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To Determine if Changing to White Light Street Lamps Reduces Crime: A Multilevel Longitudinal Analysis of Crime Occurrence during the Relighting of Leeds, a UK City

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Abstract

This confirmatory study estimates the effect on Police Recorded Crimes (PRCs) of a relighting programme that installed nearly 80,000 white-light lamps, replacing predominantly orange ones, in the years 2005 to 2013, throughout the UK city of Leeds. Time series of weekly PRCs in all 107 Middle-layer Super Output Areas, while road lighting was being almost completely relit, were analysed using multilevel modelling. The background change in PRCs in each area, when and where no lighting was changed, was separated from that associated with when and where replacement white lamps were installed, by including a polynomial for the underlying time-trend. The key interest is how the replacement by new white lamps affects the rate of crime, from the start to the finish of the relighting. The results show that over the period, there was an estimated 2% rise in daylight adjusted darkness crime associated with relighting, 95% confidence interval (CI) (−3% to +7%). Similarly associated with relighting, (unadjusted) darkness crime showed a rise of 3%, 95% CI (−1% to +8%) and the round-the-clock measure of crime (the sum of darkness and daylight crime) gave an estimated rise of 3%, 95% CI (0% to +6%). Many checks were made, all giving consistent null results; that is, giving narrow confidence intervals around zero of only a few percent wide after relighting. Therefore, no evidence was found for an improvement (or detriment) in the city's level of crime by relighting, contrary to the substantial reduction anticipated by the city council.

Keywords Lighting and crime · Road lighting · Artificial light at night · Crime · Crime at night · Multilevel models

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Introduction

The purpose of the current paper is to present a multi-level approach to estimating the impact of new street lighting on crime, when relighting a conurbation is carried out. The method is applied to the lighting change (from predominantly orange light lamps to white light ones) carried out in the UK city of Leeds during the years 2005 to 2013. The number of replacements within the scope of this study was nearly 80 thousand lights.

This report largely follows the methods given in the open access paper, Marchant and Norman (2022), concerning the impact of the relighting on road traffic collisions in the same city. Substantial (20%) night-time crime reduction was one of the claimed benefits that would be brought about by the relighting. Research evidence that this would be the case was given in Leeds City Council's successful application for Private Finance Initiative support (Leeds City Council, 2004). This current study uses Police Recorded Crime (PRC) given by West Yorkshire Police (WYP) as its measure of crime occurrence and the lighting data was given by Leeds City Council. This crime study, like its predecessor on traffic collisions, is confirmatory rather than exploratory study, as it followed a defined plan. (See Schwab and Held (2020) for the difference between confirmatory and exploratory.)

Background and Key Literature Review

To begin with some history, in the USA the review by Tien et al. (1979) of crime reduction by street lighting found no benefit. Similarly, in the UK, a Home Office Crime Prevention Unit Paper could not detect any crime prevention benefit from street lighting, Atkins et al. (1991). Also, a report to the United States Congress titled, 'Preventing crime: What works, what doesn't, what's promising', by Sherman (1997), said in its Chapter 7, 'Preventing crime at places', by John Eck, "We can have very little confidence that improved lighting prevents crime, particularly since we do not know if offenders use lighting to their advantage".

For ideas about how streetlighting might influence crime the reader is referred to the Background sections in Welsh et al. (2022) and Chalfin et al. (2021).

Work Involving the University of Cambridge

In the 1990s work done at the University of Cambridge by Painter and Farrington (1997, 1999, 2001), funded by Urbis Lighting Company, claimed to have found positive benefits in reducing crime by street lighting. Subsequently, the results from this research, along with other studies, were used by Farrington and Welsh (2002) in Home Office Research Study 251 (HORS251). This involved a meta-analysis of 13 studies each cast into a simple controlled before-after (CBA) design. This means having just one measurement of crime count in the period before getting new lighting and another count in the after period, in this the 'treatment' area. This is matched by one count before and one after measurements, in the 'control' area that keeps its same lighting throughout. This design was pursued even if there were more than 4 data points involved in a study being included in the meta-analysis. This HORS251 study was criticised in Marchant (2004), with further explanation in Marchant (2005). Some of the context surrounding this and other developments in the 1990s and 2000s is given in Marchant (2006).

The meta-analysis method has been repeated, Welsh and Farrington (2008), Welsh et al. (2022). However, the results of this work may not be correct as explained next. Issues identified that cause problems for lighting research and how the current study attempts to overcome them are now described.

Overdispersion

In HORS251, Farrington and Welsh (2002), it was assumed that counts of crime followed a Poisson distribution in which the variance equals the mean. However, this is not the case, as crime is committed by criminals and so the crime events are not statistically independent; repeat victimisation and runs of crime are manifestations of this non-independence. A consequence of this complication is that it gives rise to overdispersion, in that the variance of the count becomes greater than the mean, with the degree of overdispersion dependent on the specific circumstances in any particular situation. This becomes manifest in a fixed effect meta-analysis of crime study results, as the individual study estimates (means) vary more from each other than expected on the basis of their uncertainties (standard errors) derived on the basis of Poisson variation. Also, overdispersion is clearly apparent in the time series plots of the data from Bristol, Shaftoe (1994), and Birmingham markets, Poyner and Webb (1997), shown in Marchant (2004, 2006). (The erroneous view that crime can reasonably be assumed to follow a Poisson distribution still persists as in Uttley et al. (2024)). In the Leeds study reported here overdispersion is taken into account directly in the modelling of the crime time series.

Untrustworthy Control

In the controlled before after (CBA) studies it is assumed that that the control area is equivalent to the treatment area except for the new lighting. This cannot be guaranteed to any degree of precision. The crime trends in the two areas, unrelated to lighting, may be very different. There is no mention of randomisation in studies (except for Chalfin et al., 2017, 2019, 2021), therefore, we cannot guarantee the areas, 'treatment' and 'control', will even out in the long run. One way in which the two areas will not be equivalent is if the one chosen for lighting was because it had a higher than anticipated level of crime, in which case this will bring Regression Towards the Mean (RTM) in to operation. The problem is that the high crime rate, bringing about the new lighting, could be just a statistical fluctuation away from its usual more average level, to which it subsequently relaxes. This then is likely to lead to a spurious claim that it was the lighting that brought about the relaxation, rather than just natural statistical variation returning to its more usual level. RTM was first recognised by Galton (1886) and is described by Bland and Altman (1994), Marchant (2006), Hand (2020). Baxter and Marchant (2010) estimated the effect of RTM for bivariate lognormal and gamma distributions which may approximate the situation for CBA crime studies.

In the Leeds study reported here, RTM is not considered to be a problem. This is because it is understood, from the lighting engineers involved, that the relighting was done without regard to the levels of crime in areas, but rather just for the convenience of the installation process, and also by the fact that the whole of the city was eventually covered by the relighting. Also, it should be noted that there are 107 areas being compared, and not just two as in a basic CBA study.

Incomplete Use of the Data Provided by the Studies

Because the method chosen for their three meta-analyses (2002, 2008, 2022) was to utilise a number of simple, one before one after, CBA primary studies, it involved aggregating some data and omitting some from an intermediate period, if the relighting took an extended time to complete. An example of this pre-processing is with the data from Bristol, (Shaftoe, 1994) to arrive at a very highly statistically significant result in favour of lighting. (This claim of high statistical significance is repeated in Welsh and Farrington (2008) and Welsh et al. (2022)). This claim is in contrast to that of Shaftoe himself, who concluded there was "no association of street lighting schemes and changes in night crime levels". Just visual inspection of the time series of the data, does rather support the Shaftoe statement (see Marchant, 2006). In Farrington & Welsh (2004, p460) and Welsh and Farrington (2008) there is an attempt to justify the highly statistically significant claim by running a very specific basic regression on the Shaftoe data. However, to obtain a modestly statistically significant effect for lighting, their model involves having a statistically non-significant effect for the common time period term. When this time-term is removed from the regression model the lighting effect becomes statistically non-significant.

Note also that Welsh et al. (2022) claim that meta-analysing the studies which use the sum of day and night crime gives a highly statistically significant reduction in crime. However meta-analysing those studies just using crimes occurring at night, yields a null result. This difference between the two results seems strange. In our Leeds study we model both crimes in darkness and crimes in daylight separately and also their ratio. Here, all the 456 time points, over nearly 9 years, in all of the 107 areas are modelled simultaneously, taking into account the underlying time trends, including seasonal variation in crime.

