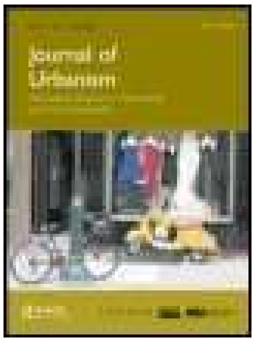

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Visual engagement with urban street edges: insights using mobile eye-tracking

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ABSTRACT

This study provides empirical insight into the extent to which pedestrians visually engage with urban street edges and how social and spatial factors impact such engagement. This was achieved using mobile eye-tracking. The gaze distribution of 24 study participants was systematically recorded as they carried out everyday tasks on differing streets. The findings demonstrated that street edges are the most visually engaged component of streets; that street edge visual engagement is impacted by everyday social tasks as well as the spatial and physical materiality of edges on differing streets; and that street edges, which attract a lot of visual engagement while undertaking optional tasks, also attract greater amounts of visual engagement while undertaking necessary tasks. These findings offer new insight into urban street edge engagement from the direct perspective of street inhabitants and in doing so provide greater understanding of how street edges are experienced.

KEYWORDS

Urban street edge; urban street; mobile eye-tracking; visual engagement; everyday tasks; spatial characteristics

Introduction

Street edges are frequently considered the most experientially important component of urban streets (Bobic 2004; Glaser et al. 2012; Thwaites, Simkins, and Mathers 2013; Heffernan, Heffernan, and Pan 2014; Kickert 2016). They span the indoor–outdoor interface of streets and provide a built frontage, or façade, which significantly affects peoples' behavior on the street (Gehl, Kaefer, and Reigstad 2006; Mehta 2008; Gehl 2010; van Langelaar & van der Spek, 2012; Dovey and Wood 2015). Their influence on peoples' perception of the wider street is also considerable, impacting how enjoyable and experientially stimulating streets are (Lynch and Rivkin 1990; Mehta2008; Montgomery 2013; Heffernan, Heffernan, and Pan 2014; Ellard 2015). Street edges consequently define more than any other aspect the overall character and feel of streets, what these spaces experientially afford, and how interesting and appealing they are to occupy and use (Bobic 2004; Glaser et al. 2012; Thwaites, Simkins, and Mathers 2013; Heffernan, Heffernan, and Pan 2014; Kickert 2016).

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The spatial and physical materiality of street edges, along with qualities and facilities housed within them, influence whether the experience pedestrians have of these realms is positive or not (Jacobs 1993; Bobic 2004; Mantho 2014). When edges are interesting and stimulating, they encourage people to linger on the street and experience what the surrounding edges have to offer both internally and externally (Gehl, Kaefer, and Reigstad 2006; Glaser et al. 2012; Thwaites, Simkins, and Mathers 2013; Heffernan, Heffernan, and Pan 2014; Kickert 2016). What pedestrians do within streets also influences their street edge experience. Edge engagement while undertaking optional activities (tasks without a specific objective) contrasts with edge engagement while undertaking necessary activities (focused and goal orientated tasks) (Gehl 2010; Mehta 2013; Simpson 2018). As a result, street edges are increasingly regarded as socio-spatial realms, whereby experience of them is influenced by a combination of their physical manifestation and the everyday social actions of people in and around them (Thwaites, Simkins, and Mathers 2013; Dovey and Wood 2015; Simpson 2018).

Equipped with the knowledge we currently have regarding urban street and edge experience, attempts have been made to produce socially driven, pedestrian-focused design guidance, and best practice toolkits (Gehl 2010; Glaser et al. 2012; Ewing & Clemente, 2013; Mehta 2013; Thwaites, Simkins, and Mathers 2013). The aim of such guidance is to direct decision-making toward the creation of streets and edges that have greater social benefit, by making them more experientially engaging for street inhabitants often in accordance with the varied activities they undertake within these spaces. However, currently, there are limitations to the knowledge underpinning such guidance. Specifically, there is a lack of empirical understanding into how people experientially engage with urban street edges explicitly from the direct perspective of street inhabitants (Harvey and Aultman-Hall 2016). The current work aims to address this gap.

The majority of knowledge detailing how street edges are engaged and experienced comes from observational and interview techniques (Gehl and Svarre 2013; Heffernan, Heffernan, and Pan 2014). Interviews require the verbalization of experiences that are often challenging to describe (Tuan 1977). Observations generally only capture visible human–environment interactions, which may result in observer bias (Kusenbach 2003; Cuthbert 2007). Interviews and observations also offer little opportunity for the systematic testing of precise experiential factors of interest, which can contribute to perceptions of the pseudoscientific nature of existing urban design theory (Marhsall 2012). Subsequently, this restricts the opportunity to guide effective, socially responsive design decision-making (Cuthbert 2007; 2010; Foroughman Araabi 2017). This current investigation seeks to build on existing street edge understanding by empirically testing how these realms are experienced. To achieve this, mobile eye-tracking was used to capture how people visually engage with urban street edges from a direct perspective that does not require observation or the verbal description of experience.

Tracking eye-movements provides quantifiable information on gaze distribution from which an understanding of human perception and cognition is possible (Holmqvist et al. 2011; Duchowski 2017). The allocation of gaze on a stimulus, and thus visual engagement with it, tends to reflect overt attention and from this the experiential significance of certain aspects of a scene can be inferred (Findlay and Gilchrist 2003; Rothkopf, Ballard, and Hayhoe 2007). Broad research areas such as environmental and cognitive psychology, sports science, landscape research, wayfinding, and marketing have used eye-tracking within the laboratory to investigate peoples' visual engagement with stimuli while research participants are static (e.g. Cristino and Baddeley 2009; Wiener et al. 2012; Nordh, Hagerhall, and Holmqvist 2013; Dupont, Antrop, and Van Eetvelde 2014; Pihel et al. 2015) and mobile (e.g. Marigold and Patla 2007; Bernardin et al., 2012; Vansteenkiste et al. 2013). Within an urban design context, a static laboratory-based application of eye-movement tracking has recently been used to assess peoples' gaze distribution on photographs of urban settings in combination with surveying visual preference (Noland et al. 2017). Significantly, this study demonstrated the utility of eye-tracking to urban researchers and designers interested in assessing peoples' visual engagement with urban environmental stimuli.

