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Perceptions of safety, fairness and risk in road spaces shared by pedestrians, cyclists and drivers

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Abstract

Designing shared road spaces that accommodate multiple modes of transport is central to promoting active travel, but engagement can be hindered by perceptions of danger and unfairness, especially among groups more worried about navigating shared spaces. This study used an online randomised experiment (N=1600) to test how design interventions, such as clearly demarcating space, removing visual obstacles and adding signage, influence perceptions across different shared spaces: pedestrian crossings, bus stop islands, car parking adjacent to cycle lanes, left turns across cycle lanes, and roundabouts. Participants were shown existing and AI-generated images of spaces with or without interventions. They rated the spaces for perceived safety, fairness, yielding frequency and injury risk. Interventions that removed visual obstacles and clearly demarcated space improved perceptions across pedestrians, cyclists, and drivers. Other interventions, such as legislative fine warnings or integrated (protected) roundabouts, had mixed or context-dependent effects. Moderation analyses indicated that interventions were as or more effective among individuals more worried about travel in daily life. These findings demonstrate that context-sensitive shared space design can harmonise perceptions across diverse road users, with implications for transport policy and urban design.

INTRODUCTION

International organisations such as the World Health Organisation (2022) and United Nations (2015) call for coordinated policies to tackle physical inactivity, poor health, pollution, and climate change. Active travel (i.e., walking and cycling) addresses these issues simultaneously by improving physical and mental health (Dinu et al., 2019; Hamer & Chida, 2008; Kelly et al., 2014; Kroesen & De Vos, 2020), cutting carbon emissions (Brand et al., 2021) and delivering economic and social benefits (Ding et al., 2024).

Despite its advantages, integrating active travel into constrained urban environments is challenging. One potential solution is shared spaces, where different road users occupy the same physical environment (Hamilton-Baillie, 2008; Karndacharuk et al., 2014). Examples include mixed-use roadways, pedestrian-cycle paths, and bus stop islands that route cycle lanes behind bus boarding areas (Transport for London, 2024). However, effectiveness depends not only on design but also on how shared spaces are perceived by different road users. Social cognitive theory emphasises that behaviour is shaped not only by objective environmental conditions but also by perceptions of those conditions (Bandura, 1986). Consequently, merely implementing infrastructure is insufficient (Timmons et al., 2024). For instance, cycling behaviour is influenced more by perceived environmental qualities than objective features (Ma et al., 2014).

Worry about travel-related incidents has been linked to risk perceptions and behaviour among both pedestrians (Kummeneje & Rundmo, 2019) and cyclists (Kummeneje et al., 2019). Perceptions related to travel safety are not evenly distributed across social groups. For example, women and older adults cycle less and report more negative perceptions of cycling environments (Kazemzadeh et al., 2024; Ma et al., 2014), and women express greater concern about cycling safety than men (Graystone et al., 2022). People with disabilities, including wheelchair users and those who are blind or partially sighted, likewise report challenges and heightened safety concerns when navigating shared spaces (Havik et al., 2015; Lawson et al., 2022). Taken together, these findings suggest that worry and negative safety perceptions are more pronounced among certain social groups, particularly across gender, age, and disability status.

Disparities in perceptions are exacerbated by a broader challenge: perceived safety can diverge from objective risk (Von Stülpnagel & Lucas, 2020; Winters et al., 2012). For example, collision data from London shows that cyclist-pedestrian crashes at bus stop islands are low compared to the wider network (Transport for London, 2024), yet many older adults and people with disabilities perceive these designs as unsafe (Low & O'Reilly, 2025; Walker, 2024). This case illustrates the challenge of designing infrastructure that is both objectively safe and perceived as safe, particularly for social groups whose confidence and mobility are potentially constrained.

Importantly, perceptions are malleable. The built environment can shape perceptions by improving visibility, predictability and separation between users (Ma et al., 2014). Effective interventions include coloured cycle lanes (Karlsen & Fyhri, 2020; Von Stülpnagel & Binnig, 2022), reducing visual obstructions such as roadside parking (Mukherjee & Mitra, 2022; Winters et al., 2012), and implementing physical separation (Lakoud et al., 2024; Vision Zero SF, 2021; Von Stülpnagel & Binnig, 2022). At roundabouts, separated cycle lanes improve cyclist safety (Jensen, 2017; Poudel & Singleton, 2021; Singleton & Poudel, 2023). For pedestrians, removing illuminated beacons at crossings reduces implementation and maintenance costs without reducing perceived safety (Jones et al., 2021). For drivers, infrastructure elements such as advance yield markings (Fisher & Garay-Vega, 2012), coloured surfaces, ramps and stripes (Anciaes et al., 2020) improve yielding behaviour. These examples imply that the design of shared spaces can improve both subjective and objective safety across user groups.

Building on this literature, the present study examines how infrastructure design shapes perceptions of shared road spaces. The study makes three novel contributions. First, we use an AI-assisted digital design tool to generate realistic representations of infrastructure interventions across a range of existing shared road spaces in Ireland. This approach enables systematic manipulation of design features and provides ecologically valid stimuli, offering a controlled yet realistic test of the designs. Second, by collecting detailed information on participants' everyday travel behaviour among a large nationally representative sample, we examine how perceptions differ across road-user groups and whether interventions that improve perceptions for one group (e.g., pedestrians) are similarly effective for others (e.g., cyclists and drivers). This multi-perspective approach contrasts with much prior research, which has focused on single user groups. Third, we adopt a multidimensional framework of perceived risk to measure perceptions, distinguishing affective responses (e.g., worry), cognitive assessments of the likelihood of a collision, and evaluations of the severity of its potential consequences. This framework has been successfully applied to other risk domains but not to perceived safety in shared spaces (Wilson et al., 2019). The approach allows us to parse intervention effects across risk components.

As well as risk perceptions, we measure perceived fairness as an indicator of public acceptance. The design of shared spaces must find a balance between the rights of way, safety and time advantages accorded to different users. Perceived fairness plays a central role in policy compliance (Tyler, 2003) and climate policy support (Bergquist et al., 2022). We also assessed knowledge of and confidence in priority rules (reported only in the Supplementary Material, available at https://osf.io/sxbkh/).

Our primary research question is whether infrastructure interventions improve perceptions of safety and fairness in shared spaces. We pre-registered (https://osf.io/sxbkh/) the hypothesis that interventions would reduce perceived danger and injury severity, while increasing perceived fairness and estimated yielding frequency. We further hypothesised that combining interventions would generate stronger effects.

Our second research question was whether the interventions are as effective for those with greater levels of general worry about transport. We tested this in two ways: first, by examining the association between general worry and perceived danger of shared spaces, and second by interacting worry with intervention type. Additionally, we conducted exploratory analysis to investigate perceived danger of shared spaces among those with disabilities, including those with mobility and/or visual impairments.

METHODS

Participants

This study was conducted in line with institutional ethics policy.

Our primary sample was recruited through the online panels of two leading market research agencies in Ireland (Red C and Ipsos B&A) using quota sampling for national representativeness by age, gender and region. Of 2190 individuals who entered the survey, 415 (18.9%) were screened out due to filled quotas and 55 (2.5%) exited during the screening questions. An additional 212 respondents passed the screening and quota checks but did not complete the survey, resulting in an attrition rate of 9.7%. Eight respondents (0.4%) were removed following data quality checks (Supplementary Methods). This resulted in a sample of 1500 participants (68.5% of those who initially entered), who completed the study between April and June 2025. These participants were paid €3 for taking part and were entered into a raffle for a €100 digital Mastercard voucher.