Other Major Studies on Lighting and Crime

The Chalfin Et al. Study Reports that Used Randomised Allocation of Lighting

Chalfin et al. (2017, 2019, 2021) is the only known study with randomised allocation of increased lighting, and concluded the extra lighting was associated with fewer night-time crimes in New York City public housing areas. The study used stratification in the randomised allocation of the 80 public housing areas to either extra lighting or to 'treatment as usual' (that is just keeping the same lighting as previous) for the six month period of the field work. It should be noted that the treatment involved adding very bright, 600,000 lm lighting, towers and not extra standard outdoor lighting, (that is said to run typically at between 5000 and 35,000 lm). A criticism of the Chalfin et al. work is that instead of just taking the outcomes from the result from the 77 randomised housing areas that remained in the study, a lot of Poisson regression was performed to achieve the final result. This involved using a host of candidate extra variables, characterising a public housing area, being added into the regressions. This puts this study in the exploratory rather than confirmatory paradigm. Initially (the 2017 report) the extra variable selection was done 'by hand' but the two later reports used LASSO regression (Tibshirani, 1996), which uses automated covariate selection. Another issue is that no mention is made of overdispersion in the counts in the two later versions. Also, it is not clear how the control group was included in the final assessment of the effectiveness of lighting. For this randomised study one might expect that a protocol, that is a plan for the proposed work, written before starting to carry it out, to be available. However, no mention is made of one.

The Leeds study has a protocol to follow and overdispersion is included in the modelling. Also, although the replacement of the Leeds lighting was not randomised, as remarked above, the new lighting was not installed with regard to previous crime and so was unbiased in this regard. It tracked crime over a longer time period, of nearly 9 years, than the 6 months of the New York public housing study.

The National Institute for Health Research Funded Study, Perkins et al. (2015), Steinbach et al. (2015)

The UK's National Institute for Health and Care Research (NIHR) funded (£414,315.32) 'Local Authority collaborators' National Evaluation of Reduced Night-time Streetlight' (LANTERNS) project could not detect an effect on the crime-rate (using 95% confidence limits) through any change to lighting, including relighting with white light, despite its extensive data. See https://fundingawards.nihr.ac.uk/award/11/3004/02 for details including protocol and outputs. The full report of the study is Perkins et al. (2015) and an abbreviated journal version is Steinbach et al. (2015).

The study involved changes to lighting using data from 62 of the 174 local authorities in England and Wales and had access to several million crime reports. Although originally designed only to detect the effect of reduced road lighting, in a variation to protocol, it also examined the effect of changing to white light on roads, such as has been done in Leeds. It used monthly measurements of crime between Dec 2010 to Dec 2013. The outcome measure for the study is the crime rate ratio (CRR) which is the ratio, after to before, of the crime occurring after the lighting change to that before. The 95% confidence interval for the CRR of changing roads to white light from the previous lighting was found to be CRR 0.89; 95% CI (0.77 to 1.03) giving a null result, as the null, 1.0, is included in the CI. The CRR for the other results are, switch off, RR 0.11; 95% CI (0.01 to 2.75), part-night lighting, RR 0.96; 95% CI (0.86 to 1.06) and dimming, RR 0.84; 95% (CI 0.70 to 1.02). The authors of the study suggest there was weak evidence for a reduction in the aggregate count of crime with both dimming and white light, presumably because their upper confidence limits are not far into the crime increase region. However, this is somewhat strange as it rather negates having chosen to use a 95% confidence interval in the first place. Also, it would be peculiar if reducing visibility through dimming and increasing it through whitening light were both to reduce crime.

The Leeds study reported here shares some similarities with the NIHR funded LANTERNS study in that both take overdispersion into account and work at the same geographical scale. However, Leeds has a longer time period of nearly 9 years and treats time in a more detailed way, e.g., weeks rather than months and uses a multilevel approach.

A Note on Protocols and Reproducibility

There was no protocol available for HORS251, however the study of Welsh and Farrington (2008), as a Campbell Collaboration systematic review, does have a protocol, Welsh and Farrington (2003). However, it is not clear that any of the component studies do. Presumably the Welsh et al. (2022) study uses the same 2003 one. It is not made clear why their 2022 study was not done as an update to the 2008 review, under the Campbell Collaboration aegis. There is no protocol made available for the study behind the Chalfin et al. reports. The NIHR funded LANTERNS project does have a protocol. The Leeds study involved producing a protocol which was sent to custodians before starting the analysis and is available; see later for access. It should be noted that the Leeds study is reproducible, as the data modelled is provided, whereas the other studies discussed are not, as their data is not given.

Introduction to the Leeds Study

Because some of the investigations have deficiencies and there has been a dearth of good quality studies on street lighting and crime, it therefore seemed worthwhile checking what the result of large and costly lighting projects do achieve in terms of safety. Leeds City Council made a successful bid to the UK Government, to acquire Private Finance Initiative funds to go ahead with the relighting of the city with white lamps to replace predominantly orange ones. The Outline Business Case, Leeds City Council (2004), for the bid made several references to claims of the effectiveness of new lighting in reducing crime. For example, it asserted, “Good lighting levels are very important in situational crime protection “and stated, “The most extensive research on the link between lighting levels and crime has been conducted by the Institute of Criminology, University of Cambridge” and mentioned “two rigorous studies at Dudley and Stoke-on-Trent”. Also, “The research suggests reduction in crime rates attributable to improved lighting of over 25%. We believe that a reduction of 20% in night-time crime only is a reasonable assumption in the context of Leeds.”

The Leeds Outline Business Case asserted that the Net Present Value (NPV) accruing from Crime Benefits alone was £109,049,000 for a full replacement of its lighting (which is what happened). It gave the Benefit to Cost Ratio (BCR) as 3.75 for the project. However, it seems that the evidence adduced by LCC for the bid for new lighting was weak. It is the aim of the present confirmatory study to check if the promised crime reduction was fulfilled.

In summary our study, detailed here, examines the effect on crime of the installation of white road-lamps that replaced predominately orange ones. The crimes are those that were reported to the police and recorded, referred to as Police Recorded Crime (PRC). The outcome measure is all crime, the majority of which is property and violent crime (See table given in Supplementary Materials of the crime types in the file given by the WYP). It is possible that lighting affects the frequency of different crime types (positively or negatively) by different amounts. Our all crime measure, assessing the overall effect of the new lighting, is equivalent to 'all-cause mortality' in determining the effect of a healthcare invention, in epidemiological research, of say the effectiveness of a vaccination programme against a pandemic.

The study uses data from the relighting of the UK city of Leeds. Nearly eighty thousand (78,189) lamps were changed in the 107 geographical areas, Mid-layer Super Output Areas (MSOAs), during the period of the study between 03 January 2005 and 29 September 2013. During this time interval there were found to be 679,452 PRCs. However, the status, daylight or darkness, could only be ascertained in 471,374 cases.

This study bears great similarity to that described in Marchant and Norman (2022) which was on the effect of the white replacement lights on Road Traffic Collisions, in the same city over the same time period. The longitudinal multilevel method described is effectively comparing each of the 107 time series of the city areas with its previous crime levels at any particular time with the current amount of relighting completed, whilst also making comparisons with all the other areas in which the lighting implementations are at a differing stage of completeness. The present study also shares some similarity with one on the effect of new street lighting on crime in London, Marchant (2011), done at a coarser scale.

The use of multilevel models is not unknown in crime research, see for example Kai Lin (2022), but we are unaware of this method being used to estimate the impact of any large-scale implementation.

Materials and Methods

Using data on the installation of the new white lamps and Police Recorded Crime (PRC), this study modelled the impact of relighting on crime in the city of Leeds. The weekly numbers of PRCs in different areas were modelled as a function of time, on the increasing number of white, broad-spectrum, road-lamps installed and operating, while comparing with other areas where lighting is changed at different times and by different amounts. The underlying trend in PRCs in the absence of changed lighting was fitted by a polynomial in time, with indicator variables for month of the year to account for seasonality and another set to account for potential differences in those weeks containing a public holiday.

