Transportation Research Part F: Psychology and Behaviour 99 (2023) 113–126

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

Pedestrian behaviour in integrated street designs: A mesoscopic analysis

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A R T I C L E   I N F O

Keywords:
Pedestrians
Behaviour
Integrated street design
Mesoscopic analysis
Video observation

A B S T R A C T

Recent trends in urban design have called for more equal treatment of all road users and have effected a shift away from the traditional concept of segregation and towards more integration. This usually translates to more pedestrian-friendly layouts with wider footways, fewer protective guardrails and lower (or even no) kerbs. Following-on from previous research on the topic, this study explores changes in pedestrian behaviour in response to integrated street design. A "mesoscopic" level of analysis is adopted, whereby the actions and revealed choices of individual pedestrians are modelled probabilistically, but without a detailed investigation into their attitudes and perceptions. Video footage from London's Exhibition Road site during periods before and after its conversion from a conventional layout to a more integrated pedestrian-oriented design is used, and an observation scheme focusing on pedestrian actions and discernible characteristics is devised. Inferential statistics methods are used to derive models expressing two behavioural traits: walking/crossing speed, and crossing on red incidence. The results suggest that the additional space provided and the reduced crowding post-redevelopment results in pedestrians walking less hastily and close to their desired speed, while the friendlier conditions created by the street layout increase their confidence to enter the road space and cross, sometimes even on a red signal. In particular, those walking alone (rather than in a group) and walking to work (rather than leisure) appear to walk faster and are also more likely to cross on red.

1. Introduction

The safe and efficient interaction of pedestrians and motorised traffic has been central to streetscape design ever since the advent of motorised vehicles. With mass motorisation after World War II and with pedestrian injuries and fatalities soaring, the "quick-fix" resolution that was adopted and continued to be routinely implemented until relatively recently was that of complete segregation. This saw the introduction of features, such as pedestrian guardrails and grade separation through subways and footbridges (Buchanan et al, 1963). In the last few decades, however, motivated by developments in architecture and urban planning, streetscape design has gradually moved away from segregation and more towards integration: as opposed to the previous "keep out" principle, pedestrians are now included in the design and are invited to share the space, ultimately asserting the role of streets as places rather than arteries. Prominent integration examples include: the concepts of "woonerf" and "home zone" in residential areas in the Netherlands and UK

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https://doi.org/10.1016/j.trf.2023.10.015
Received 15 December 2022; Received in revised form 4 August 2023; Accepted 15 October 2023
Available online 20 October 2023
1369-8478/

respectively; the “Manual for Streets” approach in the UK (UK Department for Transport, 2007; Chartered Institute of Highways and Transportation, 2010); and the “Complete Streets” initiative in the USA (McCann, 2013) (Fig. 1).

Previous research has uncovered a range of interesting findings relating to this new design approach, with the dilemma “share or segregate?” having been identified as being at the forefront of the future of urban streets (Tsigdinos et al, 2022). Rightful concerns have been expressed in terms of the potential hindrance of the mobility (and corresponding exclusion) of disabled road users, in particular in streetscapes featuring a more radical and extreme manifestation of the approach (the so-called “shared space”) that comprises little to no street furniture and, often, no kerbs (Brown and Norgate, 2019; Havik et al, 2012; Havik et al, 2015). On the other hand, several positive effects have been reported, including greater pedestrian confidence (Kaparias et al, 2016), better quality of service for pedestrians without associated reduction to that of motorised traffic (Kaparias and Wang, 2020), improved aesthetics (Hammond and Musselwhite, 2013), better accessibility (Clarkson, 2018), and also better safety due to a reduction in the severity of traffic conflicts (Kaparias et al, 2013; Kaparias et al, 2015).

Nevertheless, much of the previous research so far has explored the behaviour of pedestrians in such streetscapes collectively rather than individually. Indeed, pedestrians have usually either been treated as a homogeneous group whose members behave consistently (focusing on the “macroscopic” level, as, for example, in traffic conflicts analysis), or have concentrated on specific pedestrian subgroups to explore their views and preferences (focusing on the “microscopic” level, as, for example, in attitudinal and stated-preference surveys). While these are both valid approaches and have merits, the revealed behaviour of different pedestrians, as observed in the field, in relation to their characteristics and the streetscape, remains under-explored, and its study can offer a valuable insight into behavioural traits of pedestrians in integrated street design schemes that would be otherwise difficult to explore. Indeed, macroscopic analyses would lack the necessary level of granularity to analyse such traits, while microscopic ones would be limited by the volume and the reliability of the data that could realistically be collected (e.g. respondents may be reluctant to give honest answers to potentially controversial questions, such as whether they regularly cross the road illegally or riskily).

The present study, therefore, fills this gap by studying and identifying key pedestrian-specific behavioural changes in response to the introduction of integrated street design features (thus addressing the “mesoscopic” level). Two pedestrian behavioural aspects are investigated: walking/crossing speed and “crossing on red” incidence. The analysis is carried out through video data observation of the interaction of different pedestrian types with the streetscape in London’s Exhibition Road site during periods before and after its re-development from a conventional dual carriageway to a more integrated pedestrian-oriented design. To this extent, Exhibition Road is a case study site that is particularly well suited to the objectives of the present work, as it is the result of a high-profile street re-design scheme that features a wide range of diverse integrated street design features, such as substantial footway widening, removal of kerbs, pedestrian crossing re-design and two-way street conversion.

The rest of the paper is structured as follows. Section 2 presents the background of the study, focussing primarily on past observation-based pedestrian behaviour research to identify the attributes to be analysed and to highlight the gap in knowledge to be addressed by the study. Section 3 goes on to introduce the study site (Exhibition Road, London), to provide details on the streetscape treatments carried out as part of its re-development, and to document the data collection carried out. Section 4 presents the analysis methodology used (which comprises linear and logistic regression), reports on the results obtained, and discusses the changes in the observed behaviour in relation to the integrated design features introduced. Section 5, finally, concludes the paper and identifies areas of future research.

2. Background

Past research on pedestrian behaviour models has predominantly focused on two key behavioural traits: route choice and road crossing (Papadimitriou et al, 2009). Given the remit of the present study, only the literature on the latter is considered, and this is grouped into three categories depending on the parameter of influence studied: built environment; demographic characteristics; and other aspects.

