Evaluation of LED streetlight dimming and driver performance – Open-road methodology development

Final Report

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2 Acknowledgements

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3 Executive Summary

The purpose of this project was to develop an experimental approach for the evaluation of the impact of Light Emitting Diode (LED) streetlight dimming on quantitative and qualitative aspects of driver performance under open road, in-traffic conditions.

3.1 Main Methodological Approaches

This report provides a description of the measurement approaches and associated pilot data collected during a series of drives through regions of different technology streetlighting at different pole height levels, as well as measures of visual performance and self-reported perceptions.

3.1.1 Quantitative Methodologies: Illuminance Levels

Illuminance levels at the roof of the vehicle and at the driver's eye were measured using a series of light sensors mounted in and around the research vehicle. Pilot data collected from five participants demonstrated that the roof mounted sensors detected significant variations in the forward and upward lighting, with higher values noted for the 12m mounting (for the 4000K and 3000K lights), followed by the 15m mounting for the 4000K. Illuminance values were very low in the No Streetlighting zones. Illuminance at the eye was consistently low and varied significantly, dependent on the streetlighting characteristics ($p<0.001$). These data confirm the sensitivity of the in-vehicle system for detecting variations in illuminance at the level of the vehicle as well as at the eye.

3.1.2 Quantitative Methodologies: Pupil Size

Gaze tracking and pupil size while participants drove through different areas of streetlighting were measured using a Pupil Labs 200Hz Binocular wearable eye-tracker, consisting of a forward facing world camera recording at 60Hz, with binocular eye cameras recording at 200Hz. The pilot data from four participants demonstrated larger pupil diameters on average in the No Streetlighting zone, which would be expected in the lower lighting environment, with significant variations between different streetlighting zones ($p<0.001$). These pilot data demonstrate that pupil size is sensitive to changes in streetlighting characteristics (including both differences in light levels as well as different CCT); further data collection is required in order to make more informed inferences about the effect of different levels of streetlighting on the dynamics of pupil size while driving.

3.1.3 Quantitative Methodologies: Visual Performance

Assessment of the effect of LED streetlight dimming on visual performance under open road conditions, in the presence of traffic, requires an approach where drivers' visual performance is assessed for a range of different targets while seated in a stationary rather than a moving vehicle. In pilot studies, a series of targets of different sizes and contrast levels were developed to enable measurement of high and low contrast visual acuity and contrast sensitivity, to determine the smallest amount of detail and contrast that a driver can correctly identify. Pilot studies in the field demonstrated that the approach provides valid results, with targets providing sufficient dynamic range to enable assessment of drivers of different ages and visual characteristics.

3.1.4 Qualitative Methodologies: Self-reported Perceptions

A questionnaire instrument to determine self-reported perceptions of drivers' visibility, glare and safety when driving under the various streetlight levels was developed. Pilot data collected using this response measure demonstrated that the scale provides information that is highly relevant to the research question.

3.2 Future Work

This research involved development of a series of protocols and approaches that enable evaluation of the impact of LED streetlight dimming on quantitative and qualitative aspects of driver performance under open road, in-traffic conditions. The techniques developed involve assessment of light levels at the eye and at the vehicle, gaze strategies and pupil size, as well as visual assessment involving a stationary vehicle and a survey instrument to determine self-reported perceptions of visibility, glare and safety while driving under different streetlighting conditions. Collectively, this research provides an important basis for assessing indices of visual and driving performance under in-traffic conditions for various levels of LED streetlight dimming in future studies. This information is critical for policy makers and road safety authorities to make evidence-based decisions that allow energy savings while maximising road safety.

4 Background

4.1 Night-time Driving is Dangerous

The fatal crash rate at night is three times higher than in the day adjusted for distances driven (NHTSA 2007). These effects are even more pronounced for fatalities involving pedestrians, which are up to seven times higher than those in the day (Sullivan and Flannagan 2007). Crash statistics indicate that reduced lighting and poor visibility are the primary factors associated with these high fatal crash rates, rather than driver fatigue and alcohol consumption (Owens and Sivak 1996, Sullivan and Flannagan 2002), suggesting that drivers are often unable to recognise and respond to vulnerable road users, such as pedestrians and cyclists at night, until it is too late to avoid a collision (Rumar 1990).

