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EMPIRICAL EVIDENCE TOWARDS APPROPRIATE LIGHTING CHARACTERISTICS FOR PEDESTRIANS

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Abstract

There is a need for empirical data to review design standards for pedestrian lighting. This paper presents a summary of two ongoing UK research projects, the MERLIN project which is examining lighting for pedestrians' visual tasks, and the LANTERNS project which is examining the effect of lighting on reported crime and accidents associated with pedestrians, discussing research methodology and tentative findings from the MERLIN project.

Keywords: e.g. Road lighting, pedestrians, visual tasks, crime

1 Introduction

In the UK and the EU the target average illuminance levels for subsidiary roads (which includes residential roads) range between 2 lx and 15 lx in six classes [BSI 2003]. However, these illuminance levels do not appear to be based on appropriate empirical evidence and thus are in need of review [Fotios & Goodman, 2012]. A new TC is being established in Division 4 to do this. Two approaches to establishing appropriate light levels are a bottom-up task approach and a top-down cost-benefit approach. The task approach seeks to identify optimum lighting conditions for tasks critical to pedestrian activity: the cost-benefit approach seeks to optimise the cost of lighting provision against the benefits of pedestrian safety. The Technical Committee will also seek to consider users expectations by surveying international standards for pedestrian lighting.

2 Visual tasks

2.1 Critical tasks

One approach to establishing optimum light levels for pedestrians is to identify their critical needs and then investigate how these needs are affected by variations in lighting. These needs are typically assumed to be obstacle detection and recognition of the intent and/or identity of other road users, together with subjective evaluations of reassurance and comfort [Caminada & van Bommel, 1980; Fotios & Goodman, 2012]. Recent work has been carried out to validate these assumptions.

Eye-tracking was used to investigate pedestrians visual fixations, in daytime and after dark, with a concurrent dual task employed to better identify the fixations critical for safe walking from the unconscious (day-dreaming) and non-essential fixations [Fotios et al, in press (a)]. The output of an eye-tracking study is a video of the test participant's field of view upon which is superimposed a crosshair marking the direction of gaze – the visual fixation. A common approach to interpretation of these data is to count the frequency by which certain types of objects are fixated. This approach suffers from erroneous assumption that the object fixated is indeed of importance, and also that the frequency of occurrence of an object in a natural setting (e.g. the number of pedestrians encountered) affects the frequency of fixation – if only few pedestrians are encountered this leads to a low frequency of fixation but that does not imply that fixation on pedestrians is unimportant. The dual task approach was found to provide a good indication of critical fixations by helping to ignore the less-critical fixations and to be robust against the frequency of occurrence.

It was concluded that the near path (<4 m) and distant people (>4 m) are critical targets of visual fixation for pedestrians. Fixation on the near path may be related to identification of obstacles, and this would be aided by enhanced detection at a further distance. Fixation on distant people suggests a desire to evaluate the intentions of others at sufficient distance to take avoiding action if necessary.

2.2 Reassurance

Reassurance is the confidence a pedestrian might gain from road lighting (amongst other factors) to walk along a road, in particular if walking alone after dark, and is used here to encompass the terms perceived safety and fear of crime as used in past studies. A first question is whether there is robust evidence that lighting does indeed affect reassurance. While there is evidence from past studies to suggest that the presence of lighting enhances pedestrian reassurance, it is possible that the procedures used unintentionally led respondents toward responses that suggest a relationship between lighting and fear, for example: (i) Road lighting is presented as one of a limited set of options from which respondents must choose [Bernhoft & Carstensen, 2008]; (ii) Changes in lighting were an obvious difference between evaluated scenes, such as the photographs used by Loewen et al [Loewen et al, 1993]; (iii) Lighting and fear were the focus of rating scales [Hanyu, 1997]. and focussing on an issue encourages respondents to give an opinion about an item they would not otherwise raise [Acuña-Rivera et al, 2011].