Of particular interest to this current investigation, mobile eye-tracking has offered insight into gaze distribution in response to signage, displays and navigation during indoor shopping (Huddleston et al. 2015; Otterbring, Wastlund, and Gustafsson 2016). The experiential impact of certain spatial attributes, within a similar context to some retail-focused outdoor urban streets, has therefore successfully been explored using this technique. Task-related distribution of visual engagement, spanning planned and unplanned shopping, has also been studied across a range of store situations (Wastlund et al. 2015), highlighting the capabilities of the method for exploring the impact of differing social activities on gaze distribution. However, while these studies have provided valuable insights and highlighted the effectiveness of mobile eye-tracking, they have been undertaken within indoor, highly controlled situations disconnected from the inherent variability of real-world street settings. The intention is to use this technique outside within urban streets, enabling empirical investigation of how people visually engage with street edges in response to socio-spatial considerations.

There are relatively few studies reporting mobile eye-tracking data recorded outdoors (Uttley, Simpson, and Qasem 2018). However, recent technological advancements, notably the development of lightweight and discrete eye-tracking glasses, provide scope for exploring visual human–environment engagement outside of the laboratory. This equipment allows study participants to be placed in situations representative of everyday scenarios in real-world urban settings. In doing so, the wearer has control over what they look at and experience three-dimensionally in a true-to-life, multisensory environment. Foulsham, Walker, and Kingstone (2011) found that there are differences in gaze distribution between laboratory and natural environments, emphasizing the need for studies to be conducted in realistic and notably outdoor contexts. Recently, using mobile eye-tracking outdoors has provided insight into a range of different everyday urban actions, e.g. how people visually attend to and negotiate differing paths and stairs (Marius't Hart and Einhäuser 2012); how people distribute gaze differently across night and day (Davoudian and Raynham 2012; Fotios et al. 2014); and how people use maps during real-world wayfinding (Kiefer, Giannopoulos, and Raubal 2013; Koletsis et al. 2017). This current study builds upon these precedents, using mobile eye-tracking to capture insight into people's visual engagement with street edges as they walk along a number of urban streets while undertaking differing everyday tasks.

The current investigation seeks to answer three research questions:

1. *Are urban street edges the most visually engaged component of the urban street?*

   There is limited empirical understanding from the direct perspective of street inhabitants of how much urban street edges are visually engaged in comparison to other aspects of the street. It is hypothesized that when pedestrians walk along a street they will look at its street edges more than anywhere else. This is while they actively experience and build a comprehension of the street environment around them, along with what it affords at that point in time (Bobic 2004; Gehl, Kaefer, and Reigstad 2006; Gehl 2010; Glaser et al. 2012; Thwaites, Simkins, and Mathers 2013; Kickert 2016).

2. *Are there differences in the amount of visual engagement upon urban street edges between (i) street inhabitants undertaking different social tasks; and (ii) different urban streets?*

There is limited empirical understanding from the direct perspective of street inhabitants of the extent to which social and spatial factors impact visual engagement with urban street edges. It is hypothesized that spatial factors, particularly the physical materiality of street edges, which also encompasses the materiality of the facilities housed within these edges (Bobic 2004; Gehl, Kaefer, and Reigstad 2006; Glaser et al. 2012), and social tasks (Gehl 2010; Mehta 2013; Simpson 2018) will both significantly influence street edge visual engagement.

3. *Are urban street edges that are visually engaged to a greater extent while undertaking optional tasks also visually engaged to a greater extent while undertaking necessary tasks?*

Design guidance and toolkits have been established that seek to create streets and edges that have greater social benefit, by making them more experientially engaging for pedestrians undertaking differing everyday activities within them (Gehl 2010; Glaser et al. 2012; Mehta 2013; Thwaites, Simkins, and Mathers 2013). However, currently, there is limited empirical understanding from the direct perspective of street inhabitants into the way differing street edges are visually engaged in response to the variable social tasks that streets accommodate, i.e. how social and spatial factors interact to influence visual engagement with street edges. Building on limited existing evidence, it is hypothesized that street edges that attract a lot of visual engagement while undertaking optional tasks will also attract greater amounts of visual engagement while undertaking necessary tasks (Gehl 2010; Thwaites, Simkins, and Mathers 2013; Simpson 2018).

Methods

Participants

Twenty-four adults (12 male; 12 female) with a mean age of 35 (s.d. = 10, range = 21–61), all of whom were recruited via opportunity sampling through a volunteers list held by the University of Sheffield, participated in the investigation. Participants were nonacademic staff (17 participants) and students (7 participants). Academic staff were excluded from invitation in order to gain a sample that did not have a bias toward higher levels of education. All participants had normal to corrected-to-normal vision via contact lenses, did not know the intentions of the study at the time of participation, and had previous experience of the streets investigated.

Apparatus

This study used a SMI Glasses 2.0 Mobile Eye-tracker (shown in Figure 1; Senso Motoric Instruments, Teltow, Germany, www.smivision.com). Inside this lightweight equipment is