4.2 Streetlighting Improves Night-time Road Safety

Streetlighting is a cost-effective intervention for night-time safety. A Cochrane review demonstrated that streetlighting reduces night-time crash risk, potentially through improvement of drivers' visual capabilities (Beyer and Ker 2009). However, the majority of studies included in this review were published prior to 1990, were rated as prone to bias and confounding factors, and did not consider the safety benefits of more recently introduced streetlighting, such as Light Emitting Diode (LED) technology and dimming options. Two recent meta-analyses of crash data and streetlighting levels in the US (Gibbons 2014) and UK (Steinbach, Perkins et al. 2015), confirmed the benefits of traditional streetlighting for reducing night-time crash risk, and also demonstrated that reducing traditional streetlighting levels may not adversely reduce safety, suggesting the potential for dimming and adaptive strategies (where lighting levels are adjusted based on road users' needs). However, there is a critical lack of evidence regarding the impact of LED streetlight configurations, dimming and adaptive capacity on both visual performance and road safety (Bullough and Radetsky 2013).

4.3 LED Streetlighting

The efficiency of LED lighting technology has facilitated the introduction of LED streetlighting into Australia and worldwide. While the energy savings associated with LEDs are well known (Clinton Climate Initiative 2009, Lockwood and Selwyn 2011, Huang, Lee et al. 2012, Pipattanasomporn, Rahman et al. 2014), little is known about their impact on driving safety, particularly in terms of how the light emitted from LED streetlights will impact on night-time visual performance, driving visibility and reaction times.

4.4 Visual Implications of LED Streetlights

Of relevance to the issue of changing the nature of roadway lighting is that the performance of the human eye in the mesopic region (the low light levels typical of night driving under streetlight illumination (Alferdinck 2006)) is complex. The impact of LED streetlighting on visual capacity and hence the ability to detect, recognise and respond under these mesopic night-time driving conditions is largely unknown; this information is critical to determine the impact of the proposed installations of LED streetlights (including dimmed options) on driving visibility and road safety. One of the few relevant studies, involved a series of small scale experiments undertaken on a closed road facility and was published as a government report (Gibbons, Meyer et al. 2015). The findings demonstrated that recognition distances for pedestrians wearing non-reflective clothing were shorter when streetlighting was dimmed by a factor of four (1.25 vs 5 lux); interestingly, these differences were more marked for LED (6000K) compared to HPS (2100K) streetlight dimming. This report also presented evidence that some aspects of performance were improved under LED relative to HPS streetlighting, including off-axis pedestrian distances and target colour recognition (red and green).

4.5 Energy Savings of LED Streetlights

The high efficacies achievable by LED luminaires lead to lower energy consumption compared with older lighting technologies. However, application of smart controls can provide further energy savings through dimming and off-peak shut off during low road usage. This can result in direct energy savings of 30-70%, depending on the capacity to dim and the legacy technology that is replaced (Institute of Public Works 2016). A recent survey of Australian energy Distribution Network Service Providers indicated that half are investigating remote monitoring and control systems for LED streetlighting, yet none report having installed controls in field operating conditions. Another potential energy saving arises because at low light levels, the eye's spectral response aligns more closely with the spectral output of white LED lamps (ie, the eye is more sensitive at these wavelengths), where the eye will see better under LEDs at night; thus the light output of LEDs could be reduced further, without affecting drivers' ability to recognise potential hazards. While this seems logical in theory, very little work has been done to actually test how well drivers can detect and recognise roadside hazards and then react to critical situations under the light levels recommended at night-time for Australian roads.

4.6 Summary of Aims

The aims of this study were to develop protocols and collect pilot data for assessing indices of driving performance under in-traffic conditions for various levels of LED streetlight dimming. The research was conducted in an instrumented vehicle, with custom-built illuminance sensors measuring exterior and interior light conditions and light at the driver's eye, a driver-activated touch sensor, and GPS sensors linked to an in-vehicle logging system developed by the research team. These systems record lighting conditions, vehicle location, speeds and detection distances. We also aimed to measure visual attention, gaze strategies and pupil responses while driving using a novel eye tracking system. The study took advantage of local LED installations such as those around Brisbane (controlled by TMR) where there are streetlighting installations of different colour temperatures (CCT) and there is also the opportunity to dim streetlighting at off-peak times due to reductions in road traffic.

5 Quantitative Methodologies

The following section outlines the methodologies developed to assess a range of quantitative components of performance while driving under different levels of LED streetlight dimming under open road conditions. Given the open road nature of this study, where participants are driving under normal traffic conditions, it is not possible to manipulate objects, such as pedestrians or moving targets at the roadside as per our previous closed road study (Wood, Isoardi et al. 2018). We have thus developed or modified our previous methodological approaches in order to collect as much meaningful quantitative data as is possible under these field-based conditions.

