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The effect of ambient light condition on road traffic collisions involving pedestrians on pedestrian crossings

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ABSTRACT

Previous research suggests darkness increases the risk of a collision involving a pedestrian and the severity of any injury suffered. Pedestrian crossings are intended to make it safer to cross the road, but it is not clear whether they are effective at doing this after-dark, compared with during daylight. Biannual clock changes resulting from transitions to and from daylight saving time were used to compare RTCs in the UK during daylight and darkness but at the same time of day, thus controlling for potential influences on RTC numbers not related to the ambient light condition. Odds ratios and regression discontinuity analysis suggested there was a significantly greater risk of a pedestrian RTC at a crossing after-dark than during daylight. Results also suggested the risk of an RTC after-dark was greater at a pedestrian crossing than at a location at least 50 m away from a crossing. Whilst these results show the increased danger to pedestrians using a designated crossing after-dark, this increased risk is not due to a lack of lighting at these locations as 98% of RTCs at pedestrian crossings after-dark were lit by road lighting. This raises questions about the adequacy and effectiveness of the lighting used at pedestrian crossings.

1. Introduction

Road traffic incidents account for 1.25 million deaths across the world each year, making them one of the leading global causes of death (World Health Organisation, 2015). Road safety is a key priority for the UK Government, due not only to the public health implications of the injuries and deaths caused but also because of the economic costs of road traffic collisions, which is estimated to be in excess of £16.3 billion per year (Department for Transport, 2015a). Vulnerable road users, which includes pedestrians, cyclists, motorcyclists and horse riders, have much higher casualty and fatality rates relative to the distances travelled, compared with other road users. For example, in 2014 in the UK there were 2108 pedestrian casualties and 36 pedestrian fatalities per billion miles travelled, compared with 273 casualties and 2 fatalities per billion miles travelled by car users (Department for Transport, 2016a). The perceived danger on roads can discourage walking and act as a barrier to active travel (Jacobsen et al., 2009), particularly for children (Lorenc et al., 2008). Reducing pedestrian casualties on the road is therefore both a direct and indirect benefit to public health.

There is a range of evidence that suggests road traffic collisions (RTCs) are more likely to occur after-dark than during daylight, and more likely to lead to a severe or fatal injury if they occur after-dark. This includes RTCs that involve a pedestrian. For example, Jensen (1998) analysed Danish pedestrian casualty data from police-recorded incidents between 1993 and 1995, and found that walking one km in darkness was 2.7 times more dangerous than in daylight in urban areas, and 7.4 times more dangerous in rural areas. Pedestrian injury records from Florida in the US between 1986 and 2003 also suggested that the odds of a fatal injury reduced by 75% at midblock locations and 83% at intersections during daylight, compared with darkness and no road lighting (Siddiqui et al., 2006). Other data has also shown that conditions of darkness are more likely to lead to severe or fatal injury compared with daylight (Tay et al., 2011; Mohamed et al., 2013; Wang et al., 2013). It is also likely that conditions tending towards darkness, not just darkness itself, can lead to increased risk of an RTC. For example, daylight running lights (DRLs) can reduce the risk of daytime RTCs (Elvik, 1996). They were introduced and have been legally required in Scandinavian countries for decades, as these North European countries receive longer periods of twilight and generally lower levels of ambient light than other countries. Such conditions can lead to increased benefit of using DRLs, compared with countries at lower latitudes (Koornstra et al., 1997). Further evidence of the impact transitions to darkness can have on RTCs is provided by the regular debate over the safety impacts of biannual transitions to and from daylight saving time. One-hour changes to clock times in Spring and Autumn can lead to abrupt changes in ambient light conditions, particularly around morning and evening rush hour times, and this has been associated with increases in RTCs (e.g. Broughton et al., 1999).

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Table 1
Key features of different types of pedestrian crossing in the UK.

Feature	Type of crossing				
	Zebra	Pelican	Puffin	Toucan/ Pegasus	Traffic signal pedestrian phase
Road surface marking	✓	x	x	x	x
Pedestrian-controlled traffic signal	x	✓	✓	✓	x
Pedestrian sensor	x	x	✓	✓	✓
Provisions for non-pedestrian road-users	x	x	x	✓	✓
Traffic signal junction	x	x	x	x	✓

According to UK data, 77% of road collisions that kill or seriously injure a pedestrian occur when the pedestrian is crossing the road (Department for Transport, 2015b). Designated road crossing locations (referred to here as pedestrian crossings, but also known as crosswalks) are a design feature of transport infrastructure in most developed countries that aims to reduce the frequency of pedestrian collisions. These aim to enhance safety by alerting the driver to the presence of a pedestrian crossing and making the pedestrian more visible to allow corrective action to be taken, using a combination of road surface markings and supplementary lighting. In the UK there are four main types of pedestrian crossing, and their key features are highlighted in Table 1. Example photographs of a typical puffin crossing during daylight and after-dark are shown in Fig. 1.

Table 2 shows past studies of pedestrian risk of accident when using road crossings. There are three limitations evident from this overview of past literature. First, findings are mixed about the effect of designated crossing facilities on the risk to pedestrians – some studies (e.g. Keall, 1995; AA Foundation, 1994; Ghee et al., 1998; Al-Ghamdi, 2002) suggest crossings have a beneficial effect on pedestrian road safety, whilst others (e.g. Zegeer et al., 2005, see Table 3; Koepsell et al., 2002; Tay et al., 2011) suggest there is no effect or even a negative effect. Second, not all studies adequately control for exposure to risk, for example by accounting for the number of crossings made by pedestrians or the traffic volumes. Such data about risk exposure is difficult to obtain, and most studies that do include measures of exposure base these on estimates from a sample time period or sample of survey respondents (e.g. Koepsell et al., 2002; Zegeer et al., 2005; Keall, 1995). Third, most studies examining collisions at pedestrian crossings can say little about whether the apparent increase in risk to pedestrians during hours of darkness applies to pedestrians using designated crossings, and whether the risk after-dark is reduced at crossing locations. This is relevant not only to the design of pedestrian crossings, but also to how they are lit.

One of the purposes of a pedestrian crossing is to make the presence of a pedestrian and the likelihood of them crossing the road more conspicuous to the driver. This requires not only alerting the driver to the fact they are approaching a designated crossing, but also making any pedestrian stood at or on the crossing visible to the driver. Supplementary road lighting is widely used to increase the visibility and conspicuity of the crossing and anything on it. Local design guides specify how a crossing should be lit, for example ILP TR12:2012 (Institute of Lighting Professionals, 2012) in the UK, AS/NZS 1158.4:2015 (Standards New Zealand, 2015) in Australasia, and IESNA RP-8:2014 (IESNA, 2014) in North America. These guides do not agree however on the type and amount of light that should be used; the UK guide for example specifies ratios for horizontal and vertical illuminances (e.g. minimum horizontal illuminance on the crossing surface is 3.5 times that of the road surface illuminance), whereas the Australasian guide suggests horizontal illuminances of 16 lx for local roads and 32 lx for arterial roads. The guidance for North America instead suggests vertical illuminances of 10 lx and 2 lx for areas of high and medium pedestrian conflict. This variation in the recommendations of different guidance documents indicates a lack of consensus on what is good lighting for pedestrian crossings. A first step in resolving this lack of consensus is understanding what impact ambient light conditions have on the risk of an RTC involving a pedestrian.

