IATSS Research 48 (2024) 447–455

Contents lists available at ScienceDirect

IATSS Research

journal homepage: www.sciencedirect.com/journal/iatss-research

Research Article

Discomfort in pedestrian-electric scooter interactions during frontal approaches

Kazufumi Suzuki [a], Tatsuto Suzuki [b,*], Nick Tyler [b], Koji Suzuki [c]

[a] *Department of Civil Engineering, Shizuoka Institute of Science and Technology, Japan*
[b] *Person Activity Environment Research Laboratory (PEARL), University College London, United Kingdom*
[c] *Department of Architecture, Civil Engineering and Industrial Management, Nagoya Institute of Technology, Japan*

A B S T R A C T

Background: As urban landscapes rapidly integrate e-scooters into their transportation ecosystems, understanding pedestrian-e-scooter interactions becomes paramount for safety and planning. This study investigates pedestrian discomfort levels and avoidance strategies when encountering an e-scooter approaching from the front.
Methods: 25 participants were exposed to e-scooters approaching at three different speeds and lateral distances. Avoidance paths were plotted, and subjective discomfort levels were recorded and analysed.
Results: Our findings underscored two key behaviours: 1) As the speed of the e-scooter increased, participants initiated avoidance manoeuvres from a further distance ahead, suggesting a heightened perception of risk. 2) Regardless of the e-scooter's speed, the lateral distance maintained during passing remained fairly constant. However, when the e-scooter's initial lateral position was closer to participants, both the initiation distance for avoidance and the reported discomfort level increased noticeably.
Conclusion: The findings underscore the critical influence of lateral distance and e-scooter speed on pedestrian comfort and avoidance behaviour. These insights can guide urban planners and policymakers in designing safer and more efficient shared spaces.

1. Introduction

The Electric Scooter (e-scooter), as defined by SAE International J3194 in November 2019, is an ultra-lightweight vehicle weighing <23 kg, with a standard width of <0.9 m and a low-speed limit of up to 18mph (8 m/s) [1]. Its popularity surged in September 2017 when the micro-mobility company Bird Rides, Inc. introduced a shared e-scooter service in Santa Monica, California, USA [2]. Following this, the trend quickly spread to San Francisco, Washington, and Los Angeles by the end of 2017 and subsequently expanded across the USA, Asia, and Europe [3]. *E*-scooters offer a convenient, efficient, and environmentally friendly mode of transportation, leading to their broad adoption in cities worldwide [4]. As of July 2023 in Japan, e-scooters with a maximum speed of 20 km/h (5.6 m/s) are legally permitted on public roads. Additionally, they can be ridden on footpaths if their maximum speed does not exceed 6 km/h (1.7 m/s).

In Greece, pedestrians who prefer walking and using public transport made up the majority of shared e-scooter users [5]. An online questionnaire in Singapore aimed at understanding pedestrians' attitudes towards personal mobility devices (PMDs), like e-scooters on shared paths, revealed that the acceptance of PMDs is more influenced by environmental factors (e.g., footpath width and crowdedness) than by individual behaviour, such as the speed and movement of PMDs [6].

The rapid proliferation of shared electric scooter services in urban settings has garnered significant attention due to the rise in injuries and subsequent hospital admissions. Notable regions affected include California, USA [2], Auckland, New Zealand [3], and Tel-Aviv, Israel (Note: Tel Aviv is in Israel, not Iran) [7]. A predominant reason for these hospital admissions was injuries such as limb fractures and trauma to the head, face, and upper limbs, as evidenced by accident reports from Hamburg, Germany [8]. Additionally, it was observed that e-scooter accidents tend to occur more frequently during weekends and are often associated with alcohol consumption, in contrast to accidents involving bicycles. A comprehensive study [9], which analysed 5016 hospital admissions recorded in the National Electronic Injury Surveillance System of the United States between 2015 and 2019, revealed that the upper extremity was the most commonly fractured body part, accounting for 25.4% of cases. Furthermore, interviews with 105 injured patients in Washington indicated that the primary locations of e-scooter accidents were sidewalks (58%) and roads (23%) [10].

* Corresponding author at: Person Environment Activity Research Laboratory (PEARL), University College London, Yew Tree Avenue, Dagenham RM10 7FN, United Kingdom.
E-mail addresses: suzuki.kazufumi@sist.ac.jp (K. Suzuki), t.suzuki@ucl.ac.uk (T. Suzuki), n.tyler@ucl.ac.uk (N. Tyler), suzuki.koji@nitech.ac.jp (K. Suzuki).

https://doi.org/10.1016/j.iatssr.2024.08.004
Received 12 November 2023; Received in revised form 19 April 2024; Accepted 19 August 2024
Available online 7 September 2024
0386-1112/

Meanwhile, the rise of the e-scooter presents a novel set of challenges to pedestrian safety and comfort. Their increasing presence on sidewalks and shared pathways has heightened concerns over potential collisions and conflicts with pedestrians. It becomes crucial to understand the basic attitudes of e-scooter riders and how they navigate around obstacles or pedestrians. Adopting an ethnomethodological approach to public space and mobility, a study analysed video recordings of three e-scooter riders in Paris [4]. The findings revealed that e-scooter riders aimed to minimise appearing not only exploitative but also unexpected in public spaces and during encounters with others. The shared experiences of e-scooter riders and pedestrians have also been investigated [11]. This research suggests that the experiences of e-scooter riders and pedestrians are complicated by car-centric transport systems, which clearly define transportation space boundaries, combined with limited available pathway space. For the safety of both pedestrians and e-scooter riders, it's pivotal to examine e-scooter riding behaviours when they encounter pedestrians, akin to the case with Segways [12,13]. Based on prior studies, pedestrians most susceptible to injuries include individuals with vision/hearing impairments, young children, older adults, and those distracted by mobile devices [14].

A common and critical scenario that warrants attention occurs when an e-scooter approaches a pedestrian head-on. This situation demands both parties negotiate space and coordinate their movements to prevent a collision. The reasons we feel discomfort and instinctively avoid oncoming objects remain somewhat elusive. However, the amygdala in the human brain might trigger strong emotional reactions typically associated with personal space violations [15]. This could explain why pedestrians feel discomfort when e-scooter riders encroach on their personal space, prompting them to sidestep and maintain their boundaries. Furthermore, vision plays a crucial role in recognising objects in our immediate environment and helps us react appropriately to avoid potential hazards [16].