Fig. 1. Examples of integrated street design: a “shared space” street in Brighton, UK (left); pedestrian and bicycle paths in Houston, TX, USA (right).

2.1. Impact of built environment on pedestrian behaviour

The built environment has been found to have a significant impact on pedestrian crossing behaviour. Firstly, this involves the road type and the associated traffic conditions. Mako (2015) finds that the presence of refuge islands at junctions is associated with a drastic reduction in collisions due to pedestrians exhibiting fewer “irregular” behaviours, such as crossing on red or outside the designated crossing area. Along the same lines, Papadimitriou et al (2016) finds that poor junction design might unintentionally promote more diagonal crossings.

Some research has also explored pedestrian mid-block crossing behaviour. Sisiopiku and Akin (2003) find that pedestrians are favourable towards the mid-block crossing provision, and that these have a high compliance rate; however, the location of the crossing is a highly influential factor on this compliance, which highlights the importance of respecting pedestrian desire-lines. The study also found that even though signalisation at mid-block crossings provides better protection and channelisation to pedestrians, compliance drops significantly in low traffic conditions – a conclusion also reached by Hamed (2001). Papadimitriou (2012), correspondingly, identifies that more traffic lanes, higher traffic flows and traffic signalisation make it more likely that a pedestrian chooses to cross at a junction, whereas one-way roads, on-street parking and the presence of an attraction building (such as a department store or a museum) increase the probability of crossing mid-block.

2.2. Pedestrian behaviour and demographic characteristics

As can be expected, age plays a major part in pedestrian behaviour. A pedestrian’s walking speed has been shown to be a function of one’s value of time, risk and capabilities (Ishaque and Noland, 2008), and this justifies why older pedestrians tend to walk slower than younger ones (Griffiths et al, 1984; Zanlungo et al, 2017). On the other hand, younger pedestrians tend to exhibit riskier behaviours, such as illegal and aggressive crossing (Sheykhfard et al, 2021). In particular, the tendency of children to rely on partial information and their inability to properly take critical road factors into account lies beneath their observed behaviour of generally crossing faster and accepting shorter gaps than other age groups (Das et al, 2005). Interestingly, they also tend to exhibit more unsafe behaviours (e.g. not stopping at the kerb, not looking before crossing, and running across the road) when accompanied by adults (Rosenbloom et al, 2008).

Differences have also been identified between the behaviour of pedestrians of different genders. For example, males typically perform more violations than females, while females tend to make more conservative decisions (Rosenbloom and Wolf, 2002; Rosenbloom et al, 2004). Even though the gap acceptance behaviour is similar (Das et al, 2005), male pedestrians are likely to have shorter waiting times than females (Hamed, 2001), and they are also likely to be walking at a slightly higher speed (Ishaque and Noland, 2008; Zanlungo et al, 2017).

2.3. Other aspects influencing pedestrian behaviour

Human factors have been found to significantly influence pedestrian behaviour. Evans and Norman (1998), for instance, found that psychological variables explained more than half of the variance in intentions to cross the road, and concluded that a pedestrian is more likely to engage in a potentially hazardous behaviour if it is seen to be easy to perform. Similar trends were observed also by Narvaez et al (2019), where human factors played a significant part in pedestrian actions, including risky ones. Papadimitriou et al (2016), correspondingly, categorised pedestrian crossing behaviours as “risktaking”, “conservative” and “health and leisure-oriented”, depending on pedestrian attitudes, perceptions, preferences, compliance and motivations. Indeed, such factors have been found to result in vastly different behaviours among pedestrians with otherwise relatively similar characteristics, such as age, gender, education, physical condition and others (Sheykhfard et al, 2021).

A further influencing factor is the group behaviour of pedestrians, which is critical, as typically up to 70% of people in a crowd move in groups rather than individually (Moussaïd et al, 2010). DiPietro and King (1970) measured lower walking speeds for groups of two or more people when compared to individuals, but the opposite applies when children are involved Zanlungo et al, 2017. Ishaque and Noland (2008) found that groups tend to have shorter accepted gaps, despite the fact that groups or crowd pressure can act as a limiting factor (Bezbradica and Ruskin, 2020). Groups of pedestrians have also been found more likely to be yielded to by drivers compared to individual ones (Clarkson, 2018).

Finally, pedestrian behaviour is also dependent on trip purpose due to its association with the value of time. Hence, commuters have been observed to generally have higher speeds during peak hours than those walking for leisure (Ishaque and Noland, 2008), and to also have lower waiting times before crossing, despite the fact the usually higher traffic flows at these times. This points to more risk-taking behaviour when the trip purpose is work (Hamed, 2011).

2.4. Summary and knowledge gap

From the review of the existing literature, it is evident that a wide range of physical and behavioural elements have significant impacts on the behaviour of pedestrians. However, there is a notable absence of studies exploring the changes in behaviour as a result of the introduction of integrated street design features at the mesoscopic level, i.e. through high-level observation but considering some individual characteristics and deriving probabilistic relationships to express these changes. Therefore, the present study fills this gap by performing an observation-based analysis of pedestrian behaviour changes (namely walking speed and crossing on red incidence) before and after the redevelopment of a street site, in particular with respect to age, gender, trip purpose and group behaviour.

(a)

(b)

(c)

Source: Royal Borough of Kensington and Chelsea

(d)

Fig. 2. Exhibition Road before (left) and after redevelopment (right).

3. Data collection and analysis methodology

The data collection and analysis steps are outlined in this section. This includes a description of the site (Exhibition Road, South Kensington, London), and is followed by an account of the data collection and observation methods employed, in preparation for the reporting of the results in Section 4.

3.1. Site description

A well-known cultural quarter, South Kensington is home to three of London's most popular museums (Natural History, Science, V&A), the Royal Albert Hall, as well as a number of academic institutions (e.g. Imperial College). The area is centred on the 800 m long Exhibition Road – a street frequented by large numbers of regular and occasional pedestrian visitors, whose previous conventional 24 m wide dual carriageway layout was often crowded (a problem exacerbated by numerous pedestrian barriers) and dominated by high traffic flows and parked vehicles. This prompted the local authorities in 2008 to commission an engineering scheme, the "Exhibition Road Project", which entailed its redevelopment to a more pedestrian-friendly streetscape with various integrated street design features (Fig. 2).