The analysis used a multilevel modelling approach, (Goldstein, 2010; Snijders & Bosker, 2012) which is appropriate for the structure of the data, as the PRCs and lamp changes, implemented in a 'stepped wedge' fashion, over the time period, are nested within the 107 Middle-layer Super Output Areas (MSOAs), of the city. (MSOAs are geographical units used in England and Wales to disseminate neighbourhood statistics providing a balance between geographical granularity and data reliability. They comprise between 2000 and 6000 households and between 5000 and 15,000 persons). The stepped wedged introduction of the replacement lamps, which may be thought of as increasing the 'dose' of new lighting, constitutes a sporadically interrupted time series. To maximise transparency and help guard against reporting bias, the protocol for the study was sent to three independent custodians 22nd and 23rd June 2023, see the Acknowledgements section. A copy of the protocol is included in the Supplementary Materials.

The key aim is to determine how the daylight adjusted darkness PRC weekly rate (that is the ratio of PRC weekly rates occurring in darkness to those occurring in daylight) changes when the new lighting is introduced. This change factor, for a given amount of relighting, is the Crime Rate Ratio (CRR), as it is the ratio of the daylight adjusted darkness PRC weekly rate with the increase in relighting, to that without. The daylight adjusted measure was used to take into account processes that affect crime both day and night. The effect of the relighting on the unadjusted darkness CRR, and the sum of the darkness and daylight PRCs was also examined.

This multilevel, longitudinal, stepped-wedge introduction, method of checking the impact of an implementation could apply to topics other than lighting, where an intervention is incrementally introduced into different areas.

Lamp Data

A full street lamp inventory to the end of 2015 for the city, was made available in 2016 by Leeds City Council, for our analysis. It was subsequently made known that Part Night Lighting (PNL), whereby some lamps are switched off for the early hours of the morning, had been gradually introduced by the City Council on some roads, in various areas, commencing 1 Oct 2013. Therefore, in order to avoid the confusion of some areas having PNL, the time series used for analysis ran from Monday 03 Jan 2005 and ended on Sunday 29 Sept 2013.

Each new installed lamp was assigned to the appropriate one of the 107 Leeds MSOAs in the data file, on the basis of its geographical coordinates (Easting and Northing). The date that the new lamps were installed allowed the cumulative number of new white lamps, operating at a given time (week), in a given MSOA, to be known. By this means, the file for analysis contained the number of new lamps operating in each week in each MSOA, between week 1, starting Monday 03 Jan 2005, and week 456, starting Monday 23 Sep. 2013, inclusive. A total of 78,189 lamps were introduced up to 29 Sept 2013. Had the time series analysed continued to the end of 2015 there would have been 79,729 lamps. Thus, there was only a small reduction, of 1.9%, in the number of new lamps installed as a result of reducing the time series by two and a quarter years. Therefore, the data series used comprises virtually all the lamp changes. Note in passing that Leeds has 107 MSOAs but the numbers by which they are indexed extend up to 112. This is because the numbers 26, 36, 43, 49 and 84 are missed out.

Crime Data

The crime data used in this study is that recorded by the West Yorkshire Police (WYP) from crimes reported to them. The request was for the data from the start of 2005 to the end of 2015. There were no concerns about confidentiality as the locations of the individual crimes were only given to being in the MSOA in which they occurred, and the data contained no personal information. The file given contained 840,897 PRCs.

The key piece of information relevant to this work is the reported times and dates between which the crime had been committed. From this one might deduce whether this was a time when street lamps should be lit or should be off. This ascertainment is likely to be possible if the earliest time and date the crime could have occurred, and the latest possible time and date of occurrence are close to each other. However, if these two key times and dates span those times when road lights come on or go off, it is not possible to tell if the crime occurred in daylight or darkness. ‘Lighting up’, when road lights (and vehicle lights) should be lit, is from 30 minutes after sunset to 30 minutes before sunrise. This time period is classed as ‘darkness’ and the rest of the 24 hours is classed as ‘daylight’.

Computer code was written to determine which of the three possibilities, darkness, daylight or not known, pertain to any individual reported crime. This code was written as SPSS Syntax and based around an algorithm from the Almanac for Computers, from the Nautical Almanac Office, United States Naval Observatory (1990). This involved astronomical calculations to determine the relevant rise and set times of the Sun for both the earliest and latest possible occurrence of the crime. The calculations also involved the latitude and longitude for Leeds, 53.8008 deg. N, 1.5491 deg. W, and the start and finish of British Summer Time (BST) in the years 2005 to 2015. The output of the code was extensively checked for specific times and dates against the sunrise and sunset times for Leeds, using https://www.timeanddate.com/. The time of day given never differed by more than one minute.

As well as determining the lit status of the street lamps, the code also calculated the time interval between the earliest and latest possible occurrence of each crime. It also estimated the time and date of a crime as the mean of the two so as to be able to allocate the crime to a particular week for the analysis. The SPSS syntax for this is included in the Supplementary Materials.

Cleaning the Crime Data

The data first needed to be cleaned. There were 18,192 (2.16%) cases in the original file of 840,897 which did not have a Leeds MSOA identifier. Also, there were 894 cases in the original file where the earliest time and date given that the crime could have occurred was actually after the latest time it could have occurred. Removing both of these left 821,829 cases. It was then found that in these remaining cases there were some where the mid-point between the earliest date and time and the latest date and time of crime occurrence (the mean) was before the start of the originally designated study period Monday 03 Jan 2005 or after 27 Dec 2015. Removing these left 817,624 crimes (97.23% of the original 840,897). The mean time of the occurrence of the crime was subsequently used to allocate the crime to one of the 456 weeks of the time series. SPSS Statistics 26 was used to prepare the data file for analysis.

Producing the Datafile for Analysis

The file was sorted into the order of 1) increasing MSOA number and 2) increasing estimated time of crime occurrence within a MSOA. Then the data was aggregated into weeks within MSOAs thereby producing a file containing the number of PRCs occurring in each of the 456 weeks in each of the 107 Leeds MSOAs for each of 3 lighting conditions, darkness, daylight or not known which.

The weekly MSOA lighting data, i.e., the progress in the number of new lamps operating in each MSOA in each week, was added to the weekly MSOA crime counts. However, because of the issue of Part Night Lighting (PNL) being introduced on 1 Oct 2013, as mentioned above, the series was terminated at the end of 29 Sep 2013 rather than 27 Dec 2015. This leaves 679,452 (83%) crimes from the 817,624, had the series continued to the end of 2015.

Of these 679,452:

221,644 occurred in darkness.

249,730 occurred in daylight, making 471,374 PRCs where the lighting condition is known.

Leaving:

208,078 where the lighting condition is not known.

The variables in the analytical dataset are listed in Table 1.

The dataset is available in the Supplementary Materials.

Multilevel Modelling

It is the daylight adjusted darkness PRC rate, (= the ratio of darkness to daylight PRC weekly rates), that forms the focus of this work. The estimate of the alteration of daylight adjusted darkness PRC rate, from relighting, by a given increase in the amount of white lamps, can be obtained directly by fitting a binomial logistic model. This allows the daylight adjusted darkness crime rate ratio (CRR) to be obtained, that is the ratio of the daylight adjusted darkness PRC rates with a given increase of new lamps to that without the increase. Using this daylight adjusted measure is to compensate for changes in both daylight and darkness PRC-rates due to changes in other features of the areas involved, such as how 'busy' they are or just in the size of the criminal population. Additionally, the darkness and the daylight crime weekly rates were modelled separately, as was their sum, the latter to indicate the effect of the new lighting on the overall level of crime.

