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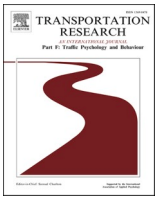

Cautious and risk-related behaviors among older pedestrians: the combined role of sidewalks, cycling infrastructure, and street trees☆

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ABSTRACT

Climate change requires rapid adoption of green street designs that encourage sustainable mobility, such as walking and cycling, while also helping to mitigate urban heat. In aging societies, these transformations must address the needs of older people. Focusing on Lisbon, Portugal, as a case study, this study explores how street configurations affect older pedestrians' walking behaviors, focusing on environmental features and behavioral dynamics. Using a mixed-methods approach, we conducted structured observations of 911 older pedestrians and 1340 cyclists in flow observations, and 174 older pedestrians in behavioral mapping, complemented by semi-structured interviews, across four streets with contrasting layouts (e.g., sidewalks and cycle lanes on the same level vs. separated, presence vs. absence of trees). Observations spanned four weeks in summer and fall, covering weekdays, weekends, and different times of day. Findings reveal that street design configurations are associated with cautious and risk-related walking behaviors. The study offers empirical insights into sustainable street design, supporting evidence-based policies to enhance older pedestrians' mobility.

1. Introduction

Active aging and sustainable cities are central challenges faced by contemporary societies. In this context, the World Health Organization's [WHO] age-friendly cities framework highlights walkable streets and green spaces as a key domain supporting older

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adults' mobility, independence, and overall well-being (WHO, 2007). Walking plays a central role in later life, contributing to older adults' autonomy and social participation (Kim & Yoo, 2024). However, walking also poses significant safety risks, increasing exposure to falls and traffic-related incidents (Al-Saaidy et al., 2025; Rahman et al., 2025; Sum et al., 2025; Tournier et al., 2016). Moreover, the transition toward sustainable urban mobility, characterized by the coexistence of multiple travel modes, such as walking and cycling, may inadvertently compromise the safety and mobility of older pedestrians, who represent a particularly vulnerable population in pedestrian-cyclist urban environments (Chong et al., 2010). Despite this, pedestrian safety research has predominantly concentrated on motorized traffic and crossing contexts, with limited attention given to everyday sidewalk environments and pedestrian-cyclist interactions (Ishrath & Rajendran, 2024). Yet, unsafe or ambiguous street designs, such as shared pedestrian-cycle lanes, may simultaneously elicit heightened cautiousness and increased exposure to risk, highlighting the need to understand older pedestrians' behaviors as adaptive responses within multimodal and spatially ambiguous environments. Understanding how cautious and risk-related behaviors emerge in such contexts is therefore crucial for informing safer street design (Samora-Arvela et al., 2025).

This study aims to address these gaps by analyzing older pedestrians' cautious and risk-related behaviors across different physical safety design configurations of street sidewalks, with a particular focus on shared versus physically separated cycle lanes. We adopt a holistic approach, considering both street situational factors and individual factors shaping older pedestrians' behavior. Using a mixed-methods design, this study combines structured behavioral observations with semi-structured interviews to capture pedestrians' perceptions and emotions, integrating objective behavioral patterns with subjective walking experiences. Overall, this study contributes primarily to age-friendly street design research by advancing understanding of how specific street design features shape older pedestrians' cautious and risk-related behaviors through a behavioral safety perspective.

1.1. Older pedestrians' cautious and risk-related behaviors

Older pedestrians face cumulative challenges when navigating street and sidewalk environments. Compared to younger adults, they tend to exhibit reduced walking speed, balance, and attentional capacity, which increases cognitive load and hinders the identification of relevant cues in complex or spatially ambiguous contexts, such as sidewalks with shared pedestrian–cycle lanes (Dommès et al., 2013; Tournier et al., 2016). These conditions may elevate perceived risk and behavioral demands, prompting adaptive walking responses reflected in cautious and risk-related behaviors.

Cautious behaviors refer to vigilance-based and self-regulatory responses adopted to manage perceived environmental risk, such as increased vigilance, attentional focus, visual monitoring, and slowed or hesitant movement (Luu et al., 2022). In turn, risk-related behaviors involve actions that increase exposure to potential hazards (Cœugnet et al., 2019; Luu et al., 2022), particularly in shared or spatially ambiguous environments, such as walking or standing in cycle lanes or engaging in pedestrian–cyclist interactions. Among the risk-related behaviors considered in this study, walking in cycle lanes is particularly relevant because it captures older pedestrians' exposure to potential hazards in pedestrian–cyclist environments. Previous observational studies showed that mode-specific violations, close pedestrian-cyclist proximity, and unprotected or weakly separated cycling infrastructure are associated with increased interactions and conflict potential (Haworth et al., 2014; Silva et al., 2019; Zheng et al., 2019). Walking in the cycle lane is therefore examined as a specific manifestation of risk-related behavior. These behaviors do not necessarily indicate low attentiveness but rather reflect adaptive responses to perceived street-level risk. Previous research shows that behaviors aimed at enhancing safety may precede or coexist with actions that increase risk exposure, reflecting a trade-off between safety and efficiency rather than a lack of cautiousness (Cœugnet et al., 2019; Luu et al., 2022; Zhu et al., 2021). Sidewalks with shared pedestrian–cycle lanes may simultaneously elicit both heightened cautious behaviors and increased risk-related behaviors, as pedestrians adapt to constrained choices and elevated environmental demands.

1.2. Conceptual framework for older pedestrians' behavior

This study applies a multidimensional conceptual framework to examine older pedestrians' sidewalk behaviors, drawing on the situational awareness model, which has been applied to pedestrian decision making and behavior, particularly in street-crossing contexts (e.g., Cœugnet et al., 2019; Luu et al., 2022). According to this model, action is informed by three interrelated levels of situational awareness that underpin decision-making: perception, comprehension, and anticipation processes (Endsley, 1995, 2015). Previous studies have adopted different analytical emphasis within this framework. Lee et al. (2021) examined pedestrians' perception and comprehension in real-world walking environments, whereas Cœugnet et al. (2019) analyzed risk, emotions, and socio-cognitive dynamics in real-world street-crossing decision-making. In turn, Luu et al. (2022) operationalized cautious behaviors in virtual-reality street-crossing scenarios. Extensions of the situational awareness framework emphasize that these processes are shaped not only by cognitive factors, but also by emotional, social, and contextual appraisals, leading pedestrians to balance safety and efficiency rather than consistently maximizing one over the other (Cœugnet et al., 2019).

Building on these contributions, this study extends the situational-awareness-based approach to older pedestrians' cautious and risk-related behaviors during continuous sidewalk walking. In line with Luu et al. (2022), rather than separating situational awareness from decision and action, this study focuses on cautious and risk-related behaviors as observable behavioral manifestations of perceptual and appraisal processes. However, unlike previous studies centered on crossing contexts or direct measures of awareness, this study examines naturalistic sidewalk behaviors in multimodal environments, where pedestrians must continuously negotiate cycling infrastructure, micromobility flows, and spatial ambiguity. Complementing these observations, semi-structured interviews capture older pedestrians' subjective perceptions, emotions, and appraisals of these environments, providing insight into the processes underlying observed behaviors. These behaviors may be influenced by street situational factors, including street configurations,

environmental conditions, and pedestrian and cyclist flow, as well as individual factors, such as demographic (e.g., age, gender), personal (e.g., use of mobility aids), and social characteristics (e.g., walking alone or in a group). While Cœugnet's framework addressed the presence of others, walking in a group as a specific behavioral context remains underexplored. Therefore, the contribution of this study is twofold. First, it extends prior situational-awareness-based pedestrian research from perception/comprehension and discrete crossing decisions to observable behavioral adaptations during continuous sidewalk walking among older pedestrians in multimodal environments. Second, it conceptualizes cautious and risk-related behaviors in this population as coexisting adaptive responses to constrained or ambiguous street conditions, reflecting a trade-off between safety and movement efficiency rather than opposing behavioral categories. Fig. 1 illustrates the adapted conceptual framework used in this study.

1.2.1. Street situational factors

Street configuration plays a central role in shaping older pedestrians' cautious and risk-related behaviors, particularly the distinction between cycle lanes at sidewalk level and physically separated pedestrian–cycle infrastructure. Observational evidence suggests that cycling infrastructure design may be more influential than age alone in pedestrian safety outcomes; for example, while age did not predict delayed street-crossing completion, cycling infrastructure was the strongest predictor (Lachapelle & Cloutier, 2017). Consistently, older pedestrians report higher perceived danger and lower willingness to walk in environments shared with cyclists, and incidents occur more frequently on shared-use lanes than on physically separated infrastructure (Bernhoft & Carstensen, 2008; Mesimäki & Luoma, 2021). This study also examines the role of nature-related elements, specifically the presence or absence of trees, in interaction with cycle lane configurations. Trees may support attentional and decision-making processes by providing visually structured spaces and a greater sense of security (Luu et al., 2022), which may be particularly relevant in complex and shared-use environments, such as sidewalks with cycle lanes at the same level. In addition, trees have been associated with improved walking experiences, including enhanced well-being, shade, and thermal comfort, which may support walking among older adults (Borst et al.,

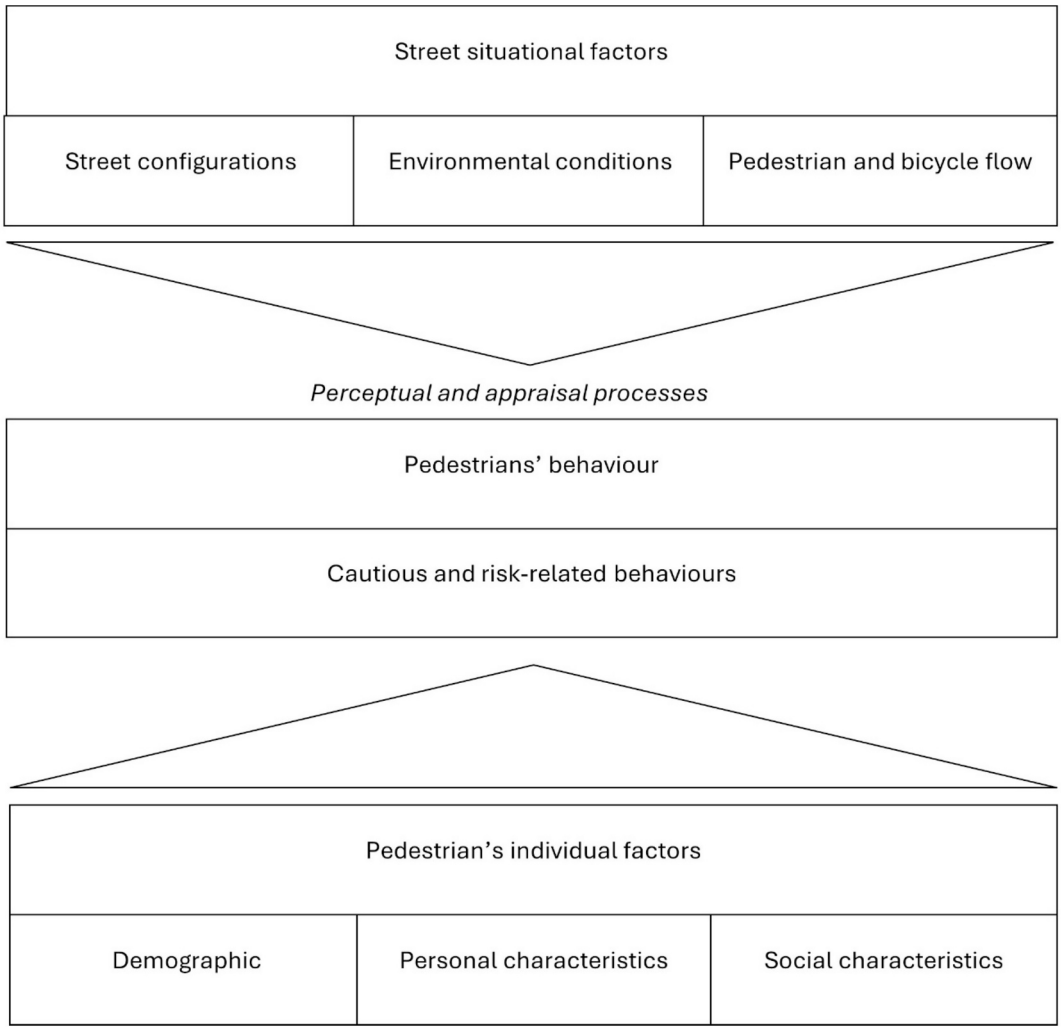

Fig. 1. Adapted conceptual framework for pedestrians' cautious and risk-related behaviors (adapted from Luu et al., 2022).