Given the specific challenges faced by people with disabilities, to improve representation we recruited an additional booster sample of 100 individuals via mailing lists of non-profit organisations providing services to people with disabilities in Ireland. The survey was adapted for screen-reader compatibility and keyboard navigation. To reduce burden for this voluntary sample, non-essential elements of the survey were omitted (further detailed in the Procedure section). Despite these efforts, the survey was inaccessible to some groups of people with disabilities and therefore their views are not represented. Of 165 consenting participants in this group, 65 did not complete the survey, resulting in an attrition rate of 39.4%. Higher attrition among participants with disabilities is consistent with known challenges in online survey participation (Christensen et al., 2025). Booster participants were entered into a separate Mastercard raffle for a €100 voucher without fixed financial compensation.

The final sample comprised 1600 participants. Table 1 shows their socio-demographic characteristics. The primary sample (n=1500) was broadly nationally representative, though with slightly more aged 18-39 years (40.1% vs. 36.9% nationally) and slightly more living in urban areas (70.3% vs. 63.6% nationally). Results are not sensitive to these discrepancies, as all models include controls for socio-demographic characteristics.

Across the full sample (N=1600), 538 (33.6%) reported having a disability (or long-term condition); 154 (9.6%) indicated having either a mobility impairment (98, 6.1%) or visual impairment (52, 3.3%) or both (4, 0.3%). Linear regression models showed no significant differences between these groups in perceived danger across the six shared spaces (p_{all}>0.100), so we combined those with visual and/or mobility impairments into a single category for exploratory analyses of perceived danger, to maintain statistical power.

Examining general travel habits among the full sample, 1340 participants (83.8%) reported driving at least occasionally (i.e., any response other than “Never” for driving frequency). 557 (34.8%) reported cycling at least occasionally, a somewhat higher rate than Central Statistics Office data from 2021 (CSO, 2021). The discrepancy likely reflects rising cycling participation in Ireland in recent years - up over 10% between 2019 and 2021 - and underrepresentation of adults aged over 75 in our sample. From a statistical power perspective, the possible overrepresentation of cyclists is beneficial, as our analysis focuses on comparisons between groups rather than precise population point estimates. Among the drivers, 833 (52.1% of the total sample) reported never cycling, whereas only 47 (2.9% of the total sample) reported cycling at least occasionally but never driving.

Table 1. Socio-demographics (numbers and proportions) of the total sample (N=1600), participants recruited through the market research companies (n=1500), the booster sample (n=100), and nationally representative proportions, as estimated by the Central Statistics Office (CSO, 2022).

		Total sample (N=1600)	Primary sample (n=1500)	Booster sample (n=100)	Ireland census data
Gender	Male	772 (48.25)	732 (48.80)	40 (40.00)	(48.9)
	Female	820 (51.25)	765 (51.00)	55 (55.00)	(51.1)
	Non-binary	6 (0.38)	2 (0.13)	4 (4.00)	NA
	Prefer not to say	2 (0.13)	1 (0.07)	1 (1.00)	NA
Age	18 to 39 years	665 (41.56)	602 (40.10)	63 (63.00)	(36.9)
	40 to 59 years	532 (33.25)	509 (33.90)	23 (23.00)	(36.4)
	60+ years	403 (25.19)	389 (26.00)	14 (14.00)	(26.7)
Education	Leaving Cert. or below	941 (58.81)	880 (58.70)	61 (61.00)	(56.1)
	Any tertiary education	659 (41.19)	620 (41.30)	39 (39.00)	(43.9)
Living area	Urban	1131 (70.69)	1054 (70.30)	77 (77.00)	(63.6)
	Rural	469 (29.31)	446 (29.70)	23 (23.00)	(36.6)
Region+	Dublin	415 (25.94)	390 (26.00)	25 (25.00)	(29.0)
	Outside of Dublin	1182 (73.88)	1110 (74.00)	72 (72.00)	(71.0)

+ n=3 missing region data from the booster sample.
Note: The CSO does not provide estimates for “non-binary” or “prefer not to say” gender categories (NA values). Additionally, the CSO estimate for area of residence is based on 2019 data, rather than 2022. The CSO estimate for educational attainment excludes those who did not report their attainment (i.e., who reported their status as ‘other’, who did not state a level or who reported being in education without stating the level of education attained).

Procedure

Participants completed the survey online using Alchemer. The survey link was distributed to market research panellists through the agency and to mailing lists maintained by disabled persons’ organisations. Figure 1 shows the overall survey structure, which is outlined below.

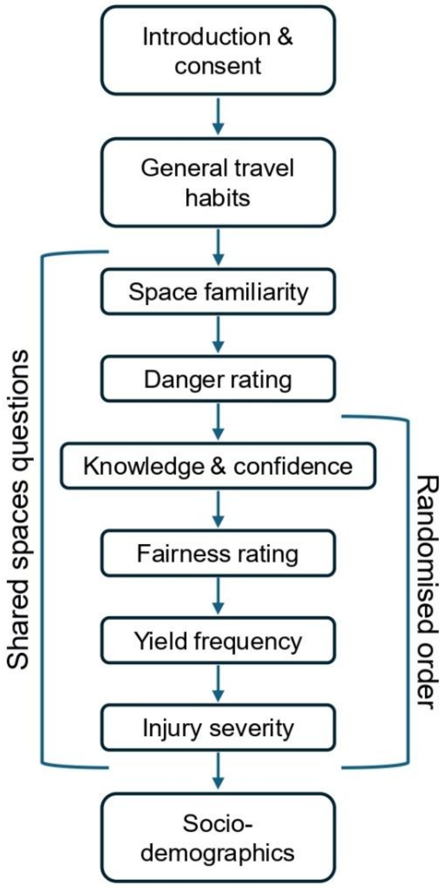

Figure 1. Survey Structure.

General travel habits

After providing consent, participants reported their general travel behaviours, including frequency and duration of walking or wheelchair use, cycling, driving, and using public transport. They also rated how worried they are when using each endorsed mode of transport in their daily lives, from 1 (not at all worried) to 7 (extremely worried). Participants reported a broad range of worry levels for each transport mode, with responses distributed across the full scale (Figure S1).