Table 1 The variables in the analytical dataset

Variable Name	The Meaning of the Variable
CaseID	Sequential case number: from 1 to 48,792 (= 107 × 456)
MSOA code	The 107 Leeds MSOA codes which are in the range 001 to 112
Week Number	The values go from 1 to 456 for the series
N_LampsAdded	The number of new white lamps installed in that MSOA in that week
Cumulative N lamps	The number of new lamps operating in the MSOA in the week
MidWkYrsFrom StartOfSeries	The number of years the mid-week is from the start of the series. Given by (7 * (WkNumber-1) + 3)/365.242
Date of the Monday	The calendar date of the Monday of the week
Month	The month in which the midweek falls: 1 to 12 (Jan. to Dec.)
Public holiday	Public holiday falling in that week: 1 to 7 (1 New Year to 7 Christmas)
Length of Darkness	Length of darkness in hours
N PRCs daylight	Number of daylight crimes (PRCs) reported in that MSOA in that week
N PRCs darkness	Number of darkness crimes (PRCs) reported in that MSOA in that week
N PRCs DK lighting	N of crimes (PRCs) with lighting unknown reported in that MSOA in that week

Weekly numbers of PRCs in each MSOA were analysed as a multilevel model; time points at level 1 and MSOA at level 2, for the natural logarithm of the response variable of interest, e.g., the daylight adjusted darkness weekly crime rate. The model used a polynomial for the underlying time trend, that is the trend for when there is no lighting change. The multilevel approach allows the time trend to be different in different areas, through having polynomial coefficients that are 'random' rather than the more well-known 'fixed' effects. We included a measure of the amount of new white lighting introduced in the model. This enables comparison of the areas, which are at different stages of relighting, at any given time point, in regard to the effect of lighting on crime. This is because the time-trend in crime that is unrelated to lighting change has been accounted for by the time-trend polynomial appropriate for that area. In the principal analysis the amount of new lighting was simply the proportion of that done of the total operating at the end of the time series in the MSOA. Indicator variables were included to reduce background effects on the PRC-rate from seasonality (months) and weeks containing a public holiday. Additionally, the effect of the relighting each week in each MSOA was also modelled as the number of new lamps operating rather than as the fraction of the implementation completed.

The progress of the relighting was denoted as the difference in the amount of white lamps operating within each MSOA in a given week from the MSOA's mean amount of white lamps operating over the series. (The 'amount' being the proportion of the MSOA's final complement or the number of new lamps, as appropriate to the approach taken). The models also included a second lighting term for the difference of a MSOA's mean amount of white lamps from the (grand) mean amount across all MSOAs giving the between area mean lighting difference. The two terms ('within' and 'between') for the build-up of white lighting were thus 'centred'. The aim of the modelling was to separate the underlying temporal change in PRC-rate from that associated with the relighting of the roads with white lamps.

The final form of the Generalised Linear Mixed Models (Multilevel Models) used had the usual link functions given below for the response variable at time point i and MSOA j:

For the daylight adjusted darkness PRC-rate we use a Binomial model at the heart of which is the Binomial distribution, Binomial(n, π), (Forbes et al., 2011).

In our case, the n-parameter of the Binomial is the total number of PRCs where the lighting condition is known, for the week in the MSOA, that is the sum of PRCs in darkness and daylight. (It can be shown that the ratio of two independent Poisson distributions, here those for darkness and daylight, is Binomial, conditional on their sum.)

The link function is logit:

$\text{logit}(\pi_{ij}) = \log(\pi_{ij}/(1-\pi_{ij}))$ where i = level 1 index and j = level 2 index and π_{ij} = the proportion of PRCs occurring in darkness $= \mu_{\text{dark } ij}/(\mu_{\text{dark } ij} + \mu_{\text{daylight } ij})$.

so $1-\pi_{ij}$ = the proportion of PRCs occurring in daylight $= \mu_{\text{daylight } ij}/(\mu_{\text{dark } ij} + \mu_{\text{daylight } ij})$.

This leads to:

$\text{logit}(\pi_{ij}) = \log(\mu_{\text{dark } ij}/\mu_{\text{daylight } ij})$ that is the logarithm of the darkness PRC-rate divided by the daylight PRC-rate. This ratio we call the daylight adjusted darkness crime rate.

and,

For the Poisson count models for the mean weekly PRC rates, (darkness, daylight, the sum of darkness and daylight), the link is log,

$= \log(\mu_{ij}) = \log(\text{mean weekly PRC-rate})$.

The linear combination of predictors in all cases was, as specified in the protocol, of the form:

$= \beta_0 + \beta_1 t + \beta_2 t^2 + \ldots + \beta_{Mk}\text{Month}_k + \beta_{Hl}\text{PubHol}_l + \beta_W(L_{ij} - \langle L_{ij} \rangle_j) + \beta_B(\langle L_{ij} \rangle_j - \langle\langle L_{ij} \rangle\rangle)$.

Where $\langle\rangle_j$ denotes the mean with respect to week i in area j, $\langle\langle\rangle\rangle$ the mean of the area means.

t = the time that the midweek is from the origin of the series. (In the analysis the series was balanced about the midpoint of the time series.)

The $\beta_0 + \beta_1 t + \beta_2 t^2 + \ldots$ polynomial, with a degree to be determined, represents the underlying secular time trend. The β_0 term, the intercept coefficient, was modelled as a random term because different areas will have different levels of crime. Other polynomial coefficients, e.g., β_1, might also be expected to be random because of different underlying temporal crime trends, separate from any lighting effect, in different MSOAs. The modelling of the time trend had time centred on halfway through the series.

The β_W term represents the effect of the deviation of the amount of white lamps, L_{ij}, from its mean $\langle L_{ij} \rangle_j$, over the time series duration, in an area, giving the all-important within-area effect of lighting change. This coefficient enables the effect of changing lighting on crime within an area to be measured. The β_B term is the between-area effect term; the effect of the deviation of the mean amount of white lamps in an area, $\langle L_{ij} \rangle_j$, over the series, from the mean of the

MSOA means $<<L_{ij}>>$. This term takes account of how areas differ in outcome separately from changes in lighting within them.

The β_{Mk} term represents the effect of the k = 1 to 11 Month indicator variables (reference = January) to account for seasonality in PRC rates.

β_{Hl} that of the 7 public holiday weeks per year l = 1 to 7 (reference = weeks which are not public holiday weeks) to account for the fact that crime in a public holiday week may be different from usual.

The models for the separate darkness only PRCs and daylight only PRCs incorporated an offset in each; the logarithm of time-exposure. That is, the logarithm of the fraction of the 24 h period when darkness or daylight applied, because, for example in winter, there is more darkness and so more opportunity for a PRC to occur in darkness. The binomial (logit) model for the darkness to daylight crime ratio incorporated the two offsets.

The predictor variables, of time and number of lights, used in the model fitting were scaled, in order to ensure that all coefficient values were of a convenient size (neither too big nor too small) in the output produced. The time variable, the time that the midweek is from the start of the series, was scaled to use the unit of ten years so the coefficient gives the effect of the passage of time of a decade on the PRC-measure. When using the number of new replacement white lamps, this was scaled to be in units of one hundred, so the coefficient gives the effect on the PRC-measure by relighting by 100 lamps.

The fitting of the multilevel models was carried out with MLwiN 3.01 (Rasbash et al., 2009; Rasbash et al., 2023). Estimation was done using Maximum Likelihood Estimation (MLE).

The selection of the most appropriate model was judged by the statistical significance of the coefficients of additional temporal terms in the polynomial for the secular time trend and also confirmed using the −2LogLikelihood statistic. Whether a coefficient was made random, or just left as fixed, was judged by the statistical significance of the variance estimate, when a coefficient was made random. Because crime events are not statistically independent (as crimes are clustered within criminals for one thing), overdispersion has to be taken into account (Marchant, 2004, 2005). That is the standard Poisson distribution does not apply as the variance does not equal the mean for crime counts, as discussed in the Introduction. Therefore, the Extra Binomial and Extra Poisson facilities of MLwiN were used. Models for counts based on the Negative Binomial distribution were also employed as this distribution for counts does not have its variance fixed equal to its mean.

The change over time in the prediction of the lighting effect from the fitted models, of the mean rates, between two time points i = a (after) from i = b (before) is found by differencing, 'after' minus 'before'. The contribution to the change in the prediction on the log scale due to the change in the amount of new lamps installed within an area j between those time points, b and a, is therefore given by:

$\beta_W(L_{aj} - <L_{ij}>_j) - \beta_W(L_{bj} - <L_{ij}>_j) = \beta_W(L_{aj} - L_{bj})$.

The difference between logarithms is equal to the logarithm of the ratio of the individual arguments (i.e., either the daylight adjusted darkness PRC rate ($\mu_{dark\ ij}/\mu_{daylight\ ij}$), in a binomial model or the mean PRC rate (μ_{ij}), in a count model).

So $\beta_W(L_{aj} - L_{bj})$ gives the relighting effect on log(PRC-rate$_a$/PRC-rate$_b$) = log(CRR from b to a).