Previous research on this topic is limited (see Table 3). Zegeer et al. (2005) found little difference in the proportion of crashes occurring in darkness rather than daylight at marked compared with unmarked crossings. These proportions do not reveal anything about the risk after-dark however, as although crash frequency was compared against pedestrian volumes, these volumes were derived from sample hours that were not systematically recorded during both daylight and after-dark conditions. Olszewski (2015) found that the probability of being killed on a zebra crossing in Poland was increased by 1.95 when it was dark with road lighting on, and by 4.08 when it was dark with no road lighting. Although this data appears to show an increased risk after-dark at pedestrian crossings it does not take account of exposure rates, and it may be that the relative number of pedestrians crossing the road at a designated crossing rather than another location increases after-dark. There may also be a range of confounding variables that are associated with darkness and an increased RTC risk, and these limit what we can conclude about the impact of darkness on pedestrian injuries and RTCs based on past research. For example, reduced traffic volumes after-dark lead to increased vehicle speeds (Department for Transport, 2016b), and these are likely to increase the risk of a collision and the severity of injury to a pedestrian (Elvik et al., 2004; Rosén and Sander, 2009; Tefft, 2013). Drivers are also more likely to be intoxicated when driving after-dark, and may also feel more sleepy and drowsy due to effects of circadian rhythm, increasing the risk of their involvement in an RTC (Summala and Mikkola, 1994). Furthermore, as hours of darkness are associated with colder temperatures and wetter weather (both from a daily and a seasonal perspective), the road conditions may be more likely to lead to an RTC than they would during daylight hours. Darkness may also be associated with differences in pedestrian behaviour compared with daylight, for example pedestrians may be more likely to be intoxicated. This is largely due to the association between

Fig. 1. Example images of a puffin crossing during daylight (left) and after-dark (right).

Table 2
Studies of pedestrian risk of accident at pedestrian crossings that do not compare day and after-dark conditions.

Study	Type of data	Control for confounds	Finding
Keall (1995)	New Zealand records of road injury accidents, 1988–91, and pedestrian exposure rates from New Zealand Travel Survey 1989–90.	Exposure for pedestrian volumes derived from survey of 8719 people.	Risk of injury to a pedestrian when crossing at a zebra crossing was significantly less than the risk when crossing at some other location on the road.
AA Foundation (1994)	Pedestrian casualty data (782 records) reported to police 1988–93, in Northampton, UK. Compared against estimates of pedestrian volumes.	Exposure for pedestrian volumes derived from 419 household surveys.	Risk of crossing the road is halved when pelican crossing used compared with no facility or a dropped kerb, but only on primary and district roads. Risk at a crossing is higher than at locations with no facility on local distributor roads.
Ghee et al. (1998)	Pedestrian crossing events (32,000 recorded) at 9 sites across the UK, with vehicle-pedestrian interactions identified within these.	Total count of pedestrians during period of measurement, but only at selective sites, and no account of vehicle traffic volumes.	Sites with pedestrian crossing facility had lower risk of an interaction or conflict between pedestrian or vehicle, compared with sites that did not have a crossing facility.
Al-Ghamdi (2002)	Pedestrian-vehicle collisions (683 records) reported by police in Riyadh, Saudi Arabia, between 1997 and 99.	No account for pedestrian or vehicle traffic exposure.	Most pedestrians (77%) were likely to have been struck whilst crossing the road either not in a crosswalk, or at a location where a crosswalk did not exist.
Koepsell et al. (2002)	Environmental, traffic and usage data from locations where pedestrian aged 65+ years had been struck by vehicle (282 case sites with crosswalk markings, 564 control sites with no markings).	Exposure estimated from 30-min count of pedestrians and 10-min count of vehicles at each site.	After adjusting for pedestrian flow, vehicle flow, crossing length and signalisation, risk of pedestrian-vehicle collision was 2.1 times greater at sites with marked crosswalk. This effect largely caused by increased risk at marked crosswalks with no traffic signal or stop sign.
Tay et al. (2011)	All traffic collisions (45,201 records) involving a pedestrian in South Korea in 2006. Examined significance of contributory factors, including whether at crossing or not.	No account for pedestrian or vehicle exposure.	Pedestrians hit whilst on a crossing were significantly more likely to be killed or seriously injured compared with pedestrians hit on the sidewalk.

Table 3
Studies of pedestrian risk of accident at pedestrian crossings that include comparison of day and after-dark conditions.

Study	Type of data	Control for confounds	Finding
Zegeer et al. (2005)	Pedestrian crash data from 2000 locations in the US (1000 crosswalk locations, 1000 unmarked control locations), 1994–98. Compared against estimates of pedestrian volumes.	Exposure estimated from 1-h count of pedestrian volume at each locations. No account for vehicle volumes.	Presence of a marked crosswalk not associated with difference in pedestrian crash rate compared to unmarked location, on two-lane roads. On multilane roads with traffic volumes > 12,000 vehicles per day, marked crosswalk associated with higher pedestrian crash rate. Raised medians associated with lower pedestrian crash rates on multilane roads. Older pedestrians had relatively high crash rates, compared with crossing exposure.
Olszewski et al. (2015)	Traffic collisions (18,850 records) involving a pedestrian at an unsignalised crosswalk in Poland, between 2007 and 12. Range of contributory factors examined, including lighting conditions.	No account for pedestrian or vehicle exposure.	The following factors were associated with increased risk of pedestrian death at an unsignalised zebra crosswalk: darkness, divided road, two-way road, non-built-up area, mid-block crosswalk and summer time period.

darkness and a later time of the day however, rather than the light condition itself.

One approach to control for exposure rates and other confounding factors is to compare RTCs at the same time of day but under different lighting conditions (daylight and after-dark). Travel behaviour is habitual (Gärling and Axhausen, 2003; Aarts et al., 1998) and therefore the time of travel is likely to be consistent on a day-to-day basis. The strengths of such habits may outweigh any potential changes in travel behaviour resulting from changes to the light conditions (e.g. Ouellette and Wood, 1998). Commuting travel in particular represents archetypal habitual behaviour that occurs frequently at the same time of day throughout the year (Aarts et al., 1998).

One approach to comparing different light conditions at the same time of day was used by Johansson et al. (2009), to compare road traffic collisions after-dark and during daylight. This method involves defining a case hour which is in darkness for part of the year and daylight for the other part of the year. The frequency of collisions in this case hour when it is dark are compared against the frequency when it is daylight, and this relative difference is compared against frequencies in the same periods of the year but during an hour when the light condition remains the same throughout the year. Johansson et al. (2009) found that the risk of a collision involving an injury increased by around 40% in darkness compared with daylight, for urban and rural areas combined.