Pedestrian avoidance behaviours during walking have been previously studied. The circumvention of both stationary and moving human-shaped objects approached from a 45-degree angle has been reported [17]. The researchers found that participants consistently maintained an elliptical personal space during circumvention, adjusting its size based on environmental factors. The regulation of personal space is instrumental in controlling locomotion. A comparison of older and younger adults, with the introduction of auditory distractions while circumventing a stationary or moving mannequin, has been documented [18]. The study revealed that older adults expanded their personal space more than younger adults, especially when auditory distractions were present. Another study involving a standing interferer was conducted [19], and no differences were found in obstacle avoidance strategies between the age groups. Collision avoidance behaviours against differently-sized human figures were explored [20]. This study analysed the effects of human body size and its orientation on the medial-lateral clearance between the interferer and participant when crossing. Additionally, research into pedestrians' avoidance behaviours against human-shaped objects approaching head-on at varying speeds was presented [21]. The primary focus was the initiation of heading changes, with spatial constraints having a significant impact, rather than the object's speed. Participants typically adopted a two-stage avoidance behaviour: changing heading direction followed by adjusting walking speed. Another study assessed path and speed adjustments when pedestrians crossed paths with non-reactive human interferers at different angles and speeds [22]. The findings indicated a robust relationship between path and speed adjustments with the crossing angle and walking speed. Specifically, crossing at acute angles (45 and 90 degrees) appeared to necessitate more complex collision avoidance strategies. In scenarios involving a 180-degree angle, there was a 0.3 m lateral distance from a passer-by.

Pedestrian perceptions of danger when passed by a Segway were explored [23]. The findings revealed two key insights: Firstly, pedestrians exhibit greater sensitivity to the distance between themselves and a personal mobility vehicle (PMV) like an e-scooter when the PMV is in front of them compared to when it is behind them. Secondly, pedestrians perceive a PMV in front of them as more threatening when they are in close proximity to it. However, when at a greater distance, they perceive a higher level of danger from a PMV approaching from behind compared to one approaching from the front.

While it is essential to understand the discomfort pedestrians may feel when encountering e-scooter riders in shared spaces, current insights remain insufficient. Moreover, no study has specifically addressed how pedestrians might avoid e-scooters. The experience of pedestrians is influenced by the approaching e-scooter's speed, trajectory, and their perception of the rider's intentions. There's a pressing need to delve deeper into these factors to better grasp their impact on pedestrian comfort and safety. Such understanding could shape the design of effective interventions and policies to reduce conflicts and enhance the overall user experience in shared urban environments. While much of the existing research on pedestrian-vehicle interactions centres on motor vehicles and bicycles, with e-scooters receiving less attention, the distinct characteristics of e-scooters—like their compact size, slower speeds, and the rider's posture—call for a specialised study to truly comprehend the intricacies of pedestrian-e-scooter interactions.

This study aims to bridge the existing gap by examining the factors influencing pedestrian discomfort when faced with an e-scooter approaching head-on, taking into account Japanese traffic conditions and extending the speed parameters to accommodate various conditions in other countries. Our objective is to identify the primary elements ensuring a comfortable pedestrian-e-scooter interaction. The insights garnered will inform the development of effective interventions, infrastructure enhancements, and policies designed to bolster safety and promote walkability in urban settings.

2. Methods

2.1. Participants

A total of 25 participants took part in this study after signing an informed consent, which was approved by the ethical committee at the Nagoya Institute of Technology in Japan. The average age of the 14 male participants was 34 ± 10 years, while the 11 female participants had an average age of 31 ± 10 years. All participants possessed either normal or corrected-to-normal vision and reported no musculoskeletal, cognitive, or eye disorders, which could influence the study results. After providing consent to participate in the study, each participant answered demographic questions and had a 10-min e-scooter ride, and then proceeded to the experiments. Each participant's trial was completed within two hours. The experiments for this study were conducted over five days, under sunny or cloudy conditions, ensuring that the road surface remained dry.

2.2. Experiment design and setup

This study was conducted on an internal road at the Nagoya Institute of Technology in Japan. The road's surface was asphalt, measuring 60 m in length and 5 m in width. This road was set up as per the experimental design depicted in Fig. 1. Both the participant and the e-scooter gears began by moving towards each other. Participants were instructed to walk along a white dotted line on the road at a natural walking speed of approximately 1.4 m/s (5 km/h). If they felt discomfort or perceived a risk of collision with the approaching e-scooter, they were advised to sidestep to the left and then return to the white line after passing the e-scooter, continuing until the end of each trial. The space on the left reserved for avoidance was 2 m wide. The e-scooter, operated by the examiner, travelled alongside light yellow dots at a lateral distance Ye and a constant speed Ve. Both the distance and speed were chosen randomly from three settings: Ye positions of 0 m, 0.75 m, and 1.50 m, and Ve speeds of 1.7 m/s (6 km/h), 2.8 m/s (10 km/h), and 4.2 m/s (15

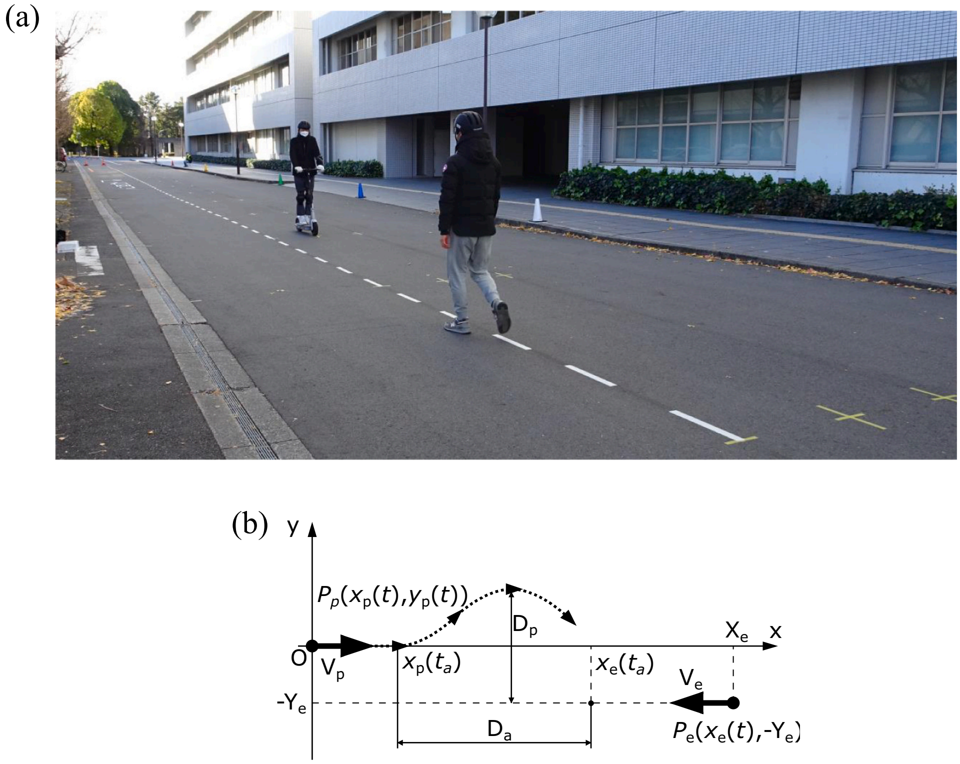

Fig. 1. a: Photo of a trial scene from this study. A participant was on the near side while the e-scooter was on the far side. b: Overview diagram of the experiment and definition of focused parameters. The participant began walking from point O, following the white dotted line on the x-axis at natural walking speed Vp. The e-scooter commenced its motion from Pe (Xe, -Ye), moving to (0, -Ye) at speed Ve. The time t_a represents the moment when the avoidance initiation occurred.