The project was implemented over almost four years (mid-2008 to late 2011). More specifically, the following three main streetscape treatments were carried out:

1. Re-allocation of street space (Fig. 2a): The previous Exhibition Road layout comprised a 16 m wide dual carriageway with one lane of traffic per direction and excess width for parking, and of two 4 m wide footpaths on either side. Post-redevelopment, traffic was shifted to the eastern side of the road to occupy an 8 m wide single carriageway (the "traffic zone"), with the western side of the former dual carriageway becoming a "transition zone", accommodating mainly pedestrians, but also parking, bicycles and coach alighting. The two 4 m wide footpaths remained in place and formed the "pedestrian zone". The space also saw the implementation of an end-to-end level surface, replacing the previous traditional "kerbed" layout.
2. Unravelling of a one-way system (Fig. 2b and 2c): In the original layout, a one-way system was in place around the South Kensington Station area, whereby the southbound traffic was led along the southern tip of Exhibition Road and along Thurloe Street, while the northbound traffic was guided along Thurloe Place. Post- redevelopment, Thurloe Place was converted to a two-way street, accommodating all traffic (both northbound and southbound), while Thurloe Street was converted to an access-only street.
3. Re-design of pedestrian crossing facilities (Fig. 2d): At the junction of Exhibition Road with Cromwell Road, there was a staggered north–south pedestrian crossing on the western side of the site, which, however was not following desire-lines and forced

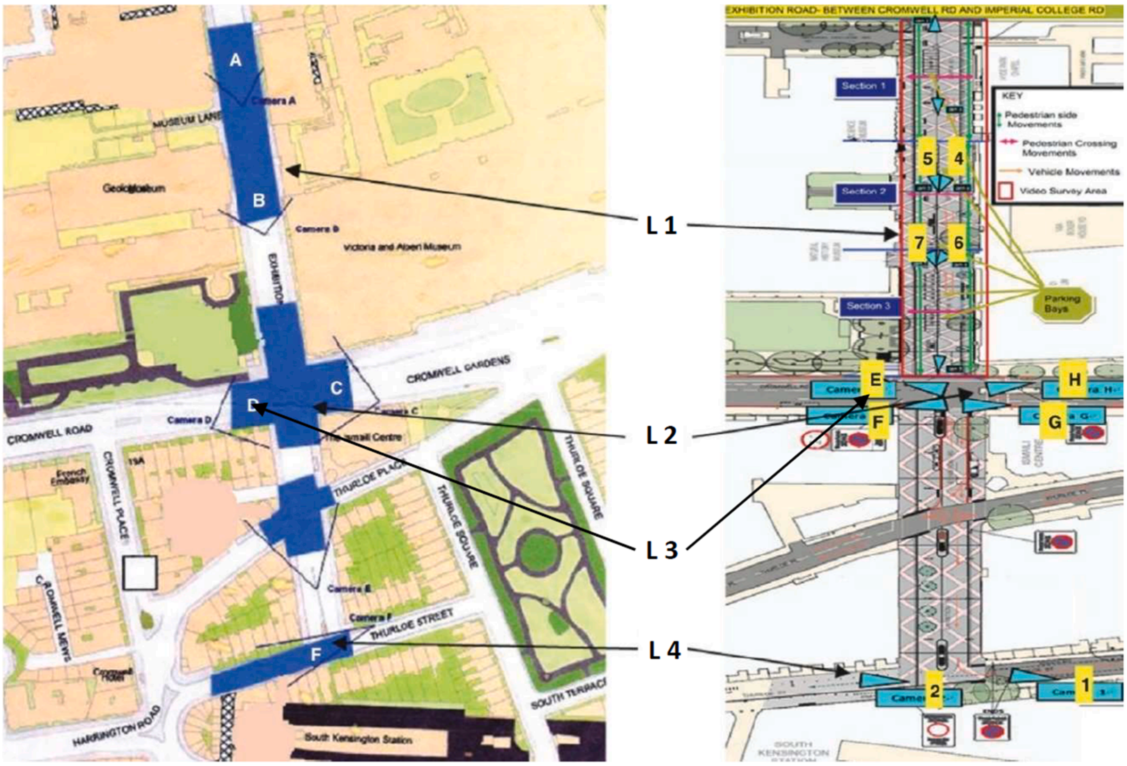

Fig. 3. Camera locations at the Exhibition Road site in the before- (left) and after-monitoring (right).

pedestrians to cross in two stages, thus resulting in a high number of jaywalkers. The redevelopment removed the staggered crossing and replaced it with a wide (12 m) straight-across crossing, allowing pedestrians to cross in a single phase. The scheme also removed pedestrian guardrails and other street clutter to further facilitate pedestrian movement.

3.2. Data collection

The data collection is carried out by means of video observation. This is an appropriate data collection method for this task, as it enables the logging of behavioural characteristics and revealed preferences without the need to perform costly, time-consuming surveys with pedestrians (whether on-site or online). Moreover, video observation is a non-intrusive method, which ensures that the behaviour of the pedestrian subjects is undisturbed by the activity, and that, therefore, the data collected are realistic.

Video footage has been collected through high-mast cameras for periods before and after the redevelopment as part of recent studies analysing traffic conflicts, behavioural interactions, gap acceptance, and quality of service in the area (Kaparias et al, 2013; Kaparias et al, 2015; Kaparias et al, 2016; Kaparias and Wang, 2020). In this study, the data collected are used to assess the impact of the new integrated design of Exhibition Road on the behaviour of different pedestrian types. In the before-case (the left part of Fig. 3), the videos refer to August 2008, prior to the start of the redevelopment works, and have been collected from four key locations around the site, marked as L1, L2, L3 and L4 on Fig. 3. For the after-situation (the right part of Fig. 3), the video footage comes from the same locations in October 2011, following the completion of the scheme. Footage has been collected from 5 cameras before (labelled A, B, C, D and F on the left part of Fig. 3) and 10 cameras after the redevelopment (labelled 1, 2, 4, 5, 6, 7, E, F, G and H on the right part of Fig. 3).