2008; Herrmann-Lunecke et al., 2021; Močnik et al., 2022; Van Dyck et al., 2015; van Hoven & Meijering, 2019). Beyond this, there is no strong evidence that street trees significantly influence perceived safety (Coleman et al., 2021).

Environmental conditions may shape older pedestrians' behaviors by increasing perceived risk and behavioral demands. Older adults may limit outdoor mobility under adverse weather (e.g., rainy or snowy) or nighttime conditions, while challenging surfaces (e.g., cobblestones, wet or leaf-covered pavements) may evoke fear of falling and constrain route choice, potentially increasing exposure to less safe walking environments (Močnik et al., 2022; van Hoven & Meijering, 2019; Zhang et al., 2024). Additionally, street activity levels and flow dynamics may further influence older pedestrians' cautious and risk-related behaviors. Crowded or overstimulating streets may discourage older adults from walking farther due to concerns about balance and losing control (Duives et al., 2019; van Hoven & Meijering, 2019; Zhang et al., 2024). Observational studies in shared-use environments indicate that higher pedestrian and cyclist densities are associated with increased behavioral conflicts and violations (Haworth et al., 2014; Zheng et al., 2019).

1.2.2. Older pedestrians' individual factors

Older age, female gender, and the use of mobility aids have been associated with higher fall risk and safety-related behavioral adaptations, particularly in demanding street contexts (Lachapelle & Cloutier, 2017; Meinhart-Shibata et al., 2005; Tournier et al., 2016). Interviews are particularly important for capturing pedestrians' emotional experiences, which cannot be directly observed through behavioral observation alone. Fear of falling is a salient emotion among older adults and strongly shapes vigilance and self-regulatory behaviors. Heightened monitoring of the walking surface may paradoxically increase subsequent risk by limiting anticipatory planning, while negative emotional responses in demanding contexts may further contribute to risk-related decisions (Avineri et al., 2012; Cœugnet et al., 2019; Ellmers et al., 2020). In addition, negative emotional responses, such as anxiety, irritation, or anger, may emerge in challenging contexts and contribute to risk-related decisions (Cœugnet et al., 2019; Nyman et al., 2013).

Furthermore, the presence of others may influence pedestrian behavior through social cues, coordination demands, and perceived safety, shaping walking speed, vigilance, and decision-making (Acela et al., 2025; Barón et al., 2024; Cœugnet et al., 2019; Faria et al., 2010; Nyman et al., 2013). Group composition, particularly in terms of age (e.g., walking with children or other older adults), may further modify pedestrians' cautious and risk-related behaviors by altering perceived vulnerability and responsibility (Barón et al., 2024; Cœugnet et al., 2019). Moreover, social companionship has been shown to increase walking frequency and duration among adults over 50 (Hwang et al., 2025). From a stress–appraisal and coping perspective (Lazarus & Folkman, 1984), social companionship may also function as a coping resource, reducing cognitive load, distributing vigilance, and providing emotional reassurance in less safe street environments.

1.3. The present study

This study examines older pedestrians' sidewalk behaviors, focusing on cautious and risk-related behaviors under different physical safety design configurations. Applying the situational awareness framework (Cœugnet et al., 2019; Luu et al., 2022) to sidewalk walking, we assess how pedestrians' behaviors are related to cycle lane configuration (at the level of the sidewalk vs. physically separated and the presence or absence of trees), considering the influence of street situational and individual factors.

This study adopts a mixed-methods design, combining structured behavioral observations of real-time sidewalk behaviors with semi-structured interviews to capture pedestrians' perceptions and experiences. Data collection was conducted across four streets with distinct design configurations: a street with trees and a separate sidewalk from cycle lane (TS); a street without trees and with a separate sidewalk from cycle lane (WS); a street with trees and a cycle lane on sidewalk level (TL); and a street without trees and with a cycle lane on sidewalk level (WL).

We hypothesize that the combination of physical separation and trees will be associated with the highest older pedestrian flow (H1) and the lowest levels of cautious and risk-related behaviors (H2). In addition, and following a situational awareness perspective, we explore whether other environmental (season, time of day, weather), street situational (pedestrian and cyclist flow), individual factors (age, gender, use of mobility aids) and social factors (walking alone or in a group) are associated with older pedestrians' cautious and risk-related behaviors in sidewalk environments. In addition to broader cautious and risk-related behaviors, we specifically examine walking in the cycle lane as a theoretically relevant indicator of risk-related behavior in pedestrian-cyclist environments.

Following the demographic patterns of other European countries, in 2024, Portugal had an aging index of 192.4 older persons for every 100 youngsters aged 14 or below, the second highest among the EU (PORDATA, 2025). Data from 2017 showed that Lisbon, with an old-age dependency ratio of over 41%, stands out as the EU capital city with the oldest citizens (Eurostat, 2019), making this an interesting case study. Moreover, Lisbon has undertaken a recent change in street design due to the introduction of mobility policies, leading to a rapid change in the street layout, with implications for pedestrians and, in particular, older pedestrians living in aging neighborhoods.

2. Study 1: Naturalistic street observation

The objective of this study is to analyze: i) pedestrian flow observations; and ii) behavioral mapping of cautious and risk-related behaviors, to determine their relationship with street design configurations and associated demographic, personal, and social determinants.

2.1. Research design

Using a quasi-experimental design, we chose four streets with similar characteristics, varying key characteristics in a 2 (pedestrian and cycle lanes design: in the same or different levels) x 2 (trees: present or absent) factorial design. This identification was conducted based on the following criteria: the presence of cycle lanes; the proportion of older people in the neighborhood; and neighborhood socioeconomic status. The two selected parishes are very similar from a sociodemographic perspective (Supplementary materials, Table 1), with their most notable difference being that the parish of Alvalade has opted for the design of streets with cycle lane on sidewalk level, whereas the parish of Areeiro is characterized by the presence of cycle lanes and sidewalks that are separated.

Four streets in two parishes in Lisbon (Alvalade and Areeiro) were selected for their differing spatial configurations: Avenida Guerra Junqueiro - TS; Avenida Afonso Costa – WS; Avenida do Brasil –TL; and Avenida Frei Miguel Contreiras – WL (Fig. 2).

2.2. Data collection and measures

Following ethical approval from the [Anonymized for Review] institutional review board, we conducted flow observation and behavior mapping of older people walking in each of the streets under analysis. The observers were blind and independent from the objectives of the study.

Following previous procedures (Cambra & Moura, 2020), data collection of both observations (flow and behavioral mapping) was conducted over two distinct observation periods: (i) during warmer weather conditions (22 July to 3 August 2024); and (ii) during cooler conditions (29 September to 12 October 2024). Observations scheduled for rainy days within the second period were postponed, ensuring consistency in environmental conditions, with the final observation taking place on 2 November 2024.

Following the methodological framework outlined by Cambra and Moura (2020), observations were carried out on four weekdays (Monday to Thursday) across five time slots: (i) morning peak – 08:00 to 09:30; (ii) mid-morning off-peak – 10:00 to 11:30; (iii) lunchtime peak – 12:30 to 14:00; (iv) mid-afternoon off-peak – 15:00 to 16:30; and (v) afternoon peak – 17:00 to 18:30. Additional observations were conducted on Saturdays during two time slots: (i) mid-morning off-peak – 10:00 to 11:30; and (ii) lunchtime peak –

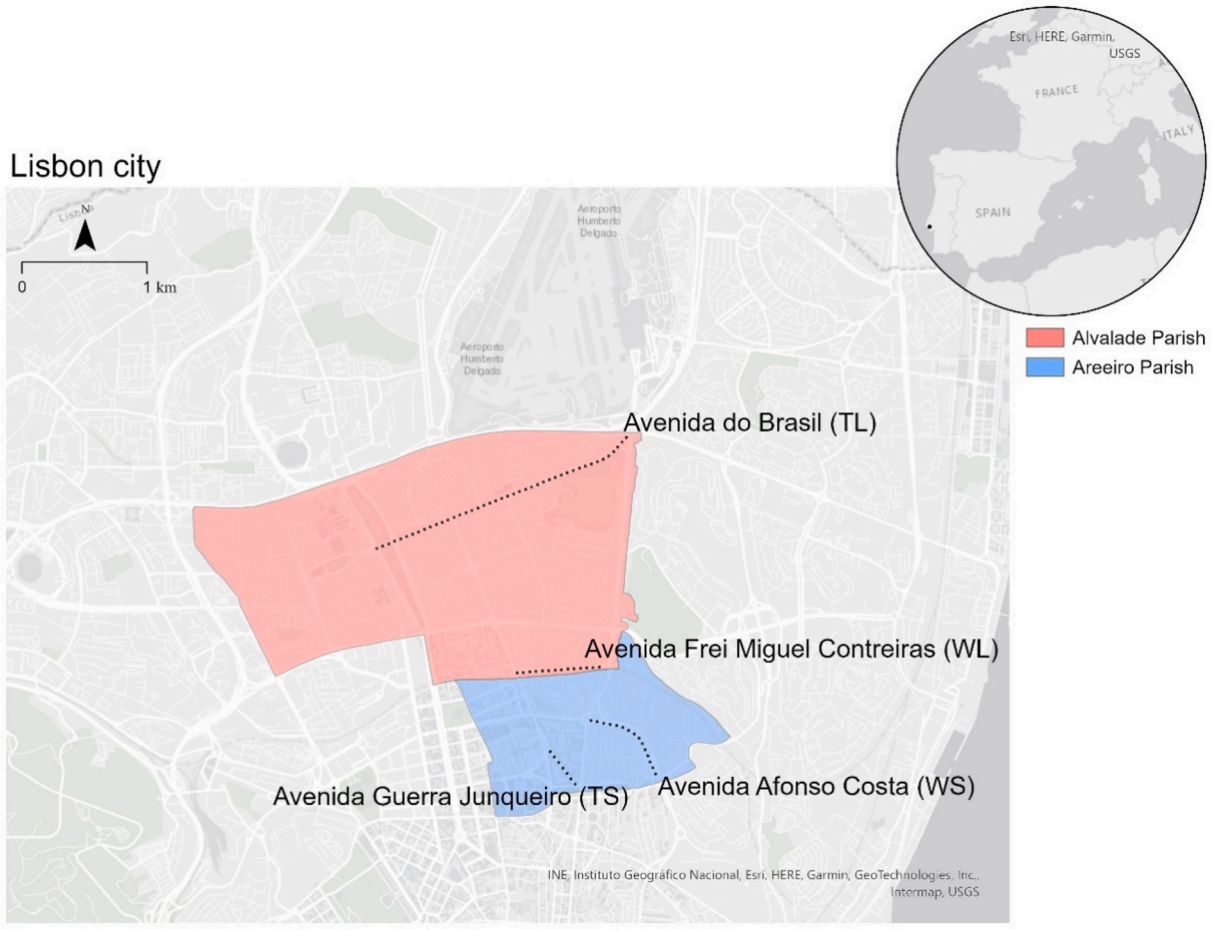

Fig. 2. Streets under observation study.

12:30 to 14:00.

Regarding the sampling of observation days and time periods (Cambra & Moura, 2020), each street allocation was randomized. On each day of observation, only a single street was observed during the aforementioned observation periods, which had two distinct observation locations where the observers were positioned. At each new observation period, the observers switched observation locations along the street.

In each street under study, one observation site was identified where a higher potential for conflict was expected (designated as Site A), and another where a lower potential for conflict was anticipated (Site B). On each day, observers alternated between the two sites (Supplementary materials, Fig. 1).

Following previous procedures (Hou et al., 2017, 2021), and in order to control potential effects of weather conditions, temperature and wind conditions were evaluated at each observation site. Air temperature, objective and perceived street temperature were measured in each observation period since these are a crucial factor of walking behavior (Southworth, 2005; Loukaitou-Sideris, Brozen & Levy-Storms, 2014; Villeneuve et al., 2018).

Prior to the data collection, both the flow and behavioral mapping observation protocols were pre-tested by two independent observers to ensure reliability. In this regard, the two observers were first trained under the supervision of a senior researcher on the project during one day, followed by a one-week pretest period, in order to ensure that each of the four streets was observed.