km/h). The starting longitudinal distance Xe between the participant and the e-scooter varied based on Ve: 30 m for 1.7 m/s, 40 m for 2.8 m/s, and 60 m for 4.2 m/s. This ensured that the e-scooter maintained its set speed for at least 5 s before approaching the participant, and that the X position when passing the participant remained roughly consistent at x = 13 m across all trials. The sequence of the nine combinations of Ye and Ve was randomised for each participant. Before the experiment commenced, the examiner underwent training to safely operate the e-scooter at the designated lateral distance Ye from the white line and at the constant speed Ve, while monitoring the e-scooter's speedometer. For added safety during the trials, both the participant and the e-scooter operator wore helmets. Additionally, the e-scooter operator wore knee protectors and was instructed to immediately stop or avoid the participant if there was any imminent risk of collision.

2.3. Experiment procedure

At the beginning of each trial, participants stood still, facing the direction of walking. Simultaneously, an examiner prepared to begin by boarding an e-scooter, the Kickscooter G30L by Segway-Ninebot, as illustrated in Fig. 1 (b). The specifications of this e-scooter are as follows: dimensions of H1146 x W472 x L1109mm, weight of 17.5 kg, tyre diameter of 254 mm (10 in.), a wheelbase of 800 mm, motor power of 350 W, and a maximum speed of 6.9 m/s (25 km/h). Before initiating a trial, the participant stood at the start of the white line, designated as the origin in Fig. 1. The e-scooter, with the examiner aboard, was positioned at a lateral distance of Ye and an initial point of Xe. The e-scooter's maximum speed was set to Ve using its mobile app. The signal to commence a trial was given by a person positioned halfway between the participant and the e-scooter. This individual raised a red traffic wand to signal the start, following which the participant began walking and the examiner accelerated the e-scooter towards the participant along the white dotted line. Participants were instructed to step to the left to avoid the approaching e-scooter if they perceived any collision risk, and afterward, return to walking on the white line until an end point.

2.4. Data collection and analysis

2.4.1. Trajectories of the participant and the e-scooter

Three video cameras with a frame rate of 30 Hz were mounted on tripods situated on the balconies of the 5th floor of a building adjacent to the experimental area at the Nagoya Institute of Technology. These cameras were adjusted to comprehensively capture the entire experimental area. The positions of both the participant and the e-scooter were extracted from these video recordings using TrafficAnalyzer [24]. Calibration was performed prior to the experiment. TrafficAnalyzer processed the data to extract the perpendicular position of the participant's head every 0.5 s and the contact point between the road surface and the e-scooter's rear tire every second. These data points were then converted into trajectories for both the participant and the e-scooter at 30 Hz after being refined by Kalman filtering. The avoidance initiation distance Da was determined as the x-axis distance between the participant's and the e-scooter's positions at the moment when the sharpest participant's leftward movement occurred deviating from an area ± 100 mm of the white line. If the participant completed their walk within 100 mm of the white line during a trial, Da was set to 0. The lateral passing distance Dp was measured as the y-axis distance between the positions of the participant and the e-scooter when their x-axis positions aligned.

2.4.2. Discomfort level

After completing each trial, participants were asked to rate their level of discomfort when passing the e-scooter on a scale from 1 to 5. The ratings corresponded to the following word expressions: 1: No discomfort at all, 2: No discomfort, 3: Neutral, 4: Slight discomfort, and 5: High discomfort.

2.4.3. Statistical analyses

Statistical analyses were performed using the Chi-square test for categorical outcomes, and the Friedman test was employed for non-parametric repeated measures.

3. Results

The present study explored the relationship between pedestrian avoidance behaviour and discomfort during encounters with an e-scooter approaching from the front at three different speeds Ve and from

