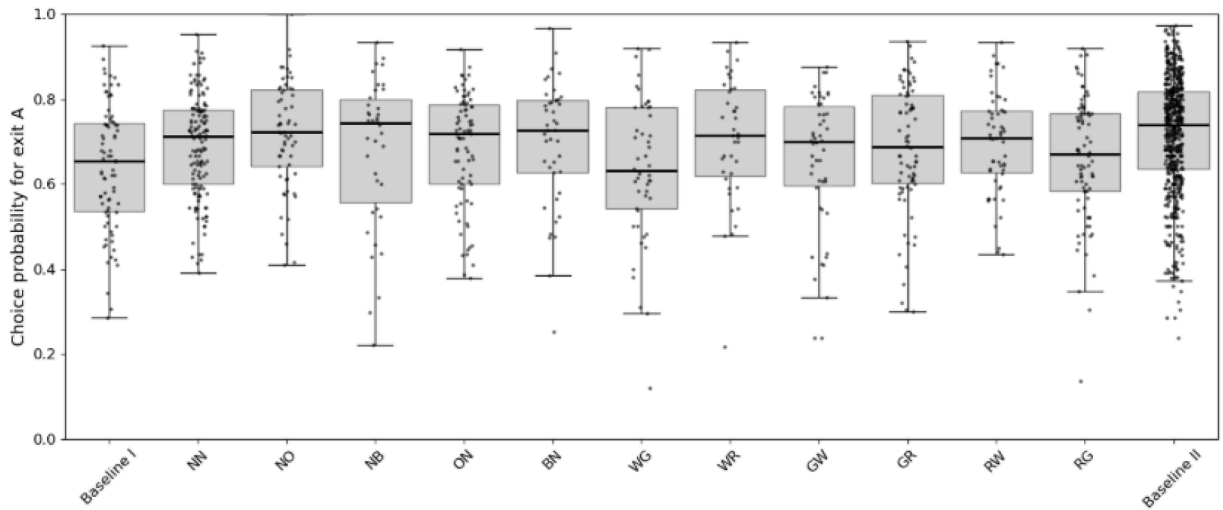


Fig. 8. Boxplot of exit choice probabilities across different light settings based on time intervals of 15 min.

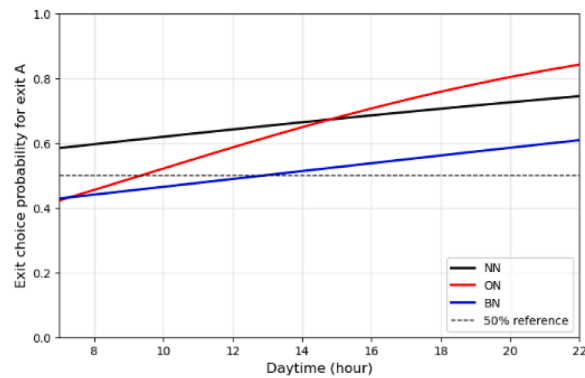


Fig. 9. Estimated exit choice probabilities for exit A as a function of daytime between 7:00 and 22:00 for the light intensity subset. This figure is derived from the MNL models for light intensity and, assuming pedestrians coming from origin 2 and with equal outflow at both exits.

evaluated the null hypothesis that all distributions were equal, i.e., whether exit choice behavior was unaffected by the light nudges. While the test can indicate whether there is a statistically significant difference in the distributions across settings, it does not identify which specific settings differ. It was assumed that the samples were independent. The Kruskal-Wallis test indicated no statistically significant difference among the light settings ( $H = 15.49$ ,  $p = 0.16$ ).

It was not possible to conclude from the current analysis whether exit choice was truly insensitive to the light nudges or whether other factors were influencing exit choice behavior. For instance, a non-homogeneous distribution across the three origins could have led to bias in exit choice. This type of bias might dampened the effect of the light nudges. This emphasized the need for a more comprehensive analysis that accounted for such factors, motivating the use of a discrete choice model in this study.

## 5.2. Modeling result: Light intensity model

An MNL model was estimated to analyze the effects of light intensity nudges on pedestrian exit choice, following the estimation procedure in Section 4.3 and the balanced data subset described in Section 4.4. Both the performance and parameter estimates of this MNL model are presented in Table 5. The R-squared of the model is 0.349, which is considered to be a fairly good fit in comparison to other recent exit choice models (e.g., Haghani and Sarvi, 2016 and Lovreglio et al., 2016). Pedestrian choice behavior is inherently difficult to predict, and previous studies have shown that MNL models in this context are typically considered satisfactory with values above 0.20 (Haghani et al., 2015).