We want the estimate of the change in the daylight adjusted darkness PRC rate ($\mu_{dark\ ij}/\mu_{daylight\ ij}$) and also the changes in the mean PRC rates (μ_{ij}) for a given lighting change, in their un-logged state. Therefore, we must exponentiate, which causes the right hand side of the linear model equation to go from a sum of terms to a product of exponentiated terms. This enables determining the result we require, that is the estimate of the crime rate ratio (CRR), the factor by which the specific quantity of interest, e.g., the daylight adjusted darkness crime rate ($\mu_{dark\ ij}/\mu_{daylight\ ij}$), or the mean PRC rate, is multiplied on increasing an area's lighting by a certain proportion of lighting completed or a certain number of lamps, that is from L_{bj} to L_{aj} from time point i = b to i = a. The factor is exp.($\beta_W(L_{aj} - L_{bj})$). Therefore, exp.(β_W) gives the effect of changing the proportion of new lighting from zero to its final completed amount of one. Whereas in the case of modelling the effect of an additional 100 new lamps being installed, this factor, expβ_W, gives the change for a one hundred lamps increase.

As stated above, the main focus is on the daylight adjusted darkness PRC rate and is done to compensate for confounding by other factors which influence general crime occurrence contemporaneous with lamp installation. The result sought is obtained directly using the binomial logit model. An additional estimate of the lighting effect on the daylight adjusted darkness PRC-rate can also be obtained by differencing the separate fitted darkness and daylight Poisson models, because again the difference in the logarithms equals the logarithm of the ratio of their arguments, the numerator being the darkness effect and the denominator being the daylight effect. The result from the direct binomial model and that through differencing can be compared and the degree of agreement observed.

The multilevel modelling package used, MLwiN 3.01 has various ways of performing the maximum likelihood estimation for discrete models, such as those applicable in the present situation. These are Marginal Quasi-Likelihood (MQL) of order 1 and order 2 and Penalised Quasi-Likelihood (PQL) of order 1 and order 2. Order 2 generally gives more accurate results than order 1 and PQL generally gives more accurate results than MQL; see discussion in Snijders and Bosker (2012).

Results

Note: Confidence limits of 95% are used throughout this work.

The Analysis Dataset

The data in the analysis consisted of the number of PRCs occurring each week in darkness, daylight and those where it was not known which, in each of the 107 MSOAs, together with the number of replacement white lamps operating for that week in that MSOA. The time series ran from the week commencing Mon. 03 Jan

2005 until Sun. 29 Sept. 2013. There are no missing data. The MSOAs form level 2 and the 456 weeks form level 1 of the multilevel analysis.

The Lamp Data

The count of newly installed lamps across the whole of Leeds, exhibits a steady increase over the period of the implementation. The broad pattern of the rise in the number of new white lamps is also evident at the level of individual MSOAs. The relighting in the different MSOAs: 1) started at different time points, 2) proceeded at different rates and 3) finished with different numbers of new lamps. This phasing of the introduction and progress of the relighting is key to assessing the effect of the new lamps on crime through our multilevel analysis as the MSOAs are at different stages of completion at different times. The pattern of the rise in the number of new white lamps in the individual MSOAs is shown for illustrative purposes in a time series graph in Marchant & Norman, 2022, Figure 2.

The increase in the numbers of new white lamps within the MSOAs over the analysis time period up to 29 Sept 2013 had the following statistics for the 107 areas: minimum = 275, maximum = 1291, mean = 730.74, standard deviation = 173.505.

The Crime Data

The time period had 679,452 recorded crimes. There were three categories: 1) The crime was known to be committed in darkness, 2) the crime was known to be committed in daylight and 3) it was not possible to tell whether the crime was committed in darkness or daylight. The number of weeks in the series (456) multiplied by the number of MSOAs in the city (107) yields 48,792. Descriptive statistics of the 48,792 crime counts are given in the Table 2.

The multilevel analysis examines the 456 weekly rates of crime in the 107 Leeds MSOAs.

Note that it is just the number of reported crimes per week in these MSOAs, i.e., the weekly rate, that is analysed. (There is no population denominator).

The display, Fig. 1 below, gives a sense of the variation of the mean rates in darkness and daylight between the MSOAs. It shows that the rate of crime in the City Centre MSOA (111) is an order of magnitude greater than in the others.

Because it might be feared that having such a discrepant level 2 unit might cause problems with the aim of getting a trustworthy result for the effect of the new white lighting on crime, additional analyses excluding the City Centre were carried out

Table 2 Statistics on the crimes: 1) in darkness, 2) in daylight and 3) where it is not known which

	Minimum	Maximum	Sum	Mean	Std. Deviation
Darkness Crime	0	152	221,644	4.54	7.79
Daylight Crime	0	155	249,730	5.12	9.19
Light Status Unknown	0	117	208,078	4.26	3.5

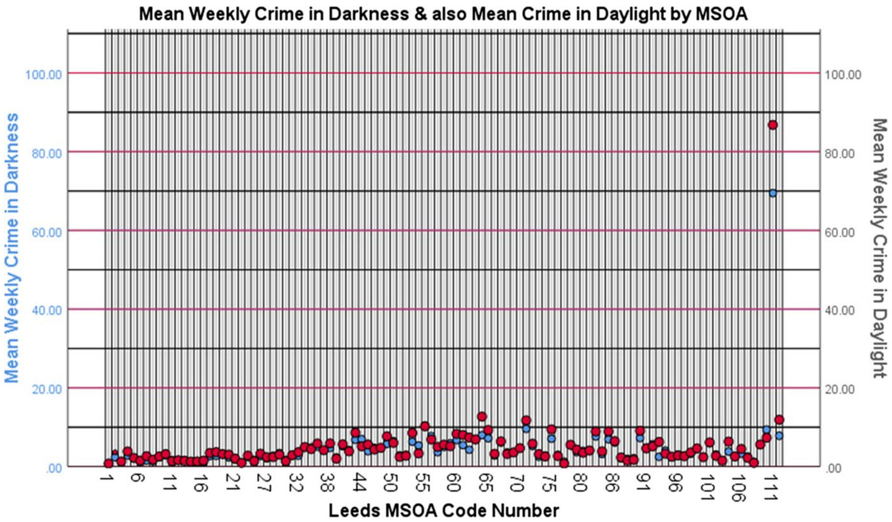

Fig. 1 The mean weekly crime in darkness and daylight in the MSOAs

(see later). It should be noted however that because there are 106 other MSOAs the number of PRCs outside the City Centre is an order of magnitude greater than the number inside.

The centiles of the MSOA mean weekly crime rates for the three conditions, when the crime was committed, are given in Table 3.

Graphs showing the weekly PRC time series and build-up of replacement lamps aggregated over all 107 areas, so as to cover all of Leeds, are given in Supplementary Materials as Figures a-e, These show a general decline in PRCs for both darkness, Fig. a, and daylight, Fig. b and for the totals of weekly PRCs, Fig. d and Fig. e, over the period of study. However, the graph Fig. c of the ratio of the number of PRCs occurring in darkness to the sum of those occurring both in daylight and darkness shows no clear evidence of a change. The graphs, Figs. a, b, c, show a strong relationship between the number of PRCs in the periods of darkness or daylight and the length of time those periods last, due to seasonality. That is there are more PRCs in darkness when it is dark for longer (winter) and similarly there are more PRCs in daylight when that lasts longer (summer).

Table 3 Centiles of the 107 MSOA mean crimes per week, by circumstances of when the crime was committed

Centile	5	10	25	50	75	90	95
Known darkness	1.246	1.450	2.400	3.320	5.430	7.104	7.936
Known daylight	1.278	1.474	2.480	3.650	5.860	8.666	9.918
Do not know which	1.832	2.042	3.020	3.930	5.040	6.882	7.668

The decline in crime in Leeds has been generally seen nationally and internationally, over recent years. This is discussed in Tilley and Farrell (2022). Some of the decline is thought to be caused by the fact that there has been increasing security, of many diverse forms, in operation over the period, so that crime has become progressively harder to commit.

The Results of the Modelling

The purpose of the modelling is to ascertain the separate effect of the change in lighting on crime, taking into account the background change in crime that occurs without any changes to lighting.