The visual estimation of apparent age was pre-tested by the two observers and subsequently was conducted following the protocol of Chung et al. (2023), through the recognition of the following characteristics: a) older adults aged 65 to 74: moderate walking pace; wider, firmer strides; more upright posture; less physical frailty (greater stability and endurance, no need to stop while walking); b) older people aged 75 and above: slower walking pace; shorter, dragging strides; more bent or forward-leaning posture; greater physical frailty (lack of balance, less stamina, more frequent stops during the walk) (Chung et al., 2023). Moreover, inter-rater agreement was used as a measurement indicator, following the practice of pedestrian observation studies (Fernández et al., 2020; Wang et al., 2025). The visual estimation of apparent age procedure was chosen as it was deemed most suitable to the non-participant observation context of the present study, which yielded strong inter-rater agreement between the two observers. In this regard, Cohen's Kappa was 0.78 for the flow observations and 0.86 for the behavioral mapping, corresponding to higher agreement levels for both measures (Landis & Koch's, 1977), thereby strengthening the validity and replicability of the data collection approach.

It should be noted that the flow counts (911 older pedestrians; 1340 cyclists and scooter users) represent passage events recorded across multiple time slots and days. The behavioral mapping subsample (n = 174) was derived from a separate, more detailed observation protocol and does not constitute a subset of the flow counts. Similarly, the 48 participants interviewed in Study 2 form an independent convenience sample and are not assumed to overlap with the individuals observed in Study 1.

2.2.1. Pedestrian and cyclist flow

Although the focus of this research was on older people's behaviors, cyclist flow was also considered in order to have a deeper understanding of potential conflicts between pedestrians and cyclists in street use. Pedestrians and cyclists were counted using the "gate method," which consists of counting people who pass an imaginary line on the pavement (Cambra & Moura, 2020; Vaughan & Grajewski, 2001). Pedestrian and cyclist flow observations lasted 15 min in each period. The count of older pedestrians considered gender (i.e., male, female), and the count of cyclists or scooters considered apparent gender and apparent age (up to 25 years; 25 to 65 years; over 65 years).

2.2.2. Behavioral mapping

Behavioral mapping was based on the methodologies of Haworth et al. (2014) and Jarrott (2010). This technique enabled a graphical representation of space usage, facilitating the association between environmental attributes, observable behaviors, and their timing (Haworth et al., 2014; Jarrott, 2010). At each observation site, an unmarked reference line, perpendicular to the road and pavement, was established between two identifiable landmarks to guide the observers (Supplementary materials, Fig. 2). Considering our research aims, during this stage, only older pedestrians, cyclists, and scooter users crossing this imaginary line were recorded.

Observers employed the following procedure: (i) they mentally delineated two circles in each observation site (with radii of 1 m and 5 m – see (Supplementary materials, Fig. 2) centered on the pedestrian, using these as spatial references to capture all nearby interactions; (ii) they observed each pedestrian's behavior for 15 s; and (iii) after the observation, a 15-s interval was used to record observed characteristics.

Observers also recorded information on the first cyclist or scooter user who crossed the reference line. In addition, each observer sketched the individual's trajectory on an observation sheet, noting any interactions that occurred during the observation period. This process was repeated continuously for 15 min for each time slot.

The behavioral mapping protocol and its corresponding observation categories were developed based on existing scientific literature, with necessary adaptations to suit the study's objectives and the specific characteristics of the target population (Do et al., 2019; Hosford et al., 2020; Lord et al., 2018; Marušić & Marušić, 2012; Silva et al., 2019). The cautious and risky behaviors to be observed were based on the following procedures: i) pedestrian fast walking speed (Silva et al., 2019); ii) older pedestrian risk interactions on the cycle lane, including pedestrians walking on the cycle lane (without bicycles present), pedestrians walking on the cycle lane (with bicycles present), pedestrians crossing the cycle lane without using a crosswalk and pedestrians standing on the cycle lane, and conflicts between pedestrians and cyclists: disruption, almost collision and collision (Haworth et al., 2014; Zheng et al., 2014; Silva et al., 2019; Mesimäki & Luoma, 2021; iii) road behaviors such as pedestrians walking on the roadway (Silva et al., 2019); iv) fear of falling on the sidewalk or cycle lane (Avineri et al., 2012; Lee & Tak, 2023; Silva et al., 2019; Tommasini et al., 2008), including pedestrians moving slowly and hesitantly, pedestrians looking both ways repeatedly/being vigilant, pedestrians frequently looking

back, pedestrians frequently looking at the ground, and pedestrians experiencing accidental falls; and v) interactions with vegetation, where the main behaviors were identified in interviews with older adults - pedestrians moving away from leaves or roots and pedestrians avoiding loose stones on the sidewalk (Supplementary materials, Table 2).

Beyond cautious and risk-related behaviors, data collection included: i) individual factors – demographic (e.g., perceived age and gender as in Chung et al., 2023; Todorov et al., 2015); ii) personal factors - use of locomotion aids; and, iii) social factors - whether older people were alone or in groups.

Environmental factors were also collected, namely: actual and perceived temperature, wind, and cloudiness (Hou et al., 2017).

2.3. Data analysis procedure

Data were analyzed using three complementary statistical approaches. First, differences in pedestrian and cyclist flow per hour across the four street typologies were examined using one-way analysis of variance (ANOVA). Separate analyses were performed for older pedestrian and cyclist samples, and flow counts were examined for women and men. Because tests of normality and homogeneity of variances indicated violations of the equal-variance assumption, the Welch-adjusted F statistic was adopted, followed by Games-Howell post-hoc comparisons, which are robust to unequal variances or sample sizes. Second, differences in the distribution of cautions and risk-related behaviors between streets were assessed using Pearson's chi-square test. When the assumption of minimum expected cell frequencies was not satisfied, the Fisher-Freeman-Halton exact test was applied (Field, 2024).

Third, factors associated with the occurrence of walking on the cycle lane were examined using exact logistic regression. This approach was selected because the outcome of interest (walking on the cycle lane) had a relatively small frequency, making standard maximum-likelihood logistic regression susceptible to biased or unstable parameter estimates (Heinze & Schemper, 2002). Therefore, exact logistic regression is specifically recommended for small-sample or sparse-data binary outcomes. Predictor variables were selected based on the study's conceptual framework and included season (Summer or Fall), weather conditions (wind and cloudiness), observation period (peak and off-peak), day type (weekday or weekend), age group (65–74; over 75), gender, use of mobility aids, walking alone or in a group, and street typology. Street typologies were entered as dummy variables (1 = presence; 0 = absence), with the street without trees and without physical separation between the sidewalk and cycle lane (WL) serving as the reference category. Prior to modeling, multicollinearity among predictors was assessed using variance inflation factors (VIFs).

2.4. Results

2.4.1. Older pedestrians and cyclist flow across street typologies

Regarding the flow counts (per hour), a total of 911 older people were observed. The associations between older pedestrian flows and the streets under study are significant (F (3,172) = 50.022; $p < .001$), both for women (F (3,172) = 53.231; $p < .001$) and for men (F (3,172) = 30.032; $p < .001$) (Supplementary materials, Tables 3–5).

The street with the highest flow of older people per hour was TS ($M = 39$; $SD = 23$), followed by WS ($M = 30$; $SD = 17$), WL ($M = 8$; $SD = 8$), and TL ($M = 7$; $SD = 5$). There were also differences regarding gender, particularly regarding women, especially in TS (M

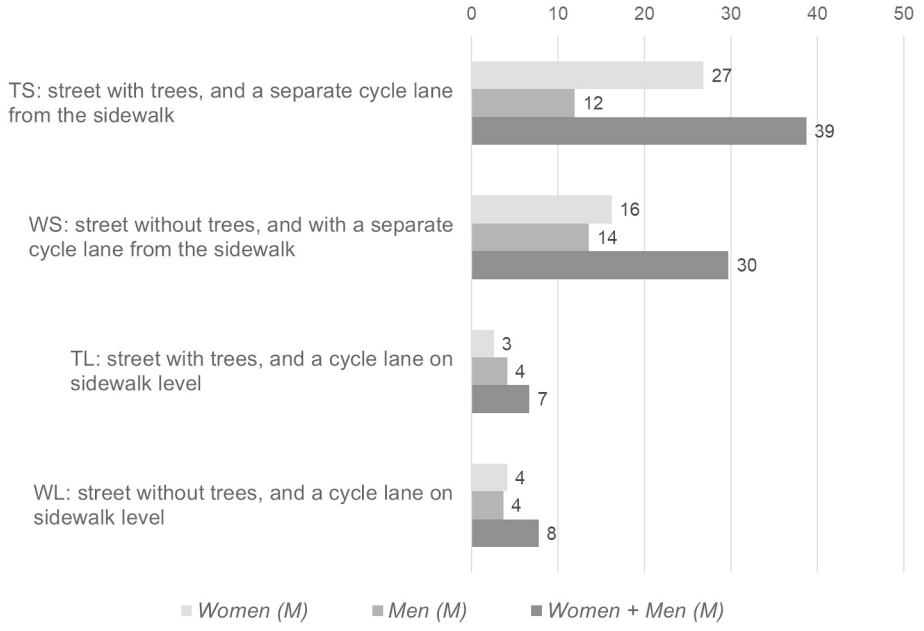

Fig. 3. Older pedestrian flow per hour on the studied streets.

women = 27; *SD* = 16).

Fig. 3 illustrates the mean hourly flow of older pedestrians, disaggregated by gender, across four streets in Lisbon.

We also tested whether season (Summer or Fall), time of day, week/weekend, and weather conditions (temperature and wind) were associated with the hourly flow of older people. In order to do this, we conducted a multiple regression procedure for total flow and by gender (Supplementary materials, Tables 6–8).

The flow of older women pedestrians was higher during the summer ($B = 8.022$; $p = .001$) and in avenues with separated footpath and cycle path (TS: B = 25.380; $p < .001$; WS: $B = 13.282$; $p < .001$) (Supplementary materials, Table 6), suggesting that the presence of vegetation may not influence the overall flow, but rather the design of the sidewalk and cycle lane. The factors included in the linear regression, such as the season of the year, being a weekday, the peak period, the meteorology (temperature, wind, cloudy), and the various street designs, explain 49.4% of the variance in older women's flows.

Regarding the flow of older male pedestrians, the summer ($B = 3.528$, $p = .021$) and the separation between sidewalk and cycle lane in TS (B = 8.757, $p < .001$) and WS ($B = 10.318$, $p < .001$) show a positive association with this flow. The same factors account for 34.6% of the variance in older male pedestrian flow (Supplementary materials, Table 7).

Looking at the overall flow (women + men) of older pedestrians, the same factors highlight their association, including the season of the year ($B = 11.550$, $p = .002$) and the separation of the footpath and cycle path in TS ($B = 34.137$, $p < .001$) and WS ($B = 23.600$, $p < .001$). The linear regression with the aforementioned factors accounts for 47.9% of the variance in the overall flow of older pedestrians (Supplementary materials, Table 8).

Additionally, a total of 1340 cyclists or scooter users were observed. The ANOVA associations between cyclist flows and the streets under study are significant (F (3,172) = 36.852; $p < .001$), both for women (F (3,172) = 15.652; $p < .001$) and for men (F (3,172) = 35.176; $p < .001$) (Supplementary materials, Tables 9–11).Regarding the mean flow of cyclists and scooter users by gender across the four streets under study (Fig. 4), each with distinct physical and environmental characteristics, the data show a consistent trend of higher male usage compared to female usage across all locations.

On TL, the highest mean flow is recorded for both genders (*M* women + men = 51; *SD* = 19), with 38 for men (*SD* = 12) and 13 for women (*SD* = 10).

TS shows a mean flow of 34 for both genders (*SD* = 14), of 26 for men (*SD* = 11) and eight for women (*SD* = 8).

The flow of cyclists and scooters is higher in the streets in TL and TS.

WS has a lower mean flow of 18 (*SD* = 12): 15 for men (*SD* = 9) and four for women (*SD* = 4).

Finally, WL recorded the lowest usage overall (*M* = 18; *SD* = 23), with a mean of 14 for men (*SD* = 17) and only four for women (*SD* = 7). This configuration appears to be the least conducive to active micromobility use.

These results suggest that street design may be associated with micromobility usage and with the presence of trees potentially enhancing comfort and safety.

