

Research

Situating *spatial determinism* in urban design and planning for sustainable walkability: a simulation of street morphology and pedestrian behaviour

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Abstract

Streets and roads have been constantly identified as key spaces to improve walkability and—by extension—the entire urban environment. Such improvements lie on planning and design theories that are often supported by qualitative evidence and as such, tend to remain highly speculative on how street design influences walkability in more deterministic ways. Drawbacks in further exploring this street-walkability correlation are partly defined by an explicit rejection to '*spatial determinism*' in urban morphology and social sciences, but also because combining differing epistemological approaches for understanding social processes linked to the physical aspects of the space is complex. In this paper, it is proposed that qualitative (social-based) theories of the space and quantitative (positivist) understandings of people's behaviour can complement each other to elaborate upon '*spatial determinism*' with focus on streetscapes and pedestrian behaviour. By using Agent-Based Modelling (ABMs), morphological components of streets linked to population characteristics are analysed to understand walkability from the perspective of spatial determinism. The findings suggest that the street settings directly affect pedestrian behaviour, and that changes in the built environment result in changes on walkability patterns. Ultimately, the modelling exercise shed light on street design and walkability, but also on wider debates on how urban design and social processes correlate in more deterministic and, therefore, predictable ways.

Keywords spatial determinism · urban design theory · walkability · pedestrian behaviour · Agent-Based modelling (ABM)

1 Introduction

Although public transportation and walkability have been proved as efficient solutions for sustainable mobility [1], encouraging walkability in contexts where it has been historically perceived as inefficient is a major challenge. Such challenge is observed in both developed and developing economies alike in which mobility increasingly relies on private cars or the use of informal modes of motorised transportation [2, 3]. Despite efforts of public agencies in linking active mobility with benefits on public health [4, 5], people choices on walkability are mainly influenced by structural factors such as safety, distances between points of departure and destinations, and quality of pedestrian infrastructure [6]. Lack of sidewalks, absence of street-crossing points, poor street lights and nigh-lighting, no safety, poor accessibility, lack of green spaces, poor material quality of pavements, presence of derelict sites, ambiguous delimitations of transport corridors, lack of protection against the rain or sun, obstructions of sidewalks, informal landfills and others, are all factors

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that discourage walkability and impact on public transport more broadly [7]. Improving the physical condition of sidewalks has been proved beneficial to motivate people to walk [8] with the difference that while in developing countries the focus is on the comprehensive provision of infrastructure, in developed countries pedestrian infrastructure focuses on last section of the residence-workplace linkages [9]. All these measures—in one way or another—correlate with the quality of the built environment but also policy priorities to tackle car-oriented planning. The inclusion of technology for sustainable mobility is also playing a role in stimulating walkability, so, electric charging points, Internet hubs, and street furniture make places socially attractive, multifunctional, and pedestrian friendly [10]. Despite efforts, however, the overall rate of walkability has not substantially increased and thereby, the question of how walkability can be further enhanced persists as one of the most intractable problems within planning and design circles [11].

In addressing such problem, empirical studies have suggested that walkability rates are associated to pedestrian behaviour, which is also linked to the morphological aspects of the space—specifically street design and urban furniture. However, there are not conclusive remarks on how the morphology of streets affect pedestrian behaviour more directly, and how individuals' characteristics determine more broadly the way of how people appropriate the space in more specific ways. In broad terms, “knowledge of how and why urban built environments influence human actions and social life is important to form sustainable strategies in urban land use planning, and this presupposes an adequate understanding of the causal nature of such influences” [12, p. 53]. Such knowledge is indeed limited partly due to the scarcity of project evaluations after implementation. Architects, planners, and urban designers are rarely back on projects to observe if imagined uses are accomplished beyond general functionality [13]. Only a small number of architectural studies have investigated how ubiquitous street furniture affects human and pedestrian behaviour [14, 15]. This might account for the various urban projects aimed at being lively places that then become empty (or inert) spaces with very limited social life [16]. This correlation has also been criticised (and even rejected) in architectural and urban design debates, as “architectural determinism” appears as an impossible (and reductive) task considering the complexity of social relationships, and the psychological and emotional impulses that render individuals unpredictable [17]. The organic nature of social life is grounded on historically and culturally rooted values that frame societal regulations while nevertheless allow human agency driven by uncertainty and unpredictable behaviour. In a different vein, however, “spatial determinism” has become a recurrent approach in transport engineering, risk assessment disciplines, and evacuation theories, supported by a varied array of models and simulations aimed at predicting not only pedestrian behaviour but also social attitudes in circumstances where individuals cannot make rational choices [18]. When individuals have short time to decide what to do—or where to go—under pressing circumstances they mostly rely on the environmental settings for intuitive decisions, which raises concerns about the extent to which the built environment helps to orientate decision-making when hazards strike. These are the cases for evacuation under natural disasters (earthquakes, tsunamis, hurricanes, wildfires) or terrorist attacks, car accidents, traffic congestion, and others in which individuals should evacuate safely and quickly without having time to think [19].

These studies have substantially advanced on pedestrian behaviour, but lack of theoretical and analytical connection with the environmental factors used in the studies of places in city planning and design. Conversely, city planning and design lack measurable correlations to inform design decisions from predictive modelling and deterministic simulations. In this paper these connections are discussed to complement quantitative studies on pedestrian behaviour with insights from social theory and the morphological analysis of places that is mainly focused on environmental features. We propose that through combining both—environmental and behavioural insights—a better understanding of the morphological aspects of places can be described, and a more comprehensive research agenda for the studies of walkability and pedestrian behaviour can be defined. This would help to the design and planning of walkable and socially sustainable places in which pedestrian behaviour can be foreseen in more accurate ways, and the liveability of places can be better enhanced beyond speculations on general functionality. Thus, the contribution of this paper relates to (i) the articulation of knowledge domains that tend to rather operate as separate (urban design, planning, and transport studies), (ii) the creation of more comprehensive and undifferentiated environment-behaviour units of analysis for sustainable walkable environments, and (iii) the improvement of simulation models that better inform design decisions.

In practical terms, this is tested through applying specific modelling of street furniture in urban settings based on modified Barnes' Agent-Based Model (ABM) of pavement [20] and by using NETLOGO—a multi-agent modelling and simulation integrated environment—to present pedestrians' behaviours towards street environment involving population characteristics. To be more comprehensive than similar existing findings, pedestrians are segregated into groups—with a range of population characteristics—and objective factors (density of street furniture) are introduced to observe the interaction of these factors on pedestrian flows and impacts they have on congestion. In the next section, the relationship between the morphological aspects of the built environment and people's behaviour is discussed. This provides

insights on urban morphology linked to social processes; a type of knowledge that has been intuitively used in urban design to promote socialisation and walkability in specific terms. The insights are then progressed in a subsequent section that focuses on walkability, streetscapes, and urban furniture. After presenting the methodology, the Northumberland Street in the city of Newcastle Upon Tyne (UK) is used as an instrumental case study to be modelled and to exemplify on pedestrian behaviour linked to street furniture. The conclusions underline the strengths and drawback of spatial determinism and modelling simulation, but more broadly on how evidence-based design would help to control pedestrian behaviour and thus, stimulate walkability. The paper finally suggests revisiting 'spatial determinism' to complement urban design with predictive modelling emanated from engineering methods for the study and planning of the social aspects of the built environment.

2 Conceptual discussion

2.1 The built environment and spatial determinism

Studies on the relationship between urban morphology and social processes are often found in spatial planning, social theory, and design traditions. Questions on how places influence societal processes at different levels have been at the core of such fields [21], and have been scrutinised at different spatial scales ranging from 'environmental' (or climate) determinism [22, 23]—when referring to behavioural patterns of groups in a large geographic area—to 'architectural' (spatial) determinism when referring to small scale places such as houses or streets [24]. In any case, the questions become whether the environment can or cannot determine a certain behaviour, to what extent, and how, and if such behaviour can be predicted, modelled, or simulated for planning and design purposes. Different from 'environmental determinism', urban planning and design focus on the built environment as it is designed, (re)produced, and changed by us and according to emerging social needs. These ideas flag the difference between the creation of 'spaces' and 'places' as 'spaces' are produced by nature while 'places' respond to a complex mix of social practices [25]. 'Places' are thereby the scenario of cultural and behavioural manifestations partly defined by functional arrangements [26]. The literature on placemaking and social infrastructure is extensive in suggesting how public buildings and public spaces, for example, help to develop social connections between strangers [27]; something that highlights the power of places in inducing people's interaction.