The association between lighting and reassurance was explored in a study using a qualitative method [Fotios et al, in press (b)]. Test participants provided photographs of locations where they would, and would not, be confident to walk alone after dark. Discussion during subsequent interviews was used to identify the reasons for the choice of locations. Lighting was associated with reassurance in 62% of the 210 locations evaluated (Figure 1), a more frequent association than physical features associated with prospect and refuge but less frequent than the availability of access to help if needed in an emergency.

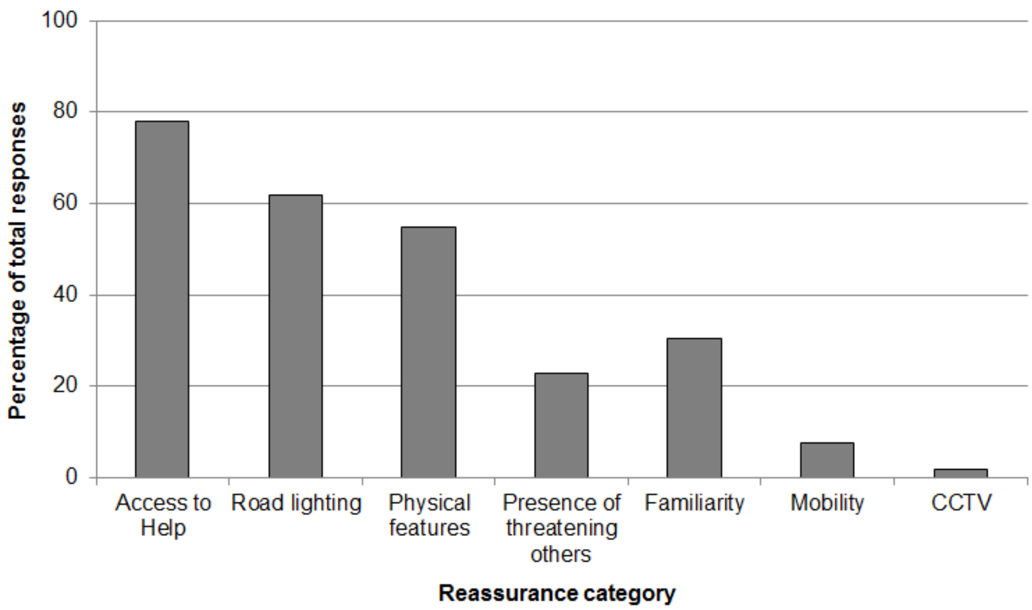

Figure 1 – Frequencies with which reasons were given for feelings of reassurance when walking alone after dark during interview with visual prompts for specific locations.

The evidence from this qualitative approach [Fotios et al, in press (b)] provides support for the findings of studies using quantitative procedures [Loewen et al, 1993; Hanyu, 1997; Bernhoft & Carstensen, 2008] that lighting enhances reassurance after dark. Having drawn this conclusion, further evidence was sought as to how variations in the characteristics of lighting effect reassurance, i.e. variations in illuminance, spatial distribution and spectral power distribution (SPD). This is reviewed in detail elsewhere [Fotios et al, in press (b)].

For illuminance, the results of several studies suggest that higher illuminance enhances reassurance [Vrij & Winkel, 1991] at least for females [Atkins et al, 1991]. This alone is insufficient evidence for setting design a target: rather than ever-higher illuminance, what is needed is evidence of an optimum illuminance. Fortunately there is such evidence from the study of Boyce et al [2000] who examined perceived safety in car parks, at daytime and after dark. Test participants were asked to describe the lighting using ratings of perceived safety. Rather than simply report the ratings, with any effect of lighting being confounded by local environmental factors, Boyce et al examined the *difference* between daytime and after-dark ratings (Figure 2). As illuminances increased, the difference between ratings of perceived safety recorded at daytime and after dark tended to decrease. These data suggest an optimum horizontal illuminance of 10 lux; higher illuminances do not tend to improve reassurance at a particular location relative to the level of reassurance in daytime at that same location. Further data are required to confirm whether these data are valid in the context of for residential roads where light levels are typically lower (2.0 to 15 lux) than the car parks surveyed by Boyce et al (up to 50 lux).