5.1 Illuminance Assessment

The experimental vehicle was an automatic transmission sedan (2015 Toyota Camry) with the halogen headlights set to low-beam for testing, to reflect general driving conditions. The vehicle was instrumented with four Konica Minolta illuminance sensors (see Figure 5-1 for a schematic representation of the system) (Wood, Isoardi et al. 2018). Two of these sensors were mounted on the roof of the vehicle to measure the horizontal and vertical illuminance at the roof of the car. One small, high-resolution sensor was attached to the eye tracker frame and worn by the driver to measure illuminance at the eye. The final illuminance sensor was placed alongside the driver's head to measure the vertical illuminance in the car. Measurements of illuminance made by the Konica Minolta illuminance meters used in the car have uncertainties of less than 5%.

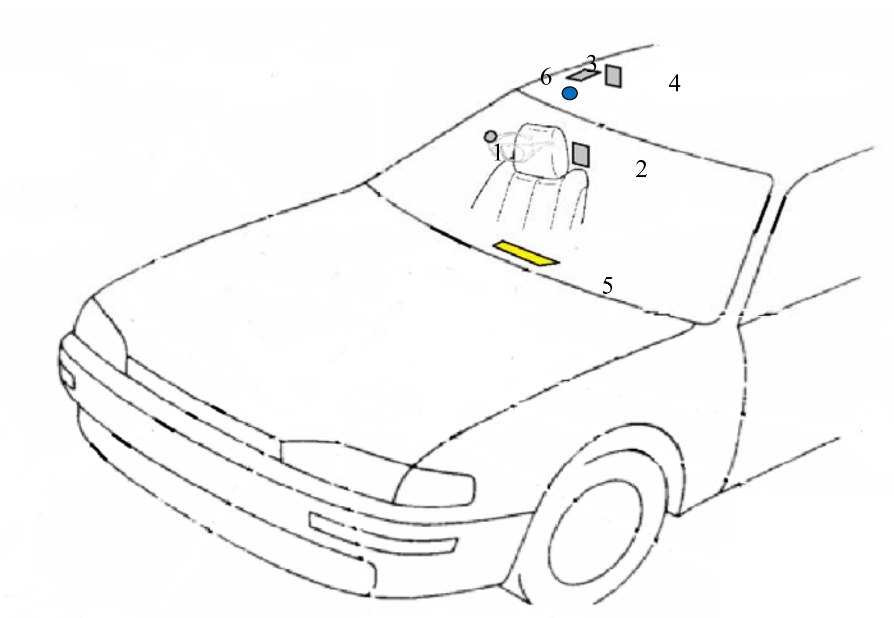


Figure 5-1: Schematic of the in car logging system sensors, showing measurement positions for: 1) illuminance at the eye, 2) vertical illuminance in the car, 3) horizontal illuminance on car roof, 4) vertical illuminance on car roof, 5) touchpad sensor, and 6) GPS tracker. All sensors are connected to a logging computer in the car, collecting readings at 4Hz.

The distance at which external targets are detected and recognised can be recorded using an in-vehicle GPS system; this approach makes it possible to record detection distances if there are locations along the on-road drive where appropriate targets can be located. This is facilitated by an in-vehicle GPS logger which records the exact location of the car when a driver responds to seeing a roadway target. It also enables the speed of the car to be recorded at any given time while driving. In addition to this, the exact locations by GPS coordinates of all roadway targets can be recorded prior to testing. The combination of the active logging GPS sensors and the known positions of all targets enables the data logging system to identify the exact moment (and distance at which) drivers first recognise any roadway objects as they drive around the route; the accuracy of the system is typically within 1.2-1.8 m. This approach will be used in future studies to assess detection distances, if there are locations along the route where this is possible and does not pose a threat to road safety.

5.2 Pupil Assessment

Gaze tracking and pupil size were measured using a Pupil Labs 200Hz Binocular (https://pupil-labs.com) wearable eye-tracker, as shown in Figure 5-2. The system consists of a forward facing world camera recording at 60Hz, with binocular eye cameras recording at 200Hz.

Prior to testing, a calibration procedure was performed with a single marker moved across a wide range of gaze angles. The in-built software system determined the pupil size, based on estimates of the 3-D eye model. Figure 5-3 shows an example of the gaze tracking and pupil detection while driving.