In the past, this causal relationship (environment-people's behaviour) was held to determine the architectural form of places in a bi-directional 'form-function' linkage. Popular Louis Sullivan's maxim *the form follows function*—a mantra for architects since the nineteenth century—established this correlation as matter of architectural consistency, but also to promote social values led by institutions of control and moral validation [28]. In the twentieth century, the question arose with the social program of Modernist architecture on how buildings—and by extension the whole built environment—determine social behaviour entirely through controlling buildings' form. After various failed attempts, however, Modernist architecture and Sullivan's mantra became contentious and syndicated as architectural positivism by mistaken that human behaviour can be fully prescribed by architectural design in the same way natural environments are determined by the laws of physics [29]. The assumption that individuals were passive objects whose actions are moulded by the interplay of elements of the built environment was proved false, and the belief that designers can influence social interaction by manipulating the physical environment was observed as reductive of human agency. Despite this—and critics around the meanings of 'function' and rhetoric on buildings as 'forms'—architects, planners, and urban designers insisted on the potential of creating not only "buildings and places that are new, functional, and attractive, (but) environments (that) change behaviour and attitudes" [17, p. 252]. Such aspiration has been revisited by assuming that "causal powers operate within the natural as well as the social world, and in the social world they include the abilities of human agents as well as social structures and discourses to influence human actions, their well-being and social life in general" [13]. Also, new inputs from behavioural psychology have helped to define nuanced approaches (not too deterministic, not too improbable) to placemaking and prospect a highly probable social behaviour [30]. This probability is matter of degree rather than absolute certainty, although the degree of (in) determinism can still be synthesised between absolute determinism v/s absolute uncertainty (Fig. 1).

This probabilistic state is also problematised by the ontological turn of the space linked to historically rooted cultural behaviour. In a church, for example, that can have a similar shape and size of a dancing room, we cannot simply dance although still physically possible. This is a case in which the meaning of the space—more than its physical settings—defines what is allowed and what is not in terms of behaviour. In a different vein, famous Churchill's observation that

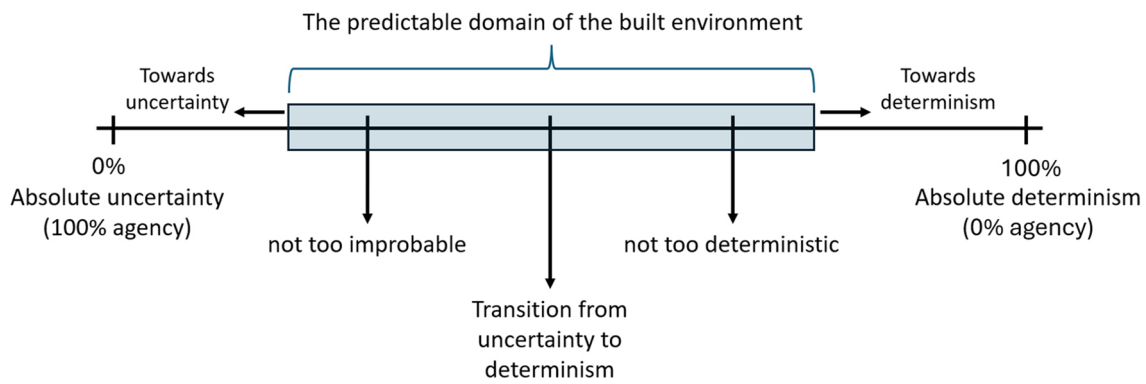


Fig. 1 The transition between absolute determinism and absolute uncertainty

the shape of the old Commons Chamber of the British parliament was responsible for the two-party system¹—which is the essence of British parliamentary democracy—entails a level of causality that is framed by cultural norms as well as form-function links [31]. Within this, the centrality of human agency in the everyday construction of meaning situates architectural determinism as an expression of culture or social values expressed through specific spatial settings [32]. Studies on the daily-life use of places confirm such level of probabilistic causality by linking the space and behaviour in ontological ways as “people actively endow aspects of their physical environments with meanings (...) on which they and others indeed do act” [33, p. 415]. This ontological turn has revalued architectural determinism by introducing symbolism into functionalism—and as mentioned—by assuming that the success or failure of places lie on the ability of planners and designers to predict human behaviour with reasonable accuracy [34]. In the study of public spaces and public life, indeed, Gehl and Svarre [35] have recalled the scientific assumptions on culturally-rooted functionalism by homologating the way meteorologists predict the weather with greater accuracy—a difficult phenomenon to predict as life itself [35]. As the weather, social behaviour is a phenomenon in constant flux that can nevertheless be predictable by using sure-fire methods applied to the use of a particular city space [35]. The authors also suggest that people’s behaviour in public spaces can be compared to studying other forms of living organisms in which counting, mapping, and direct observations become key to identify behavioural patterns.

Shah and Kesan [32] similarly proposed that detailed understanding of how places affect behaviour—and how they can be used proactively to influence behaviour—would help to enhance social interaction or reduce crime. The idea that places act as a regulatory force—like planning policies, laws, construction norms and other constraints over land uses—keeps the causal form-function correlation stable while allowing human agency. This would differ from absolute determinism defined by rigid stimulus–response (environment–behaviour) commands and would exercise individuals’ capacities to behave in more spontaneous ways within a predefined spatial setting. These are the cases of squares or streets in which sitting places makes people interact because they are sitting in front of (or beside) each other [30]. It has also been proved that places can discipline (or teach) people on how to interact, how to use the space, what path pedestrian should follow, which direction groups should take, or where to look. Essentially, places “can control the spatial ability of actors as well as define a set of rules that govern their interaction by limiting locations, paths of movement, programmed encounters, and chance encounters” [32, p. 354]. These are design principles that have been used to encourage consumerism, deter visitors of accessing properties, create liveable and walkable places, or stimulate individual’s interaction; principles that illustrate how places shape people’s behaviour regardless their personal characteristics [36]. Cases in point are housing blocks with main doors facing shared courtyards that serve as common entrance for all neighbours or alleyways where distance between houses’ doors increases chances to talk [37]. The observational work of designers and architects has generally been helpful to expand the taxonomy of patterns of occupation associated to the morphology of places (see the compilation of places’ morphology proposed by Schlickman and Domlesky) [38]. In other words, architecture and places “can act as a mnemonic device supporting a

¹ Winston Churchill in 1943 inspected the reconstruction of the new chamber agreeing that ‘confrontational design helps to keep debates lively and robust but also intimate’ and raised the famous conclusion that ‘we shape our buildings and afterwards our buildings shape us’: <https://www.parliament.uk/about/living-heritage/building/palace/architecture/palacestructure/churchill/>

certain type of behaviour, (although) cannot make you act or respond in a specific way” [24, p.172]. In that sense, spatial determinism relates more to the conditions of the built environment for certain things to occur rather than causes that explain strict form-function correlations. In that sense, places are “more or less open systems where empirical regularities rarely occur spontaneously” [34, p. 60]. On this basis, “causality in the social world should be understood in terms of generative mechanisms, that both social structures and human agency have their own properties and causal powers, and that built environment characteristics could be considered as a particular sub-set of social structures characterized by having a relatively high permanence” [34, p. 68].

2.2 Walkability and the built environment

In the same way that spatial determinism acknowledges the built environment in influencing people’s behaviour, the literature on walkability “appreciate the importance of the built environment in facilitating or constraining walking” [39, p. 1]. Studies of the influence of the built environment on walkability have become very pragmatic and mainly oriented to inform planning and design policy [40]. Empirical research has indeed extensively proved that walking environments are determined by functions, distances to destinations, safety, accessibility, legibility, orientation, spatial boundaries, separation of cycling and car pathways, connectivity, density, comfortability, attractiveness, aesthetics, traffic calming techniques, urban furniture, and the overall materiality of walking paths; all elements that we can plan, design, maintain, or change [41–43]. It is important to highlight that these factors do not work as isolated but interlinked [44], and in correlations that do not show similar results in different contexts. Increasing the number of people living in a determined area, for example, will not automatically increase the number of people walking if the area is perceived unsafe [45]. Indeed, planners and designers have different views when describing a good walkable environment. Gehl [46], for example, claims that key quality criteria (protection, comfort, and delight) are necessary to create safe and protected pedestrian spaces, while Blečić [47] argues that the qualities we claim for good public spaces (opportunities to stay, sit, contemplate, interact, play and exercise) are also key for walkability. In other cases, separating pedestrian paths from vehicle traffic and in-between parks and open spaces to break down endless lengths are claimed necessary [48].