Shared spaces

Next, participants evaluated six shared spaces, selected based on consultation with the National Transport Authority. For roundabouts, real-world designs were available within the same area of Dublin. Photographs of the roundabouts (control and interventions) were captured at the same time of day and under similar weather conditions. For all other shared spaces, no existing sites in County Dublin matched the desired intervention scenarios, necessitating the use of AI-assisted generation to create realistic and controlled representations for experimental comparison. Intervention versions of each shared space (except for the roundabout conditions) were generated using manual and AI-assisted editing of the photographed control condition through Canva. For each shared space, participants were randomly assigned to one of four designs (Figure 2 for illustrative examples):

1. **Bus Stop Island:** Control condition: a standard bus stop island; Intervention 1: the control condition with a ramp and pedestrian crossing over the cycle lane; Intervention 2: intervention 1 with the addition of a pedestrian crossing sign featuring a high-visibility yellow border; Intervention 3: intervention 2 with added signage warning “IRISH LAW YIELD” and “€40 FINE,” including an Irish-language translation.
2. **Left Turn on Cycle Lane (Location A):** Control condition: a standard left-turn configuration with adjacent cycle lane; Intervention 1: the control condition with added ground paint indicating a left turn and a yield symbol; Intervention 2: the control condition with bins and parked cars replaced by bollards and ground markings to prohibit parking; Intervention 3: a combination of interventions 1 and 2.
3. **Left Turn on Cycle Lane (Location B):** Control condition: a standard left-turn configuration with adjacent cycle lane; Intervention 1: the control condition with additional traffic lights for cyclists; Intervention 2: the control condition with more visible red paint on the cycle lane, plus bollards and concrete islands separating the cycle lane from traffic; Intervention 3: a combination of interventions 1 and 2.
4. **Parking Adjacent to the Cycle Lane:** Control condition: a standard parking configuration with adjacent cycle lane; Intervention 1: the control condition with a bike symbol painted on the cycle lane; Intervention 2: the control condition with more visible red paint on the cycle lane; Intervention 3: a combination of interventions 1 and 2.
5. **Pedestrian Crossing:** Control condition: a standard pedestrian crossing; Intervention 1: the control condition with a high-visibility yellow border on the pedestrian crossing sign; Intervention 2: the control condition with a parked car replaced by ground markings prohibiting parking; Intervention 3: a combination of interventions 1 and 2.
6. **Roundabout:** Control condition: a traditional roundabout without any dedicated pedestrian or cycle crossing; Intervention 1: a roundabout with a dedicated pedestrian path and crossing point; Intervention 2: a roundabout with both pedestrian and cycle paths and dedicated crossing points; Intervention 3: an integrated roundabout design with separated cycle lanes and overt pedestrian and cycle crossings. This is also known as a protected roundabout, as defined in the National Transport Authority’s Cycle Design Manual (2023).

Because all shared spaces were actual locations in County Dublin, participants first reported their familiarity with each space, in randomised order. Participants saw the same version for each space throughout the experiment. Hence, presenting participants with the full set of shared-space images at the outset allowed them to calibrate their responses on the rating scales, thereby reducing the risk of floor or ceiling effects, as all shared spaces were viewed prior to any rating questions. Most participants (60-87%) were unfamiliar with the spaces, aligning with proportion living outside Dublin.

Participants then rated each space, again in randomised order, on how dangerous they perceived it to be, from 1 (not at all dangerous) to 7 (extremely dangerous), from the relevant user perspective (pedestrian, cyclist, or driver) depending on the space (as indicated by the icons in Figure 2) and their own travel habits.

After the danger rating for each space, participants answered four follow-up questions in randomised order:

1. **Perceived fairness**, from 1 (not at all fair) to 7 (extremely fair).
2. **Severity of injury consequence:** participants rated how injured a vulnerable road user would likely be if a collision occurred, from 1 (not at all injured) to 7 (extremely injured).
3. **Estimated yielding frequency:** Participants estimated, on a discrete scale from 0 to 10, how many of the ten drivers or cyclists, depending on the space, would yield to the more vulnerable road user, as relevant.
4. **Knowledge accuracy and confidence:** Participants indicated who has the right of way and rated their confidence in this response from 1 (guessing) to 6 (certain). These responses are reported in the Supplementary Results (https://osf.io/sxbkh/).

These questions were presented on individual pages to minimise carryover effects. The process was repeated for all six spaces in randomised order.

Socio-demographics

Finally, participants completed a sociodemographic questionnaire, on age, gender, living area, educational attainment, disability status and chronic health conditions. Participants could also report any difficulties experienced during the survey and disclose if there was any reason their data might be unusable for analysis.

The instrumentation for the full study, including additional questions administered only to the primary sample, is available at https://osf.io/sxbkh/. Results from a quiz on the rules of the road, completed by the primary sample only (n=1500), are reported in the Supplementary Results.

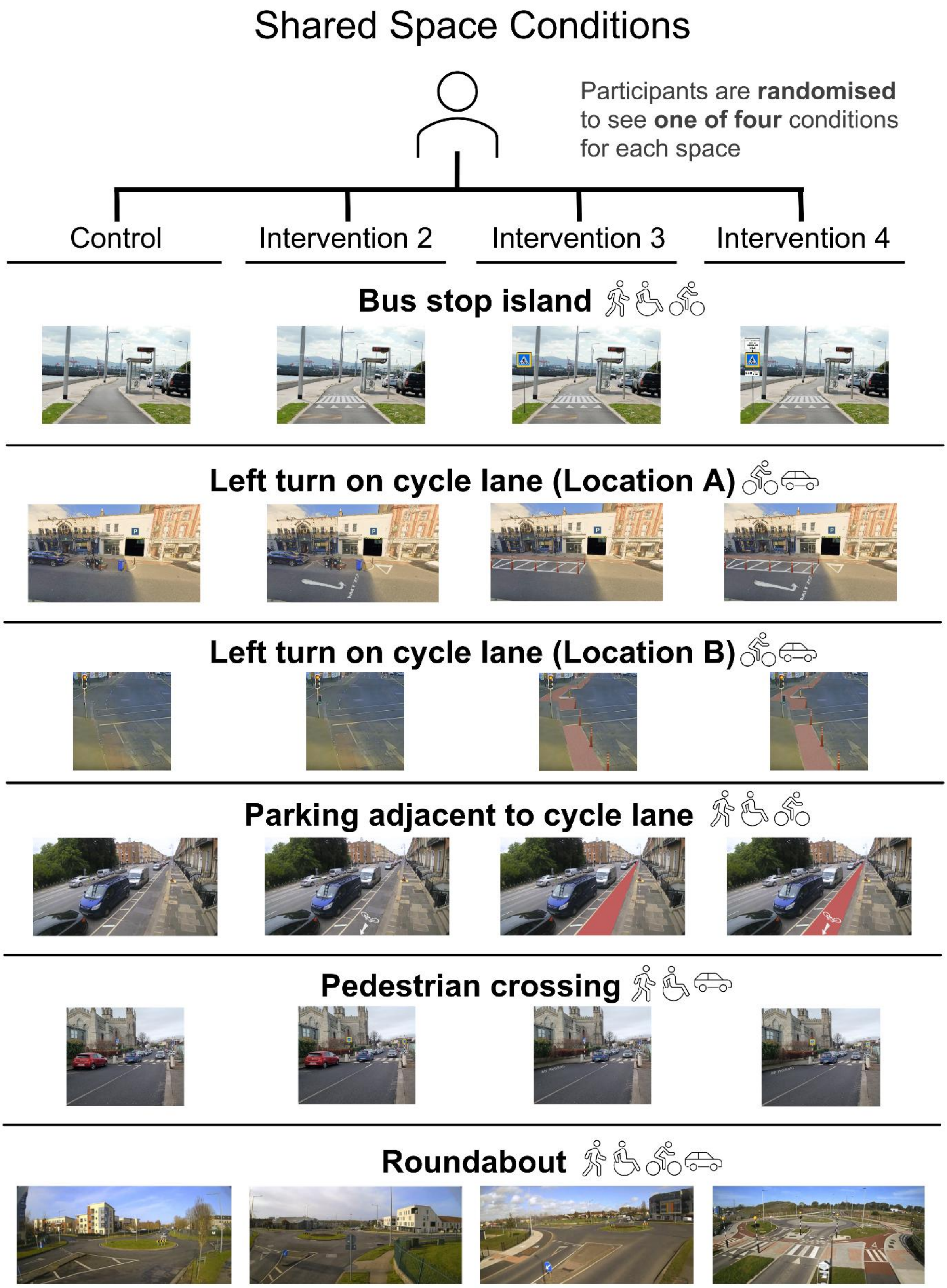

Figure 2. Conditions of the six shared spaces. Each space had four conditions: one control and three interventions. Icons indicate the perspective participants used when rating each space: pedestrian (walking or using a wheelchair), cyclist, or car driver.