Figure 5-2: Pupil Labs eye tracker

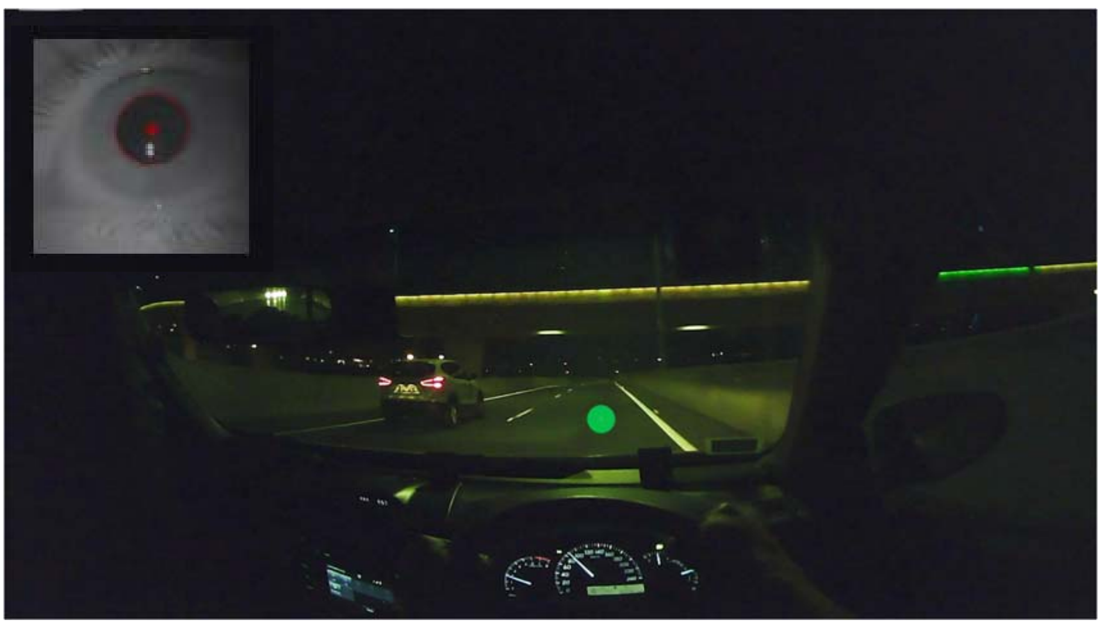


Figure 5-3: Screenshot of the eye tracking and pupil detection (upper left box)

5.3 Illuminance and Pupil: Pilot Data

For the pilot data, a 15-km in-traffic route was selected that included several variations in streetlighting, as shown in Figure 5-4. The route commenced at the southern end of the Southern Cross Motorway accessed via Kingsford Smith Drive, and travelled northbound onto the Gateway Motorway, exiting at the Nudgee turn-off. The return drive started by re-entering the Gateway Motorway travelling southbound, onto the Southern Cross Motorway, and finishing at the Kingsford Smith Drive exit.

All drives were undertaken in the research vehicle, as described in Section 4.1, with the halogen headlights set to low-beam. The vehicle was also instrumented with two forward facing cameras (HERO4; GoPro, San Mateo, CA, USA), one mounted on the roof and the other mounted internally behind the driver. The drives commenced at night-time after nautical twilight and during dry conditions.