An alternative approach to comparing different light conditions at the same time of day is to use the biannual clock changes that occur at the beginning and end of daylight saving time in many countries. Clocks are advanced one hour on a certain date in Spring and moved back one hour on a certain date in Autumn. These clock changes result in an abrupt change in ambient light conditions during the same time period before and after the change. Before the clock change in Spring, for example, the hour after sunset will be in twilight tending towards darkness. The same hour after the clock change will be in daylight, due to the clocks being advanced by an hour. This daylight savings clock change method has been used by Sullivan and Flannagan (2002) to investigate the effect of darkness on RTCs, in order to compare the likely effectiveness of adaptive headlamps in different driving situations. They showed that the risk of pedestrians being involved in a fatal crash was significantly greater in darkness than daytime, in some situations being up to seven times as risky. In the current article we extend this method to examine the effect of darkness on the risk of pedestrians being involved in an RTC on a pedestrian crossing. We examined RTCs that involved a pedestrian casualty across 11 years from the UK STATS19 database, focusing on those RTCs that occur at a pedestrian crossing. Biannual clock changes were used to compare daylight and after-dark conditions for the same one-hour period, and compared against control periods in which the ambient light condition did not change. Variables that may contribute to the RTC were also assessed to determine whether they were associated with an increase or decrease in risk at pedestrian crossings as a result of a change in light conditions.

2. Method

The impact of darkness on RTCs involving a pedestrian on a pedestrian crossing was investigated by recording the frequencies of RTCs in a case hour before and after a daylight saving clock change. The ambient light conditions during this hour were darkness one side of the clock change and daylight the other side, due to the one hour shift in local time on the day of the clock change (see Fig. 2). The relative change in frequencies were compared against changes in frequencies over the same period but during control hours in which the ambient light condition did not change either side of the clock change. The purpose of including these control hours is to account for changes in RTC rates following a clock change, potentially caused by changes in pedestrian exposure or vehicle travel, that are not related to the ambient light conditions. For example, if one side of the clock change falls on a school holiday period but the other side does not, this could affect pedestrian frequencies and vehicle travel. This would potentially have a confounding effect, but the effect is anticipated to influence RTC frequencies in both control and case hours equally and would therefore be controlled for.

The STATS19 database records all personal injury accidents that are reported to the police in the UK, and is openly accessible via the UK Government website (https://data.gov.uk/dataset/road-accidents-safety-data). Between 2005 and 2015 there were 1.78 million RTCs recorded in the STATS19 database. These records were filtered to only include RTCs that involved a pedestrian casualty, resulting in 289,923 separate incidents. A subset of records were extracted from these for the 13-day periods before and after each of the 22 Daylight Saving Time transitions that occurred between 2005 and 2015. A further selection of data was made by screening only for RTCs that occurred within two control hour periods (14:00–14:59 and 21:00–21:59) and within a case hour period.

The control periods provided consistent ambient light conditions both before and after each clock change, with it always being daylight between 14:00 and 14:59, and always being dark between 21:00 and 21:59. The case hour period was defined as the hour immediately preceding the time of sunset on the day of the Spring clock change, and the hour immediately after the time of sunset on the day of the Autumn clock change. This definition of the case hour gave the clearest difference in ambient light conditions before and after the clock change. In Spring, the case hour changes from darkness before the clock change to daylight after the clock change, with this order reversed in Autumn. It is important to note that whilst this definition of the case hour provides the clearest difference between light conditions before and after the clock change, the transition between daylight and darkness (and vice versa) is not immediate. Immediately following sunset the period of civil twilight is entered into, and illuminance levels progressively reduce towards their lowest point within the diurnal cycle. However, there is a discernible and obvious difference in illuminance levels during the case hour before and after a clock change, and for simplicity

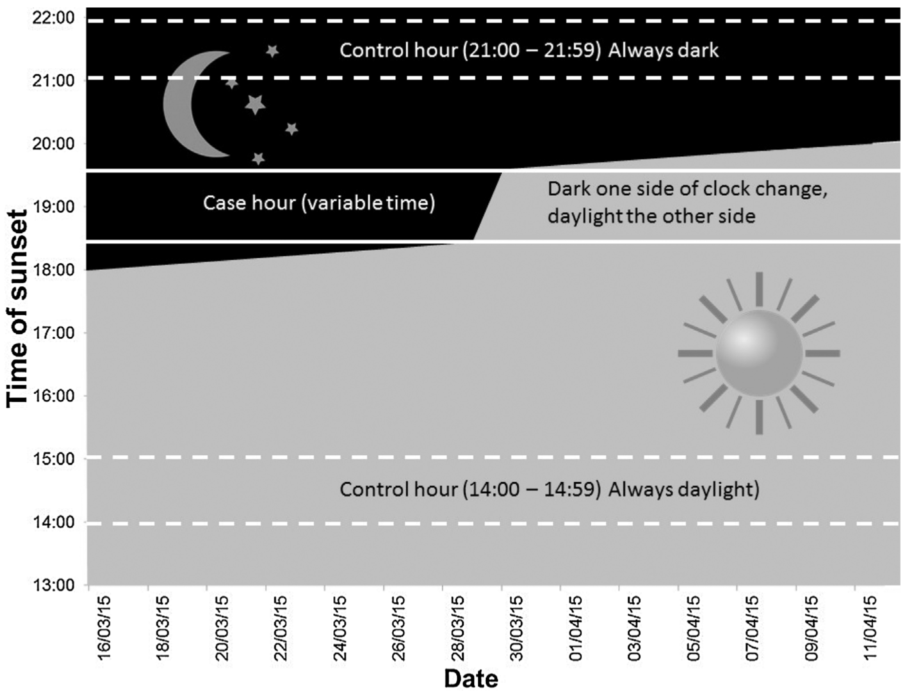

Fig. 2. Illustration of daylight saving clock change method to compare daylight versus after-dark RTCs. Spring clock change is shown, sunset times based on location in Sheffield, UK, in 2015.

we refer to this difference as the difference between daylight and after-dark.

The RTCs occurred across all regions of the UK, with a range in latitudes between +49.9° and +60.2° and longitudes between −6.3° and +1.8°. The time of sunset therefore varied not only with the date of the clock change but also the location of the RTC. This resulted in a range of sunset times between 18:14 and 19:02 (GMT) during the Spring clock change and between 16:10 and 17:11 (GMT) during the Autumn clock change. The variation within the same season is a result of the range of different latitudes and longitudes of the RTC locations. A Python script using the Astral module v1.3.1 (Kennedy, 2016) was used to calculate the time of sunset at each RTC location on the date of the clock change and hence to extract those RTCs that were within the case hour. A total of 3488 RTCs were extracted in the case hour, 2515 for the daylight control hour and 1250 for the after-dark control hour, giving a total of 7253 RTCs that were included in the set of data used for analysis.

The effect of darkness on RTCs at pedestrian crossings, and the influence of contributory variables such as the age of the driver and the road speed limit, were examined by calculating odds ratios (ORs). ORs represent the probability that an outcome (e.g. a collision involving a pedestrian) will occur given a particular exposure (e.g. during darkness), compared to the odds of the outcome occurring in the absence of that exposure (e.g. during daylight) – see Szumilas (2010). In specific terms for the analysis reported in this paper, these ORs compare the probability of an RTC occurring after-dark relative to daylight against the probability of a similar change over the same time period, but when the light condition remains constant.