The final MNL model, which features the impact of light intensity, includes four groups of variables: light condition variables, crowd behavior variables, environmental and contextual variables, and interaction variables. Underneath, the model results are presented, roughly grouped per variable type.

**Table 5**

Overview of model fit statistics and estimated parameters for the light intensity MNL model. The estimated parameters correspond to the beta coefficients for each respective variable. The cross ( $\times$ ) denotes an interaction term between the two variables.

Model fit			
Parameters	17		
Sample size	9450		
Null LL	-6,550.2		
Final LL	-4,250.3		
R-squared	0.349		
AIC	8,534.5		
BIC	8,656.1		
Estimated parameters			
	Est.	t-val	p-val
<i>Light conditions</i>			
NO	0.001	0.01	0.991
NB	-0.46	-1.46	0.144
ON	-1.24	-3.76	<0.001
BN	-0.63	-3.35	<0.001
<i>Crowding factors</i>			
N <sub>out</sub>	0.062	3.28	0.001
<i>Environmental and contextual factors</i>			
Origin 1	1.88	21.50	0.000
Origin 3	-2.10	-35.90	0.000
Daytime	0.05	8.31	0.000
Sun 1	0.16	1.80	0.072
Sun 2	-0.22	-2.94	0.003
<i>Interaction effects</i>			
Learning $\times$ NO	0.05	1.88	0.060
Learning $\times$ NB	-0.05	-1.40	0.161
Learning $\times$ ON	0.03	0.74	0.463
Learning $\times$ BN	0.14	3.83	<0.001
N <sub>out</sub> $\times$ BN	0.14	2.68	0.007
Daytime $\times$ NB	0.05	2.33	0.020
Daytime $\times$ ON	0.08	3.82	<0.001

### 5.2.1. Effect of light intensity

Table 5 shows that pedestrian exit choice differed significantly from the neutral light condition (NN) for two of the four light intensity settings: lights off-neutral (ON) and bright-neutral (BN). The estimated beta coefficients for both conditions were negative, indicating that pedestrians are more likely to choose exit B under these conditions than under NN. In the ON condition, this means that the exit with neutral white light is selected over the exit where the lights are off. In the BN condition, this means that the exit with neutral light is chosen over the exit featuring bright lighting. Where the first is in line with expectations, the latter seems more counterintuitive and suggests that exiting pedestrians might shy away from brighter exits and move towards regularly lit exits.

The light intensity model also includes interactions between light conditions and time of day. Fig. 9 depicts the choice probability for exit A as a function of daytime for three light settings: NN, ON, and BN. Here, we assumed that pedestrians departed from origin 2 and the outflow at both exits was equal, ensuring that the impact of the light nudges was emphasized by minimizing interference from other known effects.

In the ON condition, the interaction with daytime resulted in an increase in the choice probability for exit A compared to NN as time progresses during the day. This results in a threshold in the daytime at approximately 15:00. Before 15:00, pedestrians tended to avoid the unlit exit A and chose the neutrally lit exit B more often, relative to the equally lit condition NN. After 15:00, the probability of selecting the unlit exit A is higher than that under NN. Moreover, from approximately 10:00 onward, more and more pedestrians choose the unlit exit. Both results contradict hypothesis H1, which predicts that darker paths would be avoided.

In contrast, in the BN condition, the interaction of BN and time of day does not alter the directionality. The choice probability for exit A remained consistently lower than that under NN, indicating a general preference for the neutrally lighted exit B. At the same time, the interaction does change the probability of choosing exit A. For example, at 10:00, 46.5% of pedestrians exit via the brighter exit, and at 18:00, 56.1% of pedestrians exit via the brighter exit. This finding suggests that pedestrians tend to choose the exit with brighter lights more later on the day, which is partly in line with the authors' hypothesis H1.

Consequently, later in the day, the modeling results begin to align more closely with the expectations outlined in Hypothesis H1.

### 5.2.2. Effect of contextual, environmental, and crowd dynamics factors

In addition to light conditions, four contextual factors were found to impact pedestrians' exit choice behavior: pedestrians' origin, local density, time of day, and global radiation.

#### **Effect of pedestrians' origin**

Pedestrian origin is the most influential variable in the intensity model, as it contributed the most to the utility (i.e., the  $\beta$ -coefficient estimate multiplied by the variable's maximum range). When the origin variables were added to the initial model, the R-squared increased from 0.0382 to 0.333, highlighting the variable's major influence.