Spatial analysis has proven that these aspects must be conceived at both macro and micro-scales as the physical details of the environment make important differences when estimating walkability and influencing pedestrian behaviour [49]. Woldeamanuel and Kent [50] argue that clear design of sidewalks and street lighting encourage people to walk during the evening/night, while surroundings can deter pedestrian to pass through places that are perceived unsafe. Thus, adjacent land uses, boundaries, borders, neighbourhood quality and views ensure legibility, which positively influence pedestrian behaviour [51]. Ewing and Handy [52] indicate that (human) scale and material qualities—transparency, tidiness, enclosure and imageability—motivates people to walk along with enclosure, block length and edges [53]. The orientation of buildings can intensify circulations in the street, while vegetation intercepts solar radiation, providing shade, and cool the local air [54]. In university areas, well designed streets function as connectors and social venues for students [55]. The number of entrances in a block also motivates people to walk in contrast to blind walls that promote insecurity and isolation that deter people to use the space [56]. Street furniture become key to both attract or divert circulations [57], while sidewalks can be responsive to different pedestrian groups including people with shopping trolleys, walking with pets, general strolling [58], and disabled people [59]. For Lin and Chang [60] children’s walking behaviour relates to sidewalks that are equipped with trees and are fenced by building blocks that prevent unexpected crossings; children feel confident, and parents allow them walking independently. Jiang et al. [61] claim that walking behaviour is influenced by shaded walkways with active edges at the median transit-way. Southworth [62] explains that good links to other modes of transport, good quality street furniture, and varied land use patterns promote safe and attractive walking. Studies on transportation emphasise the importance of pedestrian crossing and associated devices—such as countdown timer units—to reduce the number of individuals who crosses during the red man (do not walk) signal [63]. These morphological elements, their spatial distribution, and orientation influence pedestrian behaviour all together.

2.3 Towards a deterministic walking behaviour?

Qualitative studies on walking behaviour indicates that “walking as a form of transport has received only limited attention, and much of the research on travel practices has been strongly quantitative” [64, p. 264]. This is partly true as there is abundant qualitative literature from design and behavioural disciplines that associate pedestrianisation

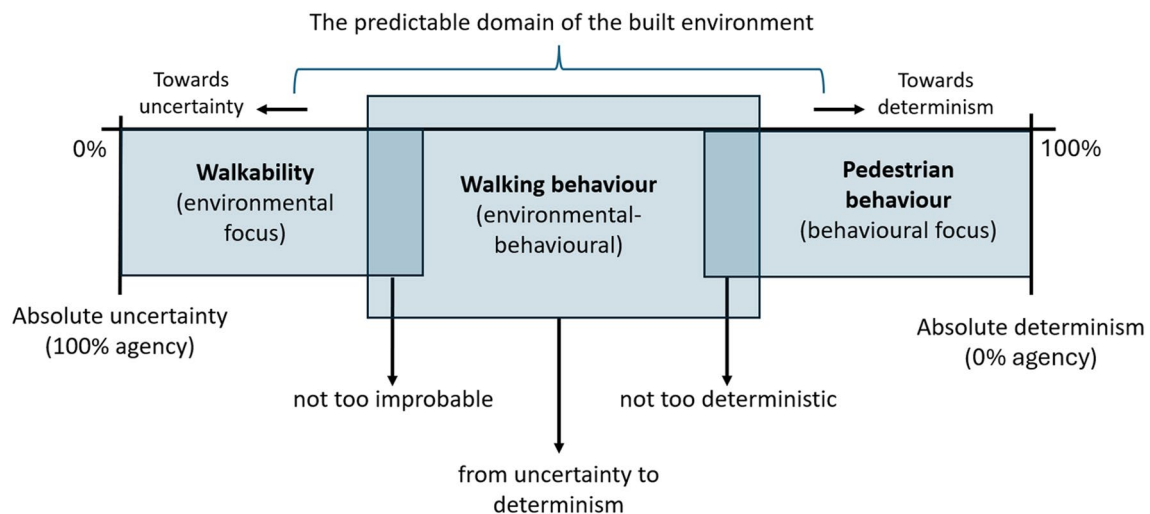


Fig. 2 The place of walking behaviour within walkability and pedestrian studies

with walkability and public space. The two terms—*pedestrian behaviour* and *walkability*—are distinguished in both disciplinary and conceptual terms as while ‘pedestrian behaviour’ is mainly used in transportation studies to refer to “the whole decision-making and transportation process between two points” [65, p. 69], ‘walkability’ is widely used in urban planning and design to refer to the environmental features that facilities (and encourage) pedestrian movement. So, while pedestrian behaviour focuses on people’s movements, walkability focuses on the environment that facilitates such movement. The connection between the two lies on the assumption that walkable environments would define more predictable patterns of pedestrian behaviour and thus, would facilitate its modelling, measuring, and scoring linked to walkable conditions. Alternatively, the notion of *walking behaviour* better amalgamates both—environmental and pedestrian characteristics—in the search of places that promote physical activity and healthy living. More broadly used in health sciences, walking behaviour highlights that people have agency to decide their own movement without relying on others but the environment [66]. On this basis, walking behaviour would bridge walkability and pedestrian behaviour as it is determined by both “cognitive, perceptual, and personal characteristics and preferences, the idea of time” and “urban environment aspects and weather conditions” [65, p. 69] (Fig. 2). This environment-behaviour link becomes relevant as most claims on pedestrian behaviour tend to overlook spatial settings or include only some environmental variables within simulation and modelling to favour short distances and efficiency from a time-spend viewpoint [64].

By introducing qualitative inputs into quantitative modelling, Woldeamanuel and Kent [50] indicate that a lack of street furniture makes walking unnecessarily long and thus, furniture can create street sections, reduce distances, and ‘interrupt’ walking with necessary stopovers to regulate walking speed. On conceptualising ‘stopover’, design studies count the implementation of kiosks, small stores, benches, information spots, telephone cabins or public toilets; all elements that take walking behaviour off from functional efficiency through making the streetscape a ‘relay race’. Other measures have been taken to reduce pedestrian traffic accidents [67, 68], including design elements associated with safety such as curb extensions, high-visibility crosswalks, pedestrian buffers, pedestrian refuges, and traffic signals inter alia [69]. Simulation models have also included transit stops, mass evacuation refuges, congestion and regular pedestrian saturation for mass events. These models—typically used in transportation analysis—are slowly transitioning into design and planning disciplines.

Batty [70] traced the beginnings of pedestrian modelling from a design angle around the 1970s when it was an extension of traffic and transit simulation models. The author, however, critically identified an ‘institutional emphasis’ on modelling road performance for automotive traffic while ignoring the microscale behaviour of pedestrians and their implications for street planning. Similarly, Hoy et al. [71] suggested that traditional modelling mainly evaluated aggregate flows overlooking specific pedestrian characteristics. More complex (and exact) models were built on behavioural questions and advances in neuroscience and Artificial Intelligence (AI) [70, 72, 73], which allowed classification of pedestrians [73] along with the introduction of differentiation factors and sources of social and physical heterogeneity [67]. These models have been—again—used to anticipate specific traffic scenarios, although the lack of concrete origin–destination settings makes the

models still very abstract and somehow detached from real-life pedestrian movement in street networks [74]. To improve predictability, ABMs of pedestrian behaviour introduce environmental elements—such as visual space—to influence agents rather than being bound only by route choice judgments [71, 75, 76]. These ABMs were designed to simulate the geometry of each agent's movement by merging the agent's location with movement and more pragmatic behaviour [71].

Further improvements in modelling have helped to accurately represent pedestrian behaviour by introducing the 'level of service' (LOS) measurements for pedestrians in walkways, vertical circulations and queues, which are used to assess facility performance [77]. Moreover, LOS assesses the outcome of the existing street arrangement and attractor sites but fails to separate the two effects or predict the impact of changes [78]. Additionally—because of the trade-off between *competitive* and *cooperative* individual decisions—the total output of these micro-level features can lead to the creation of a collective behavioural pattern. The usual scenario is when local pedestrian movements toward a specific purpose result in unwelcomed congested conditions, while the urge to behave like others (*herding* effect) can lead to congestion and fear when in closed and limited space [79]. The development of self-organisation models [80] expanded on this topic by utilising ABMs. Helbing et al. [81], for example, compared the behaviour of normally behaved versus panicked pedestrians to prove that slower movement resulting from congestion is one of the unique activities during panic or evacuation scenarios. Furthermore, pedestrian self-organisation behaviours—such as channelized flow, oscillation of flow at entrances, and avoidance behaviour in locations with competing flows—are also found under normal settings. The determination of behaviour through these modelling, however, is still insufficient as it ignores different walking speeds and destinations, and confines agent to crowds that exhibit the same behaviours with a high degree of conformity. Barnes et al. [20] illustrated the value of integrating extra population features demonstrating that durations that did not account for individual characteristics might be deceptive. These behavioural are also combined with environmental factors of streetscapes, in which street furniture affect pedestrian behaviour in various ways [14]. To introduce this into modelling various instruments have been developed, being the *Irvine Minnesota Inventory* (IMI) "one of the most comprehensive (...) yet developed for measuring the built environment features that are hypothesized to be associated with physical activity and walking for travel" [82, p. 737–738]. Such features include physical factors (pavement, street characteristics, street furniture, others), but also social that affect walking. The IMI suggests that only certain urban design features influence walking more directly, above all when pedestrian behaviour is associated with travel. Focusing on streetscapes, Salon et al. [83] found that subjective judgements (on how easy it is to cross streets) also influence pedestrian behaviour, while other empirical studies suggest that pedestrian furniture should be evaluated on how it interacts with pedestrian mobility [84]. Despite ongoing evidence, there are not conclusive remarks to gauge how effective street furniture is in influencing pedestrian behaviour.