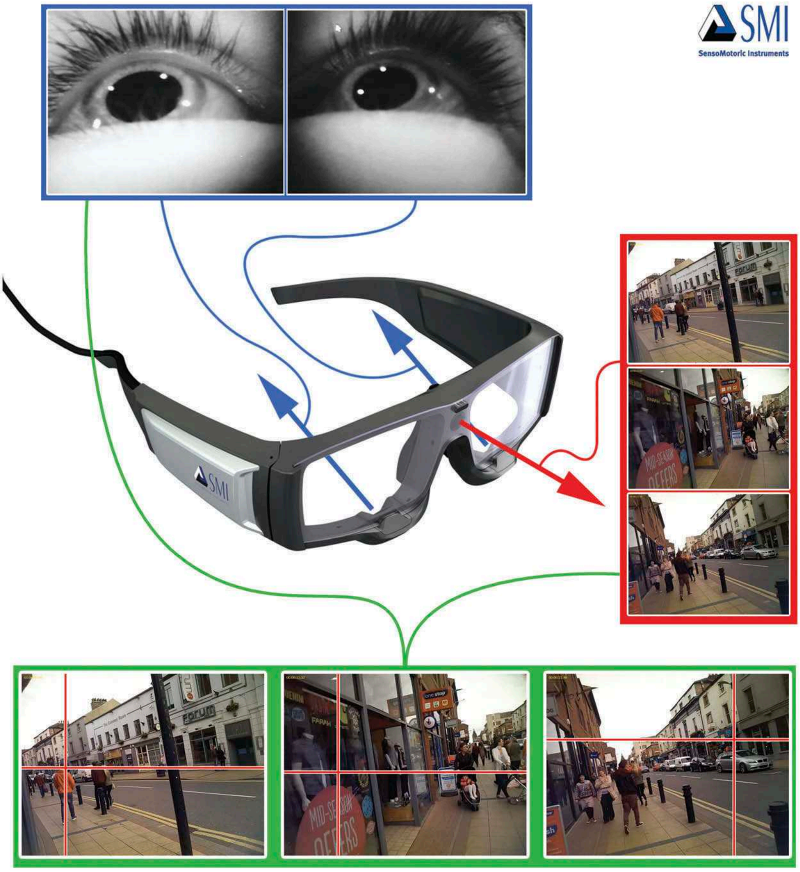

Figure 1. Mobile eye-tracker, camera configuration and video output with cross hairs showing gaze location.

a front-facing camera, which records a video of the environment in front of the wearer, and two rear-facing cameras, one under each eye, which record videos of the wearer's pupils. The information from these videos is then processed using SMI BeGaze to give a single video output, which has the front facing video with gaze location superimposed on top (Figure 1). Each participant was fitted with the mobile eye-tracker, and wore a peaked cap in an attempt to limit the influence of sunlight on data quality, consistent with previous real-world eye-tracking studies (e.g. Kiefer, Giannopoulos, and Raubal 2013).

Procedure

When the participant was first fitted with the mobile eye-tracker, a three-point calibration was undertaken. This was subsequently checked, and repeated if required. Throughout the walks, calibration checkpoints were also included. These allowed for tracking accuracy to be confirmed following the walks.

After calibration, participants were requested to walk a short route around an urban area of Sheffield, UK, which incorporated six urban streets. The walked routes were

Table 1. Task details.

Task name	Task group	Task description
Rush to work	Necessary	You are close to being late for work. Hurry to make sure you don't miss the meeting you had planned.
Drop off	Necessary	A friend has asked to borrow something and you have agreed to drop it off with them. They said they would be waiting for you on the street corner.
Wander to the bus	Necessary	You have finished all you need to do in the city centre and are on the way to catch the bus. You don't know when it will leave but you are not in any hurry as you know they depart regularly.
Break-time stroll	Optional	You are dawdling on your hour break and have decided to take a stroll to get some fresh air.
Coffee with a friend	Optional	You are on your way to meet a friend, who is always late, for coffee but you cannot remember if you said to meet in a certain place.
Window-shopping	Optional	You have kindly been given some money for your birthday and are out window-shopping to find something to spend it on.

devised in order to factor in a number of considerations. (1) Each street had a well-defined beginning and end, e.g. a junction with another street. This served to reduce any need for wayfinding within the study, which could have influenced how participants visually engaged with their surroundings. (2) Each street varied in its physical structure and material characteristics with regards to its built edges, notably, in terms of differences in architectural style, occupancy, and use. This ensured that the study participants were exposed to spatial variation of street edges in order to assess the impact of this variation. In total, 12 streets within Sheffield city center were used, comprising two routes (streets 1–6 and 7–12).

Prior to walking down each street, research participants were asked to read a task card. This introduced a social process into the study and gave the participant an everyday activity to carry out on the street. There were six tasks in total, which fell into two categories: optional and necessary (following Gehl 2010). Each task was derived from observations of public behavior on the study streets, giving them a degree of real-world validity (see Table 1 for task details).

The tasks were equally divided among the streets with each participant carrying out a task only once on a specific street (six tasks, three optional and three necessary across six streets within a single route), resulting in a total data set of 144 walked streets (six tasks across 12 streets, undertaken twice).

Data processing

Once each participant's walk was completed, their eye-tracking data for each separate street was exported as a video, with each frame indicating their location of gaze for a tenth of a second (see Figure 1 for output examples). Visual dwell duration upon predefined areas of interest (AOIs) was subsequently coded using VideoCoder (Foulsham, Walker, and Kingstone 2011). Within the current investigation, the AOIs were street edges, ground, sky, people, objects (street furniture, moving and static vehicles, other objects within the street scene), and adjacent realm (any gaze that fell outside of the boundaries of the street currently being inhabited). These AOIs were chosen as they provided opportunity to analyze visual engagement with specific street components detailed within contemporary urban design and planning literature (National Association of City Transport Officials 2013; Global Designing Cities Initiative 2017). Significantly, the AOIs did not overlap allowing all gaze allocation, and thus visual engagement within the streets, to be assigned to a single AOI. Coding the data in this way overcame issues regarding eye-movement definition within outdoor moving situations, as the raw eye-tracking video was used instead of automated classification of eye-movements as fixations or saccades (Evans et al. 2012; Vansteenkiste et al. 2015; Tomasi et al. 2016). Once coded, a log of sequential dwell durations on the predefined AOIs was exported. With this, the percentage of time that each participant spent visually engaging with the separate AOIs on the different walked streets was calculated, providing insight into where the participants' visual engagement was predominantly focused during the walks.