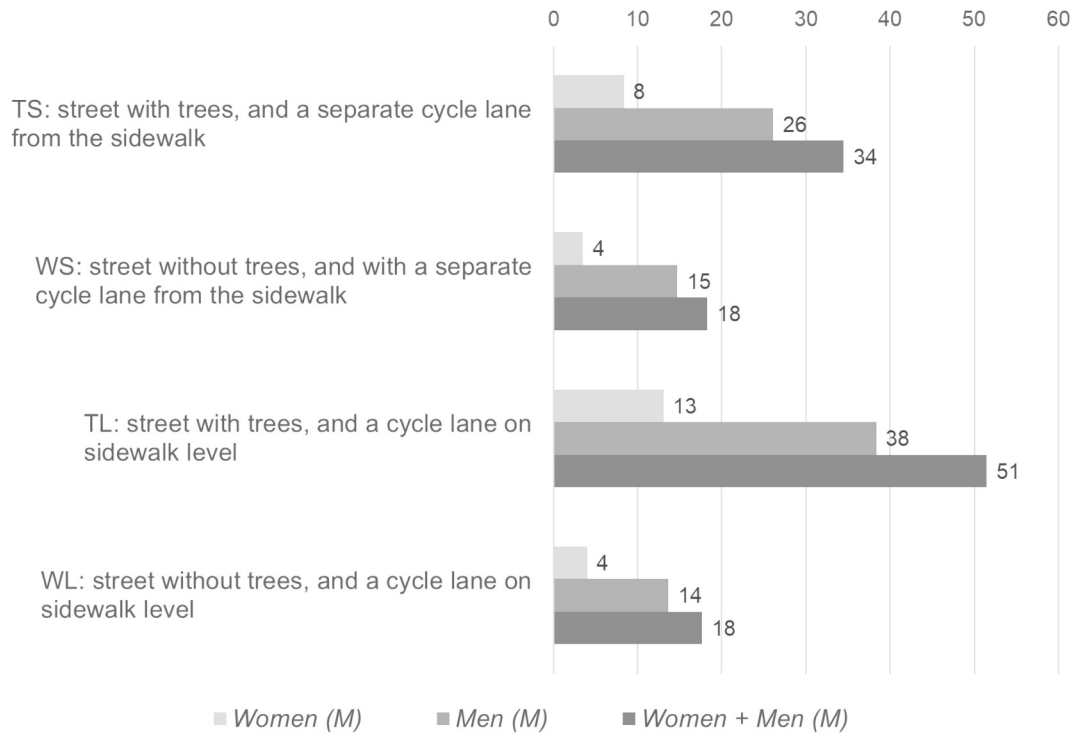

Fig. 4. Cyclist and scooter flow per hour on the studied streets.

The highest flow of female cyclists is associated with peak periods (morning peak: 8:00–9:30; lunch peak: 12:30–14:00; afternoon peak: 17:00–18:30) ($B = 3.165$; $p = .005$) and avenues with the presence of trees, namely TS (B = 5.749, $p = .002$) and TL ($B = 11.055$, $p = .001$). Factors such as the season of the year, being a weekday, the peak period, the meteorology (temperature, wind, cloudy), and the various street designs explain 26.7% of the variance in older women's flows (Supplementary materials, Table 12).

The highest flow of male cyclists is also influenced by cloudy weather ($B = 7.002$, $p = .010$) and the presence of trees, regardless of the separation between the footpath and cycle path in TS ($B = 16.688$, $p < .001$) and the footpath and cycle path at the same level in TL ($B = 29.047$, $p < .001$). All factors included in the linear regression account for 41% of the variance of this flow (Supplementary materials, Table 13).

The overall flow of cyclists (women + men) is also positively influenced by the same factors, particularly the peak periods ($B = 8.414$, $p = .001$), cloudy weather ($B = 9.310$, $p = .011$) and avenues with trees, being indifferent to the design between the footpath and cycle path (TS: $B = 22.437$, $p < .001$; TL: $B = 40.103$, $p < .001$). All factors can explain 43.8% of the variance in the overall flow of cyclists and scooters (Supplementary materials, Table 14).

2.4.2. Cautious and risk-related behaviors across street typologies

A total of 174 older adults were observed using the behavioral mapping protocol across the four streets under analysis. Environmental conditions at the observation site were similar across the four streets, with mild temperatures and wind (see Supplementary Table 15 for a summary of characteristics across the four streets).

The majority were women, aged 65–74, with no locomotion aids. The majority walked alone (for a detailed analysis of descriptive characteristics of observed differences across the four streets (Supplementary materials, Tables 16–18).

The analysis of cautious and risk-related behaviors revealed distinct patterns across the four street configurations (Supplementary materials, Table 19). The most frequently observed behavior was pedestrians frequently looking at the ground, which occurred in 40.23% of all observations, with the highest frequency on WS (18.39%), followed by TS (12.64%), WL (6.90%), and TL (2.30%), though these differences were not statistically significant (Fisher's exact test, $p = .330$). Similarly, pedestrians moving slowly and hesitantly accounted for 22.41% of observations, distributed across TS (8.62%), WS (6.32%), WL (6.32%), and TL (1.15%), with no significant variation across street types (Fisher's exact test, $p = .313$).

Several risk-related behaviors showed significant variation across street configurations. Pedestrians walking or moving on the cycle lane without bicycles represented 16.67% of observations and differed significantly across streets ($\chi^2(3) = 57.510$, $p = .001$), with this behavior being substantially more prevalent on WL (11.49%) compared to WS (3.45%), TS (1.15%), and TL (0.57%). This suggests that the level design of the cycle lane with the sidewalk and the lack of trees and their shade may bear key determinants associated with this behavior occurrence.

Vigilant behavior, characterized by pedestrians looking both ways repeatedly, was observed in 13.22% of cases, most commonly on TS (6.32%), followed by WS and WL (2.87% each), and TL (1.15%), with no significant differences detected (Fisher's exact test, $p = .340$).

Pedestrians crossing or walking on the road accounted for 13.22% of observations and also showed significant differences ($\chi^2(3) = 13.306$, $p = .004$), occurring most frequently on WS (6.32%), followed by WL (4.60%), TL (1.72%), and TS (0.57%).

The behavior of frequently looking back was observed in 5.17% of cases and demonstrated significant variation ($\chi^2(3) = 9.135$, $p = .030$), with occurrences on WL (2.87%), TS (1.72%), WS (0.57%), and none on TL.

Pedestrians crossing or walking across the cycle lane without using a crosswalk accounted for 4.02% of observations, distributed across TS (1.72%), WS (1.15%), TL (0.57%), and WL (0.57%) (Fisher's exact test, $p = .675$).

Interactions between pedestrians and soft mobility users resulting in disruption occurred in 2.87% of observations and showed significant differences across street types ($\chi^2(3) = 23.370$, $p = .001$), being most common on TL (1.72%), with occurrences on both TS and WL (0.57% each), and none on WS.

Fast pedestrian speed was observed in 2.30% of cases, occurring on WS (1.15%), TS (0.57%), and WL (0.57%), with no significant variation (Fisher's exact test, $p = .880$).

Pedestrians standing stationary on the cycle lane accounted for 1.72% of observations and occurred exclusively on WL, a statistically significant difference ($\chi^2(3) = 13.04$, $p = .019$).

Pedestrians walking or moving on the cycle lane with bicycles represented 1.72% of observations, with occurrences on TS, TL, and WL (0.57% each), and none on WS (Fisher's exact test, $p = .113$).

Other less frequent behaviors showed no significant differences across street configurations. Finally, pedestrians moving away from leaves or roots (0.57%), occurring only on WL (Fisher's exact test, $p = .259$), avoiding loose stones on the sidewalk (0.57%), occurring only on WS (Fisher's exact test, $p = 1.000$), and experiencing accidental falls (0.57%), occurring only on WS (Fisher's exact test, $p = 1.000$) were rare behaviors with no significant differences across street types.

An analysis of the pattern regarding cautious and risk behaviors reveals that many of these were considered rare events (< 5%).

Given the inferential analyses, the most significant cautious and risky behavior was walking in the cycle lane, without bicycles present (occurring 29 times: 16.67% of all behavioral mapping observations). Hence, given our hypotheses, we explored the factors associated with this specific behavior in further detail.

2.4.3. Factors associated with walking in the cycle lane

In order to test variables associated with this particular risk behavior, we considered different factors according to our model, at the individual, social, environmental, and street configuration (Supplementary materials, Table 20).

A preliminary univariate analysis considering each of these factors showed a significant association between environmental and

design factors and the occurrence of pedestrian on cycle lane walking/moving (without bicycles) behavior. Weather conditions showed a significant relationship with this behavior ($\chi^2(1) = 15.145$, $p = .001$), with pedestrians observed on cycle lanes (9.20% of all older pedestrians observed) in sunny conditions and 7.47% in partly cloudy to heavily cloudy conditions. The spatial configuration of infrastructure demonstrated particularly strong associations, with the relationship between sidewalks and cycle lanes showing a highly significant effect ($\chi^2(1) = 39.332$, $p = .001$). Specifically, when sidewalks and cycle lanes were at the same level, pedestrian presence on cycle lanes occurred in 12.07% of observations, substantially higher than the 4.60% observed when sidewalks were physically separated from cycle lanes. The presence of street trees also exhibited a significant association with this behavior ($\chi^2(1) = 15.718$, $p = .001$), with 14.94% of all pedestrians observed in street segments without trees compared to only 1.72% in segments with trees. Street type classification revealed significant differences in pedestrian behavior on cycle lanes, with WL streets showing the strongest association ($\chi^2(1) = 56.609$, $p = .001$), where 11.49% of all observations were observed, while TS type showed this behavior in only 1.15% of all cases ($\chi^2(1) = 13.366$, $p = .001$). Taken together, these findings suggest that pedestrian encroachment on cycle lanes is more likely when infrastructure does not provide any physical separation between pedestrian and cycling spaces and when visual barriers such as trees are absent, indicating that the behavior may emerge primarily as a response to inadequate pedestrian infrastructure rather than as a random occurrence. The associations between older pedestrian flows and the studied behavior of walking on a cycle lane (without bicycles) are significant ($F(1,172) = 15.614$; $p < .001$). The same happens with the flow of cyclists and scooters ($F(1,172) = 8.126$; $p = .005$) (Supplementary materials, Tables 21 and 22).

A regression was conducted taking into consideration different factors at different levels of analysis. Regression allows testing the effects of one variable while controlling for others, which yields more accurate estimates of the relationships being studied.

Results in Table 1 showed that a high cycling flow is associated with a significant reduction ($\beta = -0.028$, $p = .028$) in the occurrence of pedestrians walking on the cycle lane. This result suggests that when the cycle lane is occupied and the cyclist flow is high, pedestrians may be unable to access it.

The presence of trees and the cycle lane separated from the sidewalk (TS) revealed a significant negative association ($\beta = -2.911$, $p = .003$) with pedestrian behavior of walking on the cycle lane, as expected. Yet, the street type without trees and with the cycle lane separated from the sidewalk (WS) also showed a significant negative association ($\beta = -2.290$, $p < .001$) with older pedestrians' circulation on the cycle lane. Although the TS condition showed lower odds of the outcome, the confidence intervals for the odds ratios substantially overlapped across the two conditions (TS: $OR = 0.055$, 95% CI [0.005, 0.383]; WS: $OR = 0.102$, 95% CI [0.024, 0.379]). This indicates that the data do not provide clear evidence that the magnitudes of these two effects differ. Therefore, the presence of trees does not appear to be a decisive factor; rather, the separation between the cycle lane and the sidewalk seems to play a more relevant role. All VIF values were below commonly accepted thresholds, indicating no evidence of problematic multicollinearity (Supplementary Table 23).

2.5. Discussion

The observational study revealed distinct patterns in how older pedestrians and micromobility users interact with different street configurations. In accordance with our first hypothesis, older pedestrians' flow was significantly lower in the streets where sidewalks and cycle lanes were at the same level and without trees (WL). This suggests that this street design may not be the best one for older people to walk on. Importantly, these effects hold on even after controlling the potential effects of other environmental factors such as season, weekday, and weather.

Streets with separated pedestrian and cycling infrastructure (TS and WS) recorded substantially higher older pedestrian flows

Table 1
Predictors of the behavior "Older Pedestrian walking on the cycle lane (without bicycles)", assessed by Exact Logistic Regression.