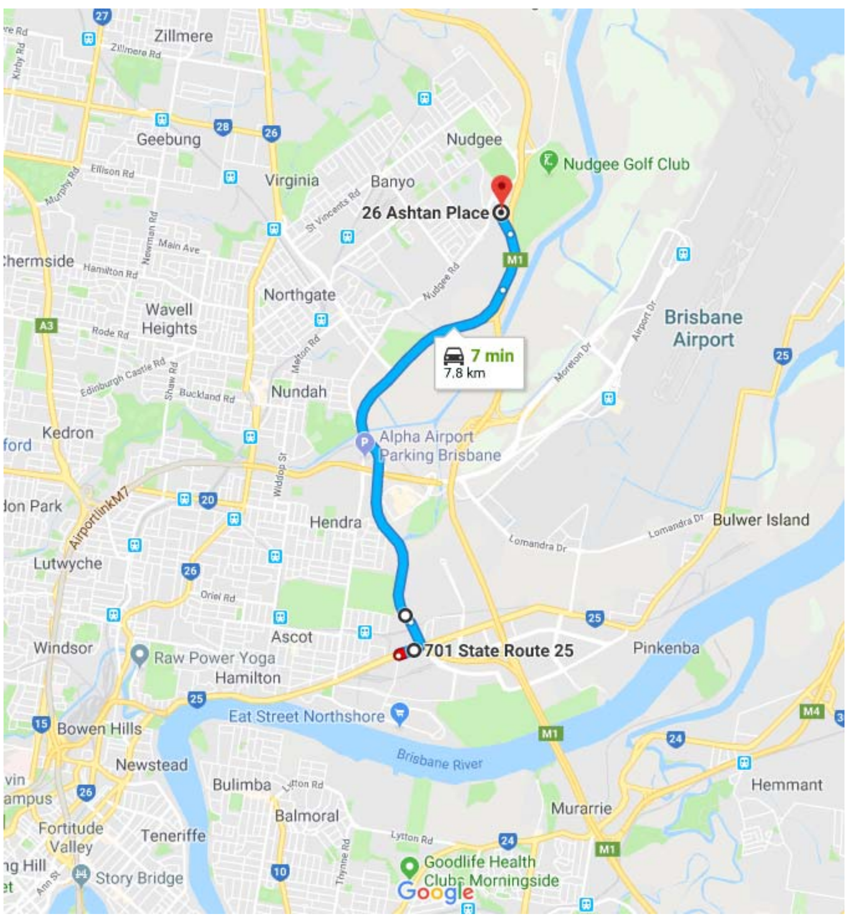


Figure 5-4: Google Map of the pilot drive

The motorway route is designed to V3 lighting standards. Several sections of the drives comprised specific streetlighting of interest, and were similar for the north and southbound drives. The four streetlighting configurations, or zones, as presented in Figure 5-5, are as follows:

- 4000K LED streetlights with a 15m mounting height,
- 4000K LED streetlights with a 12m mounting height,
- 3000K LED streetlights with a 12m mounting height,
- No streetlighting.

In total, two drives were completed, for five participants of a range of ages and included both male and female drivers. The analysis presents the illumination and pupil data within these specific streetlighting zones.

Figure 5-5: Map of the four streetlighting zones along the route

5.3.1 Illuminance Data

Table 5-1 presents the data obtained by five participants by the four illuminance meters as described in Section 5.1 which include:

- Two mounted internal and facing forward (vertically mounted) – one at the driver's eye mounted on the eye tracker frame and one mounted behind the driver's headrest;
- Two mounted externally on the roof of the vehicle – one facing forward (vertically mounted and one facing up (horizontally mounted).

As shown in Figure 5-6 for the group mean data, and for individual participants in Figure 5-7, the illuminance at the eye was consistently low, with values around 1 lux in the streetlighting zones. Importantly, these readings were much lower in the zone with No Streetlighting, around 0.2-0.4 lux. The roof mounted sensors detected variations in the forward and upward lighting, with higher values noted for the 12m mounting (for the 4000K and 3000K lights), followed by the 15m mounting for the 4000K. The values were very low in the No Streetlighting zones.

There was good consistency for the external light levels measured on the roof (both forward and up) across the five drives (Figure 5-7), considering influences of changes in traffic flow/density. These data confirm the sensitivity of the system for detecting variations in illuminance as drivers pass through different streetlighting zones.

Generalised estimating equations were used to assess for statistical differences between the illuminance levels measured at the eye of the drivers across the zones. These models account for the repeated measurements of participants between the zones. Results confirmed that there were significant differences between the four streetlighting zones (χ^2=60.1, $p<0.001$). In the post-hoc pairwise comparisons adjusted for Bonferroni correction, there was no significant difference in the illuminance at the eye between the 4000K (15m mounting) and the 3000K (12m mounting) ($p=0.25$), but all other pairwise comparisons were significantly different ($p<0.031$).

These findings confirms the ability of the experimental system to detect differences in the illuminance at the eye of a driver relating to the presence and absence of streetlighting, as well variations in lighting due to different pole heights and streetlighting of different CCT.