Variations in data quality were anticipated, as tracking accuracy in outdoor investigations is typically lower when compared with laboratory-based eye-tracking (Holmqvist et al. 2011). Data quality did indeed vary slightly but data loss was generally low, resulting in a mean tracking ratio of 93% (s.d. = 6%, range = 68–99%). All recorded data was used in the analyses.

Analysis and results

In order to visualize the time-coded log exported from VideoCoder, a data processing technique was developed using MATLAB (R2014a). This produced qualitative mappings for each participant's visual engagement with all the AOIs of a specific street walked during either a necessary or optional task. These mappings comprised a series of color-coded stacked bars resembling a DNA sequence or "Street DNA: Dynamic Narrative Articulation". This follows an approach employed by Rothkopf, Ballard, and Hayhoe (2007) and was developed during the current investigation as there are currently no standard visualization techniques that enable insight into the complex and shifting nature of visual engagement with urban contexts over time in response to the social and spatial influences.

Research question 1: Are urban street edges the most visually engaged component of the urban street?

Alongside the DNA mappings, an analysis was performed in the R statistical computing environment (version 3.0.2; R Core Team 2013) to quantitatively test what the study participants visually engaged with during their walks. A one-way analysis of variance was used to determine the significance of the effect of AOI (explanatory variable consisting of six levels – urban street edge, ground, objects, people, sky, and adjacent realm) on percentage of gaze distribution. The findings indicated that across all streets and tasks, participants visually engaged with AOI categories for significantly different periods of time ($F_{5,858} = 125.80$, $p < 0.001$). On average, they visually engaged with urban street edges to the greatest extent (37.2% of the time), in comparison to the ground (18.7%), adjacent realms (14.4%), people (11.4%), objects (10.7%), and sky (0.6%; see Figure 3). Out of the 12 streets walked, the study participants visually engaged with the urban street edges to the greatest extent across 10 of them.

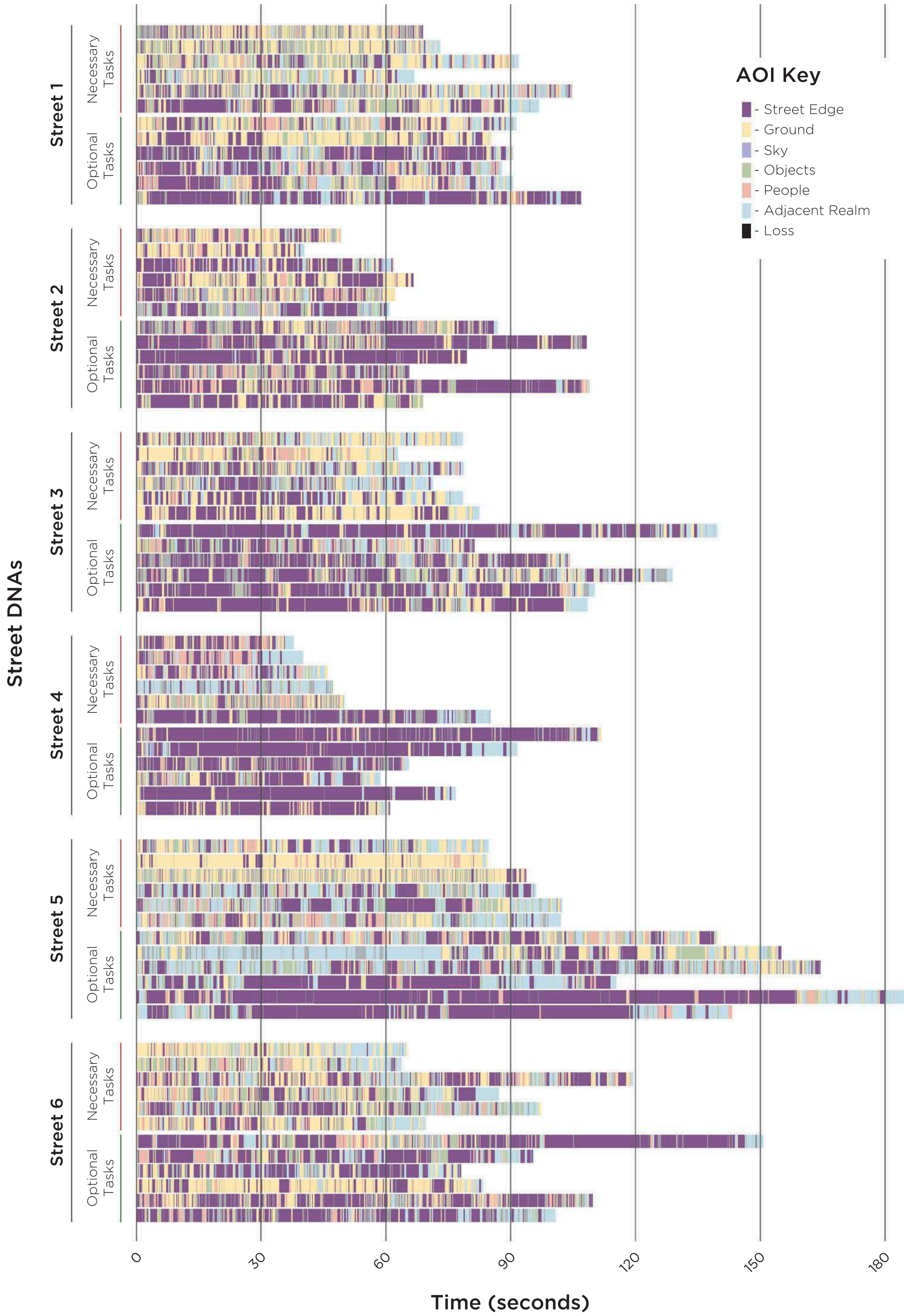

Figure 2. (a, b) Street DNAs detailing participants' visual engagement with street areas of interest (AOIs). The total length of a single DNA equates to the total duration of a participant's visual engagement on a street. The distribution of purple represents visual engagement with urban street edges.