For lamp SPD it is proposed that lighting of higher S/P ratio enhances reassurance. This proposal is derived from evidence that lighting of higher S/P ratio appears brighter [Fotios & Cheal, 2011a] and that a location with brighter lighting is considered to be safer [Blöbaum & Hunecke, 2005]. While the results of three field studies provide some evidence that lighting of higher S/P ratio leads to higher ratings of safety [Akashi et al, 2004; Knight, 2010] it remains to be validated. As to spatial distribution of light, guidance for road lighting design tends to use measures associated with variations of illuminance across the lit surface (uniformity of horizontal illuminances). The effect of uniformity on reassurance has yet to be investigated.

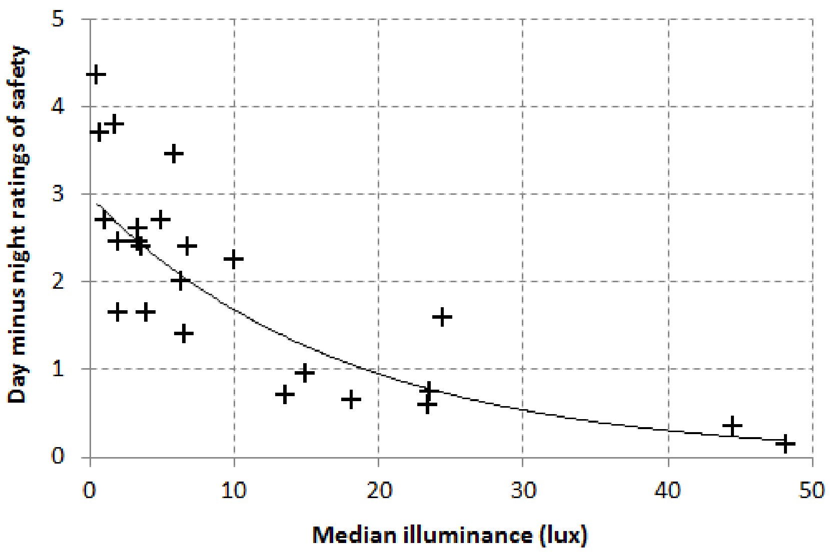

Figure 2 – Difference between daytime and night-time ratings of perceived safety of car parks plotted against median illuminance, after Boyce et al [2000].

2.3 Interpersonal judgements

One contribution of lighting to reassurance is that it should be possible for a pedestrian to recognise whether another person is likely to be friendly, indifferent or aggressive in time to make an appropriate response. Past studies in lighting have tended to investigate one limited aspect of this task, the ability to recognise the faces of others. Three tasks have been used (recognition of the face of a well-known person such as a TV celebrity [Yao et al, 2009], picking the target face from a set of several possible faces [Rea et al, 2009], and ratings of recognisability [Rombauts et al, 1989]), with evaluations using fixed distances [Rombauts et al, 1989] or stop-distances [Yao et al, 2009] of real people and of celebrities. These studies have led to mixed results, in particular regarding the effect of SPD: new research suggests that this is due to methodology: SPD is important when the task is difficult [Lin & Fotios, 2013; Fotios et al, 2013].

Two studies provide some evidence as to light levels for facial recognition. Caminada and van Bommel [1980] used a stop-distance procedure to examine facial recognition and concluded that semi-cylindrical illuminances (ESC) of 0.8 lx and 2.7 lx were needed for recognition at 4 m and 10 m respectively, while Rombauts et al [1989] suggested Esc of 0.4 lx and 3.0 lx for these same distances.