ORs were calculated in this manner for RTCs involving a pedestrian casualty at zebra, pelican (including toucan, puffin and pegasus crossings), and traffic signal crossings, and also for RTCs that were not within 50 m of a designated crossing, as defined in the STATS19 database. Eq. (1), using the terms for the overall effect of darkness vs daylight (see row 1 in Table 4), was used to calculate these ORs based on a similar method used by Johansson et al. (2009). The method for calculating the 95% confidence intervals associated with the odds ratios is given in Eq. (2).

$$\left(\frac{A}{B}\right)/\left(\frac{C}{D}\right) \tag{1}$$

$$\exp\left(\ln(\boldsymbol{Odds\ Ratio}) \pm 1.96 \times \sqrt{\frac{1}{\boldsymbol{A}} + \frac{1}{\boldsymbol{B}} + \frac{1}{\boldsymbol{C}} + \frac{1}{\boldsymbol{D}}}\right) \tag{2}$$

3. Results

3.1. Overall effect of ambient darkness

The frequency of RTCs involving pedestrians in daylight and after-dark conditions during the case hour two control hours are shown in Table 5. These frequencies are used to calculate the ORs of a RTC occurring after-dark compared with daylight conditions (Table 6), using Eq. (1). These are presented in Fig. 3, along with the lower and upper confidence intervals. The ORs for all location types are significantly above 1, suggesting the risk of a pedestrian RTC was greater during after-dark conditions than during daylight.

There is also a suggestion in Fig. 3 that the after-dark risk may be greater at crossing locations than at locations that do not have a pedestrian crossing, as the ORs are generally greater. To assess this further, the OR of a pedestrian collision occurring at a crossing after-dark compared with at a non-crossing location after-dark has been calculated and presented in Fig. 4. These ORs have been calculated using Eq. (1) with the terms for comparing the after-dark effect at crossings and at other locations (see row 2 in Table 4).

The OR for all crossing types combined was significantly above one ($OR = 1.23$, $p < 0.01$, $CI = 1.05–1.43$). The OR for pelican crossings on their own was also significantly above one ($OR = 1.25$, $p = 0.046$, 95% $CI = 1.00–1.56$. Although the ORs for zebra crossings and traffic signal crossings were also above one, they did not reach significance (zebra crossings: $OR = 1.29$, $p = 0.074$, 95% $CI = 0.97–1.71$; traffic signal crossings: $OR = 1.16$, $p = 0.201$, 95% $CI = 0.92–1.45$).

3.2. Road lighting

Data about whether the RTC location had road lighting or not was used to further investigate the impact of light conditions on pedestrian RTCs at crossings. For RTCs occurring during darkness, STATS19 records whether road lighting was lit or unlit, or whether road lighting was absent entirely at the location of the incident. This information is

Table 4
Description of Eq. (1) terms for calculating ORs to show effects of (1) darkness vs daylight, (2) crossings vs other locations, (3) road lighting vs no road lighting and (4) contributory variable vs reference variable.

	Effect measured by the OR	Terms of equation			
		A	B	C	D
1	Overall effect of darkness vs daylight	RTCs during case hour in darkness	RTCs during case hour in daylight	RTCs during control hours when case hour in darkness	RTCs during control hours when case hour in daylight
2	After-dark effect at crossings vs after-dark effect at other locations	RTCs at crossings during case hour in darkness	RTCs at crossings during case hour in daylight	RTCs not at crossings, during case hour in darkness	RTCs not at crossings, during case hour in daylight
3	Effect of lack of road lighting at crossings vs lack of road lighting at other locations	RTCs at crossings during case hour in darkness, road lighting absent/unlit	RTCs at crossings during case hour in darkness, road lighting lit	RTCs not at crossings during case hour in darkness, road lighting absent/unlit	RTCs not at crossings during case hour in darkness, road lighting lit
4	Effect of contributory variable vs reference variable	RTCs at crossings during case hour in darkness, for contributory variable	RTCs at crossings during case hour in daylight, for contributory variable	RTCs at crossings during case hour in darkness, for reference variable	RTCs at crossings during case hour in daylight, for reference variable

only relevant for RTCs that occurred after-dark, and therefore a subset of data that included only the case hour under darkness was analysed. ORs were calculated for the three types of crossings, and all crossing types combined, comparing the probability of a pedestrian RTC at a crossing under lit versus unlit conditions against the probability at non-crossing locations. These were calculated using Eq. (1) with the terms for estimating the effect of lack of road lighting at crossings compared with other locations (see row 3 in Table 4).

The calculated ORs were 0.25 ($p = 0.004$, 95% CI = 0.09–0.69) for zebra crossings, 0.24 ($p < 0.001$, 95% CI = 0.10–0.54) for pelican crossings, and 0.17 ($p < 0.001$, 95% CI = 0.06–0.47) for traffic signal pedestrian crossings. The OR for all crossing types combined was 0.22 ($p < 0.001$, 95% CI = 0.12–0.38). These ORs suggest an RTC involving a pedestrian is more likely to occur under lit rather than unlit conditions at all types of pedestrian crossing, compared with at other locations not near a crossing.

3.3. Other contributory variables

The STATS19 database includes a range of variables relating to the vehicle and driver, casualty, location and environment involved in the RTC. A number of these variables have been investigated in further detail to assess their relationship with the likelihood of an RTC involving a pedestrian casualty occurring at a crossing after-dark. These are shown in Tables 7 and 8. ORs were calculated comparing the after-dark risk of a reference level within each variable against each of the other levels, using the terms for calculating the effect of the contributory variable compared with the reference variable (see row 4 in Table 4).

The after-dark risk of being involved in an RTC was significantly greater for pedestrians aged 50+ years compared with those aged under 18 at zebra and pelican crossings. Pedestrians aged 30–49 years also had a higher after-dark risk than under-18 s at pelican crossings. The after-dark risk at a crossing was also significantly greater for female pedestrians compared with male pedestrians. Adverse weather conditions also resulted in a significantly higher risk of an RTC under darkness compared with fine weather conditions, at all three types of pedestrian crossing. Effects of driver age (< 30, 30–49 or 50+ years), casualty severity (slight, serious or fatal) and speed limit (< 30 or > 30 mph) were not suggested to be significant.

Table 6
ORs of after-dark risk for pedestrian involvement in RTC, and associated 95% confidence intervals and *p*-values, for crossing and non-crossing locations.

Location of RTC	Odds ratio[a]	Confidence intervals	p-value
Zebra crossing	1.94	1.33–2.83	< 0.001
Pelican crossing	1.76	1.33–2.33	< 0.001
Traffic signal crossing	1.53	1.15–2.04	0.004
All crossings	1.70	1.43–2.03	< 0.001
No crossing	1.40	1.25–1.56	< 0.001

[a] ORs calculated by comparing probability of after-dark RTC relative to daylight RTC against probability during both daylight and after-dark control periods combined.

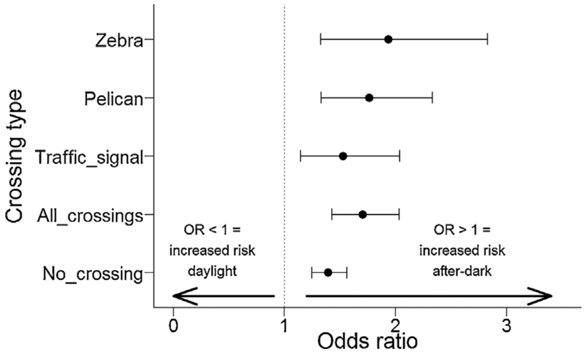

Fig. 3. ORs of pedestrian RTC occurring after-dark compared with daylight, by type of pedestrian crossing. Lower and upper 95% confidence intervals are shown.

Table 5
Frequencies of RTCs between 2005 and 2015 that involved a pedestrian and occurred 13 days before or after the Spring and Autumn clock changes, in the case and control hours.