The locations (and cameras used in the observation) are the following (Fig. 3):

- *L1: Exhibition Road main body western footpath* (*Before: Camera A – After: Camera 6*):

In the original layout, pedestrians were confined in a 4-m wide footpath, which, however, was often crowded by queuing visitors waiting to enter the various museums, thus acting as a barrier to pedestrian movement. At the same time, vehicle traffic was often interrupted by alighting buses in front of the museums. These issues have been addressed in the new layout through the provision of more pedestrian space, but also through the establishment of the transition zone.

- *L2: Cromwell Road junction, eastern crossing* (*Before: Camera C – After: Cameras E & H*) and

L3: Cromwell Road junction, western crossing (Before: Camera D – After: Camera F):

In the original layout, the facilities provided to pedestrians wishing to cross Cromwell Road to continue walking on either the eastern or the western footpaths of Exhibition Road were two staggered pelican crossings, which required detours and often long waiting times for a green phase. As a result, the majority of the pedestrians used “shortcuts” bypassing the staggered crossings and jaywalking, thus coming into conflict with right-turning southbound traffic from Exhibition Road in the case of the western crossing, or with left-turning southbound traffic in the case of the eastern crossing. The western crossing has been replaced by a wide straight-across crossing in the new layout, while the eastern one has been retained but redesigned.

- *L4: T-junction of Exhibition Road with Thurloe Street* (*Before: Camera F – After: Camera 1*):

Pedestrians using this location in the original layout were faced with two problems: the non-provision of adequate pedestrian crossing facilities, and the insufficient space for pedestrians on the southern footpath of the road. In the new layout, this location has been redesigned as “access-only”, giving more space to pedestrians.

3.3. Observation scheme

A number of observation sessions at representative times of weekday and weekend peak vehicle and pedestrian traffic have been selected. These are:

- Weekdays 08:00 (morning peak, with high vehicle traffic flows);
- Weekdays 12:00 (midday, when a large number of tourists enter and exit the museums);
- Weekdays 17:00 (evening peak, with tourists and workers leaving the area, and locals returning);
- Weekends 12:00 (midday, when high numbers of tourists visit the area); and
- Weekends 17:00 (evening, when museums close and tourists leave the area).

For consistency, weekday observations have been carried out on footage recorded on a Thursday, while weekend ones are from footage recorded on a Saturday. In total, 40 separate observation sessions have been completed (one for each of the five selected times, for each of the four locations, before and after redevelopment).

The observations have focused predominantly on the crossing behaviour of pedestrians, with the exception of L1, where the walking behaviour on the footpath of Exhibition Road is observed. Each observation session entailed watching the video footage for a set duration of time and recording, for each pedestrian observed, a number of pre-selected attributes. These include:

- *Gender*, as visually discernible based on external features;
- *Age*, as visually discernible based on external features;
- *Trip purpose* (work or leisure), as visually discernible based on clothing, gear, etc.;
- *Walking/crossing speed*, as measured from the footage;
- Walking/crossing as a *sole* pedestrian or as part of a *group*
- Crossing *location* (where relevant), i.e. using designated facilities or freely;
- Crossing *on red* (where relevant);
- Crossing *in a single or in two phases* with a stop on the median (where relevant); and
- *Running* or substantially changing speed.

The attributes have been selected on the basis of the literature review and the authors' judgement as representative of pedestrian walking/crossing behaviour across the site. For instance, age, gender and trip purpose have all been shown to have significant impacts on the pedestrians' walking behaviour (mainly on their speed) in previous studies. The same applies to walking/crossing as a sole pedestrian or as a group, and it should be noted that there are several occasions, where individual pedestrians have been observed to behave as though they were a part of an "impromptu" group, for example, when crossing together with other individuals or another group, or walking at approximately the same speed on a footpath in proximity to each other, without being related to them; this behaviour has been recorded separately so that its implications can be explored. The crossing location, on the other hand, has been chosen due to a significant proportion of pedestrians pre-redevelopment opting to not use the designated facilities and instead cross freely. Similarly, pedestrians have been observed to execute both single- and two-phase crossings (by stopping on the median, where available) on the site, seemingly depending on traffic conditions. Also, potentially risky behaviour is associated with pedestrians crossing at a red signal, running or abruptly changing their speed, so instances of this behaviour are considered in order to evaluate whether the redesign has had an impact with respect to it. An example extract of the observation carried out is illustrated on Fig. 4.

3.4. Sample characteristics

In total, 1081 pedestrians have been observed and have had their characteristics and behaviour recorded: 378 at L1, 224 at L2, 238 at L3 and 241 at L4. These are split as 513 before the redevelopment (48%) and 568 after (52%), which suggests that both cases are equally represented in the data.

Of the pedestrians observed, 610 have been classified as male (56%) and 471 as female (44%). Correspondingly in terms of age, 690 (64%) pedestrians have been classified as adults, 257 (24%) as young adults, i.e. students or older teenagers, 60 (5%) as elderly and 74 (7%) as children. Compared to the latest UK national statistics (UK Office for National Statistics, 2022), female and elderly pedestrians are slightly under-represented in the sample observed, and one of the main reasons for that may be the lack of sufficient accuracy in the classification of pedestrians solely on the basis of their discernible external characteristics (due to, for example, low video footage quality).

In terms of the other attributes, the trip purpose of 411 (38%) pedestrians has been determined as "Work", while for 670 (62%) it has been classified as "Leisure". 594 (55%) pedestrians have been observed to walk as part of a group (organised or impromptu), while 487 (45%) have been classified as sole. Specifically at the two crossing locations (L2 and L3) and the total of 462 pedestrians: 140 (30%) executed single crossings, compared to 322 (70%) who crossed in two phases; 234 (51%) crossed on a red signal, while 228 (49%) did not; and 69 (15%) ran or abruptly changed their speed, while 393 (85%) did not.

In order to explore changes in the behaviour of pedestrians as a result of the redevelopment, the dataset is analysed in greater detail by means of relevant inferential statistics techniques, as reported in the next section.

(a) (b) (c) (d)

Fig. 4. Examples of footage used as part of the video observation – before (top) and after (bottom) the re-design: (a) Exhibition Road North (L1); (b) Cromwell Road junction West (L2); (c) Cromwell Road junction East (L3); and (d) Thurloe Street junction (L4).

4. Analysis and results

Pedestrian behaviour on the four selected locations around the Exhibition Road site before and after redevelopment is analysed in terms of two attributes: walking/crossing speed, and crossing on red incidence. The analysis methodology is introduced first, followed by the results obtained.