Rather than examine facial recognition, Fotios et al [2013] examined ability to recognise the emotion conveyed by facial expressions and body postures. This decision followed evidence that facial expression and body posture contribute to social judgements that are related to evaluation of threat [Willis et al, 2011], precisely 'approachability', which might be considered the positive end of an approach-avoid dimension of evaluation of threat. This was done under a range of luminances, lamp types and equivalent interpersonal distances using a detection task. Optimum light levels were estimated from the knee in the plateau-escarpment trend displayed by the results (Figure 3). The results suggest a minimum luminance of 0.1 - 1.0 cd/m2 if facial expressions are to be identified accurately at 4 m, but a luminance above 1.0 cd/m2 for identification at 10m. These luminances are equivalent to semi-cylindrical illuminances in the range of 0.7 to 7.0 lux for the 4 m targets and 7.0 lux or greater for the 10 m targets.

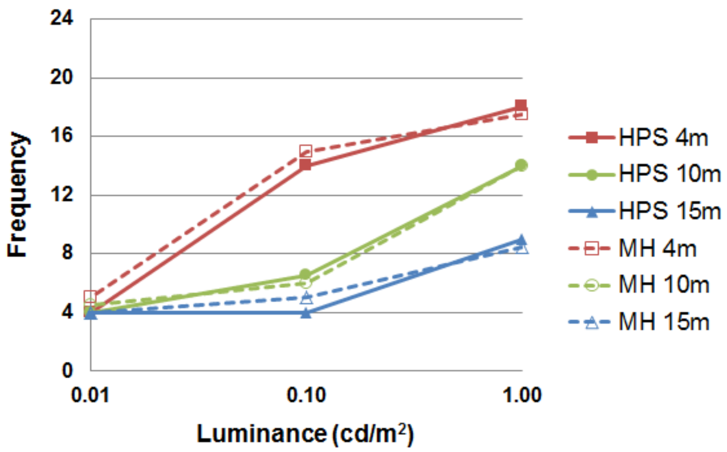

Figure 3 – Results of a facial expression recognition test [Fotios et al, 2013]

These results lead towards identification of an optimum illuminance for interpersonal judgements. To do so, however, requires further understanding of the critical task and the desirable distance at which this task can be done. Townshend [1997] suggests that at distances below 15 m the space in which pedestrians have time to react to avoid an undesirable situation becomes reduced beyond comfortable levels, determined using a field study of pedestrians after dark. Analysis of eye-tracking data [Fotios et al, in press (a)] indicates a tendency to fixate upon other pedestrians in the range of approximately 8 m to 16m, with a mode of approximately 12 m. Thus 15 m is representative of the distance at which interpersonal judgements are desirable. At a distance of 10 m, results of facial recognition trials suggest semi-cylindrical illuminances of approximately 3.0 lux [Caminada & van Bommel, 1980; Rombauts et al, 1989] while results of experiments using the facial expression task suggest a semi-cylindrical illuminance of 7.0 lux at 10 m [Fotios et al, 2013].

There is reason to suspect that SPD can affect facial judgements when the task is difficult [Yip & Sinha, 2002; Lin & Fotios, 2013]. Colour cues facilitate image segmentation (i.e. edge definition) rather than providing precise hue-related diagnostic cues to identity [Yip & Sinha, 2002]. Such segmentation may be enhanced by using light sources which enhance the discrimination between different colours, such as those with a large colour gamut. Judgements of body posture suggest an effect of SPD when task performance was within an apparent escarpment region (135 m at 1.0 cd/m2; 10 m at 0.1 cd/m2; 10 m at 0.01 cd/m2). These three cases were those in the middle of the luminance and distance combinations: when the task was either relatively difficult (i.e. small and low luminance) or easy (i.e. large and high luminance) then lamp type did not affect the task [Fotios et al, 2013]. However, judgements of facial expressions at 10 m (the greatest of the three distances examined) did not suggest a significant effect of SPD [Fotios et al, 2013].