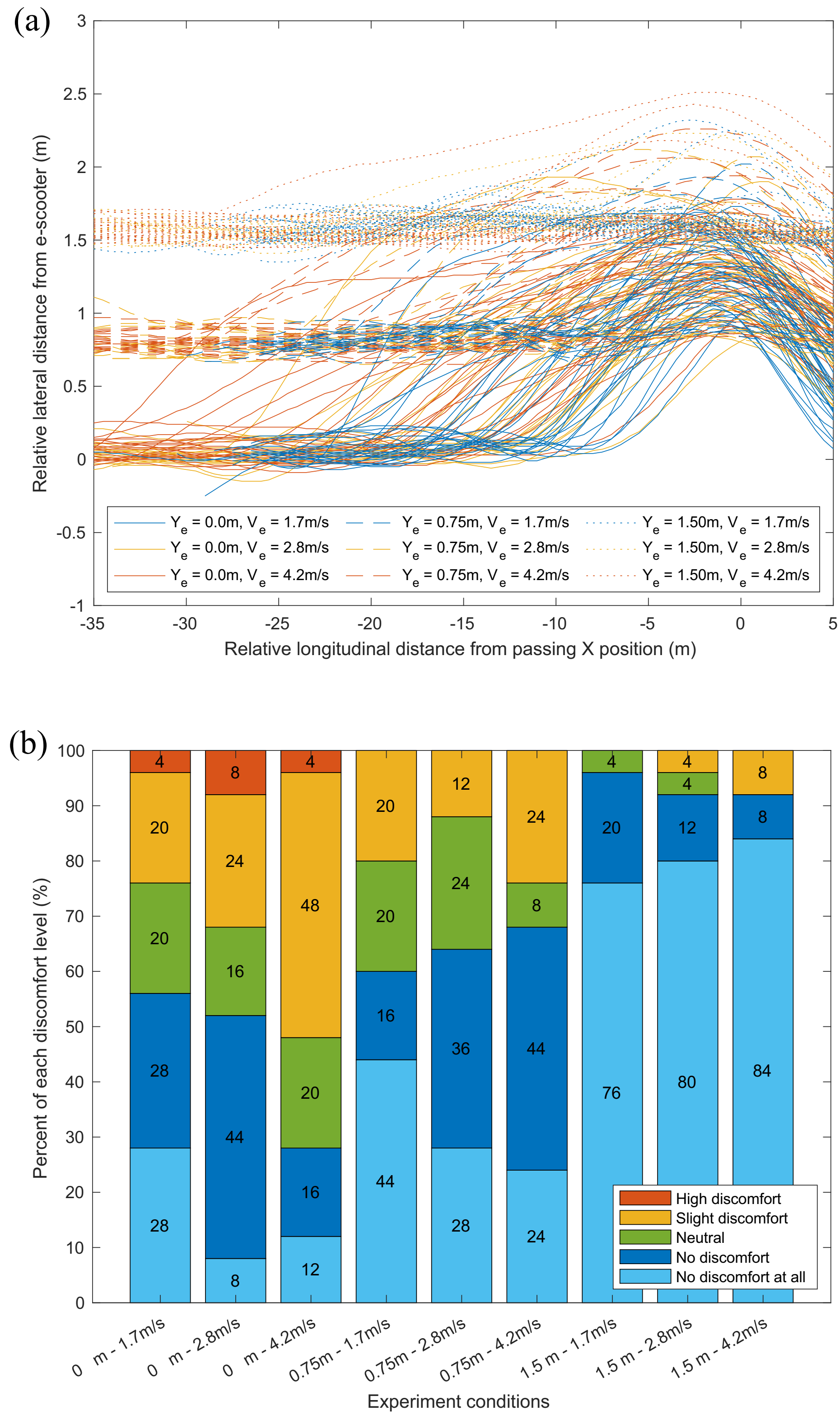

Fig. 2. a: Trajectories of all participant's avoidance of the e-scooter. The zero on the horizontal axis represents the passing point between the participant and the e-scooter. b: Discomfort level during avoidances of the e-scooter.

three different lateral distances Ye. Fig. 2a presents the avoidance paths of all participants, as extracted from the TrafficAnalyzer across all conditions. This provides an overview of participants' responses to the varying dynamics of the e-scooter's approach. While walking, all participants successfully and safely evaded the oncoming e-scooter. In the Ye = 0.00 m scenarios, every participant executed an avoidance manoeuvre. However, the number of participants who did so decreased as Ye increased. In the Ye = 1.50 m scenarios, the majority did not avoid the e-scooter and continued straight walking, maintaining the designated Ye. Some participants initiated their avoidance earlier when the e-scooter's speed was Ve = 4.2 m/s, and later for Ve = 1.7 m/s. All avoidance paths adhered to a similar trajectory as illustrated in Fig. 1. Our analysis primarily centred on two aspects: the avoidance initiation distance Da, and the lateral passing distance Dp. The distribution of the five discomfort levels is displayed as a stacked bar chart in Fig. 2b, highlighting the spread of discomfort levels across all conditions. The levels of discomfort were predominantly influenced by the e-scooter's lateral distance, Ye. 'High discomfort' ratings were exclusively linked to the Ye = 0.00 m scenario, while the 'No discomfort at all' ratings were predominant in the Ye = 1.50 m scenario. A Chi-square test revealed a significant difference in initial lateral distance Ye ($\chi^2 = 77.3653$, $p < 0.001$) but found no significant difference in e-scooter speed Ve ($\chi^2 = 9.3267$, $p = 0.3155$).

3.1. Classification of avoidance

Extract trajectories of the participant and the e-scooter are shown in Fig. 2a follwoing the method in 2.4.1 section. From Fig. 2a, participants' avoidance behaviours were categorised based on whether the participant's path deviated by >10 cm from the white dotted line. Fig. 3 displays the avoidance ratios for all Ye and Ve conditions. The avoidance ratio was 100% at Ye = 0.00 m, decreased slightly to around 87% at Ye = 0.75 m, and further reduced to approximately 25% at Ye = 1.50 m. A Chi-square test indicated a significant difference in initial lateral distance Ye ($\chi^2 = 114.7513$, $p < 0.001$), but there was no significant difference regarding the e-scooter's speed Ve ($\chi^2 = 0.3859$, $p = 0.8245$).

3.2. How avoidance occurs

The Avoidance initiation distance Da at which a participant's avoidance begins and the lateral passing distance Dp, as depicted in Fig. 1, were extracted as the two primary facets of avoidance from participants' walking paths, as classified under avoidance based on the definition in 3.1. Fig. 4a and b display the extracted results for Da and Dp, respectively. Da decreased as Ye increased, and this decline in Da was found to be significantly different in the Friedman test ($\chi^2 = 121.29$, $p < 0.001$). The average Da values by Ye were 17.3 ± 7.12 m at Ye = 0.00 m, 11.4 ± 7.62 m at Ye = 0.75 m, and 3.20 ± 6.59 m at Ye = 1.50 m. Da also rose with an increase in Ve, and this trend was found to be significantly different in the Friedman test ($\chi^2 = 17.31$, p < 0.001). The average Da values by Ve were 8.68 ± 6.85 m at Ve = 1.7 m/s, 9.96 ± 8.42 m at Ve = 2.8 m/s, and 13.3 ± 11.2 m at Ve = 4.2 m/s. The lateral passing distance Dp increased with Ye, and this increase was found to be significantly different in the Friedman test ($\chi^2 = 122.30$, p < 0.001). The average Dp values by Ye were 1.19 ± 0.237 m at Ye = 0.00 m, 1.30 ± 0.344 m at Ye = 0.75 m, and 1.63 ± 0.214 m at Ye = 1.50 m. No significant difference in Dp was observed with increasing Ve (Friedman test: $\chi^2 = 2.57$, $p = 0.277$). Average Dp values by Ve were 1.36 ± 0.310 m at Ve = 1.7 m/s, 1.36 ± 0.335 m at Ve = 2.8 m/s, and 1.41 ± 0.343 m at Ve = 4.2 m/s.