Table 5-1: Illuminance reading from the four sensors within the various streetlighting zones

	Illuminance (lux), mean (standard deviation)			
	At Eye (Forward)	**In Car (Forward)**	**On Roof (Forward)**	**On Roof (Up)**
P01				
4000K LED (15m mounting)	1.18 (0.6)	0.57 (0.46)	6.94 (3.59)	9.63 (5.17)
4000K LED (12m mounting)	1.06 (0.59)	0.96 (0.73)	14.83 (7.91)	19.97 (11.59)
3000K LED (12m mounting)	0.88 (0.48)	0.83 (0.73)	13.29 (7.94)	18.63 (12.16)
No Streetlighting	0.18 (0.14)	0.15 (0.20)	0.77 (2.12)	0.81 (3.35)
P02				
4000K LED (15m mounting)	1.08 (0.61)	0.56 (0.47)	7.36 (3.77)	10.38 (5.63)
4000K LED (12m mounting)	1.88 (1.22)	0.72 (0.53)	14.76 (8.09)	20.97 (12.14)
3000K LED (12m mounting)	1.66 (1.17)	0.71 (0.65)	13.65 (8.28)	20.14 (11.81)
No Streetlighting	0.28 (0.20)	0.25 (0.26)	1.09 (3.22)	1.56 (5.82)
P03				
4000K LED (15m mounting)	0.8 (0.37)	0.52 (0.32)	8.26 (4.41)	12.66 (7.1)
4000K LED (12m mounting)	1.16 (0.61)	0.76 (0.56)	14.6 (7.93)	20.95 (12.34)
3000K LED (12m mounting)	1.03 (0.57)	0.64 (0.61)	13.33 (8.08)	18.03 (9.71)
No Streetlighting	0.42 (0.28)	0.22 (0.27)	0.66 (0.55)	0.65 (2.29)
P04				
4000K LED (15m mounting)	1.08 (0.68)	0.35 (0.26)	6.24 (3.31)	9.24 (5.36)
4000K LED (12m mounting)	2.27 (1.55)	0.67 (0.45)	14.24 (7.82)	20.11 (11.21)
3000K LED (12m mounting)	2.04 (1.46)	0.55 (0.47)	13.41 (7.98)	19.21 (11.69)
No Streetlighting	0.42 (0.33)	0.24 (0.27)	0.76 (1.32)	0.80 (3.3)
P05				
4000K LED (15m mounting)	0.59 (0.28)	0.33 (0.2)	6.06 (3.23)	8.95 (5.23)
4000K LED (12m mounting)	1.09 (0.64)	0.63 (0.44)	14.07 (7.74)	20.27 (11.29)
3000K LED (12m mounting)	0.99 (0.70)	0.58 (0.49)	13.06 (7.76)	20.01 (11.75)
No Streetlighting	0.21 (0.15)	0.17 (0.22)	0.60 (0.79)	0.77 (3.01)
AVERAGE				
4000K LED (15m mounting)	0.95 (0.51)	0.47 (0.34)	6.97 (3.66)	10.17 (5.7)
4000K LED (12m mounting)	1.49 (0.92)	0.75 (0.54)	14.5 (7.9)	20.45 (11.72)
3000K LED (12m mounting)	1.32 (0.88)	0.66 (0.59)	13.35 (8.01)	19.2 (11.42)
No Streetlighting	0.30 (0.22)	0.21 (0.25)	0.78 (1.6)	0.92 (3.55)

Figure 5-6: Mean illuminance (lux) at the eye for all participants across various streetlighting zones