Statistical analysis

Research question 1: Do interventions affect perceptions of safety, fairness, yielding and injury risk?

We report ordinary least squares (OLS) regression analyses for perceived danger, fairness, estimated frequency of yielding and injury severity (using the lm function in R). As a robustness check, ordinal regressions were also undertaken. Intervention type was the primary independent variable of interest, with the control condition as the reference. Analyses were conducted separately for each shared space. Covariates included age group (18-39 [reference], 40-59, 60+), gender (female [reference], male, non-binary/prefer not to say), education (below undergraduate [reference], undergraduate or above), region of residence (County Dublin [reference] vs. outside of County Dublin), and residential area type (rural [reference] vs. urban):

Outcome (danger, fairness, yielding, injury severity) ~ intervention type (control as reference) + age + gender + education + region + urban

Models were stratified by perspective (pedestrian, cyclist, or driver) to account for differences in viewpoint, with pairwise comparisons of adjusted means to assess differences in the magnitude of intervention effects. We additionally tested whether certain intervention effects on perceived danger were dependent on relevant participant characteristics (e.g., cycling status: never vs. at least less than monthly; public transport use: never vs. at least less than monthly).

Research question 2a: Is perceived danger of shared spaces associated with general levels of transport worry?

To assess whether general worry was associated with perceived danger, we estimated separate OLS regression models for each space aligned by perspective (using the lm function in R). For example, for the bus stop island, the specification was:

Danger rating (from pedestrian perspective) ~ general worry (pedestrian perspective) + age + gender + education + region + urban

Exploratory analyses added general disability status (disability vs. no disability), and specific visual/mobility impairment status (visual or mobility impairment vs. other disability vs. no disability) separately as additional covariates.

Research question 2b: Do intervention effects on perceived danger depend on levels of general transport worry?

To examine whether intervention effects were dependent on general levels of worry, the worry variable was matched to the corresponding danger perspective, for example:

Danger rating (pedestrian perspective) ~ intervention type × general worry (pedestrian perspective) + age + gender + education + region + urban

All analyses were conducted in R (v.2024.04.2) using two-tailed significance tests with $p<0.050$. Tukey adjustments were made for multiple comparisons for all pairwise contrasts. Dependent variables and continuous predictors were z-scored to obtain standardised regression coefficients. Methods and analyses were preregistered on the Open Science Framework, where the analysis code and data are also available (https://osf.io/sxbkh/).

RESULTS

Research questions 1 & 2b: Effects of interventions on perceived danger, fairness, yielding and injury risk, and moderation of perceived danger effects by general transport worry.

Figures 3 and 4 present OLS regression results for intervention effects on perceived danger (Figure 3A), fairness (Figure 3B), estimated yielding frequency (Figure 4A), and estimated injury severity (Figure 4B), controlling for age, gender, education, region, and urban-rural residency. Results were robust to ordinal regression analyses (Supplementary Results, Figure S6).

Perceptions of danger and fairness

Bus stop island

Relative to other shared spaces, both pedestrians and cyclists perceived the control bus stop island as the safest and among the fairest spaces (Figure 5A-B). The combined intervention, which included a ramp, a crossing sign with a pedestrian symbol and legislative fine warning, increased perceived danger for pedestrians and cyclists (Figure 3A). For pedestrians, this effect was not dependent on general worry or whether they cycled, but a significant interaction with public transport use emerged: the intervention increased perceived danger more strongly among non-users of public transport than users.

The legislative fine intervention significantly increased fairness perceptions among pedestrians but not cyclists (Figure 3B). Cyclists' fairness ratings for the bus stop island were generally high (Figure S4). Among pedestrians, Tukey-adjusted tests showed that the ramp plus high-visibility sign was perceived as slightly more fair than the ramp alone. The legislative fine was perceived as significantly more fair than the ramp alone, but not more fair than the ramp plus high-visibility pedestrian sign.

Left turn on cycle lane (Locations A and B)

Comparing the control conditions of the six shared spaces, drivers and cyclists perceived left-turning car interactions across cycle lanes as more dangerous and less fair (Figure 5A-B). At both left-turn locations, cyclists perceived these spaces as significantly less dangerous when physical bollards were introduced (Figure 3A). Bollards also increased cyclists' perceptions of fairness (Figure 3B). For drivers, bollards also significantly reduced perceived danger and increased fairness, though the increase at Location B was not statistically significant. Pairwise comparisons indicated that, beyond the introduction of bollards, the addition of neither ground paint (Location A) nor cycle lights (Location B) further improved perceived danger or fairness. Bollard intervention effects on perceived danger held regardless of drivers' cycling habits, as no significant interactions were observed between the bollards intervention and cycling experience for either location.

When general worry was included as an interaction term, a significant effect emerged at Location B: the bollards reduced the positive association between general worry about cycling and perceived danger, indicating the intervention was particularly effective for individuals who worry more about cycling in daily life. No such moderation occurred at Location A, where bollards reduced cyclists' perceived danger regardless of worry levels about cycling in daily life. For drivers, the bollards effect on perceived danger was not dependent on general worry about driving in daily life at either location.

Car park adjacent to cycle lane

When car parking was present adjacent to a cycle lane, both adding a bike symbol alone and adding a bike symbol with red paint significantly reduced cyclists' perceived danger (Figure 3A) and increased fairness (Figure 3B). From a pedestrian perspective, all interventions slightly reduced perceived danger, while none of the interventions affected fairness. Tukey tests indicated that combining the bike symbol with red paint did not produce greater effects on perceived danger and fairness than either intervention alone. The bike symbol intervention weakened the positive link between worry and perceived danger, indicating greater effectiveness among those with higher worry as a pedestrian. For cyclists, the intervention effects on perceived danger held regardless of general worry about cycling in daily life.

Pedestrian crossing

All interventions significantly reduced perceived danger for pedestrians and drivers compared to the control (Figure 3A). The combined intervention (fluorescent-bordered pedestrian sign plus removal of adjacent parking) produced the largest reduction for pedestrians and drivers. Tukey-adjusted contrasts indicated that the combined intervention reduced perceived danger more than the sign-alone condition, but did not differ significantly from parking removal alone. Interaction analyses showed that these intervention effects were not moderated by general worry levels, as a pedestrian or driver.

Results for fairness followed a similar pattern, as the combined intervention significantly increased perceived fairness for pedestrians and drivers. Parking removal alone increased fairness among pedestrians, though the equivalent effect for drivers did not reach statistical significance. The combined intervention did not differ significantly from parking removal alone for either pedestrians or drivers. The fluorescent-bordered pedestrian sign increased perceived fairness for pedestrians, not drivers.