3.3. Discomfort level

Fig. 5 represents the discomfort level concerning Da and Dp. The contour plot in Fig. 5 displays the estimated discomfort level, calculated using nominal logistic regression with Da and Dp, after binarizing the discomfort levels into 0: No discomfort and 1: Discomfort. Ratings of 1: No discomfort at all, 2: No discomfort, and 3: Neutral were converted to the binarized discomfort level of 0, while ratings of 4: Slight discomfort and 5: High discomfort were set to 1. The numbers within the contour plot indicate the probability of discomfort levels based on Da and Dp. In the nominal regression used to estimate this probability, both Da and Dp were found to be significantly different ($p < 0.001$). The probability of

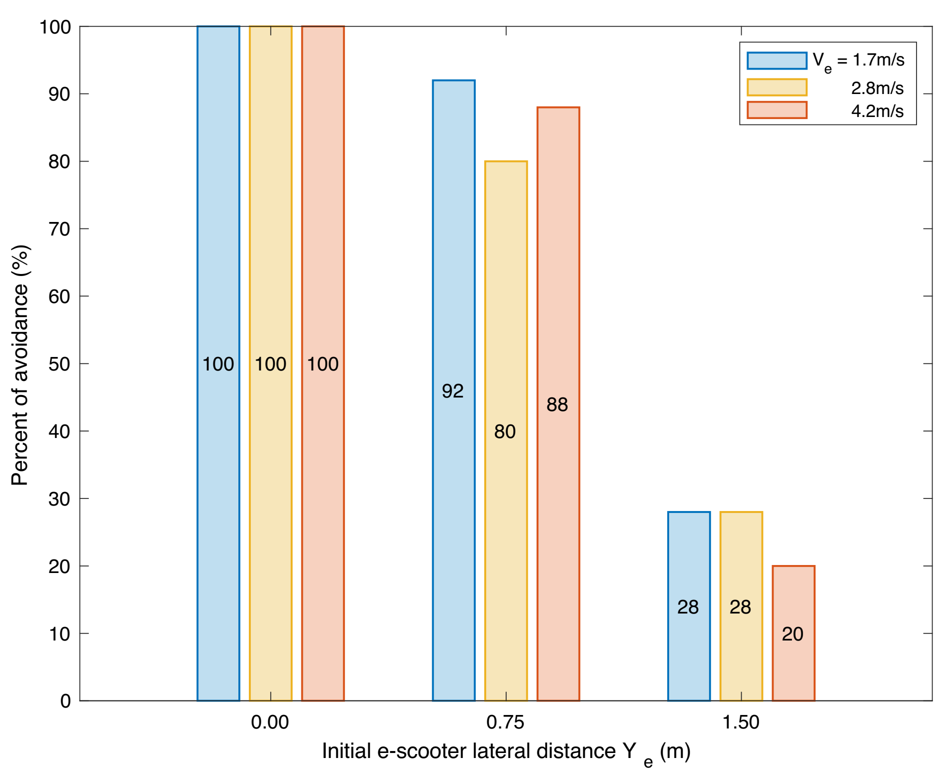

Fig. 3. Avoidance rate. The Chi-square test revealed a significant difference based on the e-scooter initial position Ye ($p < 0.001$).

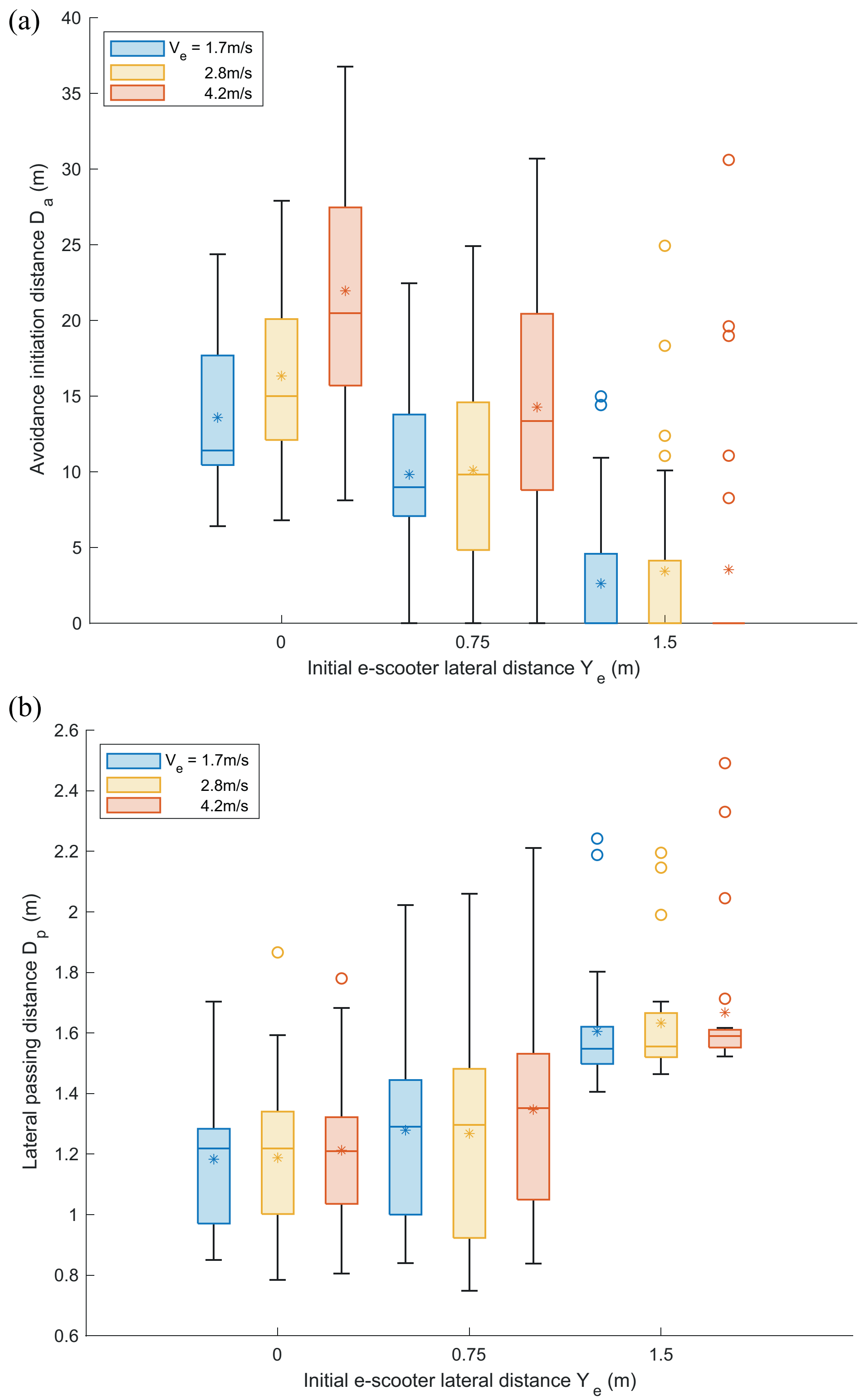

Fig. 4. a: Avoidance initiation distance Da. The Friedman test revealed significant differences based on the e-scooter's initial distance Ye ($p < 0.001$) and speed Ve ($p < 0.001$). The asterisks show means. b: Lateral passing distance Dp. The Friedman test revealed a significant difference based on the e-scooter's initial distance Ye ($p < 0.001$). The asterisks show means.