4.1. Analysis methodology

The analysis uses inferential statistics in order to identify formal relationships between the two dependent variables specified (namely walking/crossing speed and crossing on red incidence) and a set of independent variables that include most of the attributes observed, as listed in the previous section. A walking/crossing speed model is fit for each of the four locations of the Exhibition Road site before and after redevelopment, thus giving a total of eight speed models. Crossing on red incidence, on the other hand, is only meaningful at the Cromwell Road junction locations (L2 and L3), so models are fit for these two locations only, before and after redevelopment, thus giving a total of four crossing on red models.

In order to ensure comparability between attributes and models, the single categorical independent variable (age) is converted to a set of dummy binary ones, considering that the number of variables per attribute in inferential statistics methods should be n-1, n being the number of levels. Moreover, the crossing on red incidence is included as an independent variable in the speed models, while the occurrence of running is not included in the speed models due to its very high correlation with the dependent variable. Furthermore, the attributes of the crossing location and of crossing in a single or in two phases are only relevant to crossings and are therefore only included as independent variables in the L2 and L3 models. The full list of attributes and levels per model is shown in Table 1.

The analysis proceeds by fitting 12 regression models, each one having either the walking/crossing speed or the crossing on red incidence as the dependent variable and most of the attributes listed in Table 1 as potential predictors. Walking/crossing speed is a continuous non-negative variable that can be reasonably assumed to co-vary with the observed data, and so multiple linear regression is an appropriate modelling candidate for it due to its advantage of simplicity. Crossing on red incidence, on the other hand, is a binary variable that represents a choice made by the pedestrian, which makes binary logistic regression (logit) a potentially appropriate

Table 1
Attributes and levels per model (same for before and after models at each location).

Attribute	Levels	Walking/crossing speed				Crossing on red			
		L1	L2	L3	L4	L1	L2	L3	L4
Gender	Male Female	√	√	√	√		√	√	
Age	Child Young adult Adult Elderly	√	√	√	√		√	√	
Group behaviour	Sole pedestrian Pedestrian group	√	√	√	√		√	√	
Trip purpose	Work Leisure	√	√	√	√		√	√	
Impromptu group	Yes No	√	√	√	√		√	√	
Location	Within crossing Outside crossing	–	√	√	–		√	√	
Crossing phases	Single crossing Two-phased crossing	–	√	√	–		√	√	
Running	Yes No	–	–	–	–		√	√	
Crossing on red	Yes No	–	√	√	–		–	–	

model.

Regression is chosen here due to its simplicity and ease of interpretation compared to other techniques, such as non-parametric methods, factor analysis or machine learning. In order to assess, however, whether the linear and logit forms assumed by the resulting models are suitable, additional analysis is carried out using neural networks. Specifically, in addition to the eight linear and four binary logistic regression models derived, the data are used to train corresponding multilayer perceptron (MLP) feed-forward artificial neural networks with two hidden layers, each used to predict the walking/crossing speed and crossing on red incidence at each relevant location before and after redevelopment using all relevant independent variables. The fact that neural networks adopt a flexible non-fixed (and usually non-closed) model form means that they are able to achieve much higher predictive accuracy, which, when compared with that of linear and binary logit models, could act as a useful indicator of the suitability of the latter ones as "good enough" forms to model the data.

Table 2 compares the coefficients of determination (R^2) of each of the eight linear regression models and the percentage of correct predictions of each of the four binary logistic regression models with the relevant values for the corresponding MLP neural networks, calculated using the SPSS 28 statistical software package. 10 MLP neural networks are trained for each of the 12 models, and the R^2 and percentage of correct values reported in each model is the highest obtained among them. As can be seen, in most cases the linear regression achieves an R^2 within 0.1 to 0.2 of the MLP (the only exception being the L2-after model, where the difference is 0.221). Similarly, the logistic regression achieves percentage correct values within 10–20% of the MLP. More importantly, however, the two value sets are consistent with each other: in the cases where the linear and logistic regression fail to explain a large proportion of the data, this is also the case for the MLP, which suggests that the reason is in the dataset itself rather than in the chosen model form. Therefore, it can be concluded that multiple linear and binary logistic regression are sufficiently accurate methods to model this dataset.

4.2. Walking/crossing speed results

The results of the eight linear regression models fit to the data collected are shown in Table 3. Standardised model coefficients are presented in order to enable comparisons between models, and the statistically significant effects (at the 0.05 level) are highlighted. Reading the table vertically, one can identify which attributes (independent) affect the walking/crossing speed (dependent variable) across the site, before and after the redevelopment, respectively. Reading the table horizontally, on the other hand, one can see how the effects of each attribute have changed as a result of the redevelopment at each location.

It is noted that the variables relating to gender and children in all eight models are either statistically insignificant or are dropped due to collinearity. With respect to the former, it is likely that gender does not play a significant part in the walking/crossing speed of pedestrians on this particular site. As concerns the latter, on the other hand, this seems to be due to the lack of sufficient data, as there are very few observations of children and elderly in the study. In both cases the issue of potentially insufficient accuracy in the classification of pedestrians solely on the basis of their discernible external characteristics applies, and therefore, further research at the microscopic level would be required to enable more solid conclusions to be drawn.

Looking at the models relating to the western footpath of Exhibition Road (L1), it can be first observed that there is a statistically significant increase (at the 0.05 level) in the mean walking speed post-redevelopment. This can be largely explained by the fact that more effects are significantly positive in the after-case, which indicates more predictable pedestrian behaviour on the basis of the selected attributes. More specifically, a pedestrian's age plays a significant part, whereby young adults and adults generally walk more quickly. Also, people walking alone and people walking to work walk faster; they both also have positive significant effects in the before-model, in line with previous research on the topic (Hamed, 2001; Ishaque and Noland, 2008), but these have been amplified in the after-case. These findings may be evincing that people walking on footpaths of streets designed according to the integration approach are more at ease and walk closer to their desired speed due to more available space and less crowding. This is despite increased pedestrian volumes post-redevelopment, as shown by previous work that used the same footage data (Kaparias and Wang, 2020).