From the three origin variables, origin 2 (i.e., the centered origin) was set as the reference category. The signs of the parameter estimates represent the directional preference of pedestrians from each origin relative to origin 2, with positive values favoring exit A and negative values favoring exit B. In general, the light intensity model indicates that pedestrians from origin 1 are more likely to choose exit A, while those from origin 3 are more likely to select exit B.

Using the parameter estimates of the light intensity model in [Table 5](#), choice probabilities are extracted for the three origins. For pedestrians walking alone in bright daylight at noon under the reference light setting NN, the choice probability for exit A was 64.2% when coming from origin 2. Under the same conditions, the probability increased to 92.2% when coming from origin 1 and decreased to 18% for origin 3. This highlights that pedestrians were likely to use the exit directly in front of them. A plausible explanation is that pedestrians prefer to follow the path that requires the least effort, which is consistent with prior findings in the literature (e.g., [Dalton, 2003](#); [Feng et al., 2022](#); [Guo et al., 2012](#); [Seneviratne and Morrall, 1985](#)).

#### **Effect of outflow**

The modelling results also indicated that pedestrians' exit choice depends on the outflow over the two exits. The positive outflow parameter indicates pedestrians are attracted to the exit that used by preceding pedestrians. This suggests that pedestrians are following the majority of the crowd downstream. This also suggests that pedestrians exhibit an attraction toward the exit with the higher surrounding density, adjusting their preference between exits A and B as these local densities vary. Similar behavior has been established in prior research, such as [Van den Berg et al. \(2018\)](#) and [Kinader and Warren \(2021\)](#).

However, another explanation for the attraction to the largest outflow might be that pedestrians are following those in the same social group. As the group is moving towards the same exit, the outflow at that exit increases. The impact of grouping on exit choice has been described in prior research, including [Lovreglio et al. \(2014\)](#). More research is required to disentangle these two possible explanations for the impact of the outflow.

In addition, an interaction effect between the outflow and the BN condition is found. In comparison to the scenario where no pedestrians are moving to either exit, the outflow of 5 pedestrians through the brighter exit A increases the exit choice probability for exit A from 48.9% to 72.4% at 12:00. However, if those same pedestrians are walking towards exit B, the exit-choice probability for exit A decreases from 48.9% to 41.2%. This suggests that in the BN condition, the presence of other pedestrians influences the signal's effectiveness. If others follow the suggestion to avoid the darker exit, the next person is more likely to do the same. When pedestrians see others ignore the steering information, they are also more likely to do so.

#### **Effect of time of day**

Time of day also has a statistically significant effect on pedestrian exit choice. In particular, during the day, pedestrians are increasingly likely to exit via exit A. To visualize this effect, the neutral light condition (NN) was used as a reference to assess how exit choice varies during the day. [Fig. 10](#) shows the choice probabilities for exit A and B under NN as a function of daytime, limited to the building's opening hours (07:00-22:00). The probability of choosing exit A increased linearly over the course of the day, going from 58.4% at 7:00 to 75% at 22:00. In addition, the figure indicates that pedestrians were generally more likely to choose exit A, with the choice probability for exit A remaining above the 50% reference line throughout the day. This preference was consistent with the observations reported in [Section 5.1](#), which also indicated that exit choices were not evenly distributed over both exits.

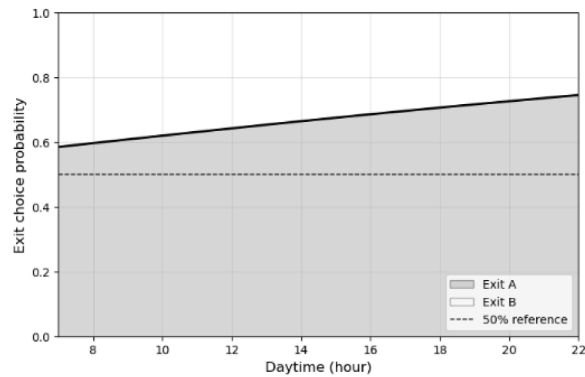
It is currently unclear why the exit probability shifts during the day. The authors expect that it has something to do with the percentage of pedestrians who are exiting the building to go home, thus need their bicycles. During the day, students often also walk from building to building, while at the end of the day, they go home by bicycle. Yet, more research is required to explain this behavior.

In addition to the main effect of Time of day, an interaction effect of time of day with the NB and ON conditions has been included in the final model. In particular, the exit choice probability for exit A increases more rapidly if the NB and ON light conditions are active. Please note that, in both conditions, this means pedestrians choose the darker of the two exits more frequently when they see others do the same.