3 Methodology

3.1 Methodological framework

The methodological framework combines insights from the urban planning and design literature (with focus on urban morphology), with quantitative findings and methods from transport studies (with focus on pedestrian behaviour). From the planning and urban geography literature the research draws on the notion of spatial determinism to contextualise walking behaviour as an embracing concept that encapsulates both environmental and population characteristics. This allows situating spatial determinism as a condition that articulates social behaviour linked to the urban environment in general, while combining qualitative and quantitative findings. The research pathway starts with an in-depth review of spatial determinism to then draw on walkability in one side and pedestrian behaviour in the other. These two lines of enquiry decant into walking behaviour as an operational term for the analysis of pedestrian behaviour but not only linked to population but also environmental characteristics. Finally, a revisited conceptualisation of spatial determinism for urban planning and design is proposed. On this basis, spatial determinism is (re)situated within the studies of places and how they help to determine social behaviour, functions and uses (Fig. 3).

3.2 Research design, case study and methods

Qualitative methods considered the critical audit of up-to-date literature on spatial determinism, walkability, pedestrian behaviour, and walking behaviour. An explorative and structured literature review of scientific publications was

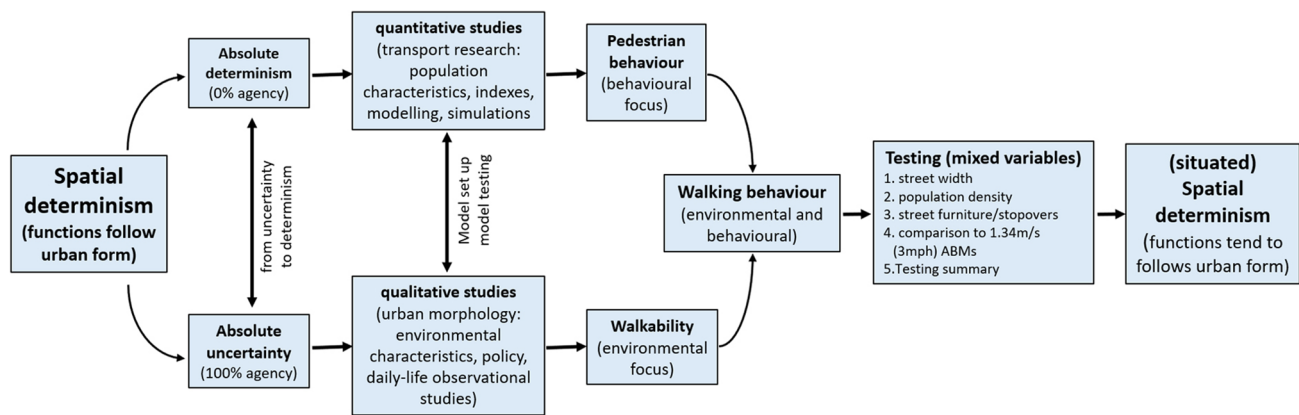


Fig. 3 Research pathway (spatial determinism through qualitative and quantitative analysis of walking behaviour)

undertaken following Fink’s framework for critical review [85], which allowed identifying, evaluating, and interpreting findings and underlying themes that support the argument of the study. Thematic analysis was implied to identify commonalities and differences in content, confirmation of findings in different contexts, trends, and potential generalisable conclusions. As part of a structured literature review, a total of 126 peer-reviewed articles mostly published since 2010 were filtered and scanned from scientific (open access) databases. A subsequent selection of articles allowed identifying those which better synthesise content and findings, then carefully scrutinised using content analysis throughout an inductive and deductive approach. In the analysis and after the synthesis exercise, four themes were found as directly influencing walking behaviour: (i) street width, (ii) in-between parks and green spaces (structural stopovers), (iii) street furniture (variable stopovers and obstacles), and (iv) population characteristics. The last has been expanded from gaps found in the transport literature on pedestrian behaviour in which population characteristics are not fully considered. These themes from walkability and pedestrian behaviour were simplified to be operationalised in the Agent Based Model (ABM), which is the core method used for simulation and extraction of quantitative data.

The observations were conducted as part of regular site visits and first-hand records on street features and urban furniture more specifically. The approach draws on critical insights on identified levels of spatial determinism in the morphology-behaviour relationship, to be then introduced into the micro-scale modelling simulations. The microscale agent-based model was constructed in NETLOGO as it provides multi-agent modelling and simulation integrated environment. Through NETLOGO a large number of mobile agents were set up to interact with each other in a two-dimensional space. To be more comprehensive than other existing results, ‘density of street furniture’ was introduced as a key variable to explore the role of street furniture in pedestrian flows and impacts this may have on street congestion. With the advance of time, the attributes of microscopic individuals were constantly changing, so were the macroscopic characteristics of the system. The virtual simulation was composed of ‘subjects’, who can accept commands and carry out activities, and ‘actions’ of subjects that would occur simultaneously.

This model was based on Northumberland Street in the city of Newcastle upon Tyne (UK). The street has been selected by its social, functional, and economic importance within the city’s fabric. This is a typical (British) high-street—also observed in the city centre of other cities and towns—that concentrates shops and services. On this basis, we take Stake [86] distinction between case studies, in which Northumberland Street has been considered *instrumental* (rather than *intrinsic*). As instrumental, we draw only lightly upon this case as a basis for abstraction and generalization as we believe the analysis is one that has salience to the vast majority of British high streets. Despite this, Newcastle’s Northumberland Street is one of the most expensive shopping roads in the UK outside London [87], and concentrates a number of shops, multinational and local bank offices, and density of pedestrians. The streetscape has also hosted different design layouts including Christmas markets and summer festivals, historic buildings and archaeological heritage, and it is currently entirely pedestrianised (Fig. 4). An evacuation scenario was hypothesised to maximise dynamics, and 1000 simulations for each attribute were undertaken after Model calibration and testing to ensure reliability. Before any modelling, direct observations on pedestrian behaviour and records towards street furniture were made on the Northumberland Street to collate simulations with real-life morphological settings.