Considering the models for the eastern crossing of Cromwell Road (L2), the mean speed is not statistically significantly different (at the 0.05 level) between the before and after cases. This is very likely because of the fact that the crossing in question had not been substantially re-designed at the time the video footage was recorded, having largely retained the original staggered layout with

Table 2
Comparison of linear/logistic regression and neural networks.

Walking/crossing speed			Crossing on red incidence		
R^2	Linear reg.	MLP	% correct	Logistic reg.	MLP
L1-before	0.274	0.463			
L1-after	0.394	0.506			
L2-before	0.276	0.297	L2-before	80.5	88.4
L2-after	0.291	0.512	L2-after	70.0	83.3
L3-before	0.314	0.449	L3-before	68.1	86.2
L3-after	0.408	0.564	L3-after	69.7	82.9
L4-before	0.295	0.476			
L4-after	0.229	0.325			

Table 3
Results of linear regression for walking/crossing speed (in km/h) across the Exhibition Road site.

Exhibition Road western footpath (L1) – Before

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		9.787	<.001
Male	0.122	1.672	.097
Sole ped.	0.321	3.730	<.001
Child	-0.065	-0.381	.704
Young adult	0.100	0.444	.657
Adult	0.074	0.301	.764
Work	0.209	2.437	.016
Impr. group	-0.053	-0.705	.482

N = 157; Mean = 4.698; St. dev. = 0.819; R^2 = 0.274

Exhibition Road western footpath (L1) – After

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		17.490	<.001
Male	0.072	1.278	.202
Sole ped.	0.413	6.224	<.001
Child	0.130	1.736	.084
Young adult	0.237	2.669	.008
Adult	0.256	2.676	.008
Work	0.279	4.222	<.001
Impr. group	-0.028	-0.472	.638

N = 221; Mean = 4.999; St. dev. = 1.031; R^2 = 0.394

Cromwell Road eastern crossing (L2) – Before

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		10.051	<.001
Male	0.161	1.807	.074
Sole ped.	0.161	1.238	.218
Child	0.059	0.477	.635
Young adult	0.150	0.981	.329
Adult	0.139	0.842	.401
Work	0.253	2.325	.022
Impr. group	-0.069	-0.705	.482
Within cross.	0.189	1.300	.196
Single cross.	0.037	0.256	.799
On red	0.189	1.743	.084

N = 113; Mean = 5.276; St. dev. = 0.723; R^2 = 0.276

Cromwell Road eastern crossing (L2) – After

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		14.467	<.001
Male	-0.147	-1.361	.177
Sole ped.	0.007	0.051	.959
Child	-0.162	-1.476	.143
Young adult	0.021	0.093	.926
Adult	-0.025	-0.111	.912
Work	0.072	0.639	.525
Impr. group	-0.007	-0.058	.954
Within cross.	-0.489	-3.309	.001
Single cross.	-0.501	-3.631	<.001
On red	0.244	2.285	.025

N = 100; Mean = 5.288; St. dev. = 0.695; R^2 = 0.291

Cromwell Road western crossing (L3) – Before

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		12.434	<.001
Male	0.121	1.259	.211
Sole ped.	-0.013	-0.096	.924
Child	-0.004	-0.045	.964
Young adult	*Dropped due to collinearity*		
Adult	-0.124	-1.273	.206
Work	-0.063	-0.541	.590
Impr. group	-0.281	-2.489	.014
Within cross.	0.047	0.315	.753
Single cross.	0.529	3.469	<.001
On red	-0.023	-0.209	.835

N = 113; Mean = 5.571; St. dev. = 1.143; R^2 = 0.314

Cromwell Road western crossing (L3) – After

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		5.398	<.001
Male	0.066	0.833	.407
Sole ped.	0.752	5.451	<.001
Child	0.524	2.118	.036
Young adult	0.646	1.634	.105
Adult	0.702	1.723	.088
Work	-0.110	-0.985	.327
Impr. group	-0.292	-2.447	.016
Within cross.	-0.092	-1.204	.231
Single cross.	0.142	1.497	.137
On red	0.218	2.119	.036

N = 119; Mean = 5.187; St. dev. = 0.731; R^2 = 0.408

Thurloe Street (L4) – Before

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		23.222	<.001
Male	0.094	1.071	.287
Sole ped.	0.409	4.103	<.001
Child	0.142	1.423	.158
Young adult	0.380	2.656	.009
Adult	0.208	1.401	.164
Work	0.141	1.463	.146
Impr. group	0.005	0.061	.951

N = 118; Mean = 4.852; St. dev. = 0.595; R^2 = 0.295

Thurloe Street (L4) – After

Attribute	Std. coeff. (β)	t-stat.	Sig.
Constant		18.422	<.001
Male	0.110	1.215	.227
Sole ped.	0.275	3.082	.003
Child	*Dropped due to collinearity*		
Young adult	0.279	2.309	.023
Adult	0.316	2.671	.009
Work	0.196	2.228	.028
Impr. group	0.093	1.062	.291

N = 112; Mean = 4.815; St. dev. = 0.812; R^2 = 0.229

pedestrian guardrails. Consequently, any behavioural changes are likely to be indirect, i.e. due to the wider changes across the site rather than any specific treatments at that location. The before-model only has one significant variable – the one relating to walking to work, which has a positive association with speed, as in the case of L1. This attribute loses its significance in the after-model, where instead the attributes relating more to the design of the crossing become dominant. Specifically, walking outside the designated crossing area and crossing on red makes pedestrians walk faster. The same applies to pedestrians crossing in two phases (with a stop on the median), not least because this behaviour is often combined with the other two. This finding is in line with the risk-taking pedestrian profile defined by Papadimitriou et al (2016). A noteworthy occurrence is that the proportion of pedestrians exhibiting such behaviours is considerably higher in the after-case, which may suggest that the re-design of the area as a whole encourages pedestrians to cross more freely; at locations where the infrastructure has not been updated, this could pose risks. The crossing in question has been more substantially re-designed since and has had the guardrails removed, so such potentially problematic issues will have been all but alleviated.