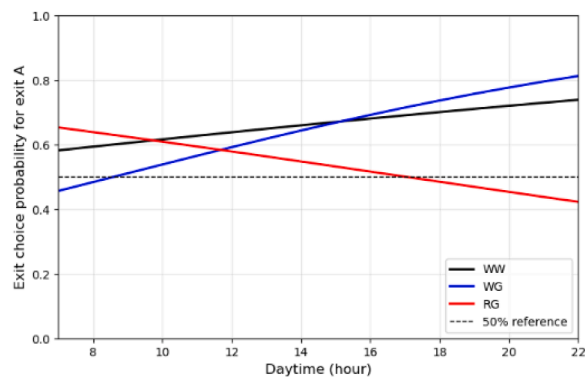
#### **Effect of learning**

Next to light conditions and context, the experiment duration is also found to affect the impact of light conditions on the exit choice probability. In particular, the longer the experiment lasts, the more likely pedestrians are to exit via exit A in the NO and BN conditions. In week 1, 67.1% and 54.2% of pedestrians chose exit A in the NO and BN conditions, respectively, increasing to 75.2% and 78.4% in week 9 of the experiment. An increase in the exit probability of exit A of respectively 8.2% and 24.2%. In both cases, the lighter condition is chosen over a darker condition, a result that is in line with hypothesis H1, which suggests that pedestrians 'learn' to avoid the darker exit.

Yet, the experiment duration does not affect the probability of choosing exit A in the NB and ON conditions. It is unclear why the experiment duration does not influence these two conditions. More research is required to unravel this seemingly directional effect.



**Fig. 10.** Estimated choice probabilities for exits A and B as a function of daytime between 7:00 and 22:00, compared to 50% reference line representing an even distribution under the assumption that pedestrians originate from origin 2, experience equal outflows at both exits, and neutral light conditions are activated.



**Fig. 11.** Estimated exit choice probabilities for exit A as a function of daytime between 07:00 and 22:00 for the light color subset. This figure is derived from the MNL models for light color, assuming pedestrians are coming from origin 2 and that the outflow is equal at both exits.

### 5.3. Light color model

An MNL model for the light-color subset was estimated using the same modeling procedure. The performance of the light color MNL model is reported in Table 6. The model can predict the pedestrians' exit choice behavior moderately well, with an R-squared of 0.341.

The final light color MNL model features four groups of variables: the light conditions, crowding factors, environmental and contextual factors, and interaction effects. First, the effects of light conditions are discussed. Accordingly, the most noteworthy results regarding the crowding factors, environmental conditions, and context are also presented.

#### 5.3.1. Effect of light color

The six light settings are evaluated relative to the white-white (WW) benchmark condition. Only two light conditions have a statistically significant effect on pedestrian exit choice: namely, white-green (WG) and red-green (RG). In particular, pedestrians originating from origin 2 at 10 AM choose exit A with a probability of 64.9% when the WG condition is active in week 1 of the experiment, compared with 72.1% when the WW condition is active. In contrast, 46.3% of the pedestrians originating from origin 2 choose exit A when the RG condition is active. Consequently, the main effect of the WG and RG light conditions is quite extensive.

However, because the WG and RG conditions also exhibit significant interaction effects with time of Day, their influence cannot be meaningfully interpreted without taking temporal context into account. The combined effect of light condition and time of day is shown in Fig. 11 for three light conditions: WW, WG, and RG.

In the WG condition, the probability of choosing exit A is lower than in the WW condition in the early morning. However, due to the interaction effect between WG and daytime, the exit choice probability for exit A increases rapidly and surpasses the WW probability at approximately 15:00. In other words. At the same time, pedestrians are initially less likely to choose exit A when the WG condition is activated; this tendency reverses at 15:00. This suggests that in the late afternoon, green lights no longer attract pedestrians toward exit B. This partially contrasts the hypothesis H2 that pedestrians tend to follow green-lit paths.

**Table 6**

Overview of model fit statistics and estimated parameters for the light color MNL models. The estimated parameters correspond to the beta coefficients for each respective variable. The cross ( $\times$ ) denotes an interaction term between the two variables.