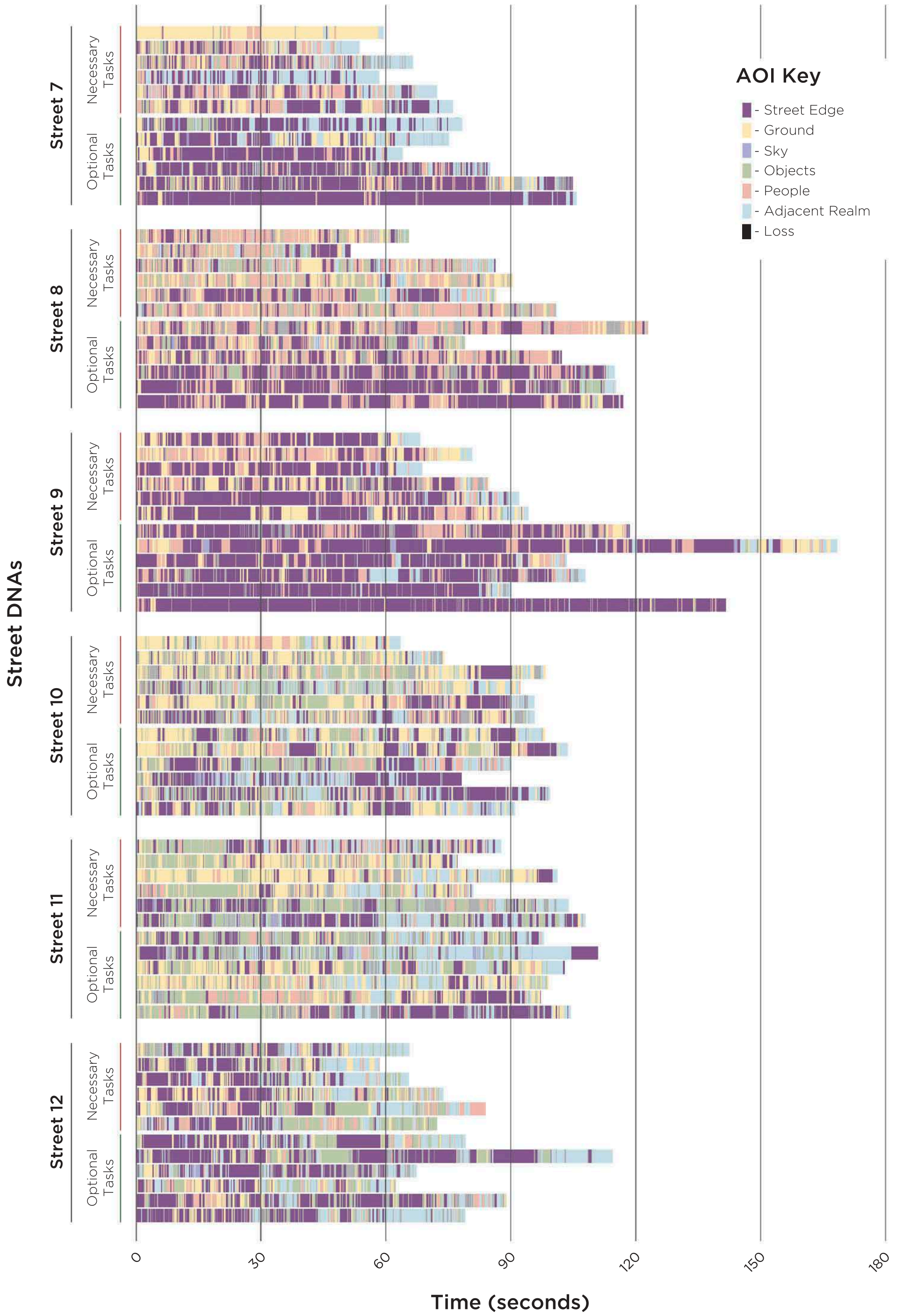

Figure 2. (Continued).

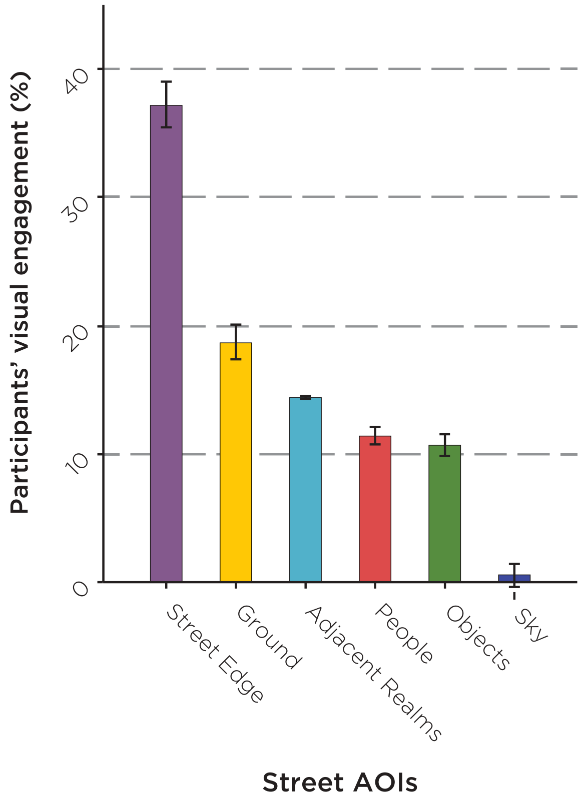

Figure 3. The percentage of participants' visual engagement with street areas of interest (AOIs). Error bars represent 1 standard error.