With regard to the models for the western crossing of Cromwell Road (L3), the mean speed is statistically significantly lower (at the 0.05 level) in the after-case compared to the before case. This is likely due to the radical re-design of the crossing from the previous staggered layout to a wide straight-across one, making pedestrians more comfortable when crossing the road. This drives also the changes in the attributes monitored. For instance: crossing in a group makes pedestrians walk slower in the after-case, while it is insignificant in the before-model; crossing in a single phase has no significant effect on speed in the after-model, when it is highly significantly positive in the before-model (possibly due its occurrences being often combined with illegitimate and risky behaviour, such as crossing on red and outside the designated crossing area); and crossing on red is associated with faster walking in the after-model, when it is insignificant before-redevelopment (likely due to it being such a common occurrence pre-redevelopment that it is confounded by the constant and the other attributes, such as crossing in a single phase). An interesting finding is also the unchanged negative effect of the impromptu group attribute, highlighting that pedestrians at this location feel more comfortable when others take the same action as them, and hence walk slower.

Finally, looking at the models for Thurloe Street (L4), no statistically significant walking/crossing speed differences are reported in the after-case compared to the before-case, though there is a fairly substantial increase in the standard deviation of the speed, indicating overall greater variability. Aside of that, however, the results show some resemblance to those of L1, where sole pedestrians walk faster both pre- and post-redevelopment, and where age and trip purpose explain an appreciable amount of the walking/crossing speed variability in the after-case. This is despite the fact that what has been monitored at L4 is the speed of crossing the road rather than that of walking on the footpaths. The reason is likely that the conversion of Thurloe Street to access-only has drastically reduced vehicle traffic and has, effectively, pedestrianised it. This results in a more relaxed pedestrian behaviour that resembles more walking on a footway and less crossing a road with motorised traffic.

4.3. Crossing on red incidence results

The results of the four binary logistic regression models fit to the data collected are shown in Table 4, with statistically significant effects (at the 0.05 level) highlighted. Again, reading the table vertically, one can identify which attributes (independent) affect the crossing on red incidence (dependent variable) at locations L2 and L3, before and after the redevelopment, respectively. Reading the table horizontally, on the other hand, one can see how the effects of each attribute have changed as a result of the redevelopment.

The first observation that is made is that a number of attributes are either dropped due to collinearity or have insignificant effects in all four models. These include: all attributes relating to age; the impromptu group attribute; and the attribute relating to crossing in one or two phases. The reason is likely that for all three there are either insufficient occurrences in the data, or insufficient variability in the observed behaviour. For instance, there are very few instances of impromptu groups crossing on red, and also very few observations of crossing on red with a stop on the median, and coupled with the small number of observations of children and elderly that also affects

Table 4
Results of binary logistic regression for crossing on red incidence at the Cromwell Road crossing.

Cromwell Road eastern crossing (L2) – Before

Attribute	Coeff. (β)	Std. Err.	Sig.
Constant	-1.980	1.783	.267
Male	0.199	.548	.717
Sole ped.	2.319	.671	<.001
Child	*Dropped due to collinearity*		
Young adult	2.212	1.322	.094
Adult	2.213	1.229	.072
Work	0.701	.648	.280
Impr. group	-1.362	.803	.090
Within cross.	-2.483	1.187	.036
Single cross.	*Dropped due to collinearity*		
Running	2.194	.887	.013

N = 113; Pseudo-R^2 (Nagelkerke) = 0.539; % correct = 80.5%

Cromwell Road eastern crossing (L2) – After

Attribute	Coeff. (β)	Std. Err.	Sig.
Constant	-3.004	1.295	.020
Male	1.236	.564	.028
Sole ped.	2.218	.779	.004
Child	*Dropped due to collinearity*		
Young adult	1.285	1.333	.335
Adult	1.775	1.256	.158
Work	-0.837	.720	.245
Impr. group	0.036	.772	.963
Within cross.	*Dropped due to collinearity*		
Single cross.	*Dropped due to collinearity*		
Running	0.297	.751	.693

N = 100; Pseudo-R^2 (Nagelkerke) = 0.334; % correct = 70.0%

Cromwell Road western crossing (L3) – Before

Attribute	Coeff. (β)	Std. Err.	Sig.
Constant	-0.336	.381	.378
Male	0.434	.486	.372
Sole ped.	0.316	.702	.652
Child	-0.975	.808	.228
Young adult	-0.286	.521	.583
Adult	*Dropped due to collinearity*		
Work	1.985	.722	.006
Impr. group	-0.056	.730	.939
Within cross.	*Dropped due to collinearity*		
Single cross.	*Dropped due to collinearity*		
Running	1.074	.614	.080

N = 113; Pseudo-R^2 (Nagelkerke) = 0.289; % correct = 68.1%

Cromwell Road western crossing (L3) – After

Attribute	Coeff. (β)	Std. Err.	Sig.
Constant	-0.316	.371	.396
Male	0.227	.432	.599
Sole ped.	2.754	.962	.004
Child	*Dropped due to collinearity*		
Young adult	*Dropped due to collinearity*		
Adult	*Dropped due to collinearity*		
Work	-2.327	.826	.005
Impr. group	0.758	.720	.293
Within cross.	*Dropped due to collinearity*		
Single cross.	*Dropped due to collinearity*		
Running	2.519	1.266	.047

N = 119; Pseudo-R^2 (Nagelkerke) = 0.330; % correct = 69.7%

the speed models, it is reasonable that these attributes have either no impact or are perfectly correlated with the dependent variable.

A further observation is that for all models but one, the constant term is insignificant. This indicates that pedestrians appear to be initially indifferent towards deciding to cross on red and that it is the various attributes and circumstances that “swing” their choice towards either position. The only exception is the L2-before model, in which the constant term is significantly negative, which suggests an initial unfavourable view towards crossing on red. This is an unexpected finding, particularly as the crossing at L2 had not been substantially redeveloped at the time of the observation, and it is a trait that could be explored in greater detail with a further analysis at a more microscopic level.