<u>Roundabouts</u>

Pedestrians viewed the roundabout as the most dangerous and least fair of all the shared space control conditions (Figure 5A-B). Similarly, cyclists rated roundabouts as relatively more dangerous and less fair. In contrast, drivers perceived roundabouts as relatively safer and fairer, highlighting a divergence between user groups for this space (further detailed in the Supplementary Results).

The integrated roundabout (including segregated cycle lanes and dedicated crossings for cyclists and pedestrians) decreased pedestrians' and cyclists' perceptions of danger and increased perceived fairness. In contrast, drivers perceived integrated roundabouts as significantly more dangerous and less fair, relative to the control roundabout. These effects were not dependent on general levels of worry for any travel mode.

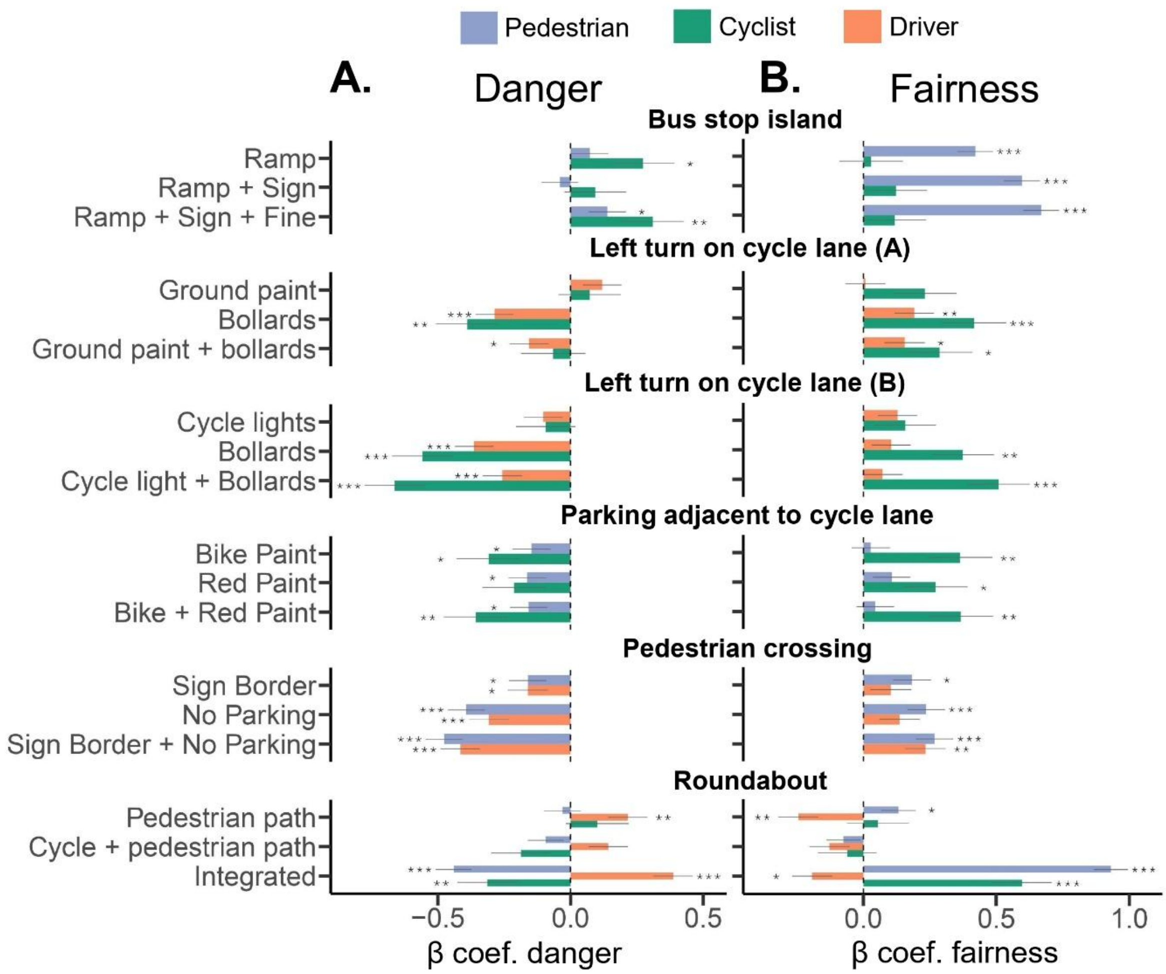

Figure 3. Effects of the interventions in each shared space on (A) perceived danger, and (B) perceived fairness. Bars represent standardised beta coefficients (β coef.), and error bars indicate the standard error from the regression model. All models control for age, gender, education, urban/rural residence, and region of residence in Ireland.

Estimated yielding frequency and injury severity

Across all participants, estimated yielding frequency and injury severity were perceived higher in spaces involving direct driver-pedestrian or driver-cyclist interactions (Figure 5C-D).

At the bus stop island, cyclists were estimated to yield to pedestrians significantly more frequently under all interventions (Figure 4A). Tukey-adjusted tests showed that adding the legislative fine warning did not significantly increase estimated yielding beyond the ramp plus sign intervention.

Bollards increased estimated yielding frequency of drivers turning left across a cycle lane at Location A but had no effect at Location B. The strongest effect on estimated yielding was for the integrated roundabout. Average estimated yielding increased from 3.67 (SD=2.76) to 6.36 (SD=2.63) out of 10 cars. Interventions at the pedestrian crossing and the parking adjacent to the cycle lane did not significantly change estimated yielding frequency (Figure 4A). Robustness checks using Poisson regression produced similar results (Supplementary Results, Figure S7).

At Location B, estimated injury severity was significantly lower with bollards alone or bollards plus cycle lights. No significant injury severity effects were observed at Location A or any other shared space (Figure 4B).

Table 2 provides a summary of the intervention effects for each shared space. Intervention effects on priority knowledge and confidence are outlined in the Supplementary Results (Figure S5).