Location of RTC	RTC frequency, 2005–2015							
	Case hour		Day light control		After-dark control		Both controls	
	Day	After-dark	Case hour in daylight	Case hour in dark	Case hour in daylight	Case hour in dark	Case hour in daylight	Case hour in dark
Zebra crossing	84	143	87	66	29	36	116	102
Pelican crossing	148	244	144	126	72	76	216	202
Traffic signal crossing	142	217	135	122	68	81	203	203
All crossings	374	604	366	314	169	193	535	507
No crossing	1037	1367	896	854	443	411	1339	1265

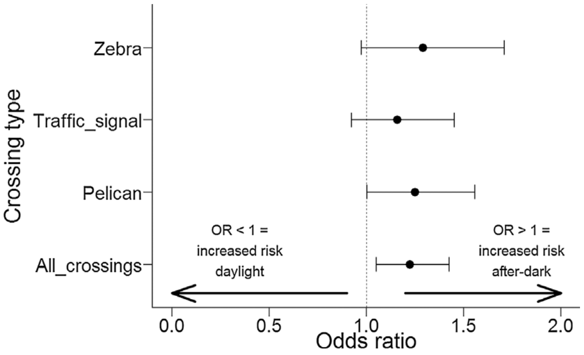

Fig. 4. ORs of after-dark pedestrian RTCs occurring at crossings, compared with non-crossing locations.

4. Discussion

4.1. Key findings

Pedestrians are vulnerable road users and suffer higher rates of injury and death on the roads compared with vehicle users. Reducing these injuries and deaths is a key strategic international priority (World Health Organisation, 2013). Encouraging people to walk to their destinations rather than use motorised transport or not travel at all is one tool for tackling two global challenges – the growing obesity epidemic in many countries, and climate change. It is therefore important to provide safe walking environments to avoid placing pedestrians in danger and to reduce a perceived barrier to walking by making the roads feel safer to walk on. The majority of pedestrian injuries in the UK occur when they are attempting to cross the road (Department for Transport, 2015b). Pedestrians are also at more risk of being involved in an RTC and being more severely injured when it is dark. Designated pedestrian crossings, which include zebra, pelican and traffic signal crossings, are road infrastructure designed to make crossing the road safer. This paper investigates whether pedestrian crossings do help reduce the after-dark risk for pedestrians, and what effect certain situational and environment factors have on the after-dark risk at crossings. We used the biannual clock changes resulting from transitions to and from daylight saving time to compare daylight and after-dark conditions during the same one-hour period of the day. This approach allows comparison of ambient light conditions whilst controlling for other potentially-confounding factors, such as pedestrian and traffic volume, alcohol intoxication amongst drivers and pedestrians, vehicle speeds and types of driver.

The overall OR for an RTC involving a pedestrian at any type of crossing during darkness compared to daylight was 1.70 (95% CI = 1.43–2.03, $p < 0.001$). This suggests using a pedestrian crossing after-dark presents a significantly greater risk of being involved in an RTC than during daylight. The major cause of this effect is likely to be the ambient light level, as use of the daylight savings clock change method to compare daylight and darkness helps control for other potential explanatory factors. We compared the risk of an RTC at a pedestrian crossing after-dark against the risk at non-crossing locations. The OR was significantly above one (OR = 1.23, CI = 1.05–1.43, $p < 0.01$), suggesting the after-dark risk (i.e. the risk of a collision after-dark compared with during daylight) was significantly greater at crossings compared with non-crossing locations.

These results not only show the increased danger pedestrians face on the roads when it is dark, but also how this danger may be increased, rather than decreased, by using a pedestrian crossing after-dark. We examined a number of potential contributory factors that could help explain this finding. One relevant factor was the effect of road lighting, and how the presence of this was associated with RTC rates. The OR for the effect of lit versus unlit crossings compared against non-crossing locations was 0.22 ($p < 0.001$, 95% CI = 0.12–0.38). This implies that RTCs at crossings are more likely to be associated with lit rather than unlit road lighting conditions, compared with RTCs at non-crossing locations. This result does not necessarily mean road lighting makes pedestrian crossings inherently less safe. One likely explanation is that pedestrian crossings may be more likely to be lit by road lighting, compared with other parts of the road network. As an illustration of this difference, 96% of RTCs at pedestrian crossings occurred in urban areas (as defined in the STATS19 database), compared with 86% of RTCs at non-crossing locations. This would lead to a greater probability of an RTC occurring at a lit rather than unlit pedestrian crossing, compared with a non-crossing location. Road lighting was absent or unlit in only 2% of after-dark RTCs at pedestrian crossings (occurring during the dark period of the case hour or any time during the after-dark control period). This suggests a lack of lighting is not a major cause of pedestrian crossing RTCs. It does however raise a question about the adequacy of existing lighting, given that we have demonstrated the significant effect ambient light conditions have on the risk of an RTC.

Table 7
Contributory variables that have been investigated to determine influence on after-dark RTCs on pedestrian crossings.

Contributory variable	Comparisons included in analysis
Age of driver	< 30 years vs 30–49 years vs 50+ years
Age of pedestrian casualty	< 18 years vs 18–49 years vs 50+ years
Gender of driver	Male vs Female
Gender of casualty	Male vs Female
Pedestrian casualty severity	Killed vs Seriously injured vs Slightly injured
Speed limit of road	≤30 mph vs 30+ mph
Weather conditions	Fine vs Rain/Snow/Fog/Other adverse weather

In the UK the British Standard BS EN 13201-2:2015 (British

Table 8
ORs showing likelihood of RTC at pedestrian crossing after-dark for contributory variables, relative to after-dark risk for referent variable. OR above 1.0 indicates increased after-dark risk, relative to referent.

Contributory variable	Zebra	Pelican	Traffic signal	All crossings
Age of driver: (reference = driver age < 30)				
30–49 years	0.99 (0.46–2.12)	0.79 (0.46–1.36)	0.91 (0.52–1.56)	0.87 (0.62–1.23)
50+ years	1.46 (0.67–3.17)	1.16 (0.63–2.13)	0.78 (0.41–1.49)	1.09 (0.74–1.60)
Age of casualty: (reference = casualty aged < 18 years)				
18–49 years	1.52 (0.82–2.81)	1.65 (1.04–2.61)*	1.36 (0.83–2.22)	1.51 (1.13–2.02)**
50+ years	2.23 (1.06–4.68)*	2.53 (1.41–4.53)**	1.42 (0.79–2.54)	1.97 (1.37–2.81)**
Gender of driver: (reference = Male)				
Female	0.60 (0.33–1.11)	1.50 (0.93–2.44)	1.32 (0.78–2.24)	1.16 (0.85–1.56)
Gender of casualty: (reference = Male)				
Female	1.44 (0.84–2.48)	1.58 (1.04–2.39)*	1.38 (0.90–2.11)	1.47 (1.13–1.91)**
Casualty severity: (reference = slight injury)				
Serious	1.43 (0.68–3.00)	0.75 (0.46–1.21)	1.00 (0.60–1.68	0.95 (0.69–1.29)
Fatal	2.54 (0.28–23.15)	1.53 (0.40–5.89)	0.32 (0.03–3.62)	1.33 (0.50–3.55)
Speed limit: (reference = speed ≤30 mph)				
> 30 mph	1.49 (0.28–7.83)	1.17 (0.55–2.51)	0.98 (0.43–2.25)	1.11 (0.66–1.88)
Weather conditions: (reference = fine weather)				
Adverse	3.78 (1.79–7.98)**	2.99 (1.71–5.21)**	2.08 (1.13–3.81)*	2.82 (1.97–4.03)**

* $p < 0.05$.
** $p < 0.01$.