Predictor	β	*SE*	95% CI	χ^2	*p*	*OR*	95% CI OR
Constant	−1.658	1.901	[−6.063, 2.382]	0.626	0.429	0.191	[0.002, 10.813]
Season (Summer)	−0.003	0.810	[−1.752, 1.768]	0.000	0.997	0.997	[0.174, 5.855]
Temperature	0.030	0.062	[−0.103, 0.167]	0.197	0.657	1.030	[0.902, 1.182]
Wind	−0.375	0.700	[−1.988, 1.063]	0.248	0.619	0.687	[0.137, 2.896]
Cloudiness	0.967	0.737	[−0.598, 2.600]	1.470	0.225	2.629	[0.550, 13.466]
Peak period	0.901	0.501	[−0.143, 2.019]	2.853	0.091	2.462	[0.867, 7.525]
Weekday	0.080	0.877	[−1.748, 2.350]	0.006	0.937	1.084	[0.174, 10.486]
Flow of cyclists and scooters	−0.028	0.013	[−0.058, −0.003]	4.819	0.028*	0.973	[0.944, 0.997]
Flow of older pedestrians	0.002	0.013	[−0.029, 0.031]	0.014	0.907	1.002	[0.971, 1.032]
Age group (65–74 years)	1.000	0.679	[−0.388, 2.659]	1.920	0.166	2.718	[0.678, 14.292]
Gender (female)	0.378	0.471	[−0.626, 1.410]	0.546	0.460	1.459	[0.535, 4.096]
Locomotion aids	0.650	0.915	[−1.507, 2.616]	0.392	0.531	1.916	[0.222, 13.683]
Alone	−0.139	0.600	[−1.411, 1.223]	0.044	0.835	0.871	[0.244, 3.397]
TS	−2.911	0.970	[−5.277, −0.961]	8.847	0.003**	0.055	[0.005, 0.383]
WS	−2.290	0.658	[−3.728, −0.971]	11.802	0.001**	0.102	[0.024, 0.379]
TL	−1.157	1.151	[−3.847, 1.218]	0.910	0.340	0.315	[0.021, 3.382]

Note. β = unstandardized regression coefficient; *SE* = standard error; CI = confidence interval; χ^2 = likelihood ratio test; *OR* = odds ratio. Overall model: $\chi^2(15) = 53.34$, $p < .001$. Wald test: $\chi^2(15) = 64.53$, $p < .001$.
*$p < .05$. **$p < .01$.

compared to streets where sidewalks and cycle lanes share the same level (TL and WL). This suggests that physical segregation between walking and cycling spaces may be associated with higher walking among older adults, potentially outweighing the benefits of tree coverage.

Regarding H2 and based on the occurrence data for cautious and risk-related behaviors (Supplementary Table 19), an aggregate total of 218 occurrences of this type of behavior was observed across 174 observations. This indicates an average of 1.25 occurrences of risk-related behavior across the set of streets studied in Lisbon. In this context, the most prevalent behaviors were looking at the ground when walking, moving slowly and hesitantly, and walking on the cycle lane without bicycles (16.67%). Physical separation does not act solely through physical barriers. It acts through perceptual affordances, eliminating the zone of ambiguity in which pedestrians must continuously re-evaluate whether the cycle lane space is accessible to them. This reduces the cognitive load associated with anticipatory monitoring, thereby freeing attentional resources that are more limited in older adults. The mechanism is therefore one of continuous attention demand reduction, rather than physical separation per se. This argument is directly supported by an existing finding: cyclist flow has a negative association with the probability of pedestrians entering the cycle lane, even when no cyclists are present at that moment. It suggests that pedestrians develop a latent risk perception based on the habitual overall flow of a route, rather than responding only to immediate threat. This could be formalized as probabilistic conflict anticipation, a cognitively distinct mechanism with specific implications for the signage and visibility of cycle lanes. Furthermore, there were no actual accidents between bicycles and pedestrians. However, although with a small frequency, cases of conflicts were registered, particularly in one of the streets, thus legitimizing people's anticipatory concerns.

This study suggests that street design, and in particular cycle lanes and trees, may be associated with older adults' walking preferences and observable risk behaviors. The findings suggest that the separation between the cycle lane and sidewalk could be associated with a lower propensity for the occurrence of risky behavior, consistent with H2, although the presence of trees was not a determining factor for this type of behavior. This suggests that the threshold for protective effectiveness appears to be reached by physical separation per se, but the combination with trees does not seem to add further protection at the level of risk behavior, in line with previous studies (Coleman et al., 2021).

While the observational findings only demonstrated significant effects at the street configuration level, this does not necessarily indicate the absence of influences from other levels. These factors may simply have been beyond the scope of what the observational methodology could capture. Consequently, a complementary qualitative study was undertaken to investigate these potential aspects, as detailed below.

3. Study 2 – Exploratory qualitative study

An exploratory qualitative study was conducted to enhance understanding of how older adults perceive street environments and the factors that are perceived as having an influence on pedestrian behavior. Interviews were carried out with older adults residing in the same parishes as the street locations examined in Study 1, who were recruited through convenience sampling from a senior university in the parish of Alvalade and a day center in the parish of Areeiro. This study addressed two primary research questions: (i) which street configuration do older adults prefer for walking, and why; and (ii) how individual characteristics and situational street factors are perceived to influence adaptive and risky pedestrian behaviors.

3.1. Method and analysis

Interviews were conducted by the first and third authors, who were researchers on the (blinded for review) project at the time of the study. No prior relationship was established between the researchers and participants before the study commenced. Participants were informed about the purpose of the research.

The interviews were guided by an interview script that included several thematic domains: climate change, active mobility and



Fig. 5. Images of the four street configurations under study.

urban design; public policies and inclusion of older people; and the physical and built environment in urban spaces. For the purpose of the paper, only the last thematic domain was analyzed. Four photographs (Fig. 5) were shown to all participants to prompt more discussion. These depicted the streets that were previously analyzed in study 1.

A convenience sample of forty-eight older adults participated in the study. The sample was composed of 50% women, with ages ranging from 65 to 87 years (M = 77; SD = 6.91). Regarding mobility, twenty-seven participants reported no mobility limitations, while twenty-one indicated limitations that affected their walking frequency (e.g., chronic diseases, balance problems, vision difficulties). Interviews averaged 27 min, and were audio-recorded, transcribed, and anonymized for data analysis. Data saturation was determined by the researcher's interpretive judgment (Braun & Clarke, 2021). Only anonymized transcripts were used for data analysis. Transcripts were not returned to participants for validation or correction. Participants did not provide feedback on the findings.

Thematic analysis followed a deductive–inductive approach (Braun & Clarke, 2006) and was conducted using MAXQDA software. Deductively, the analysis was informed by the adapted theoretical model underpinning the global study, with the aim of assessing its suitability for explaining older adults' pedestrian behavior. Inductively, the analysis remained open to the emergence of new themes grounded in participants' perspectives. Data were coded by the third author. To enhance reflexivity and minimize potential bias, team meetings engaged in critical discussions of data interpretation. Findings were reported following the COREQ checklist (Tong et al., 2007; see *Supplementary Materials*).

3.2. Results

The findings are presented in two stages. First, we describe participants' preferences regarding street configurations for walking and summarize the key reasons for these preferences. Second, we present the findings of a deductive–inductive thematic analysis to understand how street situational conditions and individual factors shape pedestrian behavior among older adults.

3.2.1. Preference for street configuration

During the interviews, participants were shown four photographs representing four distinct street configurations, in accordance with our design. Participants were asked to indicate which configuration they would prefer for walking. The frequencies of these choices are presented in Table 2.

The majority of participants preferred the TS configuration ($n = 30$). Participants cited three main reasons: trees and shade for comfort; wide and well-maintained sidewalks for safe walking; and physical separation from cyclists to reduce perceived conflict.

The second most frequently chosen configuration was TL ($n = 16$). As with the TS configuration, the presence of trees and shade was the primary reason for its selection. Participants also noted a visually distinct cycle lane, which clarified its use and reduced uncertainty. Some preferred TL over TS because level differences in TS were seen as potential barriers.

The remaining configurations, WS ($n = 3$) and WL ($n = 3$), were chosen by relatively few participants. Participants valued features such as traditional Portuguese pavement for its aesthetics and cultural significance, and implied that the absence of trees preserved pavement quality. However, these factors were generally outweighed, resulting in lower overall preference.

3.2.2. Understanding pedestrian behavior: thematic analysis

A deductive-inductive thematic analysis was conducted to deepen the understanding of older adults' perceptions of the observed street environments and to elucidate how individual and street situational factors shape pedestrian experiences and behaviors.

Three overarching themes emerged from the data: (i) *street situational factors*, which encompass natural and climatic factors and the role of sidewalk conditions; (ii) *pedestrians' individual factors*, reflecting emotional and cognitive dimensions of pedestrians; (iii) *cautious and risky behaviors*, describing how participants adapt their behavior in streets. The following analysis explores the three themes in some depth.

Theme 1: Street Situational Factors

Street situational factors emerged as a foundational theme shaping older adults' pedestrian experiences and behaviors in street environments.

Regarding cycle lane configuration, participants emphasized the importance of well-marked, legible cycle lanes, ideally complemented by physical barriers to discourage pedestrians from using the cycle lane and to promote overall security and comfort on

Table 2
Preference for street configuration.

Street configuration	N	%
Separated sidewalk and cycle lane, with trees (TS)	30	57.6%
Separated sidewalk and cycle lane, without trees (WS)	3	5.8%
Cycle lane at the same level as the sidewalk, with trees (TL)	16	30.8%
Cycle lane at the same level as the sidewalk, without trees (WL)	3	5.8%

Note: The presented frequencies represent option selection counts rather than participant counts. Four of the 48 participants selected two options. Their response contributes as one vote for each option. Please note that the four participants preferred both the TS street configuration and one of the other three options.

urban streets. A separated sidewalk and cycle lane were among the reasons participants chose TS over the TL configuration.

"I think maybe this one [the photograph with TS configuration]. (...) This one really is, there's a boundary, let's say, between the cycle path and the pedestrian walkway." (P10, age 69, woman, reported mobility limitations).

"[It should be] Better marked, so people can clearly see that it's a cycle lane." (P07, age 87, male, did not report mobility limitations).

"This curb is also a kind of barrier that will persuade people not to walk on [the cycle lane]." (P26, age 68, man, did not report mobility limitations).

Situational factors are further elaborated through two subthemes. These subthemes focus on environmental conditions and sidewalk conditions as walking surfaces.

Subtheme 1: Environmental conditions

This subtheme examines how natural and climatic conditions may influence pedestrian behavior. The presence of trees was the most identified positive feature of walking environments. This was one of the main reasons participants chose photographs that depicted streets with trees (TS and TL configurations).

"That's right, I always enjoy walking more on streets that have trees." (P17, age 75, man, did not report mobility limitations).

Participants linked the presence of trees to "purer" and "healthier" air, often contrasting perceptions of urban pollution. Nevertheless, trees were primarily valued for their contribution to thermal comfort. Shade emerged as a critical facilitator of walking, particularly during warmer periods. Some participants reported that climatic conditions, such as excessive sun exposure and high temperatures, led to behavioral adaptations (e.g., walking in streets with trees or limiting walking to specific time periods of the day).

"For me, [walking] it's where there are trees, where it's cooler." (P36, age 78, woman, did not report mobility limitations).

"If I go out, I don't go when it's hot. I choose the time when it's 'calmer' [not so hot]" (P37, age 87, woman, reported mobility limitations).

Trees were also seen to pose some risks under certain climatic conditions and due to inadequate maintenance. Participants expressed the importance of appropriate species selection and regular maintenance of these elements. One participant expressed some concern, noting that trees "cause problems when it's windy" and may "fall over" if not properly managed.

"The things I like most are when I see trees. Not trees that make a mess, especially not with persistent leaves." (P05, age 66, woman, reported mobility limitations).

"Sometimes [trees] also cause problems when it's windy or something. So I think they let them grow too much, without thinking that they grow and then often fall over." (P38, age 75, woman, did not report mobility limitations).

Subtheme 2: Sidewalk conditions

This mainly inductive subtheme demonstrates that sidewalk conditions function as a foundational layer of pedestrian behavior.

An "ideal" walking sidewalk was implicitly defined as one with non-slip, continuous pavement that allows unobstructed, safe movement. Some obstacles mentioned include cars parked on the pavement, construction work, and bollards. Participants emphasized the importance of accessibility-oriented features, such as ramps and benches, which support rest, recovery, and inclusivity. Poor pavement quality was a recurrent concern, characterized by uneven surfaces and other deformations. These were often discussed in relation to the specific characteristics of Portuguese pavements, which participants described as particularly problematic. This was one of the main reasons why participants chose the TS street configuration. In this street, the pavement is a non-slippery alternative to the Portuguese pavement.

"[I prefer the photograph of TS configuration] Because I see a much better maintained pavement, not as pretty as ours, but at least I can walk in high heels." (P05, age 66, woman, reported mobility limitations).