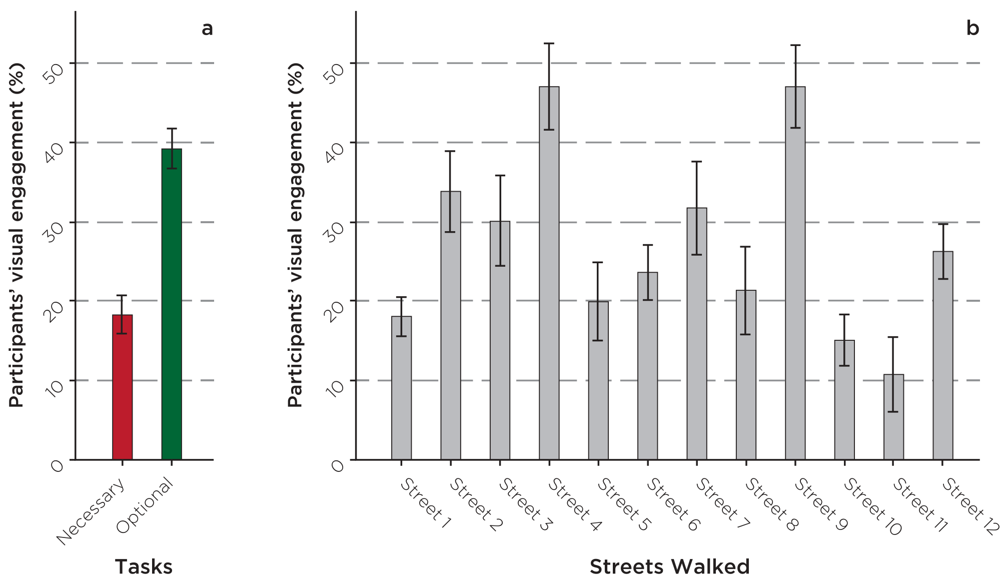

Figure 4. (a, b) The influence of task and street on the percentage of participants' visual engagement with urban street edges. Error bars represent 1 standard error.

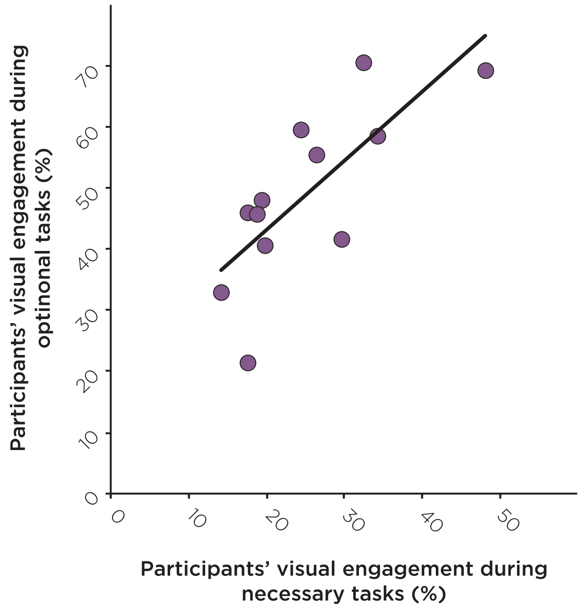

Figure 5. The correlation between the percentage of participants' visual engagement with urban street edges during optional and necessary tasks (r = 0.69). Each point is the average data for one street.

Research question 2: Are there differences in the amount of visual engagement upon urban street edges between (i) street inhabitants undertaking different social tasks; and (ii) different urban streets?

The effect of task and street upon the percentage of visual engagement on the urban street edges was determined by fitting linear mixed-effects models to the data in R ("lme4" package, Bates et al. 2014). The fixed effects were "Task" (optional or necessary) and "Street" (street number 1–12). "Participant" (participant number 1–24) was entered as a random effect, which allowed different intercepts for each participant (i.e. a differing baseline level of engagement for each participant) and differences in their response to street and task. This random effect was also included to account for random inter-participant variation in gaze behavior and for differences in how they interact with street edges depending upon socio-spatial factors. *P*-values were simulated by comparing this model to a grand mean model using a parametric bootstrapping method ("pbkrtest" package; Halekoh and Højsgaard 2014) with 10,000 simulated generations. The goodness of fit for all mixed effect models was assessed using the "R.squaredGLMM" function ("MuMin" package; Bartoń 2018) and marginal R^2 values (those associated with the fixed effects only) were high (Task: R^2 = 0.49, Street: R^2 = 0.52).

The type of task being undertaken (optional vs. necessary) had a highly significant influence upon the time participants spent visually engaging with urban street edges (Likelihood ratio test (LRT) = 35.24, p < 0.001), with participants engaging for 20.9% longer when on an optional task than when on a necessary task (39.2% vs. 18.3%; see

Figure 4(a)). The social processes, embedded within the two everyday task groups, were therefore important in determining urban street edge visual engagement.

The street inhabited, with variations in street edge materiality and qualities housed within them, had a highly significant effect upon the time participants spent visually engaging with street edges (LRT = 63.96, $p < 0.001$), with the percentage of time varying by 36.3% (10.8% vs. 47.1%) across the different streets (Figure 4(b)). The material and spatial dimensions of the urban street settings being walked and their street edges were therefore important in determining visual engagement with the street edges.

Research question 3: Are urban street edges that are visually engaged to a greater extent while undertaking optional tasks also visually engaged to a greater extent while undertaking necessary tasks?

To answer this question, the correlation between average percentage of visual engagement on street edges under optional and necessary tasks was established using Pearson's product–moment correlation in R.

The output showed that there is a significant positive correlation between the percentage of visual engagement with street edges under optional and necessary tasks ($r = 0.69$, $t = 3.04$, d.f. = 10, $p = 0.012$).

Discussion

The current investigation provides insight into the extent to which pedestrians visually engage with urban street edges and how this engagement is influenced by different everyday social tasks and differing streets with varying street edges. It achieves this through using mobile eye-tracking glasses, which captured study participants' gaze distribution on the environment around them as they walked along urban streets. As a result, it addresses current knowledge limitations that lack systematic insight into street edge experience from the direct perspective of street inhabitants.

Urban street edges were the most visually engaged with component of the streets walked, with a disproportionate amount of the participants' gaze being focused upon these realms. This can be observed through the distribution of visual engagement on this AOI across the Street DNAs (Figure 2(a,b)). The DNAs show that when street edges were visually engaged while walking along a street, such engagement was regularly frequent but fleeting or sometimes more sustained in duration. Cumulatively, these individual and grouped engagements contributed to a level of visual engagement that outweighs interaction with any other aspect of the streets walked by the study participants (Figure 3). However, while the street edges were the most visually engaged AOI, the DNAs also show how this visual engagement varied considerably across the differing streets and task groupings; this will be discussed later.