The models fit a background that is composed of a time trend which is formed from a polynomial in time, and which also has terms for months and whether the week contains a public holiday. Coefficients of the polynomial were able to be made 'random', so that MSOAs could have different values from each other to reflect their various MSOA-specific trends. Models generally include a relevant offset which is the logarithm of the temporal extent of darkness and or daylight at each midweek as is appropriate to the situation under study. This offset term is to compensate for the amount of time that is available for a crime to be committed. The extent of darkness or daylight available for committing a crime plays a major part in forming the sinusoidal patterns shown in the crime time series graphs, Figs. a, b, c in the Supplementary Materials. As stated previously, the effect of removing the offset on the estimate of effect of the new white lighting was examined.

The quantity of key interest is the within MSOA lighting coefficient which says how the crime changes as the new white lighting increases within an MSOA. The between MSOA coefficient is not of relevance as its value depends on the order that the new lighting was installed. The sequence of the installation of white lamps was just done for the convenience of the company having the contract, working around the city from its two operational bases.

The objective of the modelling was to find a suitable polynomial in time to account for the underlying level of crime, that is independent of the implementation of the new lamps, over the long term that gives a reasonable fit to the data.

The upshot of all the fitted models is that the effect of the new replacement white lamps on crime is small, with point estimates for a fully completed MSOA of only a few percent in the direction of having more crime, and with standard errors of a similar magnitude to that of the estimates. This is shown below. It should be noted that when models with less complex time-polynomials were run (which are naturally worse fitting) it was found that these models delivered larger estimates for having more crime with relighting, than the more complex ones that are given below. That is the estimates from the less complex ones were in the direction of more crime having occurred with new lamps.

It was found that it was not possible to get the models of interest to converge if the random lighting term went beyond quartic, that is the fourth power. The polynomial in time that was deemed suitable was of 6th degree with the first 4 terms random. The models included 'Extra Binomial' or 'Extra Poisson' variation appropriate for the ‘response’ of the model, in order to account for the overdispersed nature of the crime counts. (When a 7th power fixed time term was added to the logistic model that used the fraction of implementation completed, the estimate of its coefficient was seen to be not statistically significantly different from zero and neither was the drop in −2.log(Likelihood).

Models which use the fraction of new lamps installed, yield estimates for the virtually complete relighting conversion of a MSOA. (Virtually complete, because there could have been a few percent more lamps installed had the series run until the end of 2015). The method of estimating using the fraction of the number of new lamps installed at the end of each of the 107 time series is considered to be the best way, rather than the number of lamps installed, as the MSOAs vary in the size of their full complement of lamps. (Presumably the full number of lamps given to each MSOA had been deemed to be appropriate for good public safety.)

The aim of the analysis process was to fit the models with second order Penalised Quasi-Likelihood, PQL2. However, on occasion the fitting process would not converge and so a combination of first order and Marginal Quasi-Likelihood, MQL, had to be used instead to get the model fitted. When different Quasi-Likelihood methods could be used on the same model, the estimates tended to be very close.

In the following, a short hand is used to describe the models; for example, ‘T4R T6F’ means the 6th degree polynomial in time has up to and including the 4th power term as random effects and the final two terms, 5th and 6th powers, as fixed effects.

Estimates of the within MSOA coefficient, β_W, for the new white lamp effect using the fraction of the final complement of new lamps installed for various models are given below; Extra binomial logit for darkness to daylight crime ratio and Extra (i.e. overdispersed) Poisson (ODP) for crime counts.

Model #	Model	Within Estimate β_W	Within SE
1	Logit T4R T6F PQL2	0.02152	0.02530
2	Logit T4R T6F MQL1	0.02200	0.02493
3	Logit T4R T6F PQL2 No Offset	0.02045	0.02538
4	Logit T4R T7F PQL2 (T7F Not Stat. Sig.)	0.02119	0.02530
5	ODP Darkness T4R T6F MQL1	0.03400	0.02171
6	ODP Daylight T4R T6F MQL1	0.01862	0.01967
7	Darkness minus Daylight (5–6)	0.01538	0.02930*
8	AR1 Logit T4R T6F PQL2	0.02767	0.02516

*Assuming statistical independence, so given by the square root of the sum of squares of the individual SEs

Model #	Model	Within Estimate β_W	Within SE
9	ODP Sum of Darkness & Daylight T4R T6F PQL1	0.02723	0.01540

The estimates of the coefficient β_W of the within MSOA lighting term for all models are small so that when a model is returned from the log link scale by exponentiation to the unlogged state, these β_W numbers will give a very close approximation to the proportion by which crime will have increased for a unit implementation increase of new white lamps, since exp.(β_W) $= 1 + \beta_W$ approximately, for $|\beta_W| << 1$. Therefore, the coefficient β_W when multiplied by 100 is the percentage change in the crime measure for a change of one unit in the within area lighting measure. This for the measure using the fraction of the relighting completed means the estimate of the coefficient when multiplied by 100, simply gives the percentage change in the given crime measure from start to finish. For example, the percentage change in the daylight adjusted crime rate from start to finish of the relighting implementation.

Model 1 gives the daylight adjusted crime rate estimated using PQL2 and shows an approximate 2% increase in crime with a standard error of about the same size as the point estimate. This indicates a small worsening of crime as measured by the daylight adjusted crime rate, with the new lights, but this is not statistically significant. The Extra Binomial factor multiplying the standard binomial variance is given as 1.230. Model 2 is the estimate obtained for the same model using MQL1, indicating much the same as for the PQL2 estimate. The Extra Binomial factor multiplying the standard binomial variance is given in this case as 1.216. Model 3 shows that the estimate and its standard error remain much the same if the offset is not used on comparison with the estimates given by Models 1 and 2. The Extra Binomial factor multiplying the standard binomial variance is given as 1.249. Note that the binomial (logistic) models excluded the 1203 cases (2.5% of total number) for which there was no crime in a week in a MSOA, whereas all 48,792 (= 456×107) cases were used in the count models. Model 4 shows that if the polynomial is extended to a seventh power using a fixed effect coefficient, then the within area estimate is virtually the same as Model 1. The coefficient of the seventh power was not statistically significant. The Extra Binomial factor multiplying the standard binomial variance is given as 1.231.

Model 5 shows the result for the Extra (overdispersed) Poisson count model for crimes in darkness, that is when street lamps are on. This shows a 3% increase in crime with the new white lamps, but the result is not statistically significant. Note it was only possible to get convergence with MQL1 estimation. The overdispersion value was given as 1.784. Model 6 shows the result for the overdispersed Poisson count model for crimes in daylight, so the street lamps are off, and this again shows an undetectable change in crime with the new white lamps. Note again it was only possible to get convergence with MQL1 estimation. The overdispersion value was given as 1.572. Model 7 gives the difference of the coefficients of the darkness and daylight models (Model 5 – Model 6) with its combined standard error generated from the assumption of statistical independence. This differencing is another way of generating the daylight adjusted crime rate. (Note technically it gives the ratio of the estimates for the relighting effectiveness on darkness crime to that on daylight crime, rather than the estimate of the effectiveness on the ratio of the darkness to daylight crime as in Model 1 and the other Binomial logit models). It gives a small increase in crime 0.01538 with standard error 0.02930 similar, to 1 significant figure, to that in Model 1 of 0.02152 (0.02530). Therefore, there is reasonable agreement between the earlier logit results and the differencing approach.

Model 8 shows the result from an autoregressive lag1 model (AR1). This was run for exploratory purposes. It gives a slightly larger point estimate of the within MSOA lighting effect than its non-autoregressive counterpart, but it is still small and not statistically significant. The lagged term is statistically significant. The Extra Binomial factor multiplying the standard binomial variance is given as 1.232. Model 9 shows the result for the Extra (overdispersed) Poisson count model for the sum of crimes in daylight and darkness, that is round-the clock crime (all crime in 24 hours, where the lighting status for the crime is known). It again indicates no detectable change in crime due to new lights. The overdispersion value was given as 1.714.

Model 10 gives the result of the alternative of modelling the effect of the new white lamps using the number of new white lamps installed and operating in a given week, rather than the fraction of the implementation completed. The two lighting terms in the model were in units of one hundred lamps so the coefficients produced by the software would be of a convenenient magnitude, that is, one hundred times bigger than for a single lamp. Since there are around 700 lamps in a typical MSOA, multiplying the coefficient of the within MSOA lighting coefficient by 7 gives the estimate of a typical completed installation. The result is seen to be similar to those models on the fraction of the implementation completed, that is a small increase in the direction of more crime but far from statististical significance.