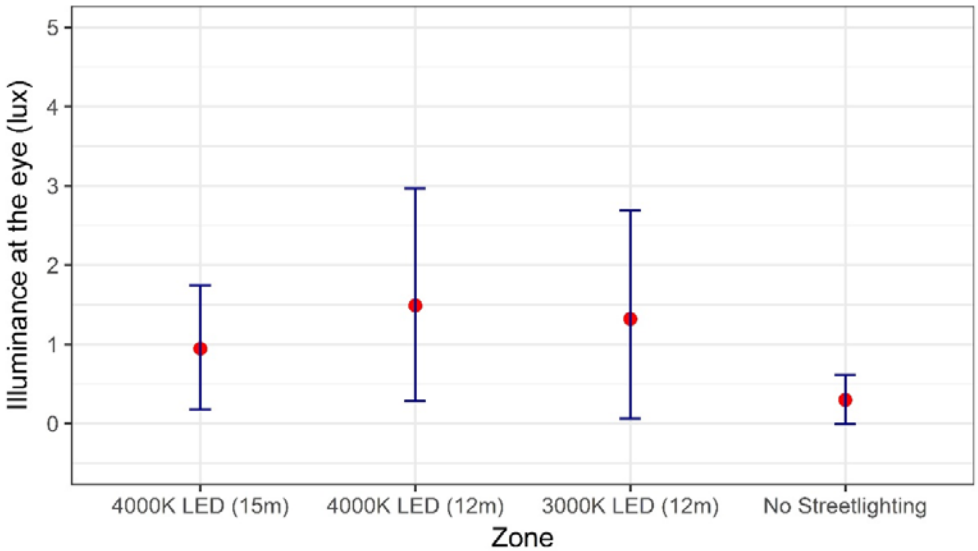
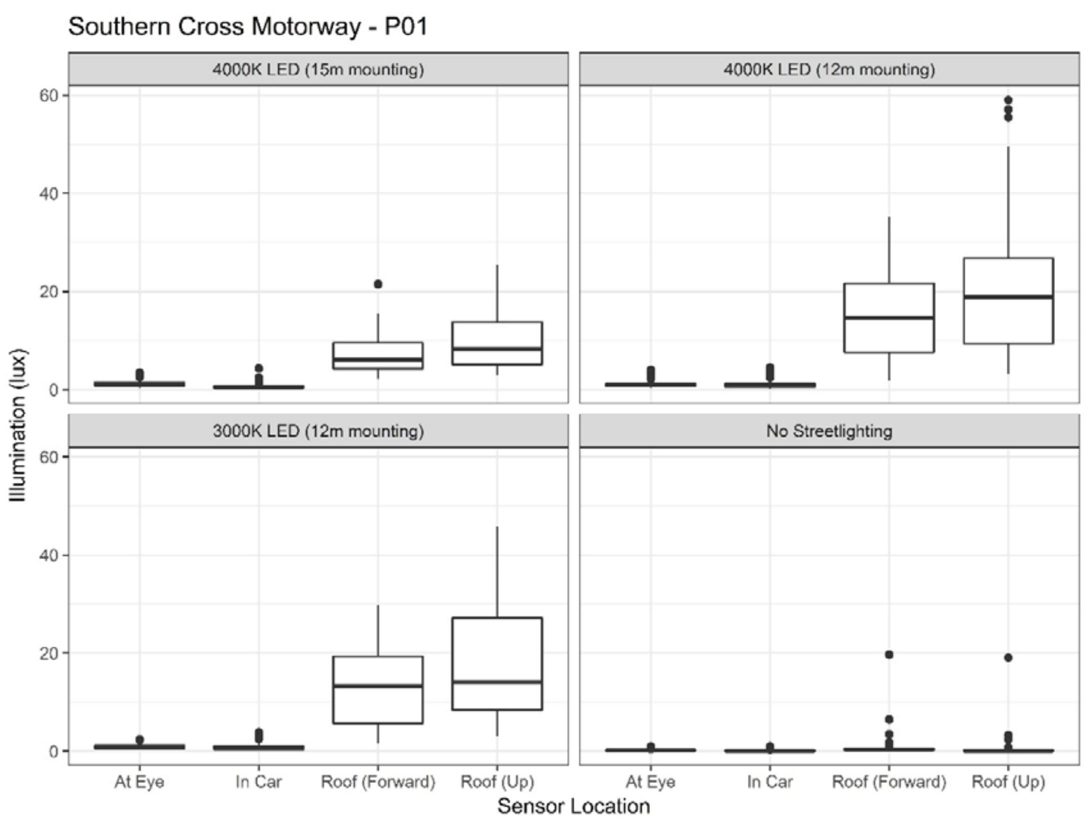