Light color model			
Model fit			
Parameters	23		
Sample size	13,230		
Null LL	-9,170.3		
Final LL	-6,022.2		
R-squared	0.341		
AIC	12,090.5		
BIC	12,262.8		
Estimated parameters			
	Est.	t-val	p-val
<i>Light conditions</i>			
WG	-0.94	-2.61	0.009
WR	-0.02	-0.081	0.935
GW	-0.02	-0.12	0.906
GR	-0.09	-0.49	0.628
RW	0.15	0.79	0.430
RG	1.07	2.28	0.023
<i>Crowding factors</i>			
$N_{out}$	0.045	3.28	0.001
<i>Environmental and contextual factors</i>			
Origin 1	1.72	25.20	0.000
Origin 3	-2.12	-39.90	0.000
Daytime	0.05	8.51	0.000
Sun 1	0.45	6.14	<0.001
Sun 2	-0.14	-2.14	0.032
<i>Interaction effects</i>			
Learning $\times$ WG	0.003	0.09	0.928
Learning $\times$ WR	-0.02	-0.44	0.659
Learning $\times$ GW	-0.01	-0.17	0.869
Learning $\times$ GR	0.05	1.75	0.081
Learning $\times$ RW	-0.004	-0.12	0.903
Learning $\times$ RG	0.07	1.94	0.052
Origin 3 $\times$ WR	-0.33	-2.34	0.019
$N_{out}$ $\times$ RG	0.23	4.25	<0.001
Daytime $\times$ WG	0.06	2.75	0.006
Daytime $\times$ RG	-0.11	-3.64	<0.001
Sun 2 $\times$ WR	0.58	4.01	<0.001

In the RG condition, the probability of choosing exit A is higher than in the WW condition in the early morning. However, as shown in Fig. 11, the probability of choosing exit A under the RG condition drops below the exit choice probability for the WW condition around 10:00. After 17:00, pedestrians are more likely to select exit B than exit A ( $P_B > 0.50$ ). This relation suggests that either the attraction effect of green light strengthens later in the day, the repulsion of the red lights increases during the day, or a combination of both effects.

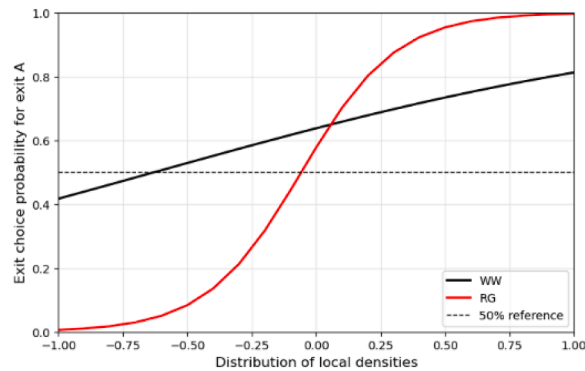
Overall, the result aligns with the hypotheses H2 and H3 regarding the impact of green and red light conditions. The only exceptions occur at the beginning and end of the day: before 10:00, the RG condition does not follow H3, and after 15:00, the WG condition similarly diverges from H2. These deviations highlight that lighting's influence is not uniform throughout the day and that time-specific contextual factors likely shape pedestrians' responsiveness to light cues.

### 5.3.2. Effect of crowding, environmental and contextual factors

In addition to light color conditions, four contextual factors were found to impact pedestrians' exit choice behavior: pedestrians' origin, local density, time of day, and global radiation.

#### **Effect of pedestrians' origin**

Table 6 highlights a similar pattern as observed in the light intensity MNL model. That is, the origin variable is the most influential predictor of pedestrian exit choice, indicating that pedestrians tend to walk toward the exit directly in front of them.



**Fig. 12.** Estimated choice probabilities for exit A as a function of the density distribution between the two exits. The distribution ranges from -1 (all pedestrians walk towards exit B) to 1 (all pedestrians walk towards exit A). These estimated probabilities are derived from the MNL model in Table 6 assuming pedestrians approaching from origin 2 at 12:00.

### Effect of outflow

Also, the light-color MNL model features the outflow as a main effect. Similar to the light-intensity model, pedestrians are more likely to choose an exit with a relative larger outflow. This effect may stem from either majority-following behavior or pedestrians staying with their social group, and further research is needed to differentiate between these explanations.

In addition, an interaction effect between the RG condition and outflow is found, suggesting that people react more strongly when the majority of surrounding participants obey or disobey with the RG light setting. To visualize this impact, Fig. 12 shows the exit choice probability for exit A as a function of the outflow distribution over the two exits for pedestrians who left the building at noon from origin 2. Here, a distribution value of -1 meant that all leaving pedestrians used exit B, 0 indicated an equal distribution of outflow across both exits, and 1 suggested that all pedestrians left through exit A.