2.4 Obstacle detection

Eye-tracking studies [Fotios et al, in press (a)] suggest that fixations at the near path are important, and one purpose of such fixations is to inspect pavement obstacles in the approaching path. Pavement obstacles include uneven pavement surfaces (e.g. static items such as a raised paving slab or manhole cover) that may cause a pedestrian to trip if it is not detected in sufficient time to plan gait adaptation to go over or around the obstacle. The success rates for implementing strategies for adjusting step length and width is greater than 80% when a visual cue is available one step ahead, while steering (a change in direction to go around an obstacle) has to be planned in the previous step cycle; success rate is near zero when only one step cycle duration is available for changing direction [Patla, 1997]. To carry out these actions requires some visual input: negotiation of an obstacle during gait requires an individual to determine the height and distance to the obstacle an plan appropriate foot placement and limb elevation for successful clearance [Buckley et al, 2011]. Continuous vision of the target is not necessary. Thomson [1980] found that his test participants were able to navigate around obstacles in a 9m travel path (no collisions in 70% of trials) when vision was only available at the start, although this was not the case beyond 9 m, subsequently suggested to indicated cognitive mapping of the path ahead for a period of 8 s.

Peripheral vision of a suddenly appearing obstacle in the travel path is sufficient for successful obstacle avoidance during locomotion: visual fixation is generally not re-directed to either the obstacle or landing area [Marigold et al, 2007]. However the near path appears to be a critical foveal fixation [Fotios et al, in press (a)]. What may be happening is that objects initially detected with peripheral vision are then fixated to feed in to the cognitive map of the approaching terrain, following which peripheral vision provides sufficient on-line information for successful avoidance action. Thus studies of obstacle detection have examined peripheral vision using a detection task, with obstacles of varying height presented at unknown peripheral locations under a range of luminances and lamp types [Fotios & Cheal, 2009, 2013]. These results demonstrate that higher luminances and higher S/P ratios improve detection of peripheral obstacles (Figure 4).

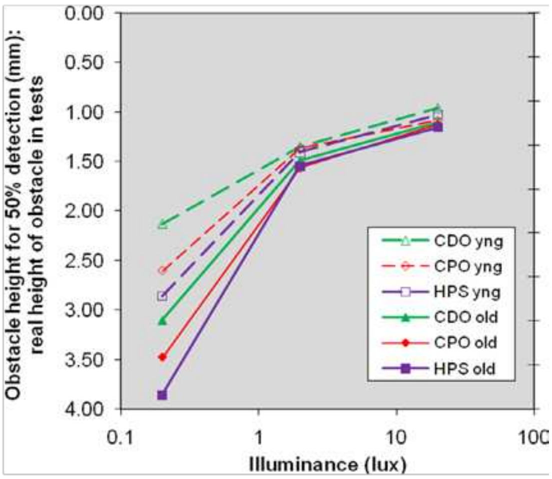

Figure 4 – Mean obstacle height for the 50% detection probability plotted against illuminance to show obstacle detection ability of older and younger observers under different illuminances for three types of lamp.

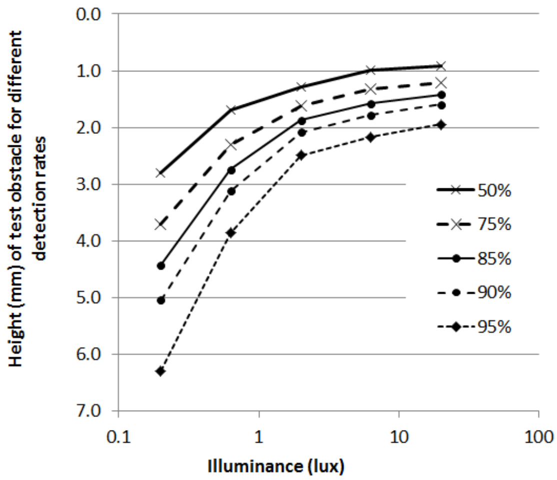

Figure 5 – Mean detection heights of obstacles 1 to 4 for detection probabilities of 50%, 75%, 85%, 90% and 95%.