discomfort, as determined by Da and Dp, can be estimated using the eq. (1), with extracted parameters B0 = −0.2291, B1 = 2.3492, and B2 = −0.1107. A clear pattern emerged: the probability of discomfort decreased with a larger Dp and a smaller Da, and given that B1 is 21 times larger than B2, Dp has a greater influence on the discomfort level than Da.

$$\text{The probability of discomfort} = 1 - \frac{exp(B_0 + B_1D_p + B_2D_a)}{1 + exp(B_0 + B_1D_p + B_2D_a)} \quad (1)$$

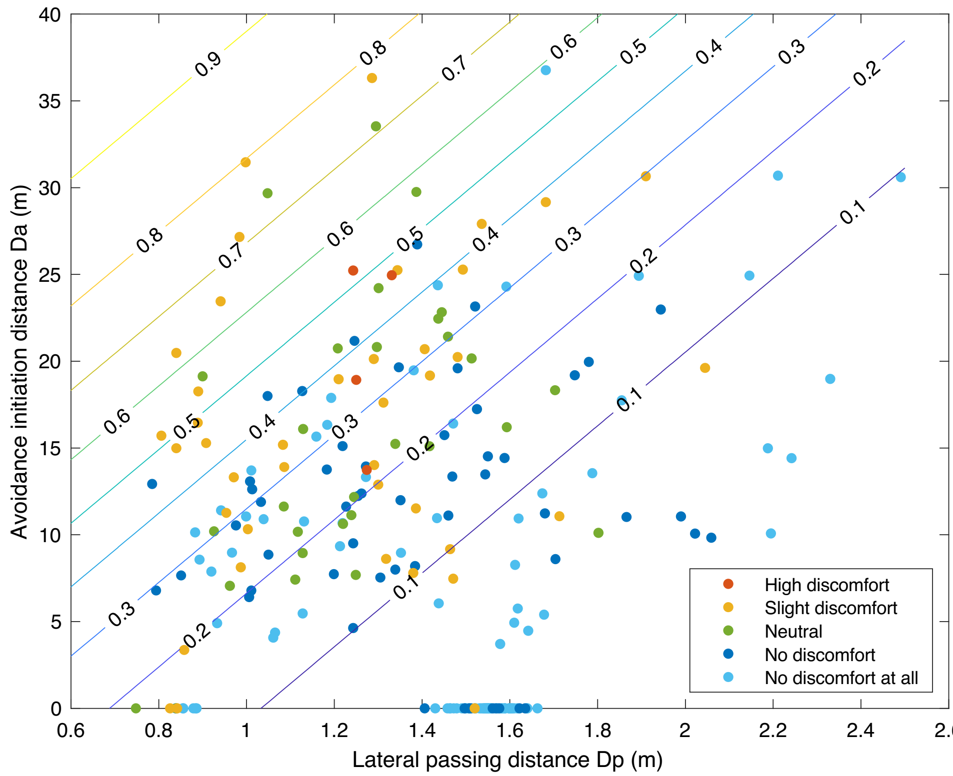

Fig. 5. Estimation of the probability of discomfort level based on avoidance initiation distance Da and lateral passing distance Dp using nominal logistic regression. The numbers on the lines indicate the estimated probability of discomfort level.

4. Discussions

4.1. Avoidance strategy

All participants were able to detect the e-scooter approaching from the front and successfully avoided it by moving to the left side as instructed. While each participant's avoidance strategy varied individually, we identified a general pattern and the origins of discomfort. In cases where the e-scooter's lateral distance, Ye = 0.00 m, participants began avoiding the e-scooter at an average distance at Da = 13.6 m and 23.0 m for Ve = 1.7 m/s and 4.2 m/s respectively. The lateral passing distances Dp, for both Ve conditions were similar at 1.18 m and 1.21 m. This implies that participants recognised the e-scooter's speed, initiating avoidance earlier when the e-scooter's speed was higher. However, they consistently maintained a lateral distance of approximately 1.19 m. The discomfort level at Ye = 0.00 m was the highest at Ve = 4.2 m/s, accounting for 50% of ratings 4 (Slight Discomfort) and 5 (High Discomfort). This discomfort reduced to 24% at Ve = 1.7 m/s. This pattern was only evident at Ye = 0.00 m, with no significant discomfort difference across Ve.

As Ye increased to 0.75 m, avoidance strategies for Da and Dp mirrored those at Ye = 0.00 m. Da lowered to an average of 11.4 m and Dp slightly extended to an average of 1.30 m. Additionally, 13% of trials saw no avoidance and the average discomfort level improved to 18.7%. At Ye = 1.50 m, 75% of trials experienced no avoidance, Da plummeted to an average of 3.20 m, and Dp widened to 1.63 m. This scenario registered the lowest discomfort level at 6.7%. For Ye = 0.00 m and 0.75 m, participants employed a similar avoidance strategy. They recognised the e-scooter's speed Ve, and initiated avoidance earlier when the e-scooter was moving faster, especially if discomfort levels were higher. However, the lateral passing distance remained consistent, even with increased speeds. For Ye = 1.50 m, most participants opted not to avoid the e-scooter due to the low level of discomfort, suggesting that participants primarily employ an avoidance strategy when Ye is closer.

With the comparison to previous study, Dp = 1.18 m at Ye = 0.00 m with Ve = 1.7 m/s was slight greater than the 0.72 m observed in circumvention cases against a stationary person [20], or 0.28 m in circumvention cases against an oncoming pedestrian [22]. The Da = 13.6 m against an e-scooter moving was 3.7 times longer than the 3.64 m observed against an air-filled human doll moving at 2 m/s [21]. This could be attributed to the available space in this study, as the e-scooter commenced from 30 m away. In contrast, the air-filled human doll scenario started with a 12 m separation between the participant and the doll.

From Fig. 5 and our statistical analysis, the participant's discomfort level correlates with the avoidance strategy comprising of Da and Dp. When Dp was more substantial, discomfort levels decreased, and when Da was closer, discomfort similarly decreased. During the avoidance process, participants first visually recognised the e-scooter and experienced discomfort due to perceived safety risks, leading to their avoidance response. Considering this process, the participant's discomfort influences their avoidance strategy, which includes both Da and Dp. A 10% discomfort level could be anticipated when Dp exceeds 1.04 m and Da is above 0, especially in cases where Ve is slower. However, if Ve is faster, Dp could increase as Da lengthens.