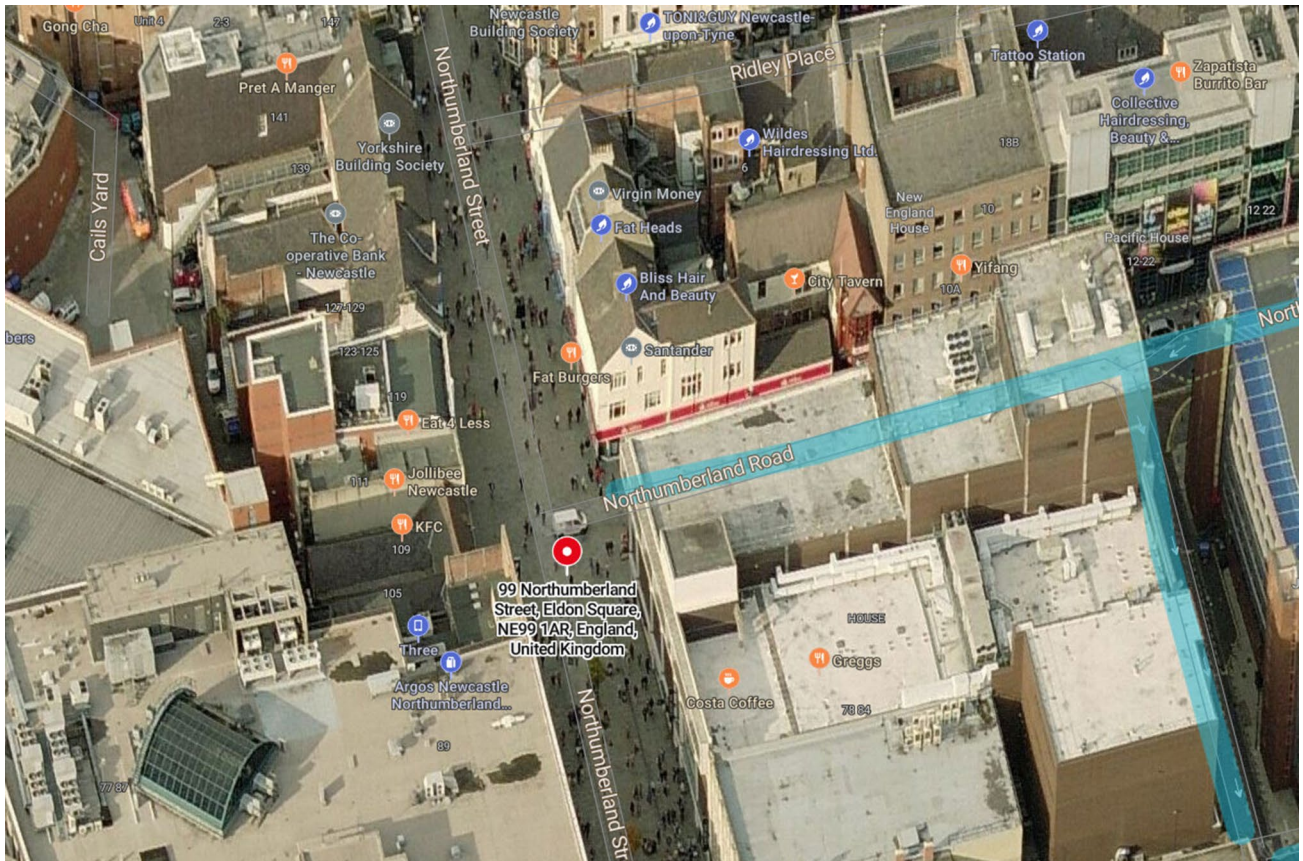


Fig. 4 Northumberland Street with location of shops and street furniture (authors' image based on Google Street map, accessed in July 2024)

3.3 Model set up, calibration and testing

The model was set up to represent population across time due to each population member acting as a separate agent. Following Barnes et al., [1] the model interface included:

- (i) *street representation*: A simplified simulation layer by road patches based on a real-life street, with different street widths represented by the number of lanes, forms the basis of the simulation, on which agents can walk from start to finish and obstacles can be randomly distributed.
- (ii) *population counters*: Multiple visualization Windows to show the number of populations in each experiment and the distribution of population groups in different characteristics.
- (iii) *a text output of the tested evacuation time in minutes*: Spreadsheets outputs after each experiment with the exact times of the evacuation (agents walking pass the street representation) among all population groups in different characteristics as well as the overall times.
- (iv) *population characteristics* (variable walking speed): Multiple different constant parameters for different walking speeds between groups with different population characteristics to find the potential effect of it on pedestrian behaviour
- (v) *environmental characteristics* (width of streets and open space): Adjustable parameters to represent different street widths in each experiment to find the potential effect of it on pedestrian behaviour
- (vi) *density of street furniture* (number of obstacles): Adjustable parameters to get different number of obstacles distributing on the street representation in each experiment to find out different pedestrian behaviour formed by different factors and their interactions.

The last factor (vi) was added to complement existing modelling and test the level of spatial determinism defined by a fine-grained definition of the streetscape. To do so, the existing code in Barnes' model was modified to generate, save, and load the obstacle positions to ensure obstacles are generated and fixed when variables remain the same. A new heading method to ensure that all agents remain moving, avoid obstacles, and avoid being stuck in one patch was also defined. Finally, a new select path directive was introduced to ensure that all agents choose the emptiest path on both sides. These new codes allow simulating pedestrian behaviour when encountering obstacles and interaction with other variables like population density, width of the street, or walking speeds. The remaining shortcoming is that there is no interaction with the agent beyond avoiding, and that the obstacle position cannot be kept constant while changing any variables. This, however, also allows the results to be more general rather than specific to one case.

Initialization involves setting up patches with default conditions, drawing roads, and defining home terrains, stoppers, and safe zones. First, patches are initialized with default conditions, and roads are drawn on the grid. Home terrains are designated as starting points for agents, stoppers are placed to prevent agents from entering the home areas immediately, and safe zones are created as destination points. Various agents are then initialized, including a general population and specific individuals like Bob, Ben, Barry, Betty, and Barbara. Obstacles are randomly placed on the grid to challenge agent navigation. Agents follow several decision rules to navigate the environment. They continuously check for obstacles by examining the colour of the patches ahead. If an obstacle is detected, they attempt to change lanes. Each agent has a patience attribute that decreases when encountering obstacles or moving slowly. If patience reaches zero, the agent changes lanes and resets its patience. Speed is adjusted based on the presence of obstacles and other agents, with procedures to speed up or slow down. Lane changes are based on the minimum distance to a clear lane, occurring when an agent's patience runs out, speed is too low, or an obstacle is detected.

Before undertaking the modelling, calibration and validation were made to ensure the validity and accuracy of the model. For this experiment, several observations were carried out to verify the anticipated behaviours, such as, (1) are agents travelling within their lanes, (2) are agents capable of switching to alternate lanes, and (3) once an agent has switched lane are, they correctly placed in a lane. NETLOGO Behaviour Space will be utilized to carry 100 runs for each to do (1) sensitive analysis (2) robustness checking. Model will be run multiple times and key outputs will be reported as an average, minimum value of each run will be assessed to see how model results vary for each internal run in order to produce internal stable results. The results shows a consistence between the average value and the minimum value (difference ≤ 0.1), which proved the model to be robust and stable. Once the model was calibrated successfully, it was theoretically considered able to output a reasonable evacuation time. After this, several tests were performed to show the impact of interaction of street furniture and population characteristics on evacuation times using parameters shown in Table 1. Following experiments were mainly based on comparing tests with previous related models with less influence from population characteristics and other variables to get a way to make assessment about the impact of the variables on evacuation time. In these experiments, the variables were adjusted to: (i) width of street, (ii) population density, and (iii) number of street furniture and open space, which changed in each single time of experiments. Thus, to find out what role that each variables play, the testing part is divided into four procedures: (a) effect of width (number of lanes), (b) effect of population density, (c) effect of number of street furniture (obstacles), (d) Comparison to 1.34 m/s (3mph) standardised ABMs, as shown in Table 1.

Table 1 Proposed testing procedure and questions

No	Variable(s) Tested	Research questions
1	Effect of width (number of lanes)	Whether the width of the pavement (number of lanes) have an impact on pedestrians' travel time
2	Effect of population density	Whether the population density have an impact on pedestrians' travel time
3	Effect of density of street furniture (obstacles)	Whether the density of street furniture have an impact on pedestrians' travel time
4	Comparison to 1.34 m/s (3mph) standardised Agent-Based Models	Whether these micro-scale pavement model differs from the calculated standardised model

3.4 Limitations of the study

The limitations of the study are identified within two domains. First, this study considered a limited number of environmental variables that although represent real-life streetscapes is still reductive of streets' complexity of morphological aspects. Morphological studies have identified various built environment elements that influence walkability, but this study has only considered a few to simplify and test pedestrian behaviour. Such environmental variables are deemed as obstacles although inferences were made on how such obstacles can instead become stopovers on walkable paths in accordance with morphological studies. In that sense, other variables—such as buildings' form, land plot subdivisions, connectivity layouts, weather condition and service level of infrastructure to name some—can be presupposed but were not added in the presented modelling. Second, the study cannot present a detailed analysis of pedestrian experience in real life based on qualitative data on behavioural attitudes towards street environments captured through surveys and interviews. In that sense, although observation was taken to offer a holistic perspective in the analysis of pedestrian behaviour, it is yet not adequate to examine some categories of activities. Despite limitations, the propose theoretical idea and instrumental scope entails further room for a more comprehensive articulation of both environmental and behavioural variables in the understanding of walking behaviour.

4 Determining walking behaviour

4.1 Environmental characteristics

It is important to ensure the pavement model—in terms of length and breadth—is indicative of real-world pavements as otherwise it will not be instrumental when applied to city planning. It is also noticed that when evacuations happen people tend to use roads existing in front of them—including some narrow streets or market streets—and thus, different widths, density of street furniture, and preferred interpersonal distance must be considered as per introducing social differences (cultures or familiarity). Based on Hall's interpersonal distances [88, 89] the lowest estimation for every distance would be 0.46 m (personal), 1.22 m (social), and 2.10 m (public). These distances are used as the maximum and minimum limits for the variable which reflects on the number of lanes in the model and ranging from three to ten (Fig. 4).