	Model	Within Estimate β_W	Within SE	X7 Estimate for full implementation	X7 SE for full implementation
10	Logit PQL2 T4R T6F	0.00238	0.00324	0.01666	0.02268

Examining the random effects in the above models shows that all of the variance estimates, in the variance-covariance matrix, are statistically significant, as are most of the covariance terms. It should be said that the estimates of the within MSOA lighting coefficients when estimated using the same model form but other than PQL2 were very similar to those when using PQL2. Also, Logit AR2 (Autoregressive with 2 lags) modelling was investigated by adding lag1 and lag2 terms. (An AR2 T4R T6F model would not converge at all. But an AR2 T3R T5F model would run but only as MQL1 (Model 12). The equivalent model but without the lagged terms is Model 11. However, as can be seen, the key coefficient β_W estimate from Model 12 was close to that produced by the simpler polynomial model without any autoregressive terms.

	Model	Within Estimate β_W	Within SE
11	Logit T3R T5F PQL2	0.05164	0.02352
12	Logit AR2 T3R T5F MQL1	0.05177	0.02319

Although the results for both these 5th degree models show a statistically significant result of worsening crime, it is considered that the slightly more complex 6th degree models, which return results which give somewhat smaller and therefore statistically non-significant within MSOA lighting coefficient estimates, are more valid.

It is important to recognise that adding each lagged variable gives a missing value for each of the 107 MSOAs at the initial time point, so the number of extant cases is progressively reduced as the number of lags increases.

Checking Results with Negative Binomial Models

Running models based on the Negative Binomial distribution, that were of the same form as for the overdispersed Poisson count, Models 5 and 6, was thought to be worthwhile. This is because the Negative Binomial distribution is a 'proper' distribution for counts with a defined form (See Forbes et al., 2011). It has a variance which is different from its mean (unlike the basic Poisson). The estimates for the within area lighting coefficient, $\beta_{W,}$ from the Darkness and Daylight models, and the difference taken (as above) are given here.

	Model	Within Estimate β_W	Within SE
13	Neg Bin Darkness T4R T6F MQL1	0.03055	0.02189
14	Neg Bin Daylight T4R T6F MQL1	0.01559	0.01989
15	Darkness minus Daylight (13–14)	0.01496	0.02958*

*Assuming statistical independence, so given by the square root of the sum of squares of the individual SEs

It is also possible in MLwiN to run Negative Binomial models which include extra dispersion, additional to the embodied overdispersion, so these were run too but the there was little requirement for the extra overdispersion. The results, which are very similar for those without extra overdispersion, are given here.

	Model	Within Estimate β_W	Within SE
16	ED Neg Bin Darkness T4R T6F MQL1	0.03042	0.02188
17	ED Neg Bin Daylight T4R T6F MQL1	0.01558	0.01989
18	Darkness minus Daylight (16–17)	0.01484	0.02957*

*Assuming statistical independence, so given by the square root of the sum of squares of the individual SEs

These Negative Binomial Model results are close to their Overdispersed Poisson equivalents, Models 5, 6, 7.

The Negative Binomial equivalent of the ODP Model 9, for the Sum of Darkness & Daylight PRC, was run.

Model #	Model	Within Estimate β_W	Within SE
19	Neg Bin Sum of Darkness & Daylight T4R T6F PQL1	0.02937	0.01593

The estimate of the within area lighting coefficient was found to be close to the ODP value from Model 9 of 002723 (0.01540).

All the estimates of the model parameters obtained from four binomial analyses on the daylight adjusted darkness PRC rate are given side by side in Table 4 so that comparisons can be easily made.

Table 4 All the estimates of some of the logistic binomial models for the daylight adjusted darkness PRC weekly rate. (the standard errors of the coefficients of the first model are also shown)

	Model 1		No Offset Model 3	Lag1 Model 8	100 Lamps Model 10
	Estimate	S.E.	Estimate	Estimate	Estimate
Intercept (Random)	0.22487	0.02821	0.72399	0.11187	0.22497
February	−0.07391	0.01664	−0.33890	−0.06360	−0.07394
March	−0.13270	0.01663	−0.74769	−0.10544	−0.13277
April	−0.19185	0.01826	−1.18789	−0.14647	−0.19192
May	−0.12814	0.01877	−1.51880	−0.07001	−0.12816
June	−0.10264	0.01801	−1.68716	−0.03697	−0.10268
July	−0.07935	0.01767	−1.56296	−0.01572	−0.07943
August	−0.06640	0.01739	−1.21280	−0.01503	−0.06648
September	−0.12917	0.01697	−0.89167	−0.08929	−0.12924
October	−0.08086	0.01690	−0.47791	−0.05346	−0.08090
November	0.13194	0.01715	0.04774	0.13714	0.13193
December	0.06871	0.01876	0.15878	0.06591	0.06873
New Year Week	0.43339	0.03142	0.49223	0.42088	0.43339
Good Friday Week	0.06380	0.02630	0.08153	0.06060	0.06380
Easter Week	0.09911	0.02606	0.06257	0.10011	0.09907
May Day Week	−0.00608	0.02872	0.12083	−0.01481	−0.00615
Spring Bank Holiday Week	0.19960	0.02715	0.17515	0.19393	0.19958
Summer Bank Holiday Week	0.06723	0.02546	0.08053	0.06703	0.06721
Christmas Week	0.18622	0.03360	0.21241	0.18433	0.18618
Within Area Lamp	**0.02154**	**0.02530**	**0.02045**	**0.02767**	**0.00238**
Between Area Lamp	0.45856	0.17505	0.46003	0.46623	0.01132
Offset	1.00000			1.00000	1.00000
Time in units of 10 years R	0.04766	0.10435	0.04480	0.02107	0.05807
(Time in units of 10 yrs)^2 R	0.94940	0.53915	1.31718	1.01950	0.93334
(Time in units of 10 yrs)^3 R	−4.16168	1.32127	−4.29595	−3.72052	−4.20922
(Time in units of 10 yrs)^4 R	−26.81044	6.93924	−32.25577	−27.06963	−26.81168
(Time in units of 10 yrs)^5 F	14.72583	5.84062	15.56760	13.04934	14.79029
(Time in units of 10 yrs)^6 F	99.64448	25.80020	118.83663	99.96617	100.10003
Lag1				0.16319	

R = Random F = Fixed

The key point to note from Table 4 is that all the estimates for the within MSOA lighting effect are broadly comparable, including the model based on the number of lamps rather than on the fraction of relighting completed, when multiplied by 7 (for the typical MSOA) as $7 \times 0.00238 = 0.01666$.

When the offset is removed (Model 3) the magnitudes of the values of the Month coefficients are much larger. This is because in this case the Month is doing the 'extra work' of the absent offset in accounting for the changing amount of daylight and darkness available for criminality. The Public Holiday week coefficients and those of the polynomial terms are broadly comparable between the models in the table. (Mayday week does seem somewhat different, however). The coefficient estimates of the AR1 model (Model 8) are comparable to those of Model 1 as are those of Model 10 which uses the number of lamps rather than the fraction of the implementation completed, apart from the expected reduction in the within area coefficient. The latter is brought in to line (0.01666) when scaled by 7 for a typical MSOA's full complement of lamps, as stated above. Note, standard errors are only shown for the first model as those of the other models are of similar size, with the exception of those of the lighting terms for Model 10 (which uses the unit of 100 lamps).

The overall result is found to be that the effect on crime of relighting the city, with 78,189 new white lamps over the time period, is undetectable and very little at most. The analysis suggests there was about a 2% worsening of daylight adjusted darkness crime for the point-estimate within a confidence interval of around (−3% to +7%). These figures are from the point estimate of the daylight adjusted Crime Rate Ratio (CRR) of 1.022 and CI (0.972 to 1.074).

The unadjusted darkness crime (Model 5) showed a rise was about 1% larger than the daylight adjusted value. That is the unadjusted darkness crime point estimate showed a rise of about 3% within a confidence interval of around (−1% to +8%) from its CRR point estimate of 1.034 and CI (0.991 to 1.080).