The figure indicates that pedestrians are susceptible to the actions of the majority of the crowd in both light conditions. However, this effect is noticeably stronger under the RG light setting. The exit choice probability changes rapidly as soon as one exit becomes more frequently used, approaching 0% and 100% when all pedestrians left through one of the exits.

This result suggests that the effectiveness of RG in guiding pedestrians is strongly influenced by the outflow: a higher share of pedestrians using the green-lit exit increases the probability that others follow the light-based guidance, whereas a higher share of pedestrians using the red-lit exit increases the probability that other pedestrians also disregard the red lights.

### Effects of time of day

The probability of choosing exit A is also found to increase linearly with time of day, following a pattern similar to the relationship depicted in Fig. 10. That is, pedestrians increasingly prefer exit A throughout the day.

Similarly to the light intensity MNL model, interaction effects between light conditions and time of day are also established. The positive relation between the WG condition and time of day suggests that pedestrians are increasingly more likely to choose the green exit B as time progresses. In particular, between 10:00 and 17:00, the probability of selecting exit A increases from 64.9% to 79.9%. This finding indicates that, over time, an increasing number of pedestrians choose the white-lit exit instead of the green-lit exit, which does not support Hypothesis H2.

The negative relation between the RG condition and time of day, moreover, indicates that pedestrians are increasingly less likely to choose exit A and more likely to move towards the green exit B. In particular, between 10:00 and 17:00, the probability of selecting exit A decreases from 72.9% to 63.9%. This finding indicates that, over time, an increasing number of pedestrians choose the green-lit exit B over the red-lit exit A, which is consistent with and supports Hypothesis H3. In total, however, more pedestrians choose the red-lit exit A over the green-lit exit B.

### Effects of learning

Lastly, the experiment duration is also found to influence the effect of light color on the exit choice probability. Specifically, the longer the experiment continues, the more likely pedestrians are to choose exit A in both the GR and RG conditions. The effect size of both interaction effects is limited. Between the first and last week of the experiment, the probability of choosing exit A in the GR/RG conditions changes from 71.3% / 72.9% to 78.8% / 82.5%, respectively. The results appear counterintuitive because hypotheses H2 and H3 imply that GR should exhibit an effect opposite to that of RG. The authors expect that pedestrians have 'learned' to ignore the light cues throughout the experiment.

Interestingly, all other interaction effects featuring a combination of the experiment duration and the light conditions (learning x {WG, WR, GW, RW}) are found to be insignificant.

## 5.4. Summary of the main results

The light-intensity MNL model shows that two lighting conditions (ON and BN) significantly affect exit choice. In general, pedestrians are more likely to choose a neutrally lit exit than an unlit or brightly lit one. Contextual factors, in particular pedestrian origin, pedestrian outflow, and time of day, are found to exert a much stronger influence on exit choice than the light conditions alone, with

pedestrians tending to follow the most direct path or the crowd downstream. Learning effects were observed only in the NO and BN conditions, where pedestrians increasingly chose the lighter exit over time, whereas no such adaptation was observed in NB and ON.

The light-color MNL model shows that only two color conditions—white-green (WG) and red-green (RG)—significantly influence behavior, with both effects strongly shaped by time of day. As in the intensity model, contextual factors such as pedestrian origin, pedestrian outflow, and daytime exert substantial influence, and crowding particularly amplifies responses to the RG condition. Learning effects are weak but indicate that, over time, pedestrians increasingly choose exit A in both GR and RG conditions, a pattern that contradicts the expected opposite directional effects of these two cues.

Despite the variety of light settings applied in the experiment, the results remained remarkably stable across conditions. This consistency reflects the dominance of habitual factors in pedestrian routing: individuals tend to follow the most direct path and rely on established routines. Both of which strongly outweigh the more subtle visual cues. Contextual variables exert much larger effects than lighting, thereby dampening the effect of the lighting interventions.

## 6. Discussion

The discussion is structured in three parts. First, the observed effects of light intensity and color are discussed in relation to our hypotheses and the research literature. Thereafter, the practical implications of these findings are considered. Accordingly, potential explanations are proposed for the observed differences between this study's findings and other studies in literature.

### 6.1. Comparison of light effects with respect to the research literature

The MNL model estimations indicate that light conditions did not systematically influence pedestrian exit choice. While both light intensity and light color showed statistically significant effects in certain scenarios (e.g., the bright-neutral and red-green settings), these effects were not consistent across all light settings.