Standards Institute, 2016) sets out lighting requirements for road lighting. It includes an Annex which gives some guidance on the lighting of pedestrian crossings, but this is described as 'informative', rather than as specific requirements. Further guidance is provided by the Institute of Lighting Professionals in the Technical Report TR12:2012 (Institute of Lighting Professionals, 2012) but this only provides information about good practice and it is not a statutory requirement to follow the advice it contains. It would therefore be useful to know the extent to which Local Authorities follow this guidance, and the type of lighting that is generally provided at pedestrian crossings. Further research should also assess the efficacy of the lighting recommendations provided in making the crossing and any pedestrians more visible to the driver.

The increased risk after-dark at pedestrian crossings compared with at other locations may be due to a pedestrian being over-confident of being seen by an approaching driver who will therefore stop to let them cross. The purpose of pedestrian crossings is to make it safer to cross the road, and a pedestrian may legitimately feel more confident to cross when using a designated crossing. This confidence may not be adjusted when it is dark to account for the potential reduction in how visible they are to the driver. Pedestrians generally perceive themselves to be more visible in low light conditions than their visibility as found/perceived by drivers (King et al., 2012). When asked to indicate when they thought they were visible to an approaching driver, pedestrians overestimated their visibility distance by 59 m, and also underestimated the visibility benefits of wearing reflective clothing or retroreflective markings (Tyrrell et al., 2004). This could lead to pedestrians endangering themselves because they believe they can be seen by an approaching driver when this may not be the case. This is more likely to happen at a crossing as the pedestrian has an expectation that an approaching vehicle will stop. In addition, pedestrian crossings are more likely to be lit by road lighting than other locations. Glare and light adaptation levels of the eye of the pedestrian may influence their ability to make safety judgements about any oncoming vehicle, compared with locations that are not at crossings and may not be as lit by road lighting. This could be a further explanatory contribution to the increase after-dark risk at pedestrian crossings compared with non-crossing locations, although this remains only a hypothesis at this stage.

Older pedestrians (aged 50+ years) appear to be at greater risk using a pedestrian crossing after-dark compared with younger pedestrians (aged under 18). There is some supporting evidence for this finding in previous work. For example, Zegeer et al. (1993) analysed extensive records about pedestrian crashes in the US and found that dark lighting conditions were more hazardous to older pedestrians, suggesting this was a result of their reduced vision, slower reactions, and them being more likely to wear dark clothing. Oxley et al. (1997) recorded the road-crossing behaviour of young and old pedestrians, and found that older pedestrians were more likely to cross when there was close moving traffic, and generally adopted less safe road-crossing behaviour than younger pedestrians. They suggested that age-related cognitive and perceptual deficits are likely to be a factor in the crashes that involve older pedestrians. It is possible that the increased risk to older people using a pedestrian crossing after-dark, relative to younger people, could be due to increased age-related visual impairment, or potentially to increased but inappropriate confidence or impaired cognitive judgements about when it is safe to cross. For example, older people may have greater confidence crossing the road at a designated crossing rather than at another location, compared with younger people (Bernhoft and Carstensen, 2008), but this confidence is more likely to be misplaced when it is dark as the driver may be less likely to see the pedestrian standing at or walking across the crossing.

Results suggested that the risk of a female pedestrian being involved in an RTC at a crossing after-dark compared with daylight was greater than the risk for a male pedestrian. This suggests there is an interaction between the ambient light level and the gender of the pedestrian. There are a number of possible explanations for this effect. It is possible that the number of female pedestrians using crossings after-dark increases, relative to the number of males using them, which would lead to an increase in RTCs involving female pedestrians at crossings. Males may have riskier road-crossing behaviour (e.g. Diaz, 2002; Ferenchak, 2016) resulting in a greater propensity to cross the road without using pedestrian crossing facilities. An alternative explanation for the increased after-dark risk for female pedestrians may be down to gender differences in road-crossing judgements and decisions. For example, gender differences exist in factors associated with road-crossing decisions, and these may relate to experience of driving which often differ between male and female pedestrians (Holland and Hill, 2010).

Weather conditions also have a significant effect on the risk of an RTC at a pedestrian crossing after-dark. Adverse weather conditions, defined here as involving rain, snow, fog or mist, were associated with a greater after-dark risk at pedestrian crossings compared with fine weather conditions. This implies poor weather conditions interact with the ambient light conditions to heighten the risk of an RTC at a pedestrian crossing after-dark. It seems likely that visibility may play a key role in this effect. Ambient light conditions have been shown to be an important factor involved in fatal RTCs under inclement weather conditions (Owens and Sivak, 1996), and visibility was seen as an important explanation for this.

4.2. Limitations

One limitation with the work presented in this paper is the definition we have used to describe the after-dark period in the case hour. For simplicity we have described the case hour before the Spring clock change and after the Autumn clock change as being in darkness, but in reality the light condition will have been twilight progressing to darkness, as it does not immediately become dark as soon as the sun sets. The time of sunset marks the onset of civil twilight and the transition to true darkness can take approximately 30–45 min in the UK, depending on the location and time of year (TimeAndDate, 2017). Ambient light conditions will get continuously darker throughout this time. We therefore suggest that the effects of darkness on RTCs at pedestrian crossings demonstrated in this paper are conservative estimates, and it may be that when true darkness is contrasted against daylight, the risk of an RTC becomes even greater than that suggested by the current findings.

In this paper we have used odds ratios as an analytical approach to illustrate any increased risk associated with darkness and the occurrence of RTCs at pedestrian crossings. The use of Daylight Savings Time clock changes to compare RTC frequency in different ambient light conditions, and the use of control periods over the same periods of time which do not experience a change in ambient light, attempts to control for a number of confounding factors. However, the analysis of RTC data presents a number of methodological issues that may influence the reliability of any conclusions drawn (Mannering and Bhat, 2014). These issues and potential limitations include unobserved heterogeneity, selectivity bias, risk compensation, under-reporting of RTCs, and the choice of methodological approach. We now briefly discuss some of these issues in the context of the analysis provided in this paper, and present an additional analysis using a regression discontinuity design that attempts to address them.

Unobserved heterogeneity refers to the range of different variables that may influence the likelihood of an RTC but are unobservable, or unavailable to the analyst. It can lead to erroneous conclusions and the misinterpretation of causal effects on RTC frequencies. Our analysis of RTC frequencies using the odds ratio method suggests an effect of ambient light conditions on pedestrian RTCs at crossings. It is possible however that such a conclusion doesn't account for unobserved heterogeneity associated with other causal variables that may co-vary with ambient light conditions or the clock change. In Table 9 we highlight some of these possible confounding variables and discuss their impact on our conclusions in the context of the daylight saving odds ratio

Table 9
Potential confounding variables and implications for current analysis of pedestrian RTCs at crossings. Confounds selected from those discussed in Mannering et al. (2016).