Two methods have been used to interpret an optimum light level from these data, a performance approach and a legal approach. The first of these employed the apparent plateau-escarpment relationship between obstacle detection ability and illuminance, and assumed that the transition between plateau and escarpment defines an optimum: higher illuminances offer diminishing increase in obstacle detection while lower illuminances lead to rapidly diminishing performance. According to Figure 4 this transition lies at approximately 2.0 lux [Fotios & Cheal 2009]. Clearly, the transition in Figure 4 may be a result of a graph drawn from only 3 data points (luminances) and hence the second study was carried out using 5 luminances to better define the curve [Fotios & Cheal, 2013]. This is shown in Figure 5. In this study the change in curve with detection probability was explored. The ideal probability remains to be confirmed: we assumed 95%. The 95% probability curve suggests a more pronounced plateau-escarpment relationship than does the 50% probability curve, with a knee in the region of 2.0 lux.

The second approach to identifying the optimum illuminance is to ask what size of obstacle lighting is expected to reveal and what probability of detection should be expected, and this was considered from the point of view of a local authority demonstrating that it is taking reasonable steps towards meeting its obligations for pedestrian safety. This might be considered the legal approach because many solicitors are keen to encourage legal action should a pedestrian suffer a trip accident. The critical physical size of obstacle was concluded to be 25 mm (above or below the pavement surface), this determined from local authority guidelines as to when a pavement defect should be rectified and information from solicitors as to the conditions likely to lead to financial compensation for a tripping accident. The visual size of a 25 mm surface irregularity changes with viewing distance. Corrections to gait require that the obstacle is detected at least two steps ahead [Patla, 1997]. Hence detection of the 25 mm obstacle was considered when placed at forward distances of two, four, six, eight and ten paces, with the distance of a pace defined as 600mm. An illuminance of approximately 0.6 lux is required to detect an obstacle of the smallest size (13.5 minutes, i.e. 6 m ahead) and 95% probability of detection [Fotios & Cheal, 2013]. Note that these data are from observations by young people under HPS lighting: lower illuminances would be expected when using lighting of higher S/P ratio such as metal halide lamps, and higher illuminances would be expected when considering older people.

Having drawn these two conclusions, Figure 4 leads to interesting conclusions regarding the effects of lamp SPD and observers age. At 2.0 lux, defined as the transition between plateau and escarpment, effects of age and SPD are not significant: while at 0.6 lux, there are significant effects of age and SPD.

2.5 Summary

Table 1 shows a summary of tentative estimates of optimum design criteria established through consideration of three visual tasks considered to be important for pedestrians: evaluation of reassurance, ability to interpret the intent of other pedestrians, and detection of pavement hazards. For all three tasks there are estimates of optimum illuminance. Current design guidance focusses primarily on horizontal illuminance; while this may be suitable for reassurance and obstacle detection tasks, interpersonal judgements may be better characterised using the illuminance on vertical surfaces, such as semi-cylindrical illuminance.

Table 1 – Tentative estimates of optimum design criteria established through consideration of visual tasks. Note that these require much validation

Visual task	Illuminance	SPD
Reassurance	10 lux horizontal (tbc for residential roads)	High S/P ratio
Interpersonal judgements	Semi-cylindrical illuminances: • 3 lux for facial recognition at 10 m • 7 lux for facial expression at 10 m	High gamut area
Obstacle detection: i) Legal approach ii) Transition in performance curve	 0.6 lux horizontal illuminance 2.0 lux horizontal illuminance	 High S/P ratio No effect of SPD.