"The Portuguese pavement is awful, I'm very afraid to use it because it's so uneven and slippery, and a fall at my age is very complicated. So, I avoid those pavements, honestly." (P24, age 76, man, did not report mobility limitations).

"I would like there to be no surprises, such as stones that are out of place (...). I would like there to be more attention to the public space." (P12, age 88, man, did not report mobility limitations).

Sidewalk conditions were also linked to green elements. Participants noted that inadequate maintenance could lead to pavement damage caused by root growth. This was one of the reasons participants chose streets without trees.

"We have trees that, when they grow, their roots start to make the ground uneven. And then, if you get distracted for a moment, you can have problems." (P17, age 75, man, did not report mobility limitations).

Theme 2: Pedestrians' individual factors

Pedestrians' individual factors capture subjective experiences, emotional responses, and beliefs of older adults in urban streets.

Some participants described feelings of well-being and enjoyment, most often in relation to the presence of trees or the overall experience of walking on streets. However, these positive emotions seem to be overshadowed by concerns about safety.

Fear and insecurity were the most salient emotional states expressed in participants' narratives about walking in urban environments. Fear of falling was linked to sidewalk conditions and interactions with other street users, particularly cyclists. Additional sources of insecurity included perceptions of crime and broader environmental conditions.

"I can't walk on the sidewalk because I'm afraid of falling." (P02, age 72, woman, did not report mobility limitations).

"I have been scared several times by people on scooters and bicycles." (P05, age 66, woman, reported mobility limitations).

Preconceptions about cyclists' behaviors capture participants' beliefs and assumptions regarding cyclists' conduct in public spaces. Common perceptions included the belief that cyclists use sidewalks instead of designated cycle paths, ride at excessive speeds, and fail to respect pedestrians.

"They [the cyclists] walk around as if they were kings and lords, they don't look at animals or people with disabilities, they don't look at anything." (P05, age 66, woman, reported mobility limitations).

"We are the ones who have to be very careful. Because they [the cyclists] just want to move forward, move forward. They don't care about anything." (P16, age 77, woman, did not report mobility limitations).

"I've already been warned, you have to be careful... Because they ride their scooters here so fast and run people over..." (P41, age 81, woman, reported mobility limitations).

As the last citation illustrates, these perceptions appear to circulate socially, becoming part of shared 'warnings', pointing to the role of social and contextual appraisals in shaping how older adults comprehend street environments The presence of cyclists is perceived as a source of threat, drawing on accumulated beliefs and socially transmitted understandings. They appear to encourage heightened caution, route modification, or the avoidance of certain streets altogether, as illustrated by one participant's decision to avoid a street altogether based on its association with fast cycling.

"Here, in [the photograph with TL configuration], I wouldn't go because, when it comes to bicycles, they ride, as I say, in a great hurry." (P05, age 66, woman, reported mobility limitations).

Theme 3: Cautious and risk behaviors

This theme highlights how street conditions and individual perceptions shape pedestrian behaviors. Participants described both cautious and risk-taking actions as adaptive strategies to manage perceived threats related to street design, sidewalk quality, and other users. These behaviors are understood as observable manifestations of the perceptual and appraisal processes described in Theme 2.

Cautious behaviors were most frequently reported regarding cyclists' conduct. In the presence of cycle paths, the behavioral responses participants described included heightened vigilance (such as frequently looking in multiple directions) and adjusting their walking position.

"Bicycles appear behind me, they pass by very quickly, and I think, if there's some imbalance on my part, I could get hit by a bicycle. I can't always be looking back and forth. When I cross a street, now I have to look both ways." (P24, age 76, man, did not report mobility limitations).

"I always have to watch out for bicycles and scooters. (...) So when I walk on the sidewalk, I walk closer to the buildings. That way, I give them space to pass." (P20, age 81, woman, did not report mobility limitations).

As the last citation illustrates, one participant explained that they deliberately walk closer to buildings to create distances from faster-moving users. This participant was not reacting to cyclists in that necessary moment but managing an expected threat from prior comprehensions of cyclist behavior, consistent with the preconceptions identified in Theme 2.

Street situational factors, in particular sidewalk conditions, further shaped adaptive behavior. Uneven surfaces prompted slower, more hesitant walking, as participants adjusted their pace given the specific conditions of the street. As the following citation shows, sidewalk conditions perceived as hazardous appear to generate behavioral adjustments.

"Sometimes the streets are rocky, right? (...) I walk more slowly, then a little faster..." (P03, age 71, man, did not report mobility limitations).

Risky behaviors emerged from the intersection of individual factors and street situational factors, most prominently when safety concerns about sidewalk conditions led participants to use cycle paths as an alternative walking space.

"Because of the pavement. I go there [on the cycle path] often. I walk right on the edge. I don't look behind me. But if bicycles come from the front, I step aside. (...) . The bicycle passes, and I continue walking." (P04, age 85, woman, reported mobility limitations).

"Because apart from the Portuguese pavement, I go into the cycle lane." (P11, age 72, woman, did not report mobility limitations).

Risky behaviors appear to reflect a situation in which two concurrent phenomena (sidewalk conditions and preconceptions about cyclists' behaviors) are weighed against each other, leading participants to select the option perceived as less dangerous in the moment, even when that option introduces a new risk. Critically, this outcome seems to be shaped by sidewalk conditions that fail to provide older adults with a genuinely safe alternative, forcing a negotiation between competing hazards. To mitigate the new risk introduced by walking in the cycle lane, participants described adapting their behavior, such as staying at the edge of the lane and relying on visual cues to monitor approaching bicycles. Although explicit accounts of negative outcomes were limited, participants acknowledged the possibility of serious consequences arising from pedestrians walking in the cycle lane.

3.3. Discussion

This qualitative study explored how older adults perceive street environments and how these perceptions shape cautious and risky pedestrian behavior. The findings highlight how street design, environmental conditions, and individual factors are perceived to influence walking behavior.

Regarding the first research question, older adults preferred the TS street layout due to three key features: trees, physically separated cycle lanes, and well-maintained sidewalks. The presence of trees was highly valued for aesthetic, environmental, and psychological reasons (as TS and TL were the two most frequently selected options). These findings corroborate that trees and shaded areas promote walking and enhance the overall experience (Borst et al., 2008; Herrmann-Lunecke et al., 2021). Physically separated cycle lanes reduced perceived risks from cyclists, reflecting research showing that shared sidewalks often feel unsafe (Bernhoft & Carstensen, 2008). Well-maintained sidewalks further contributed to a sense of safety and comfort, highlighting the importance of accessible, age-friendly pedestrian infrastructure in promoting walking among older adults (Van Cauwenberg et al., 2011; WHO, 2007).

Regarding the second research question, the findings highlight the interplay between individual characteristics and situational street factors in shaping pedestrian behaviors. Aligned with our conceptual framework, pedestrian cautious and risky behaviors are shaped by an ensemble of contextual and individual factors.

Regarding street situational conditions, a novel finding of this study is the identification of sidewalk conditions as a source of fear of

falling and insecurity. Perceptions of uneven or poorly maintained pavements prompted cautious (e.g., reduced walking speed) and risky behaviors (e.g., walking in cycle lanes when sidewalks were perceived as unsafe). Poorly managed tree root growth was linked to pavement damage, further intensifying feelings of insecurity. Additionally, some pedestrians adapted their mobility patterns in response to weather conditions, such as choosing shaded streets or walking only at certain times of day.

At the individual level, fear and insecurity were the most salient emotional states expressed in participants' narratives about walking in urban environments. Preconceptions about cyclists' behavior heightened feelings of fear and insecurity. Participants reported increased vigilance and maintaining distance from cycle lanes to manage perceived conflicts, reflecting common views of cyclists as speeding, disregarding pedestrians, or failing to use cycle lanes. Although age and gender are associated with pedestrian behavior, these factors did not emerge in the present study. Participants tended to emphasize situational features of the street environment, which may have overshadowed individual characteristics in their narratives.

Our findings corroborate that multiple factors may influence pedestrian cautiousness and risk-related behaviors in sidewalk environments. Older pedestrians' behaviors seem to vary in terms of cautiousness and risk exposure depending on cycle lane configuration, the presence or absence of trees, and sidewalk conditions.

4. General discussion

This mixed-methods investigation of older pedestrians' behaviors in urban environments provides novel insights into how street design configurations, environmental conditions, and individual perceptions collectively may shape mobility patterns and walking behaviors. By integrating systematic naturalistic observations (Study 1) with in-depth qualitative interviews (Study 2), this research explores the multifaceted nature of street design and highlights critical implications for urban planning.

The convergence of findings across both studies reveals a consistent preference among older adults for streets with physically separated sidewalks and cycle lanes. As detailed in section 2.4, Study 1 showed that this pattern is consistent with both hypotheses (H1 and H2).

As reported in Section 3.2.1, Study 2 corroborated these patterns through participants' articulated preferences, with the majority explicitly choosing the TS configuration as their preferred walking environment. Interestingly, while in the interviews (Study 2), the second most preferred configuration was TL. The observational data (Study 1) showed that WS was the second configuration with the highest older pedestrian flow. This discrepancy suggests that, although trees may enhance perceived comfort and preference, the physical separation between sidewalks and cycle lanes appears to play a more decisive role in shaping actual walking behavior.

From a situational awareness perspective, physically separated infrastructure may reduce environmental ambiguity and facilitate clearer perceptual and anticipatory processes, thereby reducing the need for compensatory adaptive or risk-related adaptations (Luu et al., 2022).

As discussed in Section 2.4 (Study 1), infrastructure design also played a critical role in safety-related behaviors, with cycle lanes separated from the sidewalk associated with lower risky behavior among older pedestrians. Study 2 provided a critical contextual understanding of why older pedestrians engage in this behavior, revealing that deteriorated sidewalk conditions, characterized by uneven Portuguese pavement, narrow widths, and obstacles, compelled older adults to seek alternative walking surfaces despite their awareness of potential conflicts with cyclists and scooter users. Rather than reflecting noncompliance or a lack of awareness, walking in the cycle lane can be interpreted as an adaptive response to constrained environmental conditions, illustrating how behaviors that increase potential exposure to hazards may nevertheless represent pragmatic adjustments to maintain mobility. This interpretation is consistent with previous work suggesting that pedestrians balance safety and efficiency when navigating complex environments (Cœugnet et al., 2019; Luu et al., 2022; Zhu et al., 2021).

In terms of environmental conditions, older pedestrian flow was higher during the summer in Study 1. In Study 2, participants reported preferring shaded streets and limiting walking to specific times of day in response to weather conditions. Additionally, cyclists' flow was associated with lower pedestrian risky behavior (i.e., walking on the cycle lane when no bicycles are present). These findings reinforce the importance of environmental factors in shaping outdoor mobility among older adults (Močnik et al., 2022; van Hoven & Meijering, 2019; Zhang et al., 2024).

The integration of both studies illuminates the psychological mechanisms underlying these behavioral patterns. Study 2, in section 3.3, identified fear and insecurity as dominant emotional states influencing older pedestrians' navigation decisions, with participants describing heightened vigilance and cautious behaviors, particularly in the presence of cyclists and scooters. These subjective experiences help explain the behavioral observations from Study 1, where older pedestrians demonstrated adaptive responses such as walking closer to building facades and maintaining constant vigilance when cycle lanes were nearby. Such emotional responses can be understood as appraisal processes influencing attention allocation and anticipatory judgments (Cœugnet et al., 2019; Ellmers et al., 2020). The qualitative data also revealed widespread preconceptions about cyclists' behaviors, perceptions that they are fast, unpredictable, and inconsiderate, which appear to circulate socially and intensify feelings of vulnerability. These socially constructed representations may shape risk evaluation and decision-making, illustrating how social context may operate as an individual-level situational factor within the conceptual model. This finding suggests that improving age-friendly mobility requires addressing not only physical design features but also behavioral norms governing these spaces.

This pattern is consistent with the conceptual framework adopted in this study, which posits that behavioral outcomes reflect the interaction between individual and situational factors. Although age, gender, use of mobility aids (e.g., Lachapelle & Cloutier, 2017; Tournier et al., 2016), and the presence of others (e.g., Barón et al., 2024; Cœugnet et al., 2019) have been associated with pedestrian behavior in previous research, these factors did not emerge as significant predictors in the present study. In the present context, street-level configurations may have increased environmental demands to such an extent that they became the dominant determinants of

cautious and risk-related behaviors, potentially attenuating or overshadowing the effects of individual characteristics within this context.