Source of confounding/ unobserved hetereogeneity	Description of possible effect	Impact on conclusions
Age and gender (driver and pedestrian)	Risk of involvement in RTC may vary depending on gender and age of either driver or pedestrian (e.g. Massie et al., 1995). Systematic variation of gender and age before and after clock could influence frequency of RTCs	Detailed data about gender/age of road users is unavailable. However, the use of control hours in the odds ratio method accounts for any systematic change in the numbers of male or female drivers or pedestrians after a clock change – any change in numbers is expected to affect the control and case hours equally.
Vehicle type	Certain types of vehicle may be more likely to be involved in a police-reported RTC, and the number of these vehicle types using the roads may systematically vary before and after a clock change.	Use of the control hours is designed to account for any changes in the vehicle types using the roads before and after a clock change, as any change due to systematic reasons is expected to affect both control and case hours equally. Pedestrian crossings are usually located in similar, urban locations, e.g. not on major trunk roads with national speed limits. We expect vehicle types to be similar across the majority of pedestrian crossing locations.
Roadway characteristics	Changes in ambient light level could be associated with changes in the volume of traffic using different types of road with different characteristics, such as those with more road lighting. This could result in more RTCs at locations on the types of roads with these characteristics.	We are not aware of any evidence suggesting the types of road pedestrian crossings are located on would receive greater use after-dark compared with during daylight. Pedestrian crossings are situated in similar locations, for example with similar road lighting and speed limits. We therefore do not expect road characteristics to systematically vary with the change in ambient light. To illustrate this, 80% of RTCs at crossings in the case hour occurred in a single-carriageway road during both daylight and after-dark conditions.
Vehicle and pedestrian volumes	The number of vehicles and pedestrians using a road will have a direct correlation with the number of RTCs. If there is an association between vehicle/pedestrian volume and the periods before and after a clock change, or the change in ambient light, this is likely to influence the frequency of RTCs.	Control hours in the odds ratio method we have used aim to control for seasonal changes in traffic volumes – any change in volumes following a clock change should be reflected in both control and case hours. Furthermore, the daylight savings transition allows the same time of the day to be compared, whilst the ambient light condition changes, helping to keep traffic volumes constant. However, we cannot rule out a change in traffic volumes and therefore in risk exposure associated with a change in ambient light. The expected direction of change would be for a decrease in vehicle and pedestrian numbers after-dark (e.g. Uttley and Fotios, 2017). This would suggest our results underestimate the increase in risk after-dark at crossings.
Driver/pedestrian behaviour	Driver or pedestrian behaviour may vary before and after a clock change, or when ambient light conditions change. This may change the likelihood of involvement in an RTC.	Comparison of RTCs before and after a clock change at the same time of day aims to control for variations in driver and pedestrian behaviour. One behavioural factor that may have contributed to our results however is a potential change in alertness as a result of the time shift produced by the clock change. The time change following Spring clock change may reduce how much sleep is obtained, and this may not be counterbalanced by an increase in sleep for the Autumn clock change (Harrison, 2013; Barnes and Wagner, 2009). Any net reduced alertness could increase RTCs. However, any increase should affect RTCs in the control hour and case hour equally.

method we have used.

Table 9 discusses potential confounding variables and their relevance and implications for the existing analysis of RTCs at pedestrian crossings. Our empirical approach, using odds ratios, control periods and the daylight savings time transition to compare changes in ambient light at the same time of day, is capable of accounting for most of these. One limitation that should be highlighted though is the potential change in exposure due to changes in vehicle and pedestrian volumes that could occur either side of a clock change, and the transitions in ambient light. We assume constant frequencies of pedestrians and drivers before and after a clock change in the same one hour period. The habitual nature of travelling (Gärling and Axhausen, 2003) means we can have some confidence in this assumption, particularly because the case hour (ranging between 16:10–19:02, GMT, depending on location and season) coincided with evening commuting times and commuting behaviour is a strongly habitual behaviour (Aarts et al., 1998). Nevertheless, it is possible that exposure rates varied before and after the clock change. However, it is anticipated that any difference would likely be due to an increase in travellers during daylight compared with after-dark (Uttley and Fotios, 2017). If this is the case, the estimates of increased risk to pedestrians on pedestrian crossings after-dark compared with during daylight presented in this paper are likely to be an underestimate, as we would anticipate increased exposure during daylight than after-dark.

Whilst we have used odds ratios as our method for illustrating any risk associated with after-dark conditions, a number of other analytical methods could have been used which may also have provided some protection against potential confounding factors, such as random parameter models, latent class models or regression discontinuity (Mannering et al., 2016). The choice of analytical method used could potentially influence the conclusions that are made, particularly because there is no current consensus on which method is superior (Mannering and Bhat, 2014). As a final validation of our conclusions therefore, we have used an alternative method to odds ratio, regression discontinuity, to assess whether our main conclusion about the increased risk of an RTC at a crossing after-dark, holds true.

4.3. Regression discontinuity analysis

Regression discontinuity (Thistlethwaite and Campbell, 1960) – RD – is an analysis method that helps account for unobserved heterogeneity and allows causal conclusions to be drawn from non-randomised designs. The method can be applied to compare two groups of data, where these groupings are assigned based on a predetermined threshold value on an ‘assignment’ variable. An example of such an assignment variable might be student academic achievement as measured through a test score or ranking, and whether the student then receives a scholarship or not based meeting a threshold value on this test score (e.g. Zhang et al., 2016). The fixed threshold on the assignment variable creates a ‘discontinuity’, with subjects on one side of this discontinuity being assigned to one group and those on the other side being assigned to another group. Theoretically, the subjects just below and just above this cutoff are highly comparable, and a comparison of two separate regression models fitted to the data below and above this cutoff can reveal whether there is a difference between the two groups of data. Further explanation of the logic behind RD designs can be found in Imbens and Lemieux (2008).

The daylight savings time transitions used in our analysis provide a clear discontinuity, with RTCs occurring in one light condition on one side of the clock change, and in another light condition on the other side. This method has been used in previous research involving daylight saving time and vehicle collisions (Smith, 2016). RD analysis was carried out using the *R* package *rddtools* (Stigler and Quast, 2015). The number of RTCs at pedestrian crossings during the case hour were summed for each day within the 2-week period before and after the clock change in each year and season. Each day was labelled with its position (*DayN)* in terms of the number of days it occurred before or after the day of the clock change (clock change day, always a Sunday, was zero). For example, the first Monday after the clock change was DayN +1, the last Friday before the clock change was DayN −12. The DayN values for the Spring clock change had their sign reversed, with DayN +1 becoming DayN −1 and so on. This ensured that a positive DayN consistently represented the period when the case hour was in darkness, and a negative DayN represented the period when the case hour was in daylight. RTC frequency varies depending on the day of the week, with particular variations observed at weekends (Broughton et al., 1999). Pedestrian frequencies, and therefore exposure rates, may also vary depending on the day of the week. Therefore, data falling on a Saturday or Sunday were excluded from the RD analysis, and the remaining data was demeaned by subtracting the mean frequency of RTCs at pedestrian crossings for the appropriate weekday and year from the RTC sum for each DayN, following Smith (2016). The resulting dataset of demeaned values for each DayN, season and year were checked against assumptions required for carrying out a regression discontinuity analysis, following methods outlined in Thoemmes et al. (2017). The McCrary sorting test (McCrary, 2008) was not significant ($z < 0.001$, $p = 1.0$), indicating no violation of the assumption that there are no discontinuities in the assignment variable (DayN). Placebo tests were also carried out, with treatment effects plotted at different cutoff thresholds ranging between DayN ± 3 and DayN ± 10. This showed that all placebo cutoffs had confidence intervals that substantially covered a treatment effect of zero, suggesting no violation of the assumption that the treatment effect (i.e. a change in the number of RTCs at pedestrian crossings) only occurred at the cutoff (DayN = 0, day of the clock change). Regression discontinuity analysis was deemed to be appropriate based on the results of these assumption tests.