4.2 Population characteristics

Population characteristics parameters for the modelling adopted previous model parameters proposed by Barnes et al. [20] (Table 2). As the test city is geometrically based on Newcastle, it appeared reasonable to rely on local data to determine the population distribution. Thereby, children represent 17% of the population, Male Adults 34%, Female Adults 35%, Male Old Age Pensioners (OAPs) 7%, and Female OAPs are 7% [90]. Barnes et al. [1], also pointed out that walking speeds were strongly correlated with age and gender, and five main population types were used: Children Walk at 0.8 m/s (1.8 mph), males at 1.34 m/s (3 mph), women at 1.12 m/s (2.5 mph), male OAPs at 0.78 m/s (1.74 mph), while female OAPs walk at 0.76 m/s (1.7 mph).

Table 2 Typical user variable values in the city model

Population Size	> 1000
Newcastle's population distribution	Children = 17% Male Adults = 34% Female Adults = 35% Male OAPs = 7% Female OAPs = 7%
Varied Walking Speed	Children = 0.8 m/s (1.8mph) Male Adults = 1.34 m/s (3mph) Female Adults = 1.12 m/s (2.5mph) Male OAPs = 0.78 m/s (1.74mph) Female OAPs = 0.76 m/s (1.7mph)

4.2.1 Test 1: effect of width

Firstly, the width of the street has been explored. In most cases, the width of the pavement varies within a certain range and can be divided into several lanes. Considering that different cities have different population densities and evacuation pressures, a range of numbers of pavements were tested, from 3 to 10. Figure 5 shows the results of 1000 simulations introducing different walking speeds, presented with different population types and average travel times. As shown, there are significant differences in the average travel times for different population types with different speeds (also confirmed by Barnes et al. [20]). Another point to note is whether the average travel time is significantly affected by the number of lanes, and to figure this out, the standard deviation of the average travel time through three to ten different numbers of lanes per population type is calculated. By calculating through eight different numbers of lanes, the standard deviation was obtained to be only 0 min for children, 0.01 min for male and female OAPs, and only 0.03 min for female adults, with the largest value for male adults at 0.06 min. The standard deviation for the different population types above shows that the average travel time is not significantly influenced by the width of the road. Therefore, increasing the number of roads is not a necessary condition in the micro-pedestrian model.

4.2.2 Test 2. effect of population density

Average travel time with different population density as variable in the range of 0.1, 0.3, 0.5, 0.7, 0.9, while introducing different walking speeds for population types; the pavement was also explored. After 1000 simulations of the pavement, the results were compiled into Fig. 6. These show that when population density rises, the average travel time increases. Specifically, it has been calculated that the average travel time on the pavement increased from 18.15 min to 21.86 min. Also, it is worth noting that the standard deviation of the five average values decreases gradually, from 3.87 at 0.1 population density to 1.25 at 0.9 population density, which means that the average travel time is less varied when the population density rises. In addition, on the pavement the standard deviation of the five average values of Children and Male and Female OAPs is only 0.81, 0.69 and 0.43 min, while the values of Male and Female adults reach 2.85 and 2.04 min. This means that the average travel time of faster male and female adult agents is more affected by population density than slower children and OAPs agents. Based on this, it can be inferred that the expected travel time increases with population density as when population density rises the chance of each agent encountering congestion and giving way increases. It can also be inferred that travel time increases with population type because faster agents are hindered by slower agents, and when population density rises the difference in travel time decreases because everyone is affected by greater demand of giving way. Therefore, it is possible to indicate that density of population must be included if the 'business' of the street environment needs to be firmly changed in the micro-scale pavement model.

Fig. 5 Average travel times per population group when the pavement width is between three and ten lanes, for each population type: mean (standard deviation), children: 20.7 min (0 min), male adults: 12.34 min (0.06 min), female adults: 14.66 min (0.03 min), male OAPs: 21.24 min (0.01 min) and female OAPs: 21.79 min (0.01 min)

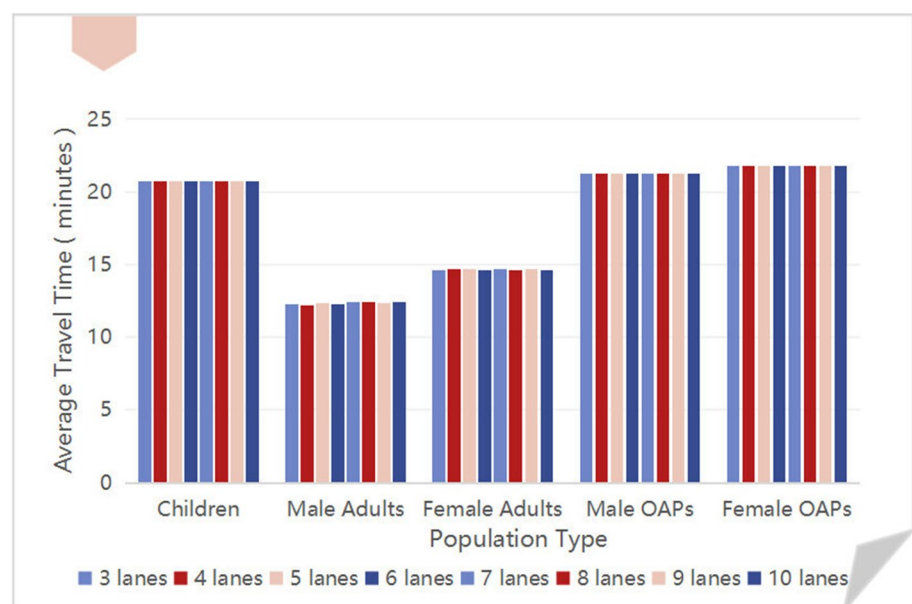


Fig. 6 Average Travel Times for each population group on different densities of population in the range of 0.1, 0.3, 0.5, 0.7, 0.9, for each population type: mean (standard deviation), children: 21.11 min (0.81 min), male adults: 15.51 min (2.85 min), female adults: 17.16 min (2.04 min), male OAPs: 21.59 min (0.69 min) and female OAPs: 22.06 min (0.43 min)

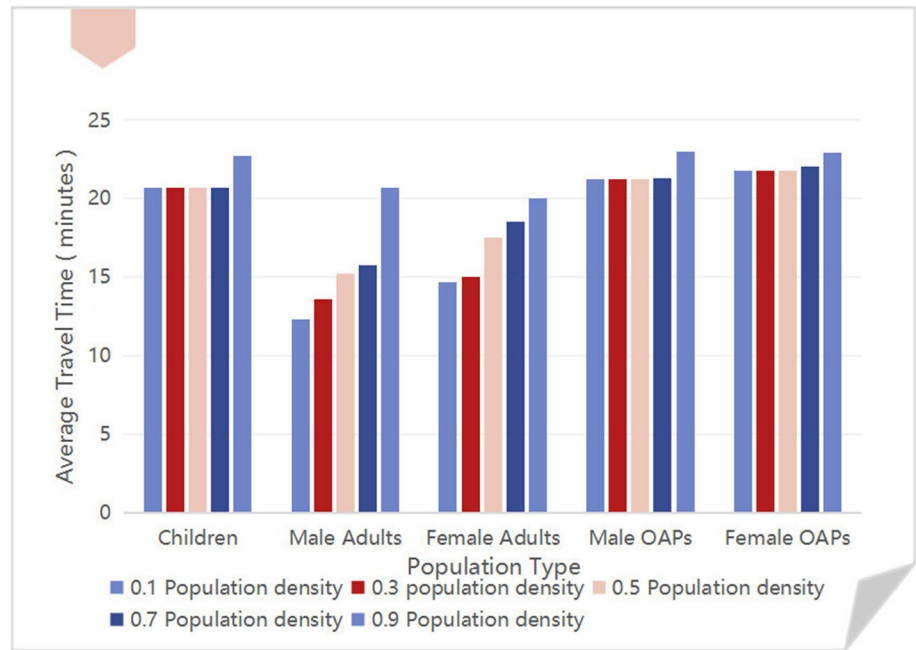
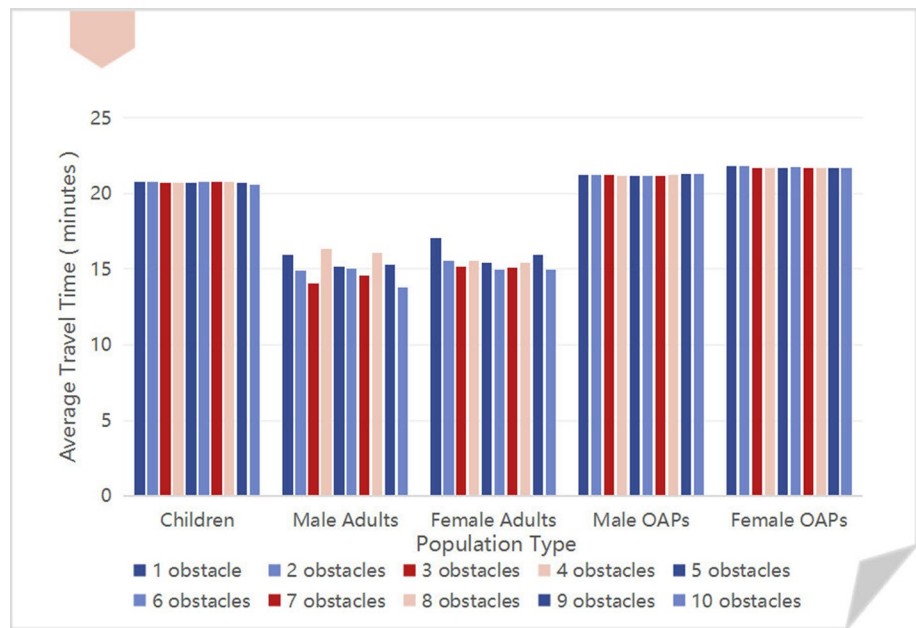