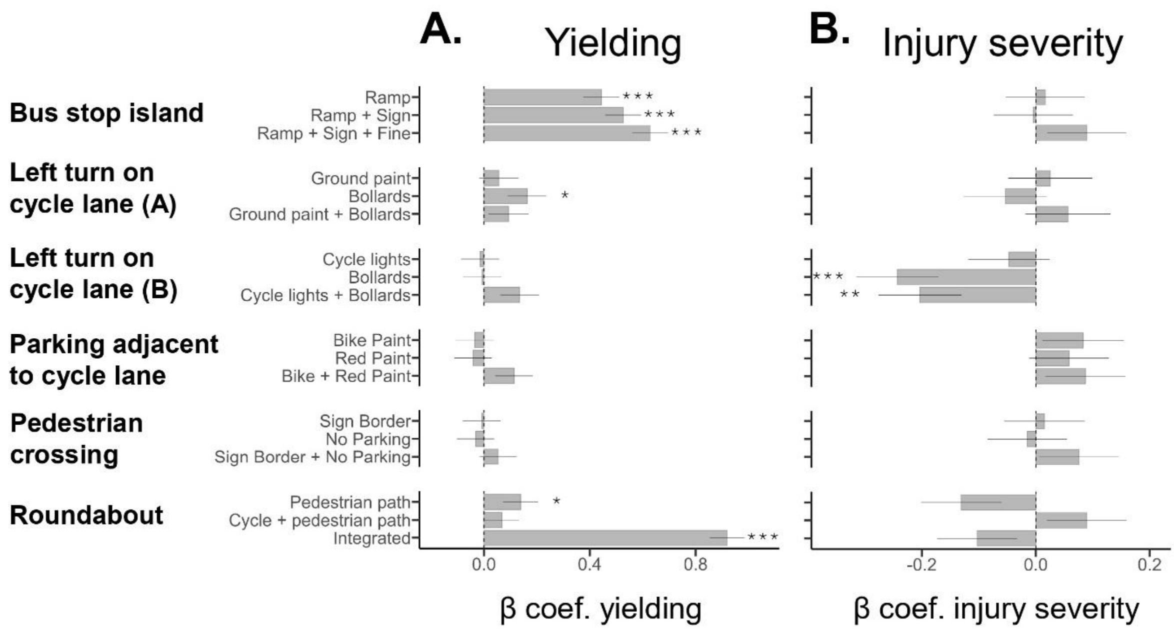

Figure 4. Effects of the interventions in each shared space on (A) estimated yielding frequency, and (B) estimated injury severity. Bars represent standardised beta coefficients (β coef.), and error bars indicate the standard error from the regression model. All models control for age, gender, education, urban/rural residence, and region of residence in Ireland.

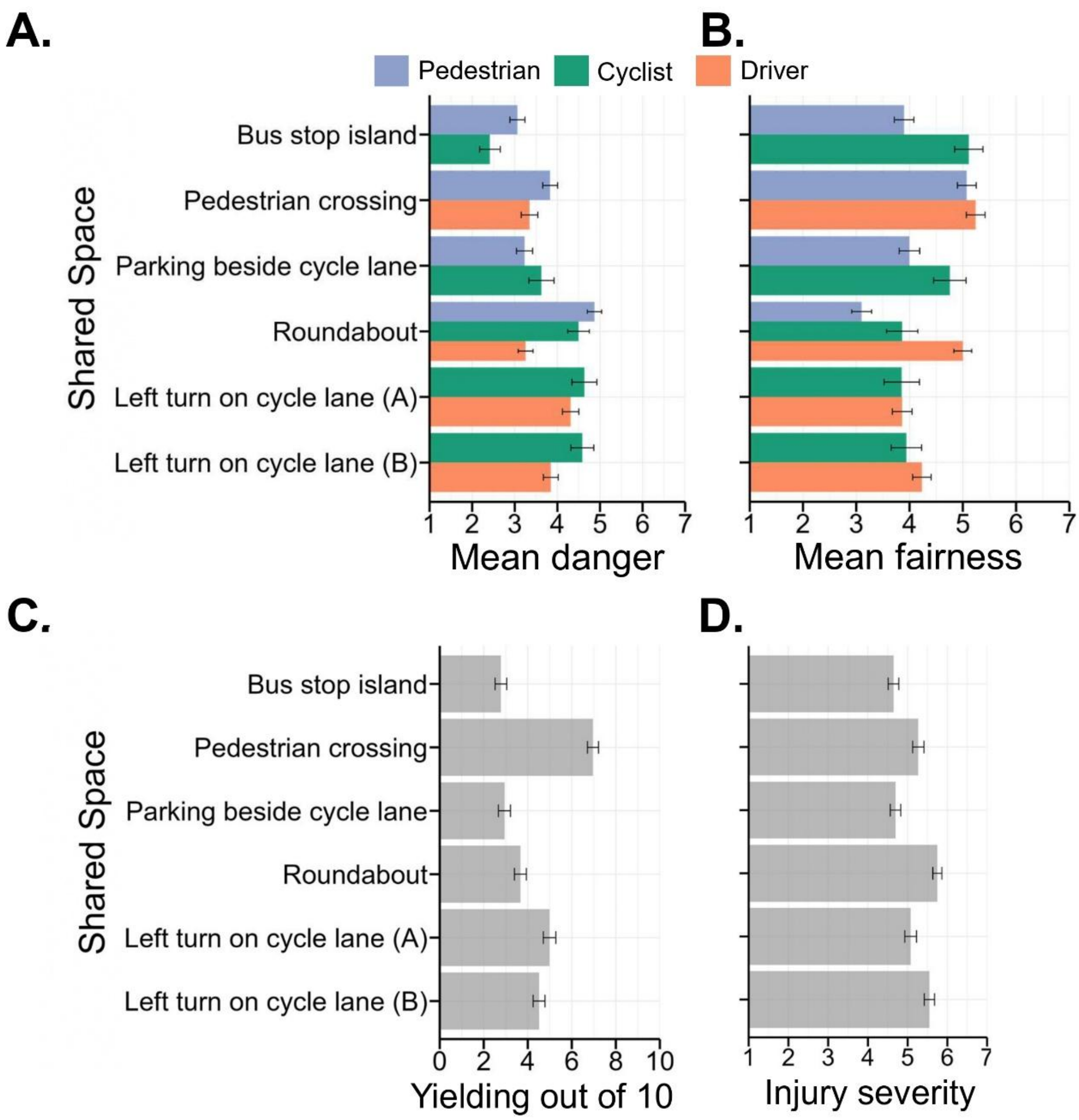

Figure 5. Perceptions of danger (A), fairness (B), estimated yielding frequency (C), and expected injury severity (D) for control conditions of each shared space. Plots A-D show mean ratings with error bars representing 95% confidence intervals. A complete statistical summary for this figure is provided in the Supplementary Results.

Table 2. Summary of intervention effects on perceived danger, fairness, expected yielding and expected injury severity

Space	Perceived Danger	Fairness	Expected Yielding	Expected Injury Severity
Bus Stop Island				
Ramp	Increased among cyclists only	Increased among pedestrians only	Increased	No effect
Ramp + Sign	No effect	Increased among pedestrians more than the Ramp alone	Increased	No effect
Ramp + Sign + Fine	Increased among pedestrians and cyclists	No additional effect for pedestrians beyond Ramp + Sign	No additional effect beyond Ramp + Sign	No effect
Left Turn on Cycle Lane (A)				
Ground Paint	No effect	No effect	No effect	No effect
Bollards	Reduced among cyclists and drivers	Increased among cyclists and drivers	Increased	No effect
Ground Paint + Bollards	No additional effect beyond Bollards	No additional effect beyond Bollards	No effect	No effect
Left Turn on Cycle Lane (B)				
Cycle Lights	No effect	No effect	No effect	No effect
Bollards	Reduced among cyclists and drivers	Increased among cyclists	No effect	Reduced
Cycle Lights + Bollards	No additional effect beyond Bollards	No additional effect beyond Bollards	No effect	Reduced
Parking Adjacent to Cycle Lane				
Bike Symbol	Reduced among pedestrians and cyclists	Increased among cyclists only	No effect	No effect

Ground Paint	Reduced among pedestrians only	Increased among cyclists only	No effect	No effect
Bike Symbol + Ground Paint	No additional effect above Bike Symbol or Ground Paint	No additional effect above Bike Symbol or Ground Paint	No effect	No effect
Pedestrian Crossing				
Sign Border	Reduced among pedestrians and drivers	Increased among pedestrians only	No effect	No effect
No Parking	Reduced among pedestrians and drivers	Increased among pedestrians and marginally for drivers*	No effect	No effect
Sign Border + No Parking	No additional effect above No Parking	No additional effect above No Parking	No effect	No effect
Roundabout				
Pedestrian Path	Increased among drivers only	Increased among pedestrians but decreased among drivers	Increased	No effect
Cycle + Pedestrian Path	No effect	No effect	No effect	No effect
Integrated	Decreased among pedestrians and cyclists but increased among drivers	Increased among pedestrians and cyclists but decreased among drivers	Increased	No effect

Note: The presence of an effect is indicated by $p<0.05$ in statistical models.
* $p=0.073$ for the marginal effect among drivers.