It is important to consider the reasons for the high proportion of visual engagement with urban street edges observed in the current study as well as the significance of this finding. Street edges are where the variable functions and facilities of streets are regularly housed (Bobic 2004; Glaser et al. 2012). They are where people frequently socialize and meet as well as linger individually within streets (Mehta 2013; Thwaites, Simkins, and Mathers 2013). Also, they are the point at which public/private thresholds are re-enforced spanning indoor and outdoor realms (Dovey and Wood 2015). Street edges are, therefore, often not only the most visually stimulating but also multisensory and dynamic aspects of streets for pedestrians, from which they can build an impression of what the surrounding environment offers and affords (Gehl, Kaefer, and Reigstad 2006; Heffernan, Heffernan, and Pan 2014). Contributing to this is the fact that people are horizontal viewers, with their gaze naturally being distributed ahead and sideways (Sussman and Hollander 2015; Ellard 2015). The positioning of street edges means they are located conveniently to the side of people and therefore where people can easily look while walking down a street. As a result, many have argued the social and experiential importance of street edges, notably Bobic (2004) who propose the street to be a *place between the edges* as well as Gehl, Kaefer, and Reigstad (2006); Gehl (2010); and Glaser et al. (2012) who detail the impact of edge ground floors on how people experience the *city at eye level*. Similarly, Montgomery (2013); Ellard (2015); and Goldhagen (2017) have recently described the experiential importance of edge ground floors; and Heffernan, Heffernan, and Pan (2014) and Kickert (2016) have examined the significant benefit of active edge frontages for pedestrians. The current investigation adds greater insight and evidence to this body of work, from the direct perspective of street inhabitants, while showing how a disproportionate amount of pedestrians' vision engages with street edges in comparison to other components that establish urban streets.

Quantifying visual engagement in this manner is significant as it provides systematic knowledge that can be used to justify where effort and attention should be focused for the experiential benefit of pedestrians during urban planning and design decision-making, thus, addressing points raised by Cuthbert (2007, 2010); Marhsall (2012); and Foroughman Araabi (2017). Over recent years, there has been a noticeable shift toward street design guidance and action that focuses on aspects and components of the street that sit between their edges (ground, street furniture, vehicles), e.g. within Urban Street Design Guide (National Association of City Transport Officials 2013); and Global Street Design Guide (Global Designing Cities Initiative 2017). Such guidance accepts the experiential significance of street edges; however, often their importance tends to be overshadowed. Street edges are aspects of streets that should not be considered of secondary importance. But, as essential to the experiential responsiveness of contemporary and future urban streets, based upon the understanding that they capture far greater amounts of visual engagement than any other street component.

The amount of time that participants spent visually engaging with urban street edges was significantly influenced by the social task they undertook (Figure 4(a)), with optional tasks promoting greater levels of visual engagement with street edges than necessary tasks. The Street DNAs highlight this, with the presence of visual engagement with this AOI often more pronounced across the DNAs grouped by optional tasks in contrast to those representing necessary activities (Figure 2(a,b)). This result is consistent with findings from previous eye-tracking studies that found differing tasks significantly influence visual attention distribution (Rothkopf, Ballard, and Hayhoe 2007; Holmqvist et al. 2011; Duchowski 2017). However, while previous investigations tend to consider the effect of task when observing images and video (Yarbus 1967; Rothkopf, Ballard, and Hayhoe 2007) or during indoor mobile situations (Land, Mennie, and Rusted 1999), the current investigation provides greater insight into the influence of differing tasks within dynamic outdoor contexts.

Understanding the experiential impact of different everyday social tasks upon visual engagement with urban environments has previously been challenging to capture and quantify. The current investigation achieves this and in doing so adds insight to the work of Gehl (2010), who has argued that everyday actions should be considered when seeking to comprehend how people behave and experience urban settings. The current investigation used Gehl's (2010) activity groupings and thus aligns directly with this work spanning a consideration of optional/necessary activities. The current findings also add to insights gained by Mehta (2008, 2013), during which the essential need for attention toward what people do within streets is encouraged in order to understand how they operate socially. The insights obtained similarly complement Pafka's (2018) examination of streetlife micro-rhythms and functional mixes broadly categorised by live, work, and visit, supplementing this work with greater direct insight from a street inhabitant's perspective.

Overall, by showing how task influences visual engagement with street edges has been highlighted the need to consider the way urban streets regularly accommodate a range of variable activities, and in turn, differing levels of visual engagement with street edges. Without such social consideration, street edge understandings could become synchronized, in response to a single function, rather than pluralistic and thus dis-aligned with realistic street situations (Karrholm 2009).

The different urban streets, which had variations in the physical materiality of their edges and facilities manifested within their edges, influenced the amount of time that the study participants visually engaged with street edges (Figure 4(b)). The Street DNAs display this with the street groupings highlighting variable proportions of time spent visually engaging with this AOI across the different streets walked (Figure 2(a,b)).