Assuming Da is the major axis and Dp is the minor axis of an ellipse representing personal space, Da typically exceeds Dp, aligning with findings from previous studies such as [17]. Yet, the size of the personal space expands with higher e-scooter speeds. Furthermore, the size of personal space when encountering an e-scooter at Ve = 1.7 m/s was larger than that observed when encountering a pedestrian walking at 1.4–1.5 m/s [17]. The projection size of an e-scooter with a rider might influence personal space dimensions, akin to varying human sizes [20].

The discomfort level would be critical when passing the e-scooter as the distance between the participant and the e-scooter becomes minimum. Da and Dp happened before passing the e-scooter, and we defined the discomfort level when passing the e-scooter as the effect, and Da and Dp as the cause. So the discomfort level can be determined by Da and Dp using eq. (1). This suggests that an elongated major axis and a shortened minor axis of personal space heighten discomfort levels. It further implies that pedestrians might adjust the dimensions of their personal space based on their level of discomfort, taking into account the nature and approach of others around them. Discomfort level could determined by Da and Dp with eq. (1) and it suggests that a longer major axis and a shorter minor axis of personal space increase discomfort levels. This suggests that pedestrians may adjust the size of their personal space based on discomfort, gauging the nature and approach of others towards them.

4.2. Design recommendation

It appears that a pedestrian can avoid an e-scooter approaching from the front, provided there's a side space of up to 1.2 m, even if the e-scooter doesn't alter its trajectory at Ve = 1.7 m/s. In this scenario, the discomfort probability is 34%, as per eq. (1), given Da = 17.3 m and Dp = 1.2 m. Increasing the lateral distance from an e-scooter or decreasing the e-scooter's speed can effectively reduce discomfort due to the resulting increase in Dp and decrease in Da. Based on this, creating separate lanes for pedestrians and e-scooters would generally reduce discomfort. If segregation isn't feasible, then the e-scooter's speed should be limited to below 1.7 m/s, and the pedestrian footway should be wider than 1.5 m.

4.3. Limitations and future research

There are several limitations to this study. The experimental area had cross slope for drainage under Japanese road regulation, however the effect of the cross slope to participant's walking direction would be minimum as all participants lived in Japan and were familiar with walking on Japanese footway and road surfaces having cross slopes for drainage. The e-scooter's range for Ye and Ve was not finely segmented, and maximum Ve was not maximum Japanese legal limit at 20 km/h (5.6 m/s). We had a limited participant pool of 25 individuals. With a larger sample size and a more precise division of Ye and Ve, it might be possible to better model the avoidance strategy, characterised by Da and Dp, against an approaching e-scooter. The scenario in this study involved a one-to-one interaction between a pedestrian and an e-scooter in a spacious environment. Real-world situations present multiple variables, including other pedestrians, walking directions, street furniture, lighting, weather conditions, footway surfaces, and their widths. Exploring how pedestrians navigate and avoid e-scooters in such multifaceted scenarios would be insightful. Our participant group did not include individuals with visual, auditory, or mobility impairments. Future research should investigate how these demographics experience discomfort in similar situations. While discomfort is a dynamic experience, our study assessed it via post-trial questionnaires. This method captures feelings from the start to the end of the encounter. Probing discomfort using physiological markers like heart rate, galvanic skin response, or electroencephalograms at peak discomfort moments could provide deeper insights. We did not measure participants' head and body rotations or changes in walking speed. Such data might reveal interesting facets of pedestrian behaviour, as suggested by [21,25]. While we didn't delineate the precise shape of personal space through varied angular distances between a pedestrian and an e-scooter, as detailed in [17], we did determine the lengths of the major and minor axes of personal space during front-facing e-scooter encounters. Exploring e-scooters approaching from different angles might offer a more realistic scenario for study. The approach angle, as evidenced by [22], plays a crucial role in pedestrian avoidance behaviour and would be an intriguing area for future investigation.

5. Conclusions

The primary objective of this study was to explore the discomfort pedestrians experience when navigating around an e-scooter approaching from the front, taking into account Japanese traffic conditions and extending the speed parameters to accommodate various conditions in other countries. Experiments were designed to observe participant avoidance behaviours in relation to e-scooters moving at varying speeds and initial lateral positions. Our findings indicate that as the e-scooter's speed increases, participants initiate avoidance manoeuvres from a further distance ahead. However, the lateral distance maintained during passing remains relatively constant regardless of the e-scooter's speed. Additionally, when the e-scooter starts closer to participants (in terms of lateral position), there's a notable increase in both the initiation distance for avoidance and the level of discomfort reported by participants. Building on these observations, it seems plausible to predict pedestrian discomfort levels based on the initial avoidance distance and the lateral distance maintained during passing, especially in shared spaces with e-scooters approaching head-on. In line with theories of personal space outlined in previous research, our study suggests that the perceived personal space of a pedestrian expands forward and contracts laterally when confronted with a potential discomfort source, such as an oncoming e-scooter. This research provides valuable insights that could be instrumental in designing pedestrian-friendly footways in shared spaces, ensuring comfort even with the integration of personal mobility devices like e-scooters. As urban infrastructure continues to evolve, understanding these nuances becomes crucial in creating harmonious shared environments for pedestrians.

CRediT authorship contribution statement

Kazufumi Suzuki: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Tatsuto Suzuki:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Nick Tyler:** Conceptualization, Supervision, Writing – review & editing. **Koji Suzuki:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft.

Declaration of competing interest

We confirm that there are no conflicts of interest to declare.

Acknowledgements

The authors would like to express their sincere gratitude to the International Association of Traffic Safety and Sciences (IATSS) for providing the research fund (2008 A, 2108B, 2208C) that supported this study. The guidance and resources provided by IATSS have been invaluable in enabling us to undertake and complete this research. We appreciate the trust and support extended to us, which played a pivotal role in the realization of this work.

References

[1] S. A. E. International, Sae J3194 Taxonomy & Classification of Powered Micromobility Vehicles, 2019.

[2] T.K. Trivedi, C. Liu, A.L.M. Antonio, N. Wheaton, V. Kreger, A. Yap, D. Schriger, J. G. Elmore, Injuries associated with standing electric scooter use, JAMA Netw. Open 2 (1) (2019) e187381, https://doi.org/10.1001/jamanetworkopen.2018.7381.

[3] L.J. Mayhew, C. Bergin, Impact of E-scooter injuries on emergency department imaging, J. Med. Imaging Radiat. Oncol. 63 (4) (2019) 461–466. https://onlinelibrary.wiley.com/doi/pdf/10.1111/1754-9485.12889.