Research question 2a: Is perceived danger of shared spaces associated with general levels of worry?

Cyclists reported the highest general worry (M=4.15, SD=1.70), followed by drivers (M=3.73, SD=1.73) and pedestrians (M=3.21, SD=1.79). Linear mixed-effects models, controlling for socio-demographics and including participant random intercepts, confirmed that these differences were statistically significant. Specifically, worry was lower for walking/using a wheelchair and driving compared to cycling.

Examining socio-demographic correlates of general worry from a pedestrian perspective, male participants reported lower worry than female participants, and participants in urban areas reported slightly higher worry than those in rural areas, while no significant associations were observed for age, education, or region.

Across all spaces, higher levels of daily-life worry about transport were significantly associated with greater perceived danger for the more vulnerable road user (Figure 6). A one-standard deviation increase in worry corresponded to a 0.13 to 0.21 standard deviation increase in perceived danger, depending on the space. Thus, people who worry more about transport tend to view all of these shared environments as more dangerous, even after accounting for socio-demographic characteristics.

Exploratory analyses showed that, on average, those with a disability reported more worry about daily-life travel by foot or wheelchair (M=3.49, SD=1.82) than those without a disability (M=3.07, SD=1.77), controlling for socio-demographics. Adding disability status to the models above (i.e., controlling for general worry and socio-demographics) revealed no significant associations with perceived danger from a pedestrian perspective at the bus stop island, the pedestrian crossing, the roundabouts, parking adjacent to a cycle lane, or from a cyclist perspective at the left turns on cycle lanes. Removing general worry from the models did not change the results.

Individuals with visual or mobility impairments reported higher worry about navigating public spaces (M=3.90, SD=1.98) than those with other disabilities (M=3.32, SD=1.72) or no disability (M=3.07, SD=1.77). Using visual or mobility impairment as the reference, worry was significantly lower among individuals with other disabilities and individuals with no disability, controlling for socio-demographics.

Replacing general disability status with visual/mobility impairment status (yes/other disability/no disability) in the models (i.e., controlling for general worry and socio-demographics) showed no significant differences in perceived danger across the shared spaces for those with visual or mobility impairments versus no disability. Rerunning these models without general worry as a covariate yielded the same pattern.

In summary, those with higher levels of worry about navigating public spaces in their daily lives perceived shared spaces as significantly more dangerous. Relative to socio-demographic characteristics (age, gender, education living area, urban/rural status, general disability status and current visual/mobility impairment), general travel-related worry was the only factor that consistently correlated with perceived danger across all shared spaces.

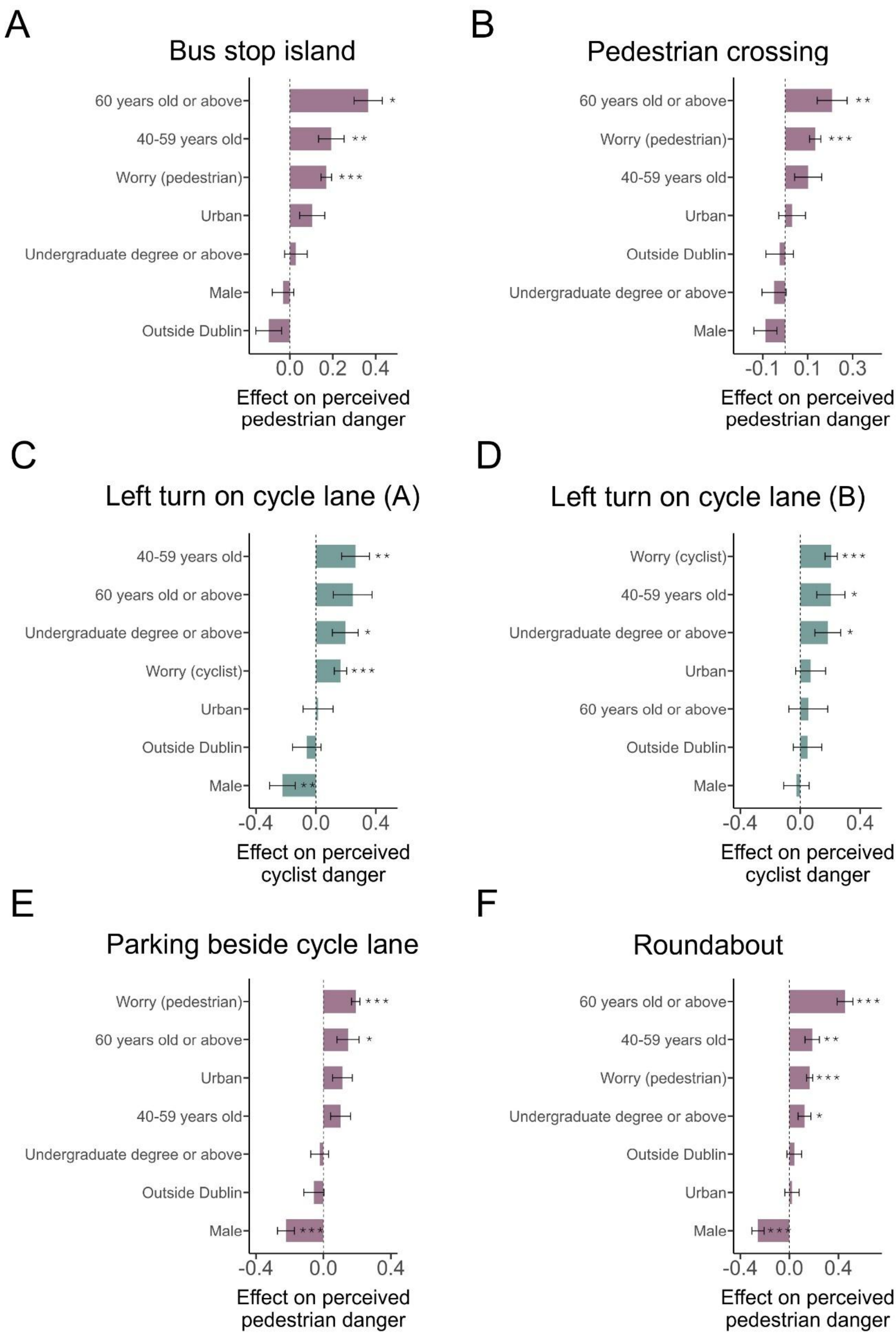

Figure 6. Regression coefficients showing the relationship between perceived danger for each shared spaces and general worry about transport and other demographic variables, for pedestrian (purple) and cyclist (green)

perspectives. Bars represent standardised beta coefficients, and error bars indicate the standard error from the regression model. Coefficients are ordered from the strongest positive to the strongest negative for each space.

DISCUSSION

This study examined how design interventions influence perceived safety and fairness from the perspectives of pedestrians, cyclists, and drivers. The multi-perspective approach enabled direct comparison of how these different road-user groups respond to the same infrastructure changes. By incorporating participants' everyday travel behaviour, we identified when interventions generate shared benefits and when they entail trade-offs.