Fig. 7 Average Travel Times for each population group when considering the number of obstacles (street furniture) ranging from 1 to 10, for each population type: mean (standard deviation), children: 21.72 min (0.05 min), male adults: 15.03 min (0.85 min), female adults: 15.31 min (0.32 min), male OAPs: 21.21 min (0.06 min) and female OAPs: 21.70 min (0.02 min)



4.2.3 Test 3. effect of density of street furniture

This mainly explores the influence of the number of obstacles (street furniture) ranging from 1 to 10 as a variable on the pavement model simulating different walking speeds and other variables. After obtained the results of 1000 simulations, another plot was completed (Fig. 7), which shows that the number of obstacles has no significant effect on the type of slower agents (Children and OAPs) as the standard deviation ranges from 0.02 to 0.06 min for ten averaged values.

However, the number of obstacles has some effect on the faster agent type (Male and Female Adults), which causes the average travel time to fluctuate and decrease overall. In terms of Male Adults, the average travel time fluctuates from 16.33 to 13.77. For Female Adults, the average travel time fluctuates from 17.03 to 14.95, which suggests that a larger number of obstacles leads to an increase in the number of overtaking in the model, so the faster agent can pass the road with more obstacles faster. Therefore, to robustly vary the representation of congestion, the number of obstacles needs to be considered. One thing needs to be noticed is that the fluctuation of the average travel time of Male and Female Adults may be related to the location of obstacles in each test because the location of obstacles inevitably changes with the change of variables.

As stated above, population density is also a significant variable to consider, so a further plot was compiled to combine varied population density and number of obstacles within the micro-scale pavement model (Fig. 8). It indicates that the average travel time rises when the population density increases and so does the travel time variance. This is quite opposite to previous result when just considered population density, showing that both population density and number of obstacles are to be considered in micro-scale pavement model when necessary to vary the capacity and congestion of the street environment.

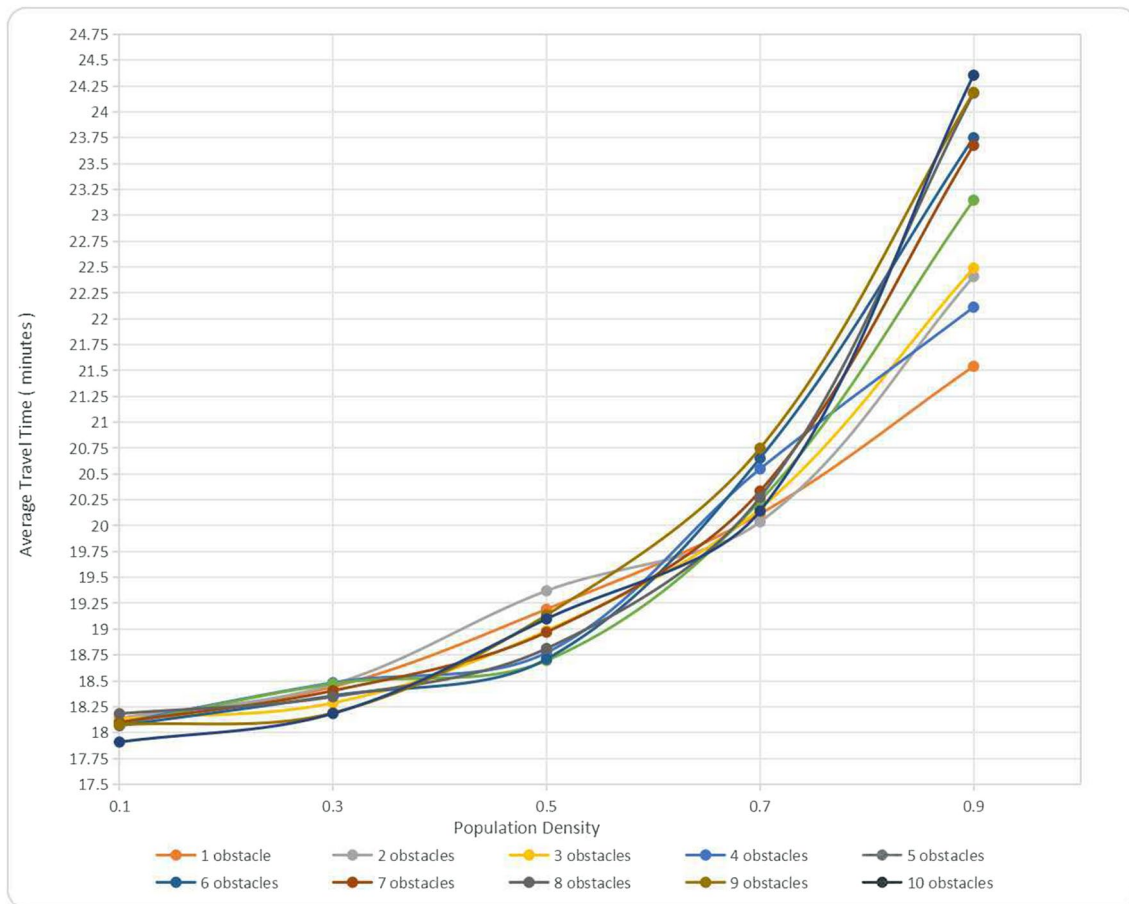


Fig. 8 Average Travel Times based on Population Density between 0.1 and 0.9 and number of obstacles between 1 and 10 for each number of obstacles: mean (standard deviation), 1: 19.49 min (1.23 min), 2: 19.68 min (1.52 min), 3: 19.61 min (1.61 min), 4: 19.60 min (1.51 min), 5: 19.73 min (1.86 min), 6:19.91 min (2. 12 min), 7: 19.90 min (2.04 min), 8: 19.96 min (2.24 min), 9: 20.07 min (2.27 min) and 10: 19.94 min (2.34 min)

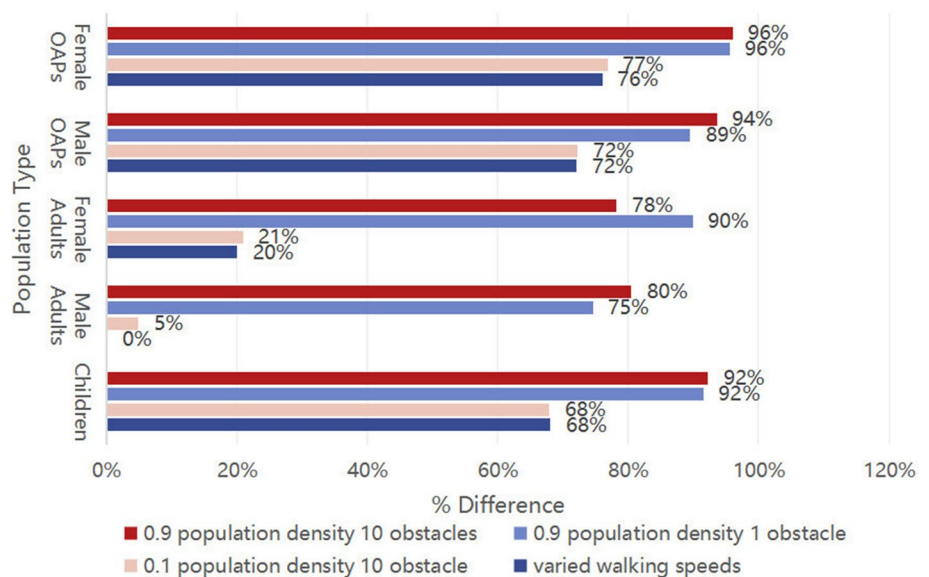
4.2.4 Test 4. comparison to 1.34 m/s (3mph) ABMs