For SPD, it appears that lighting of higher S/P ratio and higher gamut area will be of benefit to pedestrians. Note, however, that whether or not the effect of SPD is significant may depend upon the illuminance used, as has been found in the studies of obstacle detection and interpersonal judgements. Recent guidance developed for the UK [Fotios & Goodman, 2012] proposed to use CIE general colour rendering index (Ra) instead of gamut area, partly because Ra is more widely available lamp property than gamut area and partly because it gives better correlation with judgements of preferred appearance [Fotios & Cheal, 2011b]. Unfortunately there is currently insufficient information regarding uniformity of illuminance – either estimates of an optimum or trade-offs between uniformity and illuminance.

Further work is on-going to improve these estimates, including a repeat of the Boyce et al [2000] study of reassurance but in residential roads rather than car parks and obstacle detection imposing cognitive distraction on the test participants (i.e. walking and a non-static fixation point).

3 Lighting and Crime

The cost-benefit approach of setting light levels requires evidence of street crime and lighting conditions in residential areas. Research is on-going in the UK within the LANTERNS project.

3.1 Background

Several local authorities of England and Wales are considering reducing, or have reduced, some street lighting provision. This is partly to reduce costs, but also to contribute towards climate change mitigation and help reduce environmental light pollution [Royal Commission 2009]. Many proposals to reduce street lighting, particularly in urban areas, have attracted considerable public and media concern. Expressed concerns have centred on crime, public perceptions of safety, and road safety. However, potential positive impacts of reduced lighting have also been noted, in particular for amateur astronomy, and reductions might, in theory, mitigate the negative health impacts some have claimed from ‘light at night’ such as disrupted sleep [Navara, 2007]. To date, there is little robust evidence on which to judge whether these concerns are well-founded [Welsh and Farrington, 2008; Beyer and Ker, 2010; DeFRA, 2011]. There are therefore policy imperatives to generate good quality evidence on whether reductions in street lighting provision are associated with public health effects. The LANTERNS project is analysing data from across England and Wales to make a more reliable assessment of the possible impact of street lighting reductions on two important public health outcomes, road traffic injuries and crime.

3.2 Methods

One aim of the LANTERNS project is to statistically assess evidence for any changes to road traffic injuries (including pedestrians injured in collisions with vehicles) and any changes to crime (including violence against the person) that are associated with switching off street lights at night (e.g. part-night lighting) or with reducing lighting levels (e.g. dimming or trimming). The project also aims to compare the societal costs of lighting adaptation schemes against the societal benefits in a cost-benefit analysis framework, and to explore public opinion on the potential for reducing streetlight at night.

Data sources Every local authority in England and Wales was approached in 2013 with a request for the specific locations of all street light columns where part-night lighting, dimming or trimming has either been implemented or is planned, together with the month and year that changes were introduced. For road traffic injuries, STATS19 data for the period 2000-2012 were obtained – this is the official dataset of personal injury road collisions and casualties that occur on the public highway in the UK. These data include the date, time of day, location, severity (slight injury, serious injury, fatal injury) by type of casualty (pedestrian, cyclist, car occupant, powered two-wheeler) for all road collisions. For crime, data from the police.uk website have been obtained from December 2010. These data include the month, name of roads where incidents occurred, approximate geographic co-ordinates, and type of crime. A disadvantage of this publicly available data set is that time of day is not included, however the project will assess the validity of these results by comparing them with results using samples of detailed crime data (i.e. including exact time and location) from a sample of police forces.