Capturing the influence of spatial and material differences on street edge visual engagement provides quantification to existing theory that proposes the experiential significance of varying street edge characteristics (Bobic 2004; Gehl, Kaefer, and Reigstad 2006; Gehl 2010; Glaser et al. 2012; Mantho 2014). Although systematic analysis of the specific influence of different physical street edge properties on visual engagement with street edges was not a goal of the current work, it is important to consider the characteristics of street edges that resulted in greater amount of visual engagement. Many of the street edges that were visually engaged more than others had well-defined ground floors that provided the verticality of the street edges with human-scaled opportunities for engagement. Such an insight aligns with Gehl, Kaefer, and Reigstad (2006); Gehl (2010); and Glaser et al. (2012) who argue the essential need for human-scaled street edge characteristics. Transparent and permeable street edges, across their indoor/outdoor gradient, captured greater levels of visual engagement than opaque and closed-off street edges. This finding supports proposals made by Gehl, Kaefer, and Reigstad (2006); Thwaites, Simkins, and Mathers (2013); and Ewing & Clemente (2013) who argue for the experiential significance of permeable and transparent edges. Many of the streets with street edges that were visually engaged more so than others had street edges that defined these spaces through being continuous and unbroken while having human proportioned street width so that people's visual engagement did not need to be projected over considerable distances. An experiential insight into the influence of these factors furthers the ideas of those who argue that streets should have room-like qualities, with street edges enclosing the open space of the street

(Jacobs 1993; Bobic 2004; Gehl 2010; Thwaites, Simkins, and Mathers 2013; Mantho 2014). Lastly, the street edges visually engaged to a greater extent had a level of detailed and diverse grain running along them. This was established through conditionally emerging and variable qualities as the streets were journeyed along rather than a singular function or dominating individual materiality. Such an insight adds quantified understanding to Cullen (1971) and his ideas relating to *serial vision* as well as Gehl (2010) and Glaser et al. (2012) who describe the experiential benefit of continually emerging edge interest when walking through streets. Further work would be required to systematically analyze the street edge characteristics detailed. This could be done by measuring street and street edge properties, e.g. street width or the amount of transparency, in a manner aligning with Porta and Renne (2005) and Ewing & Clemente (2013) followed by analysis of peoples' visual engagement with these characteristics using mobile eye-tracking methods similar to the current investigation. Such an approach would provide further systematic understanding of what specific physical and material street edge characteristics are experientially significant.

The current work has demonstrated that in combination both everyday social tasks and spatial characteristics influence the amount of time that people visually engage with urban street edges. This provides evidence that these realms are experientially socio-spatial. Such an insight builds on the ideas of Thwaites, Simkins, and Mathers (2013); Dovey and Wood (2015); and Simpson (2018) who have previously described urban edges as socio-spatially manifested. The current investigation also goes further to explore the relationship spanning social and spatial influences, questioning whether street edges that are visually engaged to a greater extent while undertaking optional tasks also visually engaged to a greater extent while undertaking necessary tasks. This was found this to be true (Figure 5). This finding is important as it highlights how the edges of some streets were visually engaged more than others across the differing tasks that study participants carried out. Additional work would be required to explore the physical characteristics of the street edges that were visually engaged to a greater extent across both optional and necessary activities. However, the insights gained during the current investigation justify detailed exploration. Through establishing strengthened insight into the experiential impact of specific edge characteristics, there will be greater opportunity to guided and design street edges for the social and experiential benefit of street inhabitants.

Overall, the current investigation has provided insight into peoples' visual engagement with urban street edges; however, there are some limitations. Urban streets and their edges are inherently variable, in terms of their spatial and physical characteristics and the everyday activities that they accommodate. As a result, generalized conclusions relating to how they are engaged are potentially challenging to make. The current investigation took place within a specific context (Sheffield) and used everyday tasks associated with the streets and edges explored. It remains to be seen whether the findings generalize to other social and cultural contexts. Mehta (2009) has highlighted that there are significant culturally manifested differences spanning Western and Eastern streets; therefore, emphasizing the need for further work to establish the extent to which the current study findings are generalizable. Linked to this is the way that participants who took part within the investigation may have impacted the findings gained. Even though participant variation was considered as a random effect within some of the models employed, previous experience of the streets walked and personality traits could have influenced peoples' distribution of visual engagement. Methodologically, mobile eye-tracking in outdoor situations is still in its infancy. Data loss is still an issue, caused regularly by bright light conditions and the wearer's head and body movements (Evans et al. 2012; Tomasi et al. 2016). The equipment may also have been intrusive for some wearers who are not used to wearing glasses. For some participants, there may have been a disconnect between where they were visually engaging and what they were cognitively engaged with; potentially thinking about something else rather than what they were looking at. This is a general limitation of eye-tracking as a methodology for capturing visual attention, especially outdoors when so many stimuli are competing for our attention (Uttley, Simpson, and Qasem 2018). It is generally accepted, however, that eye-tracking is the best method we currently have for gaining an insight into how people visually engage with a given setting. This current investigation used manual coding of dwell durations, following similar techniques in other eye-tracking studies (Foulsham, Walker, and Kingstone 2011; Vansteenkiste et al. 2015). Such an approach is time-consuming and requires the interpretation of the researcher to assess where gaze was being allocated. Further technological developments may allow opportunity for automation of the process, and improvements in fixation definition for outdoor eye-tracking data could help streamline this method in the future (Vansteenkiste et al. 2015). At this point in time, however, the techniques employed within this current investigation were the most effective way of analyzing the data acquired.

Even though there are associated limitations, the current investigation still provides new empirical understanding of the extent to which people visually engage with street edges and in doing so greater understanding of how street edges are experienced. Such insight has been captured through the use of mobile eye-tracking, a method that has received limited use within complex outdoor contexts such as urban streets. Consequently, the findings provide a precise account of street edge experience that furthers the evidence-based foundations of planning and urban design theory while not relying on observation and interview techniques that have associated methodological issues (Kusenbach 2003; Cuthbert 2007). The insights obtained, building upon current ideas and discourse, show how urban street edges are the most visually engaged component of urban streets. Social and spatial influences have been systematically tested. The findings demonstrated that peoples' engagement with urban street edges is impacted by everyday tasks, spanning optional and necessary activities, and the different streets with variable street edges. It has also been shown that street edges that are visually engaged to a greater extent when undertaking optional activities are also visually engaged to a greater extent undertaking necessary activities. Looking to the future, there are further experiential understandings to be captured in response to urban street edges and mobile eye-tracking is a method which offers opportunity to unlock such insights. Within the current investigation, mobile eye-tracking provided a systematic technique for capturing peoples' visual engagement with urban street edges from a new direct perspective that has previously been challenging to capture and comprehend.

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