A parametric, global regression approach was selected for the analysis, this being preferred to a local, non-parametric method because it includes all data rather than a selection of data around the cutoff at DayN = 0. Although there is an immediate difference in ambient light condition following a clock change, in practical terms this distinction is likely to increase the further away from the cutoff DayN progresses, as the time the case hour is in twilight reduces and the difference in ambient light condition before and after the clock change becomes more extreme. Therefore using a local approach which selects only a subset of data within a bandwidth around the day of the clock change may underestimate the effect of the discontinuity in ambient light. The parametric global method was implemented using the *rdd_reg_lm* function in the *rddtools R* package. Linear regression rather than a higher-order polynomial was used (Gelman and Imbens, 2014). Fig. 5 shows the results of the regression discontinuity analysis. Note that a positive DayN indicates the ambient light condition was darkness, as the DayN order for Spring clock changes was reversed. Also note that the plot in Fig. 5 shows mean values for each DayN, averaged across all seasons and years, however the regression discontinuity analysis utilises all values, not just the averaged values. These results suggest the darkness was associated with an increase in the frequency of RTCs at pedestrian crossings during the case hour of 0.72 per day, and this increase was statistically significant ($p = 0.03$). It is also noticeable that following the DayN = 0 cutoff, the regression line follows and upward slope. This suggests the frequency of RTCs may increase as the distance from the day of the clock change increases. This may be because the magnitude of darkness is also increasing. Although the clock change results in a qualitative shift in ambient light condition, the case hour in the after-dark period is actually twilight tending to darkness. The transition between twilight and true darkness becomes earlier each day, the greater the number of days from the clock change. This upward slope therefore provides further suggestive evidence that changes in ambient light conditions are causally linked to the risk of an RTC at a pedestrian crossing.

As further confirmation of the effect of ambient light, a similar regression discontinuity analysis was also applied to RTCs that occurred

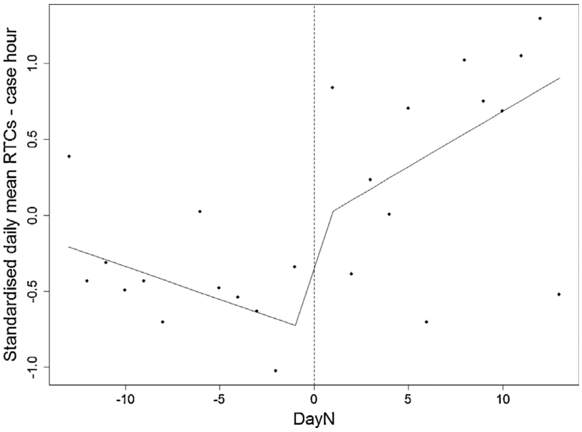

Fig. 5. Regression discontinuity plot for RTCs in case hour, showing standardised daily mean RTCs by DayN, with DayN = day of clock change. Standardised daily mean calculated by subtracting appropriate weekday mean from each indivdiaul DayN value for each season and year. DayN represents number of days from day of clock change, with order of days around Spring clock change reversed so that DayN > 0 is in dark ambient light conditions.

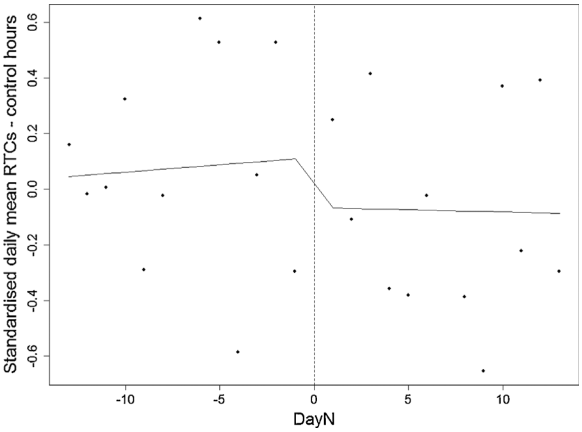

Fig. 6. Regression discontinuity plot for RTCs in control hours, showing standardised daily mean RTCs by DayN, with DayN = day of clock change. Standardised daily mean calculated by subtracting appropriate weekday mean from each indivdiaul DayN value for each season and year. DayN represents number of days from day of clock change, with order of days around Spring clock change reversed so that DayN > 0 is in dark ambient light conditions.

in the control hours, when the ambient light did not change at the cutoff (DayN = 0). The results are plotted in Fig. 6. There is no statistical difference ($p = 0.50$) in the standardised frequency of RTCs in the control hours, before and after a clock change. This is the anticipated result, as the ambient light condition did not change in the control hours following a clock change.

As a final sensitivity check, the regression discontinuity analysis was run again but instead using a non-parametric, local linear regression approach, using the *rdd_reg_np* function in *rddtools*. An optimal bandwidth of 10.6 was selected using the Imbens-Kalyanaraman estimator (Imbens and Kalyanaraman, 2012). This approach also produced a significant difference before and after the cutoff, with an estimated increase in daily frequency of RTCs at pedestrian crossings in the case hour of 0.77 ($p = 0.04$).

5. Conclusion

This paper demonstrates that the ambient light condition has a significant impact on the risk of a pedestrian being injured in an RTC at a pedestrian crossing. The risk after-dark at a crossing appears to be greater than at other locations on the road. It is clear that this risk is not due to a lack of road lighting at crossings, as road lighting was present at 98% of pedestrian RTCs at a crossing after-dark. However, this raises the question of whether the lighting at crossings is adequate and sufficiently improves its conspicuity and the visibility of any pedestrians waiting at or walking on it. A further factor that may be linked to the increased risk at pedestrian crossings after-dark is the confidence a pedestrian may have when deciding to cross, and the anticipated behaviour of approaching drivers. The decision to cross a road relies on accurate judgement of the speed, distance and intentions of any approaching vehicle. These judgements are likely to be impaired under low light levels. For example, the light levels generally found on roads after-dark are mesopic. Vision under mesopic conditions relies predominantly on the rod rather than cone photoreceptors, and motion perception, spatial and temporal resolution are all impaired as a result (Gegenfurtner et al., 1999; Boyce, 2014). This can lead to poor judgements of speed under low light levels (Plainis et al., 2006), which may give pedestrians a false impression of whether it is safe to cross the road. Crossing at a designated crossing may heighten confidence further, and give pedestrians the belief that an approaching vehicle may be slowing, or that they have been seen by the driver.

The findings reported in this paper suggest two important areas of research that require further work. The first relates to the lighting of pedestrian crossings, in particular whether existing lighting is adequate and how it could be improved to make the crossing itself as well as any pedestrians using it more visible. The second relates to the crossing behaviour of pedestrians, and investigating the judgements about the safety of crossing the road at a designated crossing after-dark in particular.

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