[4] S. Tuncer, E. Laurier, B. Brown, C. Licoppe, Notes on the practices and appearances of E-scooter users in public space, J. Transp. Geogr. 85 (2020) 102702. https://www.sciencedirect.com/science/article/pii/S0966692319309408.

[5] A. Nikiforiadis, E. Paschalidis, N. Stamatiadis, A. Raptopoulou, A. Kostareli, S. Basbas, Analysis of attitudes and engagement of shared E-scooter users, Transp. Res. Part D: Transp. Environ. 94 (2021) 102790. https://www.sciencedirect.com/science/article/pii/S1361920921000948.

[6] J.-Y. Kuo, A. Sayeed, N.T. Tangirala, V.C.Y. Han, J. Dauwels, M.P. Mayer, Pedestrians' acceptance of personal mobility devices on the shared path: A

structural equation modelling approach, in: 2019 IEEE Intelligent Transportation Systems Conference (ITSC), IEEE, 2019, pp. 2349–2354. https://ieeexplore.ieee.org/abstract/document/8917167.
[7] I. Shichman, O. Shaked, S. Factor, Emergency department electric scooter injuries after the introduction of shared E-scooter services: a retrospective review of 3,331 cases, World J Emerg Med 13 (1) (2022) 5–10. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC867792.
[8] H. Kleinertz, D. Ntalos, F. Hennes, J.V. Nüchtern, K.-H. Frosch, D.M. Thiesen, Accident mechanisms and injury patterns in E-scooter users: a retrospective analysis and comparison with cyclists, Dtsch. Arztebl. Int. 118 (8) (2021) 117. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8204371.
[9] E.H. Tischler, S.H.L. Tsai, A.J. Wolfert, N. Suneja, Orthopedic fracture hospitalizations are revving up from E-scooter related injuries, J. Clin. 23 (2021) 101607. https://www.sciencedirect.com/science/article/pii/S0976566221004914.
[10] J.B. Cicchino, P.E. Kulie, M.L. Mccarthy, Severity of E-scooter rider injuries associated with trip characteristics, J. Safety Res. 76 (2021) 256–261. https://www.sciencedirect.com/science/article/pii/S0022437520301663.
[11] H. Gibson, A. Curl, L. Thompson, Blurred boundaries: E-scooter riders' and Pedestrians' experiences of sharing space, Mobilities (2022) 69–84. https://www.tandfonline.com/doi/pdf/10.1080/17450101.2021.1967097.
[12] S. Miller, J.A. Molino, J.F. Kennedy, A.K. Emo, A. Do, Segway rider behavior: speed and clearance distance in passing sidewalk objects, Transp. Res. Rec. 2073 (1) (2008) 125–132. https://journals.sagepub.com/doi/pdf/10.3141/2073-14.
[13] M. Iryo, C. Dias, H. Kato, K. Shimono, K. Nakano, Experimental analysis of personal mobility maneuver reacting to pedestrians and cyclists, Seisan Kenkyu 68 (4) (2016) 281–284. https://www.jstage.jst.go.jp/article/seisankenkyu/68/4/68_281/_pdf.
[14] N. Sikka, C. Vila, M. Stratton, M. Ghassemi, A. Pourmand, Sharing the sidewalk: a case of E-scooter related pedestrian injury, The American Journal of Emergency Medicine 37 (9) (2019) 1807, e5-1807. e7, https://www.sciencedirect.com/science/article/pii/S0735675719303948.
[15] D.P. Kennedy, J. Gläscher, J.M. Tyszka, R. Adolphs, Personal space regulation by the human amygdala, Nat. Neurosci. 12 (10) (2009) 1226–1227. https://www.nature.com/articles/nn.2381.
[16] A.E. Patla, Understanding the roles of vision in the control of human locomotion, Gait Posture 5 (1) (1997) 54–69. https://www.sciencedirect.com/science/article/pii/S0966636296011095.
[17] M. Gérin-Lajoie, C.L. Richards, B.J. Mcfadyen, The negotiation of stationary and moving obstructions during walking: anticipatory locomotor adaptations and preservation of personal space, Motor Control 9 (3) (2005) 242–269. https://journals.humankinetics.com/view/journals/mcj/9/3/article-p242.xml.
[18] M. Gérin-Lajoie, C.L. Richards, B.J. Mcfadyen, The circumvention of obstacles during walking in different environmental contexts: a comparison between older and younger adults, Gait Posture 24 (3) (2006) 364–369. https://www.sciencedirect.com/science/article/pii/S0966636205002328.
[19] K. Shimizu, Y. Kihara, K. Itou, K. Tai, T. Furuna, How perception of personal space influence obstacle avoidance during walking: differences between young and older adults, Physical Therapy Research 23 (1) (2020) 31–38, https://doi.org/10.1298/ptr.E9988.
[20] S.M. Bourgaize, B.J. Mcfadyen, M.E. Cinelli, Collision avoidance Behaviours when circumventing people of different sizes in various positions and locations, J. Mot. Behav. 53 (2) (2021) 166–175. https://www.tandfonline.com/doi/pdf/10.1080/00222895.2020.1742083.
[21] M.E. Cinelli, A.E. Patla, Locomotor avoidance behaviours during a visually guided task involving an approaching object, Gait Posture 28 (4) (2008) 596–601. https://www.sciencedirect.com/science/article/pii/S0966636208001033.
[22] M. Huber, Y.-H. Su, M. Krüger, K. Faschian, S. Glasauer, J. Hermsdörfer, Adjustments of speed and path when avoiding collisions with another pedestrian, PloS One 9 (2) (2014) e89589. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0089589.
[23] Y. Hasegawa, C. Dias, M. Iryo-Asano, H. Nishiuchi, Modeling pedestrians' subjective danger perception toward personal mobility vehicles, Transport. Res. F: Traffic Psychol. Behav. 56 (2018) 256–267. https://www.sciencedirect.com/science/article/pii/S1369847817307131.
[24] K. Suzuki, H. Nakamura, Development and performance evaluation of a video image processing system for traffic flow analysis - trafficanalyzer, Doboku Gakkai Ronbunshuu D 62 (3) (2006) 276–287, https://doi.org/10.2208/jscejd.62.276.
[25] H. Yamamoto, D. Yanagisawa, C. Feliciani, K. Nishinari, Body-rotation behavior of pedestrians for collision avoidance in passing and cross flow, Transp. Res. B Methodol. 122 (2019) 486–510. https://www.sciencedirect.com/science/article/pii/S0191261517300085.