The findings regarding tree coverage reveal a more nuanced pattern. Study 2 revealed that older pedestrians perceive trees primarily for thermal comfort and aesthetic quality, following previous research (e.g., Borst et al., 2008; Herrmann-Lunecke et al., 2021; Močnik et al., 2022). However, participants also articulated concerns about trees contributing to sidewalk deterioration through root growth and maintenance issues, such as falling leaves and branches. From the perspective of the conceptual framework, trees may simultaneously support perceived security and attentional structuring (Luu et al., 2022), while, when poorly maintained, may induce increasing environmental unpredictability and adaptive responses. These findings suggest that tree presence alone is insufficient; rather, integrated design approaches that combine tree coverage with robust sidewalk maintenance, adequate width, and appropriate infrastructure placement are essential to support age-friendly environments. Thus, trees belong to the former category: they influence the *decision to use* a street (pedestrian flow, stated preference) but do not seem to structure behavior during use (risk-taking). This is consistent with affordance theory and can be articulated as follows: trees are invitational affordances, whereas physical barriers are constraining affordance which is consistent with previous studies (Coleman et al., 2021). The fact that trees are the second most important factor for *stated preference* (Study 2) but do not seem to be for observed risk behavior (Study 1) may reflect an explicable tension: trees operate primarily at the level of thermal comfort and perceived experience, functioning as a condition that invites walking, but do not create behavioral channelling in the way physical barriers do. These findings contribute to understanding the distinction between elements that promote the use of spaces and elements that structure and channel behavior safely.

Taken together, the qualitative findings from Study 2 provide interpretive depth to the behavioral patterns observed in Study 1, moving beyond description toward explanation. For instance, the quantitative association between separated cycle-lane infrastructure and reduced risky behavior is clarified by interview accounts describing deteriorated sidewalk conditions (uneven pavement, narrow widths, obstacles) as the practical driver compelling pedestrians to occasionally walk on cycle lanes despite awareness of the danger, reframing this behavior as an adaptive trade-off rather than noncompliance or carelessness. Finally, the more ambiguous quantitative relationship between tree coverage and pedestrian behavior is illuminated by the qualitative "tree paradox": participants valued trees for thermal comfort and aesthetics, while simultaneously associating poorly maintained trees with root damage and debris that increase environmental unpredictability. In each case, the qualitative material does not merely corroborate the quantitative results but supplies the underlying psychological and situational reasoning that the observational data alone could not capture.

Overall, the findings suggest that cycling infrastructure may play a more relevant role in explaining the observed behavior than tree presence alone. However, uncertainty surrounding the estimated effects (Study 1) prevents robust conclusions regarding the independent contribution of tree presence. Future studies should therefore examine the specific role of street trees using study designs that can more clearly disentangle the effects of vegetation from those of cycling infrastructure configuration. Additionally, these findings carry significant implications for urban planning policy and practice. First, physically separated pedestrian and cycling infrastructure appears to reduce environmental ambiguity and support safer behavioral adaptation among older adults. Second, sidewalk quality and maintenance emerge as foundational conditions for effective mobility. The Portuguese pavement, although culturally valued, was consistently identified as a barrier to confident walking. Design interventions that reduce cognitive load, perceived vulnerability, and emotional insecurity may decrease the need for adaptive responses that increase exposure to hazards, thereby supporting safer and more autonomous mobility in aging populations.

4.1. Limitations and implications

Several limitations warrant consideration. Study 1 was conducted in two demographically similar parishes in Lisbon during specific seasonal periods, potentially limiting generalizability to other contexts. The behavioral observations, while systematic, captured an exploratory snapshot moment rather than longitudinal patterns.

Although age classification based on visual estimation may have introduced some degree of misclassification, this limitation is inherent to unobtrusive pedestrian observation where direct interaction with participants would compromise the non-reactive nature of the research design. To minimize this risk, observers underwent protocol training and inter-rater reliability testing, achieving substantial to almost perfect agreement. Moreover, given that age was used to identify a broad target group rather than as the primary explanatory variable, any residual classification error is unlikely to have substantially affected the study's conclusions.

Although a priori power calculations are generally recommended, they were not feasible here given the absence of reliable prior estimates of effect sizes and event frequencies, compounded by the practical constraints of intensive naturalistic observation. The relatively small sample size for detailed behavioral mapping ($n = 174$) in four selected streets may have limited statistical power. The limited number of observations and the use of only four street segments restrict our ability to account for spatial clustering and unobserved street-level heterogeneity. We therefore used exact logistic regression in order to address data sparsity, and effect sizes are reported alongside 95% confidence intervals. Nonetheless, the lack of a prospective power analysis means the study may have been insufficiently powered to detect smaller effects, and findings of non-significance should therefore be interpreted with caution. However, exact logistic regression was selected precisely to address biased estimation under maximum likelihood in low-event conditions (Field, 2024; Heinze & Schemper, 2002). The analysis of the behavior of walking in the cycle lane without bicycles was conducted with a modest observational sample ($n = 29$), which constrains the statistical power to detect small effects for less frequent behavioral categories. While exact logistic regression is robust to small sample sizes by design, the findings related to infrequent behaviors are best understood as indicative rather than confirmatory. In this context, multilevel modeling should be a priority for future studies with larger samples.

Study 2 may be influenced by recall or social desirability biases, although triangulation with behavioral data strengthens

confidence in the findings. Additionally, the cross-sectional design precludes causal claims about the direction of relationships between design features and behaviors. Furthermore, although the streets were matched on key sociodemographic characteristics, the quasi-experimental design does not fully account for other potential confounding factors, including differences in surrounding land use, motorized traffic volumes, local commercial activity, beyond the variables directly measured. These uncontrolled factors may have independently influenced the behavioral patterns observed. Thus, all findings should therefore be interpreted as indicative of associative rather than causal relationships.

Future research should continue testing the proposed conceptual model across diverse contexts (e.g., varied climatic, cultural, and socioeconomic) to further clarify how perceptual, emotional, and social appraisal processes mediate the relationship between street design and behavioral outcomes. Longitudinal studies tracking how individuals' mobility patterns and route choices change following street redesign interventions would provide stronger causal evidence. Comparative research examining how different age groups (e.g., young adults, middle-aged adults) interact with the same street configurations could illuminate age-specific needs versus universal design principles. Additionally, investigating the experiences of older adults with varying levels of functional limitations would help ensure that design solutions serve the full spectrum of aging populations.

5. Conclusions

This study contributes to the growing body of research on age-friendly urban environments by examining how street design features and environmental conditions are associated with walking behaviors of older pedestrians, given the particular challenges posed by green street design to adapt to climate challenges. Through structured observation and exploratory interviews, the study identified clear patterns of pedestrian and micromobility flows and the occurrence of cautious and risky behaviors affecting older people's walking experiences.

Findings indicated that street designs with physically separated cycle lanes were significantly associated with lower levels of cautious and risk-related behavior, consistent with the study's hypotheses. The results suggest that promoting walking among older adults requires careful attention to both physical infrastructure and environmental comfort under varying climatic conditions.

These findings extend prior pedestrian behavior research, which has typically examined infrastructure and psychosocial factors separately (e.g., Cœugnet et al., 2019; Luu et al., 2022), by integrating systematic behavioral observation with qualitative accounts of older pedestrians' lived experience within a single conceptual framework. Whereas earlier studies have associated cycle-lane separation with perceived safety in general pedestrian populations, the present study offers quantitative evidence, obtained through exact logistic regression suited to sparse naturalistic data, that physically separated cycling infrastructure is specifically associated with reduced risk-related behavior among older pedestrians, a group underrepresented in pedestrian–cyclist conflict research to date. Moreover, in contrast to prior work that has tended to treat street trees as a uniformly protective design feature (e.g., Coleman et al., 2021), the present findings reveal a more nuanced role: trees shaped stated preference and perceived thermal comfort but did not significantly structure observed risk behavior. This distinction, between elements that invite the use of a street and elements that channel safe behavior within it, represents a novel conceptual contribution to age-friendly mobility scholarship and clarifies why tree-planting alone may be insufficient as a safety intervention.

Overall, this study suggests that urban design choices may significantly shape older people's ability and willingness to engage in active mobility. By triangulating systematic behavioral observation with older adults' own accounts, this study addresses a methodological gap in age-friendly mobility research, where behavioral and self-reported data are rarely combined, and thereby provides a more comprehensive and context-sensitive understanding of older pedestrians' safety-related behavior than studies relying on either method alone. This research provides evidence to inform public policy and planning interventions aimed at creating safer, more inclusive, and age-friendly public spaces.

Future research should extend this approach to include different age groups and broader urban contexts, further exploring how intersectional factors such as gender, health status, and social interaction influence street use dynamics.

CRediT authorship contribution statement

André Samora-Arvela: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carla Branco:** Writing – review & editing, Writing – original draft. **Mariana Montalvão:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miguel R. Ramos:** Writing – review & editing, Methodology. **Joana Mendonça:** Writing – review & editing, Methodology. **Leonor Bettencourt:** Writing – review & editing, Methodology. **Sibila Marques:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sara Eloy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2026.103847.

Data availability

Data will be made available on request.

References

Acela, L. M. B., Sousa, E., Faria, S., Almeida, R., & Freitas, E. F. (2025). Pedestrian crossing behavior in social groups: Exploring cultural contexts through a comparative study. *Case Studies on Transport Policy, 19*, Article 101333. https://doi.org/10.1016/j.cstp.2024.101333

Al-Saaidy, H. J. E., Alobaydi, D., & Abdullah, S. F. K. (2025). Street networks and urban sustainability by quantifying connectivity, accessibility, and walkability for resilient cities. *Civil Engineering Journal, 11*(6), 2421–2439. https://doi.org/10.28991/CEJ-2025-011-06-015

Avineri, E., Shinar, D., & Susilo, Y. O. (2012). Pedestrians' behaviour in cross walks: The effects of fear of falling and age. *Accident Analysis and Prevention, 44*(1), 30–34. https://doi.org/10.1016/j.aap.2010.11.028

Barón, L., Faria, S., Sousa, E., & Freitas, E. (2024). Analysis of pedestrians' road crossing behavior, in social groups. *Transportation Research Record, 2678*(3), 387–409. https://doi.org/10.1177/03611981231180206

Bernhoft, I. M., & Carstensen, G. (2008). Preferences and behaviour of pedestrians and cyclists by age and gender. *Transportation Research Part F: Traffic Psychology and Behaviour, 11*(2), 83–95. https://doi.org/10.1016/j.trf.2007.08.004

Borst, H. C., Miedema, H. M. E., de Vries, S. I., Graham, J. M. A., & van Dongen, J. E. F. (2008). Relationships between street characteristics and perceived attractiveness for walking reported by elderly people. *Journal of Environmental Psychology, 28*(4), 353–361. https://doi.org/10.1016/j.jenvp.2008.02.010

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2021). One size fits all? What counts as quality practice in (reflexive) thematic analysis? *Qualitative Research in Psychology, 18*(3), 328–352. https://doi.org/10.1080/14780887.2020.1769238

Cambra, P., & Moura, F. (2020). How does walkability change relate to walking behaviour change? Effects of a street improvement in pedestrian volumes and walking experience. *Journal of Transport & Health, 16*, Article 100797. https://doi.org/10.1016/j.jth.2019.100797

Chong, S., Poulos, R., Olivier, J., Watson, W. L., & Grzebieta, R. (2010). Relative injury severity among vulnerable non-motorised road users: Comparative analysis of injury arising from bicycle-motor vehicle and bicycle-pedestrian collisions. *Accident Analysis and Prevention, 42*(1), 290–296. https://doi.org/10.1016/j.aap.2009.08.006

Chung, E., Lee, S., Lee, H., & Kim, Y. (2023). Comparative study of young-old and old-old people using functional evaluation, gait characteristics, and cardiopulmonary metabolic energy consumption. *BMC Geriatrics, 23*(1). https://doi.org/10.1186/s12877-023-04088-6

Cœugnet, S., Cahour, B., & Kraiem, S. (2019). Risk-taking, emotions and socio-cognitive dynamics of pedestrian street-crossing decision-making in the city. *Transportation Research Part F: Traffic Psychology and Behaviour, 65*, 141–157. https://doi.org/10.1016/j.trf.2019.07.011

Coleman, A. F., Ryan, R. L., Eisenman, T. S., Locke, D. H., & Harper, R. W. (2021). The influence of street trees on pedestrian perceptions of safety: Results from environmental justice areas of Massachusetts, US. *Urban Forestry & Urban Greening, 64*, Article 127258. https://doi.org/10.1016/j.ufug.2021.127258

Do, D. T., Mori, S., & Nomura, R. (2019). An analysis of relationship between the environment and user's behaviour on unimproved streets: A case study of Da Nang City, Vietnam. *Sustainability, 11*(83). https://doi.org/10.3390/su11010083

Dommès, A., Cavallo, V., & Oxley, J. (2013). Functional declines as predictors of risky street-crossing decisions in older pedestrians. *Accident Analysis and Prevention, 59*, 135–143. https://doi.org/10.1016/j.aap.2013.05.017

Duives, D. C., Sparnaaij, M., Daamen, W., & Hoogendoorn, S. P. (2019). How many people can simultaneously move through a pedestrian space? The impact of complex flow situations on the shape of the fundamental diagram. *arXiv preprint arXiv:1908.07208*.