Perhaps surprisingly, perceptions of safety and fairness were often aligned across different road users (Table 2). Interventions such as bollards at left turns across cycle lanes and removing parking adjacent to crossings were consistently rated as safer and fairer across perspectives, building on prior research from a single road user's perspective (e.g., Mukherjee & Mitra, 2022; Von Stülpnagel & Binnig, 2022; Winters et al., 2012). Given these findings, measures that prioritise vulnerable road users (i.e., pedestrians and cyclists) have the potential to enhance perceived safety and fairness while maintaining driver support, thereby increasing overall acceptance among all road users (Bergquist et al., 2022; Tyler, 2003).

However, not all interventions produced the hypothesised improvements in safety and fairness perceptions. At the bus stop island, adding a legislative fine warning to the pedestrian crossing sign increased perceived danger among both pedestrians and cyclists. The warning was intended to motivate yielding by cyclists and expectations of yielding among pedestrians, but may have instead amplified the salience of potential hazard (Choi et al., 2025; Clarke et al., 2021). While the warning increased perceptions of fairness among pedestrians and expectations of yielding, these effects were no greater than those from the standard pedestrian crossing sign and ramp, suggesting limited added value (see also Arhin et al., 2022). Similarly, in parking-adjacent cycle lanes, a simple bike symbol enhanced cyclist's perceptions of safety and fairness, but analyses in the Supplemental Material show it reduced accuracy in identifying pedestrian priority. These findings highlight the risk of unintended consequences of intervention design and, therefore, underscore the benefit of pre-testing interventions.

There were also instances where responses of the different road-user groups diverged. Pedestrians and cyclists perceived roundabouts as less safe and fair than other spaces, consistent with other evidence (Singleton & Poudel, 2023). The integrated roundabout significantly improved perceived safety and fairness for these groups, aligning with studies that show benefits of separated bicycle facilities (Jensen, 2017; Poudel & Singleton, 2021; Singleton & Poudel, 2023). In contrast, drivers rated the control roundabout as relatively safer and fairer compared to the other spaces, with ratings declining when the design was integrated. This divergence may reflect cultural norms that roads, and traditional roundabouts in particular, are driver-priority spaces. Integrated designs challenge these expectations by reallocating space and priority, consistent with a reduction in perceived fairness among drivers. They also increase the complexity of the driving environment (e.g., more yielding points, greater interactions), which can elevate driver stress (Ye et al., 2025). While perhaps unwelcome for drivers, this response may be beneficial for safety. Prior research shows that simple interventions like ground paint and ramps (Anciaes et al., 2020) or advanced yield markings (Fisher & Garay-Vega, 2012) promote driver yielding to pedestrians. Similarly, our study found that the integrated roundabout produced the largest improvements in expected driver yielding behaviour and right-of-way knowledge (Supplemental Material). Therefore, increased danger perception among drivers may encourage more cautious driving and greater yielding, enhancing safety for all road users.

Taken together, the results highlight the value of using AI-generated, visually realistic representations to pre-test infrastructure designs. By evaluating perceptual responses across multiple shared spaces in a controlled way, this approach goes beyond single-site studies. The findings show that responses to infrastructure interventions can demonstrate consistency across contexts and perspectives, strengthening generalisability. Furthermore, this study demonstrates that online randomised experiments provide a cost-effective avenue to gather foundational evidence before real-world construction of active travel infrastructure.

Finally, the strongest and only consistent correlate of perceived danger was general worry about travel in daily life, exceeding the influence of socio-demographic factors such as age, gender, education, disability status or certain disability types (visual and mobility impairments). This finding extends prior research that links travel-related worry to risk perceptions among pedestrians and cyclists (Kummeneje & Rundmo, 2019; Kummeneje et al., 2019) and highlights worry as a psychological mechanism behind why diverse road-user groups perceive heightened danger in shared spaces. Although worry may be justified where objective risks and accessibility challenges exist, these findings suggest that variation in perceived safety may be better explained by travel-related anxiety than fixed demographic traits or features of the environment. Importantly, however, levels of general worry are not evenly distributed: individuals with disabilities, particularly visual or mobility impairments, report higher worry, consistent with prior research (Havik et al., 2015; Lawson et al., 2022), underscoring the need for equitable and accessible intervention design.

From an intervention perspective, the consistent association between general worry and perceived safety has practical implications. In environments with relatively low objective risk, training- and education-based interventions that address general worry about navigating public spaces may be promising complements to structural safety improvements, though their effectiveness requires further experimental validation. In our analyses, several interventions boosted perceived safety across participants, and effects were sometimes stronger among individuals with higher levels of worry. This suggests that targeted deployment may be most beneficial where travel-related worry is more pronounced, particularly when co-designed with affected communities and integrated with ongoing efforts to enhance physical accessibility and safety.

Limitations & Future Directions

Several limitations should be acknowledged. First, our study relied on perceived safety and expected behaviour only, rather than observational or objective collision data. While these measures provide valuable insights into psychological mechanisms, they are proxies and may not predict actual behaviour or changes in safety. Future research that triangulates perceptual findings with longitudinal or naturalistic measures of behaviour and collisions would be beneficial.

Second, the use of static, daylight images with minimal presence of road users enhanced experimental control but may have constrained ecological validity. Real-world perceptions may be shaped by dynamic factors such as time of day, weather and traffic density. For example, the fluorescent-bordered pedestrian sign we tested may perform better under low-light conditions. Future work could explore more realistic and immersive stimuli, such as virtual reality, travel simulators or field-based pilots to investigate this variability (e.g., Kwon et al., 2022).

Third, effects on estimated injury severity were minimal, with reductions observed only for bollards at one left-turn location. This limited sensitivity may reflect a view that collisions in these scenarios are likely to result in serious injury regardless of infrastructure. While this measure provides a more complete account of how interventions shape perceptions of risk (Wilson et al., 2019), future studies could explore whether other forms of infrastructure interventions (e.g., traffic slowing measures) influence injury severity perceptions.

Fourth, while we included diverse road users, subgroup analyses were constrained by sample sizes, particularly for individual types of disabilities. Moreover, individuals who lack the capacity or access to complete online studies were underrepresented. These groups likely face distinct challenges navigating shared spaces. Addressing this gap, for example through participatory approaches that focus on the experiences of underrepresented groups, would enhance both equity and effectiveness, ensuring interventions are inclusive and responsive to the needs of road users most at risk.

Conclusion

This study demonstrates that design interventions meaningfully influence perceptions of safety, fairness and risk in shared spaces. Across pedestrians, cyclists, and drivers, infrastructure that clarifies right-of-way, demarcates space and removes visual obstructions generally improves perceptions, supporting safer and fairer road-user interactions. However, some interventions produced unintended effects, such as heightened perceived danger or reduced perceived fairness among certain groups. This highlights the need to carefully consider and preferably pre-test the diverse experiences of road users when designing shared spaces.

Overall, the results indicate that relatively simple, low-cost infrastructure changes can meaningfully improve perceptions of safety and fairness in shared spaces across user groups, demonstrating that good design can align perspectives rather than divide them. While perceptual improvements do not guarantee behavioural change, they are a precursor to engagement with active travel that can foster healthier and more sustainable communities.

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