Looking at the models relating to location L2, it can be seen that the sole pedestrian attribute is significantly positive, both before and after the redevelopment. This is not surprising and could suggest that pedestrians that are part of a group are more likely to wait for a green signal, perhaps due to a reluctance of breaking the group, or because it is more difficult to make a risky crossing decision if other people need to be accounted for. Beyond that, the crossing location and running attributes are significant in the before-model, indicating that a pedestrian is more likely to cross on red when outside the designated crossing area and when running; they are both insignificant or perfectly correlated in the after-model, most probably due to lack of data variability rather than a behavioural change. On the other hand, gender is insignificant in the before-model but becomes significant in the after-model, suggesting that male pedestrians are more likely to cross on red than female ones. While this is a reasonable trend and in line with previous findings, it may well also be due to confounding with the strongly negative constant term. So on balance, there seems to be no notable difference between the two models, which may be explained by the aforementioned non-substantial re-design at the time when the footage was recorded. Nevertheless, the results are also coupled with a notable increase in crossing on red occurrences post-redevelopment (49% of observed crossings, compared to 36% before), and this supports the conclusion reached as part of the speed analysis that the re-design of the area as a whole encourages pedestrians to cross more freely, potentially posing risks at locations where the infrastructure has not been updated.

Finally, considering the models relating to location L3, it should be first noted that crossing on red is a more frequent occurrence than at L2, with 60% of pedestrians doing so before and 53% after the redevelopment. This explains the large number of attributes being collinear or having insignificant effects, particularly in the before-model, as crossing on red behaviour is unpredictable cannot be explained by the chosen categories. As can be seen, only one attribute (walking to work) has a significant (positive) effect on crossing on red incidence in the before-case, and this supports the findings of the speed analysis and of past research. In the after-model, on the other hand, a slightly more predictable pattern is observed, likely due to the re-design making pedestrians more at ease and rendering crossing on red a less prominent behaviour, and the effects of walking alone and running emerge as significantly positive, in line with the speed models and the L2 crossing on red models. A surprising finding is that walking to work now has a negative impact, meaning the pedestrians going to work are less likely than leisure walkers to cross on red post-redevelopment. While the exact causes of this finding should be explored in a more detailed analysis at a microscopic level, a possible explanation may be that workers in the area are familiar with the crossing and the anticipated wait times, when leisure (and usually first-time) visitors are not. On one hand, this may be making them more impatient to get to their destination quicker, while on the other, the wide straight-across crossing layout may be encouraging them to do so when they feel it is safe, even if it means crossing on red.

5. Conclusions

In light of recent urban design trends away from segregation and towards integration, which call for more equal treatment of all road users, the present study has conducted a mesoscopic video-observation-based analysis of pedestrian behaviours at crossings and footpaths on the Exhibition Road site in London, before and after its conversion from a conventional single carriageway to a more integrated and pedestrian-oriented design. Linear and binary logistic regression have been used to derive models expressing the walking/crossing speed and the crossing on red incidence, respectively, at different locations around the site.

The results suggest that the greater space provided and the occurrence of less crowding has led pedestrians to walk in a more relaxed manner and at a speed close to their desired one. At the same time, the friendlier conditions created by the street layout make pedestrians feel more confident to enter the road space and cross, sometimes even on a red signal. These findings are in line with previous research that focused on pedestrian-vehicle interactions (Kaparias et al, 2015) and on pedestrian gap acceptance (Kaparias et al, 2016), and also observed increased pedestrian confidence. In most cases, the main drivers of pedestrian behaviour have been found to be membership of a group and trip purpose, with those walking alone and walking to work appearing to walk/cross faster and also being more likely to cross on red compared to the ones walking in groups and walking to leisure activities. With only few exceptions, these trends have been amplified following the redevelopment.

But while the study has shed some light onto the previously unexplored topic of pedestrian behaviour changes as a result of the introduction of integrated street design features at the mesoscopic level, work in this direction continues. For instance, a limitation of this research is that the post-redevelopment video footage used is from late 2011, i.e. from the period immediately after the completion of the Exhibition Road redevelopment. It is, therefore, possible that the behaviour observed may be affected by transitional effects that could have emerged as users would adapt to the new environment and may, as such, not be fully representative of the conditions at a later stage, when users would have gotten used to the changes. While the results would be unlikely to significantly differ (the most probable effect would likely be a further solidification of the observed pedestrian behaviour), it would be useful to repeat the observation study on the same site using videos collected at a later time in order to confirm the validity of the findings.

Furthermore, a limitation of the present study is the fact that, due to data availability and time and resource constraints, only selected short time periods of video footage per location could be analysed for the before and after cases. While every effort has been made in order to ensure that the chosen periods are as representative as possible, the eventuality of a bias in the results due to potential one-off events cannot be completely ruled out. It would be, hence, useful for future research to concentrate on analysing more time periods in order to confirm that the behavioural traits observed and the conclusions drawn are adequately reliable.

Moreover, the analysis is constrained by the fact that, despite its numerous advantages, the chosen linear and binary logistic regression methods have, like all fixed effects models, certain limitations. These are comprehensively appraised by Hill et al (2020), but the most important ones in the context of this study are potential limited external validity and unobserved heterogeneity. Indeed, the eventuality of the sample of observed pedestrians not being representative enough must be acknowledged (e.g. it is possible that the observed behaviours are skewed by British cultural customs and norms, which may be different in other countries), as should be the likelihood that additional variables may have effects on the walking speed and crossing on red incidence (e.g. it is possible that the behaviour of different pedestrians is influenced by pre-conceptions and ideas, which cannot be captured in an observation-based study). A further limitation of the analysis is that interaction effects between variables have not been explored. Time and resource constraints have meant that these issues could not be investigated here, but future work could concentrate on exploring them further through additional microscopic analysis (e.g. with on-site perception surveys), and by employing more advanced analysis methods, such as mixed or random effects regression.

Finally, it would be useful for future research to concentrate on exploring ways to increase the volume and accuracy of the video analysis by means of image processing techniques, which will allow assimilating of a more reliable and larger dataset to the one that the present study's constraints permitted. This will likely enable the analysis of the behaviour of additional and more precisely-defined user groups, pedestrians (e.g. disabled), but also others (e.g. bicyclists and e-scooter riders). Moreover, it is planned to further explore behaviours beyond speed and crossing on red incidence, such as, for example, the number and frequency of course changes and the walking direction in relation to the key origins and destinations across a street site. This will provide valuable input to macroscopic and microscopic pedestrian movement simulation models. Finally, it is intended to extend the study's remit to other street sites in the UK, as well as internationally, in order to investigate how different manifestations of the integrated street design concept influence road user behaviour.

CRediT authorship contribution statement

Ioannis Kaparias: Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Supervision. **Ivelin Tsonev:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgement

The authors would like to thank the Royal Borough of Kensington and Chelsea for supporting this work by providing data and guidance.

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