Ellmers, T. J., Cocks, A. J., & Young, W. R. (2020). Evidence of a link between fall-related anxiety and high-risk patterns of visual search in older adults during adaptive locomotion. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences, 75*(5), 961–967. https://doi.org/10.1093/gerona/glz176

Endsley, M. R. (1995). Measurement of situation awareness in dynamic systems. *Human Factors, 37*(1), 65–84. https://doi.org/10.1518/001872095779049499

Endsley, M. R. (2015). Final reflections: Situation awareness models and measures. *Journal of Cognitive Engineering and Decision Making, 9*(1), 101–111. https://doi.org/10.1177/1555343415573911

Eurostat. (2019). Old-age dependency ratio. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/EDN-20191030-1.

Faria, J. J., Krause, S., & Krause, J. (2010). Collective behavior in road crossing pedestrians: The role of social information. *Behavioral Ecology, 21*(6), 1236–1242. https://doi.org/10.1093/beheco/arq141

Fernández, C., Vicente, M. A., Carrillo, I., Guilabert, M., & Mira, J. J. (2020). Factors influencing the smartphone usage behavior of pedestrians: Observational study on "Spanish smombies". *Journal of Medical Internet Research, 22*(8), Article e19350.

Field, A. (2024). *Discovering statistics using IBM SPSS statistics*. Sage publications limited.

Haworth, N., Schramm, A., & Debnath, A. (2014). An observational study of conflicts between cyclists and pedestrians in the city centre. *Journal of the Australasian College of Road Safety, 25*(4), 31–40.

Heinze, G., & Schemper, M. (2002). A solution to the problem of separation in logistic regression. *Statistics in Medicine, 21*, 2409–2419. https://doi.org/10.1002/sim.1047

Herrmann-Lunecke, M. G., Mora, R., & Vejares, P. (2021). Perception of the built environment and walking in pericentral neighbourhoods in Santiago, Chile. *Travel Behaviour and Society, 23*, 192–206. https://doi.org/10.1016/j.tbs.2021.01.002

Hosford, K., Cloutier, M., & Winters, M. (2020). Observational study of pedestrian and cyclist interactions at intersections in Vancouver, BC and Montréal, QC. *Transportation Research Record, 2674*(6), 410–419. https://doi.org/10.1177/0361198120919407

Hou, T., Lu, M., & Fu, J. (2017). Microclimate perception features of commercial street in severe cold cities. *Energy Procedia, 134*, 528–535. https://doi.org/10.1016/j.egypro.2017.09.559

Hou, Y., Moogoor, A., Dieterich, A., Song, S., & Yuen, B. (2021). Exploring built environment correlates of older adults' walking travel from lifelogging images. *Transportation Research Part D: Transport and Environment, 96*, Article 102850. https://doi.org/10.1016/j.trd.2021.102850

Hwang, H., Haddad, A. J., & Bhat, C. R. (2025). Multivariate analysis of frequency, duration and companionship in walking behaviors among adults over 50. *Journal of Transport & Health, 44*, Article 102161. https://doi.org/10.1016/j.jth.2025.102161

Ishrath, N., & Rajendran, B. G. (2024). Exploring trends and patterns in traffic safety culture of pedestrians: A bibliometric analysis. *SN Social Sciences, 4*, 186. https://doi.org/10.1007/s43545-024-00981-y

Jarrott, S. E. (2010). *The intergenerational observation scale training manual* (Available from Jarrott, Dept. Human Development (0416), Virginia Tech, Blacksburg, VA. 24061–0416).

Lachapelle, U., & Cloutier, M. S. (2017). On the complexity of finishing a crossing on time: Elderly pedestrians, timing and cycling infrastructure. *Transportation Research Part A: Policy and Practice, 96*, 54–63. https://doi.org/10.1016/j.tra.2016.12.005

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 159–174. https://doi.org/10.2307/2529310

Lazarus, R. S., & Folkman, S. (1984). Coping and adaptation. In W. D. Gentry (Ed.), *The handbook of behavioral medicine* (pp. 282–325). Guildford Press.

Lee, D., & Tak, S. H. (2023). A concept analysis of fear of falling in older adults: Insights from qualitative research studies. *BMC Geriatrics, 23*(1). https://doi.org/10.1186/s12877-023-04364-5

Lee, M., Lee, H., Hwang, S., & Choi, M. (2021). Understanding the impact of the walking environment on pedestrian perception and comprehension of the situation. *Journal of Transport & Health, 23*, Article 101267. https://doi.org/10.1016/j.jth.2021.101267

Lord, S., Cloutier, M., Garnier, B., & Christoforou, Z. (2018). Crossing road intersections in old age—With or without risks? Perceptions of risk and crossing behaviours among the older people. *Transportation Research Part F: Traffic Psychology and Behaviour, 55*, 282–296. https://doi.org/10.1016/j.trf.2018.03.005

Loukaitou-Sideris, A., Brozen, M., & Levy-Storms, L. (2014). Placemaking for an aging population: Guidelines for senior-friendly parks. https://escholarship.org/content/qt450871hz/qt450871hz.pdf.

Luu, D. T., Eom, H., Cho, G. H., Kim, S. N., Oh, J., & Kim, J. (2022). Cautious behaviors of pedestrians while crossing narrow streets: Exploration of behaviors using virtual reality experiments. *Transportation Research Part F: Traffic Psychology and Behaviour, 91*, 164–178. https://doi.org/10.1016/j.trf.2022.09.024

Marušić, B., & Marušić, D. (2012). Behavioural maps and GIS in place evaluation and design. In *InTech eBooks*. https://doi.org/10.5772/47940

Meinhart-Shibata, P., Kramer, M., Ashton-Miller, J. A., & Persad, C. (2005). Kinematic analyses of the 180° standing turn: Effects of age on strategies adopted by healthy young and older women. *Gait and Posture, 22*(2), 119–125. https://doi.org/10.1016/j.gaitpost.2004.08.005

Mesimäki, J., & Luoma, J. (2021). Near accidents and collisions between pedestrians and cyclists. *European Transport Research Review, 13*(1). https://doi.org/10.1186/s12544-021-00497-z

Močnik, Š., Moogoor, A., & Yuen, B. (2022). Exploring facilitators and barriers of older adults' outdoor mobility: A walk-along study in Singapore. *Journal of Transport and Health, 26*. https://doi.org/10.1016/j.jth.2022.101386

Nyman, S. R., Ballinger, C., Phillips, J. E., & Newton, R. (2013). Characteristics of outdoor falls among older people: A qualitative study. *BMC Geriatrics, 13*, Article 125. http://www.biomedcentral.com/1471-2318/13/125.

PORDATA. (2025). Índice de envelhecimento em Portugal. https://www.pordata.pt/pt/estatisticas/populacao/populacao-residente/indice-de-envelhecimento-e-outros-indicadores-de.

Rahman, M. M., Rahim, M. A., Ayman, U., Sohel, A., et al. (2025). Real-time vehicle type detection and counting for emission pollution monitoring and traffic violation identification. *Emerging Science Journal.*. https://doi.org/10.28991/ESJ-2025-09-02-023

Samora-Arvela, A., Marques, S., & Montalvão e Silva, M. (2025). Analysis of active mobility and active aging: Insights on green street design and age-friendly policies in Portugal. *Cities & Health.*. https://doi.org/10.1080/23748834.2025.2482913

Silva, C., Clifton, K., & Moeckel, R. (2019). Observational method and coding framework for analysing the functionality of unprotected bicycle lanes. *Transportation Research Procedia, 41*, 559–571. https://doi.org/10.1016/j.trpro.2019.09.100

Southworth, M. (2005). Designing the walkable city. *Journal of Urban Planning and Development, 131*(4), 246–257. https://doi.org/10.1061/(asce)0733-9488(2005)131:4(246)

Sum, S., Wisutwattanasak, P., Champahom, T., Jomnonkwao, S., & Ratanavaraha, V. (2025). A comparative study of a series of supervised learning models for motorcycle crash injury severity prediction. *Civil Engineering Journal., 11*, 4246–4261. https://www.civilejournal.org/index.php/cej/article/view/6364.

Todorov, A., Olivola, C. Y., Dotsch, R., & Mende-Siedlecki, P. (2015). Social attributions from faces: Determinants, consequences, accuracy, and functional significance. *Annual Review of Psychology, 66*, 519–545. https://doi.org/10.1146/annurev-psych-113011-143831

Tommasini, C., Talamini, R., Bidoli, E., Sicolo, N., & Palese, A. (2008). Risk factors of falls in older people population in acute care hospitals and nursing homes in North Italy. *Journal of Nursing Care Quality, 23*(1), 43–49. https://doi.org/10.1097/01.ncq.0000303804.15080.76

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care, 19*(6), 349–357. https://doi.org/10.1093/intqhc/mzm042

Tournier, I., Dommès, A., & Cavallo, V. (2016). Review of safety and mobility issues among older pedestrians. *Accident Analysis and Prevention, 91*, 24–35. https://doi.org/10.1016/j.aap.2016.02.031

Van Dyck, D., Teychenne, M., McNaughton, S. A., De Bourdeaudhuij, I., & Salmon, J. (2015). Relationship of the perceived social and physical environment with mental health-related quality of life in middle-aged and older adults: Mediating effects of physical activity. *PLoS One, 10*(3), Article e0120475. https://doi.org/10.1371/journal.pone.0120475

van Hoven, B., & Meijering, L. (2019). Mundane mobilities in later life: Exploring experiences of everyday trip-making by older adults in a Dutch urban neighbourhood. *Research in Transportation Business and Management, 30*. https://doi.org/10.1016/j.rtbm.2019.100375

Vaughan, L., & Grajewski, T. (2001). *Space syntax observation manual.* University College London.

Villeneuve, P. J., Ysseldyk, R. L., Root, A., Ambrose, S., DiMuzio, J., Kumar, N., Shehata, M., Xi, M., Seed, E., Li, X., Shooshtari, M., & Rainham, D. (2018). Comparing the normalized difference vegetation index with the Google Street View measure of vegetation to assess associations between greenness, walkability, recreational physical activity, and health in Ottawa, Canada. *International Journal of Environmental Research and Public Health, 15*(8), Article 1719. https://doi.org/10.3390/ijerph15081719

Wang, Z., Lv, H., & Li, G. (2025). Promote older adults active travel on neighborhood streets: An observation study in Daokou ancient town in China. *BMC Geriatrics, 25*, 790 (2025) https://doi.org/10.1186/s12877-025-06321-w.

WHO. (2007). *Global age-friendly cities: A guide*. World Health Organization. https://iris.who.int/bitstream/handle/10665/43755/9789899556867_por.pdf?sequence=3.

Zhang, C. Q., Zhang, R., Baker, J. S., Hagger, M. S., & Hamilton, K. (2024). A qualitative investigation exploring neighbourhood environment, risks and fear of falling, and fall prevention strategies among urban-dwelling older adults in a high-density city. *Ageing and Society, 44*(10), 2155–2176. https://doi.org/10.1017/S0144686X22001209

Zheng, L., Ismail, K., & Meng, X. (2014). Traffic conflict techniques for road safety analysis: Open questions and some insights. *Canadian Journal of Civil Engineering, 41*(7), 633–641. https://doi.org/10.1139/cjce-2013-0558

Zheng, L., Sayed, T., & Guo, Y. (2019). Investigating factors that influence pedestrian and cyclist violations on shared use lane: An observational study on the Brooklyn Bridge promenade. *International Journal of Sustainable Transportation, 14*(7), 503–512. https://doi.org/10.1080/15568318.2019.1575495

Zhu, D., Sze, N. N., & Feng, Z. (2021). The trade-off between safety and time in the red light running behaviors of pedestrians: A random regret minimization approach. *Accident Analysis and Prevention, 158*. https://doi.org/10.1016/j.aap.2021.106214