To find out whether these micro-scale pavement model differs from the standardised model with no additional variables and walking speed of only 1.34 m/s (3mph), the results of 1000 micro-scale pavement simulations with population type, population density and number of obstacles as variables were compared with the standardised model. The calculated travel time for 1.34 m/s pavement model is 12.26 min. Compared to 1.34 m/s pavement model, there are differences in travel time of 1000 micro-scale pavement simulations for all population types (Fig. 9). As shown—when considering only the application of different walking speeds (as expected)—the percentage time differences are greatest when it comes to the slower population groups because their speeds were greatly reduced compared to 1.34 m/s. On the pavement—when both population density and the number of obstacles is considered—male adults and female adults are significantly affected in travel time, but slower population groups (children and OAPs) are less affected as they have less need to overtake but contribute to congestion for adults. As Fig. 9 shows, when the population density is low (0.1) and the number of obstacles is high (10), the average travel time of male adults increases by 5% and that of female adults increases by 21%, while for Children, Male and Female OAPs the figures are 68%, 72% and 77%. What is more, when the population density is high (0.9) and the number of obstacles is low (1), the average travel time of Male Adults increases by 75%. For Female Adults, the average travel time increases by 90%. For Children, it increases by 92% and that of Male and Female increase by 89% and 96%. Finally, when the population density is high (0.9) and the number of obstacles is also high (10), the average travel time of Male Adults increases by 80%. For Female Adults, the average travel time increases by 78%. For Children, it increases by 92% and that of Male and Female increase by 94% and 96%.

These data show that the travel time of the slower Children and OAPs is mainly affected by population density, while the number of obstacles does not have a significant effect on it. In other words, their travel time increased mainly with population density. For faster Male and Female adults, population density is the biggest factor affecting their travel time, but the number of obstacles also has a significant impact, especially when both the number of obstacles and population density are at a high level. By comparison, variables such as different walking speed, population density, and the number of obstacles will have relative influence on travel time. In these simulations, the location of obstacles, the interaction between obstacles and population density, the function of obstacles, and the purpose of travel may all affect the travel time. Similar variables should be reflected in future micro-scale models to explore more factors.

affecting human behaviour on the pavement.

Fig. 9 Comparison to 1.34 m/s (3mph). Calculated Model and ABM Values show the introduction of varied walking speeds for different population types only, then the effect of varied walking speeds of different population groups combined with population density and number of obstacles



5 Discussion

By introducing a series of variables such as the number of lanes (width of street), population density and street furniture density, the simulation of the pavement environment becomes more reliable. The simulation includes not only different walking speeds for different populations, but also overtaking and give-way behaviours, which is necessary to include in the model as these occur objectively on the pavement in real life. By changing the variables—i.e., changing the size of the pavement, population density and the number of obstacles to replicate the street furniture on the pavement—more real-life street environment similarity is achieved. The same occurs when introducing open spaces as stopovers. Compared with the calculated 1.34 m/s standardised pavement simulation, the simulated travel time is very different. The average time difference is between 40 and 90%, and in the worst case this range increases to between 78 and 96%. This indicates that the existing pavement simulation may have a large bias in terms of travel time. Furthermore, travel time increases when population density increases and fluctuates when number of obstacles increases. Besides, there is a certain interaction between population density and the number of obstacles. When altering population density only, the variation of travel time decreases; however, when adding obstacles as an additional variable the variation of travel time increases. Therefore, ignoring obstacles and the interaction between obstacles and population density will also lead to inaccurate pavement simulation of travel time.

The ABM at micro-scale has been developed to assess the influence of streetscapes and population characteristics on walking behaviour. Through the modelling, it has been proved that walking behaviour is indeed linked to key morphological features of the space, and the way of how people behave in walkable scenarios. In this case, the walking behaviour can be predicted with a reasonable level of accuracy. The environmental variables used in the models also provide a comprehensive depiction of standardised streetscape scenarios and population characteristics for simulation. Average travel times, for example, are clearly affected by changes in the environment—or population characteristics—in which density and street furniture, for example, have direct incidence in behavioural patterns. On this basis, the discussion and the analysis presented in this paper raises further questions around the need of having more interdisciplinary conceptual and methodological frameworks needed for the understanding of places and social behaviour. In particular, it draws on how ABMs can be used to plan, design, and prospect sustainable walking environments that also help to reverse undesirable indicators such as quantities of injuries resulting from the lack of awareness on walking behaviour, or lack of spatial legibility under evacuation scenarios. The findings, in that sense, confirms the mnemonic character of the built environment and the power of places in influencing people's use of the space.

6 Conclusions

Debates on spatial determinism have pendulated between absolute certainty and the unpredictability of social behaviour. The last has gained traction in urban planning and design circles as predictable modelling has tended to be reductive and simplistic of social processes. However, the presented discussion and findings suggest that spatial determinism can be revisited and better situated around less rigid and yet well informed and calculated ways of prediction. This becomes more evident when analysing walking behaviour—a conceptual term that better encapsulates both environmental and behavioural characteristics—as it enables controlled simulations of streetscapes and how pedestrians react to environmental elements. Walking behaviour gives credit to findings emanated from urban planning, urban design and social theory, to finally frame a more comprehensive understanding of the urban morphology of places. Concurrently, walking behaviour allows introducing quantitative insights from transport studies which have drawn on measuring efficiency associated to distances, obstacles, stopovers, and the implementation of high-quality pedestrian infrastructure. Ultimately, walking behaviour allows revisiting spatial determinism from a more interdisciplinary perspective in which both quantitative and qualitative analysis converge. This convergence, however, suggests theoretical and practical endeavours. It has been discussed that spatial determinism is difficult to prospect as the link between qualitative analysis and quantitative modelling poses not only practical but also epistemological challenges considering their differing conceptual and methodological basis. In this vein, qualitative evidence would offer a *degree of* spatial influence on social behaviour, while quantitative analysis must keep evolving into more intuitive, complex, and comprehensive modelling by introducing characteristics that further represent the social reality and the environments in which it deploys. As proposed in this paper, both—(situated) spatial determinism and comprehensive simulation—can help to better depict the conditions of the built environment for social processes to occur; something that counts for improvements of urban planning, design, and transportation policies alike. In that sense, the susceptibility of (situated) *spatial determinism* to both qualitative and

quantitative ontologies calls for the development of theories and methods of urban analysis that places positivism and constructivism in planning and design as less opposite analytical frameworks.

Further research can be done at both theoretical and empirical levels. In terms of theory, inputs from behavioural disciplines associated with the use of the space (sociology, anthropology, psychology, and social behaviour) can form a second pillar for the understanding of spatial determinism and walking behaviour. Behavioural surveys and interviews can also be done to identify factors that determine attitudes towards environmental elements of streets that affect walking behaviour. The modelling can also introduce dynamic (three-dimensional) environmental characteristics and social (subjective) elements—such as weather conditions, microclimates, strong winds, air pollution, noise, sense of safety, aesthetics, sight distractions, or cultural enforcements—that influence walking behaviour in more nuanced ways. The introduction of more socially inclusive population characteristics—such as blind and disable people, families, groups, elders, scooters, wheelchairs, and other ‘pedestrians’—would also contribute to better represent the diversity of real-life scenarios. The creation of such advanced (and unified) modelling frameworks would level up the analysis and add in a more inclusive observation and other research techniques to achieve more comprehensive results for representing real life rhythms.

Author contributions C.S wrote the main manuscript text and prepared Figs. 1, 2 and 3. C.S. also prepared the whole theoretical framework of the study and the article—including title, abstract, literature review, thematic analysis of references, structuring of the main body, and conclusions. The quantitative modelling was done by S.X. who ran the software, took the samples, and made the counts of the modelling and other quantitative data. S.X. also prepared Figs. 4 to 9 distilled from the modelling and edited the referencing in previous and final versions of the manuscript. All authors reviewed all versions of the manuscript and agreed with the final one for submission.

Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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