Regarding the impact of *light intensity*, existing studies consistently reported that participants preferred brighter-lit paths or exits in different experimental conditions (van Beek et al., 2024; Feliciani et al., 2024; Taylor and Socov, 1974; Vilar et al., 2013). The results of this study only partially agree with their conclusions. In particular, for the light setting lights off-neutral (ON), pedestrians avoided the unlit exit. They used the exit with neutral lights more frequently than in the baseline condition (neutral-neutral), consistent with the hypothesis that darker exits are less attractive. This effect, however, was observed only before 15:00, suggesting a potential time-of-day dependency.

The impact of the remaining three light intensity settings was inconsistent with the hypothesis and the existing literature. For two settings (neutral-lights off and neutral-bright), exit choice probabilities were not statistically significant, indicating no effect on exit choice relative to the baseline condition. In the bright-neutral setting (BN), the results contradicted expectations: pedestrians chose the neutral-lit exit more frequently than the bright-lit one.

Regarding the effects of *light color*, a previous VR study (van Beek et al., 2024) found strong effects of green- and red-lit paths in a virtual maze. Similarly, the evacuation scenarios of Frantzych and Nilsson (2004), Nilsson et al. (2005, 2008) indicated that exits were chosen more frequently when applied with green flashing lights. The MNL color model only partially corroborated these previous findings.

In particular, significant effects in exit choice were observed for the red-green (RG) and white-green (WG) light settings. In the red-green setting, pedestrians chose exit B more frequently than in the baseline condition (white-white), indicating an attraction to the green-lit exit and a repulsion to the red-lit one. The apparent contradiction before 10:00 was likely due to the limited amount of data during that time (4% of the dataset). This tendency to follow green-lit paths aligns with the hypotheses and findings of van Beek et al. (2024), though the observed attraction in this study is weaker. Similarly, for the white-green settings, a preference for the green-lit exit was observed relative to the baseline condition until 15:00, partially supporting the hypothesis regarding green lights. In contrast, in the white-red, green-white, green-red, and red-white light settings, pedestrian choice behavior did not differ significantly from the baseline condition. Thus, in this study, the effects of light color on pedestrian exit choice were not consistent across all light settings.

### 6.2. Comparison of light effects with respect to the expectations of practitioners

Research on the effects of light nudges on pedestrian choice behavior remains scarce. Therefore, it is valuable to consider practitioners' experiences and expectations regarding these effects.

Practitioners especially expect strong effects in the lights-off condition, as it relates to pedestrians' perceived social safety (Haans and De Kort, 2012; Kaplan and Chalfin, 2021; Painter, 1996). They argue that pedestrians avoid unlit spaces to maintain a level of social safety. In the present study, this effect is partially observed in the lights off - neutral setting, as pedestrians tended to avoid the unlit exit for part of the day. Yet, this effect was neither as consistent nor as strong as expected.

Regarding light color, practitioners also anticipate particular effects. People are used to associating certain colors with particular meanings in various contexts, ranging from colored flags signaling danger of the sea to traffic lights regulating traffic. Following the same logic, light-colored exits could influence pedestrian behavior. The findings partially support this, as reported in Section 5.3. Pedestrians were more likely to choose the green-lit exit in the white-green and red-green light conditions. Yet, the exit-choice

probability did not differ across the other light settings compared to the baseline condition (white-white). This inconsistency indicates that the effects of light color are context-dependent rather than universal.

### 6.3. Explanations for the contradicting behavioral results

This discussion has identified a few disagreements between this study's findings, the proposed hypotheses, the existing literature, and practitioners' expectations, which are challenging to explain. Not only were the observed effects substantially smaller than anticipated, but in some scenarios the direction of the effects also diverged from what theory and prior empirical work would predict. The following section provides additional explanations for the differences identified above regarding the impact of light intensity, light color, and confounding factors.

#### *Light intensity*

Practitioners hypothesized that pedestrians would avoid the darker exit, yet this study does not support this hypothesis. This discrepancy between their expectations and these findings could be explained by the lack of social safety concerns at this location, where the unlit area is small, the line of sight is clear, and ambient lighting is present directly beyond the exit. Pedestrians feel safer in our study location than, for example, in an unlit urban alley, making them less susceptible to unlit spaces.

#### *Light color*

Based on the VR study of van Beek et al. (2024), the authors expected very strong effects of green and red lights. Previous research in evacuation scenarios has also found that different types of colored flashing lights can affect exit choice (Frantzich and Nilsson, 2004; Nilsson et al., 2005). Although these studies differ in light sources (i.e., flashing lights versus ambient light) and context (i.e., emergency versus everyday conditions), they establish a color-based impact on pedestrian choice behavior.