The sum of darkness and daylight crime rose by around 3% within a confidence interval of roughly (0% to 6%) from its CRR point estimate of 1.028, and CI (0.997 to 1.059) of Model 9.

The data where the lighting status was unknown was not used in the analysis as there was a long tail to the distribution of the temporal gap between the earliest possible occurrence and the latest possible occurrence of the crime being reported, For example there were 24,194 crimes where the gap between the earliest possible occurrence and the latest possible occurrence was more than one week (and 16,332 crimes where it was more than two weeks). This uncertainty of when the crime occurred means that it is not possible to ascribe the week in which the crime occurred accurately.

As mentioned earlier there was some concern that including the city centre MSOA might be causing problems because of its much higher level of crime and therefore giving a questionable measure of the effect of lighting on crime, and it also might be a cause of modelling stability problems. However, this does not appear to be the case, because when doing analysis excluding the city centre, the estimates were similar to those with it included and still there were issues of stability. (As noted above, the other parts of the city combined do have an order of magnitude more crime than the city centre.) Another anomaly considered was MSOA005, as the time series of crimes was spikey, possibly suggesting recording errors. An analysis was run that excluded this MSOA giving a result for the lighting effect that was much the same as with it included. It is to be noted that the mean weekly crime rates (darkness, daylight, and don't know) of this area are below or around the lower quartile of the 107 MSOA-means. Therefore, because the contribution to the study of this MSOA was small, the data was kept in the analysis. Therefore, all the official PRC data was used, apart from the modest reduction due to the data-cleaning.

Instead of having an offset as Model 1 or no offset as Model 3, having the offset entered into the model as a covariate was tried. This gave a very similar result to the other two, for the within area coefficient, 0.02166 (0.02530). The estimate of the coefficient for the 'offset' entered as a covariate was 1.098, very close to 1 which is the imposed coefficient of an offset.

Further exploratory work was done following a conversation with a member of the Centre for Multilevel Modelling, hosted at the University of Bristol, after describing the difficulties of getting convergence with the Extra Binomial and Extra (overdispersed) Poisson models. The suggestion was to try putting in a Gaussian framework. Therefore, a variety of additional models based on counts were run. These included having all terms of the 6th degree time polynomial made random and including a series of high order lags, up to lag 6. No convergence problems were encountered in fitting them. Although of course such models are not properly appropriate for the data in the present case, all the estimates of the within area lighting coefficients β_W were again small. This indicated that the new white lighting had had little effect on crime, just the same as the more formally correct Extra Binomial, Extra (overdispersed) Poisson, and Negative Binomial models (1–19) above.

The absence of a major effect on crime from relighting the city by having the nearly 80 thousand new white lamps was contrary to part of the rationale for spending the money to have them installed by the city council.

Discussion

This present study on the relighting of Leeds shares some similarities with the large scale study funded by the UK's NIHR, National Institute of Health and Care Research, https://fundingawards.nihr.ac.uk/award/11/3004/02#/. The results were published as Steinbach et al. (2015) and Perkins et al. (2015). Similarities and differences between the two studies are given in Table 5.

The results between the two studies are consistent. This is because from the Leeds study we see that the round-the-clock measure (the sum of darkness and daylight crime) rose by around 3% for its point estimate, within a confidence interval of approximately (0%, 6%) while the NIHR LANTERNS confidence interval for white light was (−23%, 3%). Reverting to the natural log scale, on which both analyses were carried out, it is possible to evaluate the z-statistic for a test of difference of means. and calculate $z = 1.89$, $p = 6\%$ so the difference of means is not statistically significantly different from zero. It is to be noted that the confidence interval for the Leeds result is considerably narrower than that of the NIHR LANTERNS

Table 5 Comparison of the NIHR-funded LANTERNS and the Leeds studies

LANTERNS	Leeds
Uses only 4 types of crime recorded by police, (Police Recorded Crime, PRCs): burglary, vehicle crime, robbery, and violence. It uses data from multiple local authorities.	Uses all crime recorded by police, Police Recorded Crime (PRCs), in the City of Leeds.
Uses 1,855,244 PRCs. Whether it was daylight or darkness when crime was committed is unknown, so only the round-the-clock crime (24 hr) count was used. It could not produce estimates for the daylight adjusted crime rate, nor the darkness only crime rate.	Used 471,374 PRCs. Daylight or darkness at the time of the crime is known. Therefore, it produced estimates for the impact of the relighting on the daylight adjusted crime rate, also the darkness only crime rate and the round-the-clock crime rate.
Uses 3 years of data, in months, Dec 2010 to Dec 2013.	Uses nearly 9 years of data, in weeks, 03 Jan 2005 to 29 Sep 2013.
Uses Overdispersed Poisson modelling.	Uses Overdispersed Poisson and Extra Binomial modelling and also Negative Binomial modelling.
Uses monthly crime counts. Months have different lengths and so different activity patterns as these will have a different number of weekends included. It includes month indicator variables for seasonality.	Uses weekly crime counts, so more subtle variation can be modelled. Weeks have the same length with the same weekday/weekend pattern. It includes month indicator variables for seasonality.
Uses 36 month indicator variables for the time trend.	Uses a smooth polynomial secular time trend.
Does not appear to allow for local variation within areas.	Multilevel approach allows individual MSOA variation.
Does not have open data despite being collected through the publicly funded NIHR.	Has open data and so allows reproducibility checks on the results.

result. It is disappointing that the data used in the NIHR LANTERNS study is not made available, despite being requested, which means that further analysis cannot be performed by others, using for example a multilevel approach. The Leeds result is different from that of Chalfin et al. and that of the work involving Welsh and Farrington with the exception of the latter's most recent work which does not detect an impact of lighting on night-time only crime.

This Leeds crime and lighting study gives a null result, like that for the study of road traffic collisions and lighting, Marchant and Norman (2022). That is no safety benefit from relighting could be detected in both cases.

Directions for Further Work

In the future, as well as getting more precise estimates of the effect of lighting on all crime, it would also be of interest to investigate the effect of lighting on different crime types. This could in principle be achieved by extending the models used here to multivariate outcome equivalents of those described in this report. The multivariate outcome-set would consist of those crime types given in data files obtained from the police. It would require considerable computation to estimate all the additional parameters in such a model. It would also require more data than ours to obtain good estimates of the different crime types.

It is unfortunate that the large data set from the NIHR-funded study, resulting in Steinbach 2015, is not made available. This large data would seem to be suitable for applying multivariate outcome, multilevel modelling, as from that paper it can be seen there were over 2 million offences committed, just concerning property and violent crime in the period Dec. 2010 to Dec. 2013.

Conclusion

The conclusion of the study is that changes to the level of crime, positive or negative, could not be detected following relighting down at the level of just a few percent. This null result was despite the large dataset, 471,374 crimes and 78,189 replacement white lamp installations, that essentially comprised the complete relighting of the whole city of Leeds. The null result is consistent with that from another large longitudinal study, funded by the UK's NIHR, National Institute of Health and Care Research.

One can say that the Leeds study suggests the following range of impacts for comprehensive relighting.

1) The daylight adjusted darkness crime rate, that is the ratio of the darkness to daylight crime rate, going from before the relighting to after, showed a 2% increase in crime for its point estimate within a 95% confidence interval of (−3% to +7%).
2) The unadjusted darkness crime point estimate showed an increase in crime of around 3% within a 95% confidence interval of (−1% to +8%).
3) The round-the-clock measure of crime (the sum of darkness and daylight crime) rose by around 3% within a 95% confidence interval of (0% to +6%).

That is the crime reduction anticipated using the evidence adduced in the Leeds City Council's bid to government for relighting was not found.

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Author Contributions PM conceived the study, carried out the modelling and produced the first draft of the manustrict. PN helped with data preparation, to discussions of the modelling strategy and edited the manuscript.

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Declarations

Competing interests PM has concerns about light pollution affecting astronomical observations and biodiversity, so has been motivated to examine the claims of benefit for increased public lighting. He has previously published work critical of claims of substantial public safety benefit from increasing lighting. PN has concerns that public money may be being wasted on schemes that have no proof they are achieving what they are supposed to.

Disclaimer The manuscript has been written paying attention to STROBE guidelines for cohort studies, see www.equator-network.org, where the MSOAs constitute the inanimate cohort. We affirm that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned have been explained.

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