Sample size and power The study's sample size calculations have assumed that street light reduction schemes have been implemented on streets on which only 1% of pre-intervention traffic injuries and crime events occurred. For road traffic injuries, statistical power will be maximised by using data for 10 years before street lighting changes were implemented. If 150 night-time injuries per year are expected on intervention roads this would give 1,500 night-time injuries on intervention roads during 10 years before light reduction schemes were implemented, and 150 injuries one year after, providing 90% power to detect an increase of 32% above pre-intervention injury levels. This magnitude of effect is consistent with that estimated in a Cochrane review [Beyer and Ker, 2010]. For crime, if around 20,000 day and night-time crimes per year are expected on intervention roads, then the study will have 90% power to detect a 5% increase in crimes above pre-intervention levels, and for major crime sub-categories (e.g. violence against the person) it will have 90% power to detect increases of about 10% in crimes. As data have been received from local authorities, it is already apparent that a greater proportion of crime and road injuries occur on intervention streets, which means that these power calculations are conservative.

Analysis Using a Geographical Information System (GIS) we will link data sets to a road segment database that includes the characteristics of all classified and unclassified roads. Each road segment will be classified according to the type of street lighting reduction scheme (e.g. part-night switch-off; 'dimming'; etc.) and by the census 'Lower Super Output Area' within which it is located. GIS will also be used to generate adjacent areas around streets (i.e. streets that are not part of lighting reduction schemes but which are adjacent to streets that are). From the combined dataset, counts of crimes and road traffic injuries for each road segment will be generated by month and by year. The road segments will allow stratification of results by area deprivation (i.e. based on Index of Multiple Deprivation of areas) and whether they are adjacent to streets where lighting has been reduced. As it is difficult to define appropriate population denominators to estimate rates on individual road segments, analyses will be based on change in counts within each road segment.

For optimal control of confounding the proposed analysis will compare change in counts of crimes and traffic injuries in the street before and after lighting is reduced, relative to trends seen on other roads. The estimated effect is therefore specific to roads with decreased lighting compared with other roads.

Conditional fixed effects Poisson models will be used. The number of injuries (or crimes) $Y_{s,t}$ in road segment *s* in year *t* is therefore modelled as follows:

$$Y_{s,t} \sim \text{Poisson}(\mu_{s,t})$$

$$\log(\mu_{s,t}) = \alpha_s + S(t,z_s) + ßx_{s.t}$$

… where α_s is the road segment effect, $S(t,z_s)$ is a function of year to allow for nationwide trends in injuries and crime incidents, dependent on road segment characteristics z_s, $x_{s.t}$ is a vector of indicator (0,1) variables identifying road segments with 'reduced lighting' and (separately) adjacent areas, after the lighting reduction had been implemented, and ß is a vector of coefficients representing the effect of decreased street lighting and adjacent areas on injuries and crime incidents. The α_s nuisance parameters are "conditioned out" in the conditional fixed effects Poisson model, allowing models to be based on annual counts of injuries and crime incidents within each road segment. For transparency, the underlying trends in injuries and crime incidents $S(t,z_s)$ will be fitted with linear terms.

Additional analyses will examine potential biases relating to 'regression to the mean' (arising from the fact that low numbers of traffic injuries and crimes may be factors in the decision to reduce street lighting in some areas). For this, the analyses will be repeated excluding data for periods of one and two years before changes to street lighting were implemented. Evidence for diffusion of crime and displacement of road accidents and crimes from better-lit nearby roads will also be investigated, and evidence for a 'lag' effect of street lighting reduction will be examined by modelling change in effects on events by month since implementation of lighting reduction.

For the cost-benefit analysis the monetary values of street lighting provision (infrastructure cost, maintenance costs, and energy consumption) are being obtained. Data on the monetary values (i.e. economic and societal costs) of road traffic injuries are being assembled, as well as the economic and societal costs of crimes by type of crime using Home Office definitions [Home Office, 2005]. The societal costs of street lighting schemes will be compared against the societal benefits in a cost-benefit analysis framework.

By the end of 2013 data had been received from a total of 42 local authorities of England & Wales. Part-night lighting had been introduced in 14 (33%) of these areas, dimming of lights in 24 (57%) areas, and trimming lighting times in 16 (38%) areas. A national workshop is to be convened at the end of 2014 with local authorities and third sector organisations to learn how our results might be of most use.

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