Our study only partly corroborates these two hypotheses regarding the impact of light color. Still, the magnitude of the lighting effects is very limited and inconsistent when one of the two colors is combined with white light. One potential explanation for the smaller effect size in this study is that the pedestrians in the faculty building are not actively searching for environmental cues to guide them, while the participants of van Beek et al. (2024), Frantzich and Nilsson (2004), and Nilsson et al. (2005) were actively searching their way out. In both a maze and evacuation context, light color might be more strongly associated with go (green) and stop (red) (Bergum and Bergum, 1981).

#### *Confounding factors*

Another key difference is that the VR study was designed to minimize external factors that could influence pedestrian choice behavior, effectively creating a near-ideal scenario. As a result, the estimated effects reflect an ideal scenario. They may overestimate the influence of lighting nudges compared to real-world environments, where pedestrian choice behavior is shaped by numerous additional confounding factors (e.g., social interactions, built environmental features, and contextual constraints).

This study also finds a smaller impact of lights than in other controlled experiments and than our expectations. The authors expect that the presence of competing environmental cues and contextual constraints is influencing the effectiveness of light nudges. First, the participant population itself likely contributes to the conservative nature of the observed effects. Most pedestrians exiting the building are students who are highly familiar with the environment, having frequented the building for years. Their movement patterns have become routinized to the point that subtle environmental cues, including variations in lighting, have little influence, and they appear disinclined to deviate from habitual routes even when instructed to do so. This long-term familiarity dampens the likelihood of lighting-induced behavioral change. Second, pedestrians using exit A typically have a clear functional goal, i.e., reaching their bicycles in the bicycle parking lot, which is instrumental for moving around on campus between faculty buildings. Their motivation stems almost exclusively from the destination, not from guidance offered along the way. Third, university students are accustomed to navigating large groups and dense crowds on the campus, and may therefore be less responsive to cues designed to improve flow efficiency or reduce crowding. Fourth, the lighting cues do not entail meaningful consequences: choosing the "counterintuitive" option, such as taking the red door instead of the green one, does not result in any delay, penalty, or negative feedback. Given this absence of reinforcement, there is little incentive to adjust future choices. Combined, these four reasons create conditions under which only minimal lighting effects are likely to occur.

## 7. Conclusion

This study examined how different light settings influence pedestrian exit choice in a university building. The case study was systematically designed to allow for statistical analysis, providing an initial evaluation of choice behavior under different light settings. The initial evaluation did not reveal significant differences across the light settings. To provide a more comprehensive analysis, two multinomial logit (MNL) models were developed.

The model estimates indicated that lighting conditions exerted a selective influence on pedestrian exit choice. Pedestrians used the unlit exit less frequently in one scenario compared to the reference one, and chose exit B more often when it was illuminated with green lights. This indicates partial support for the hypotheses. The exit-choice probability for the other light-intensity and color settings did not differ significantly from the baseline. In addition, the model captured two well-known pedestrian choice behaviors: a preference for the shortest path and a tendency to follow the majority.

These findings suggest that lighting can influence pedestrian choice behavior in this specific context, though the effects are inconsistent across different lighting conditions. Importantly, these findings are based on a single field study in a university building with a relatively homogeneous population. As such, the results should be interpreted as context-specific and cannot be generalized to other environments, populations or crowd conditions without further empirical validation. The inconsistencies observed in this study highlight the importance of context when examining the effects of light-based nudges, which aligns with prior research and practitioner experience.

While the present study relies on an MNL model, this specification is limited in its ability to capture unobserved population heterogeneity and time-dependent correlations in pedestrian decision-making. Future research should explore more flexible discrete choice models, such as mixed logit, latent class models, or latent-state choice models, provided that the data allow repeated or identifiable observations per individual.

At the same time, the variability in our results points to underlying behavioral processes that remain insufficiently understood. We therefore welcome contributions from experts in behavioral science who can potentially offer deeper theoretical explanations, such as differences in salience, attention, perceptual load, or habitual decision-making mechanisms, that could account for the magnitude and direction of the effects observed in this study.

For practitioners, this means there is no universal method for using lighting as a crowd management strategy. They have to conduct a systematic analysis of their environment and crowd to determine whether light intensity or color could be used as a nudging method to manage crowds. Future research is needed to understand better the context-dependent nature of these light nudges, so they can be utilized to manage large crowds effectively.

### CRediT authorship contribution statement

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

### Data availability

Data will be made available on request.

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