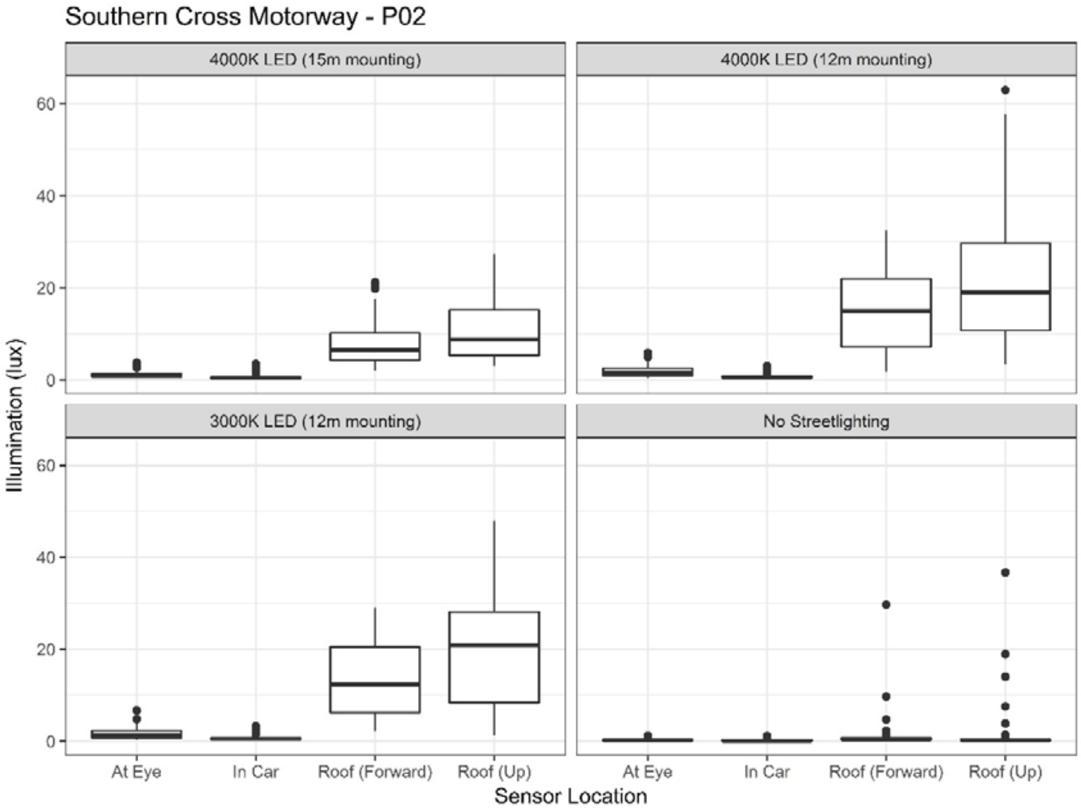
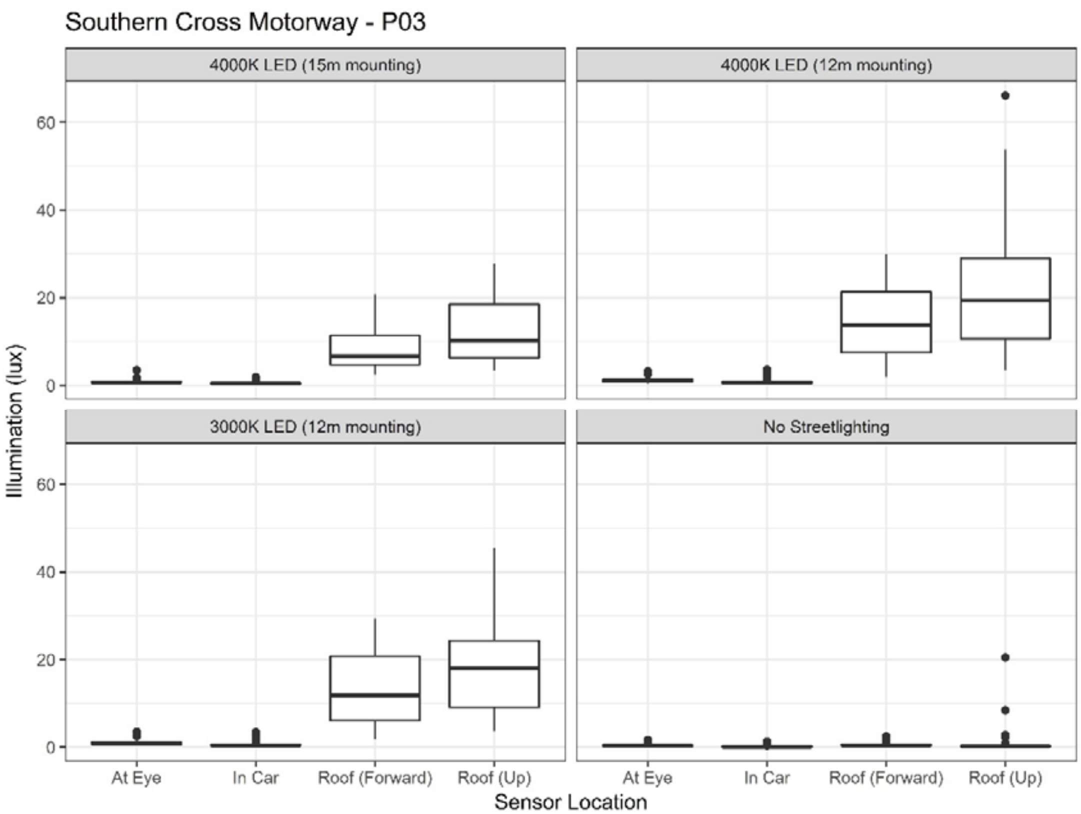
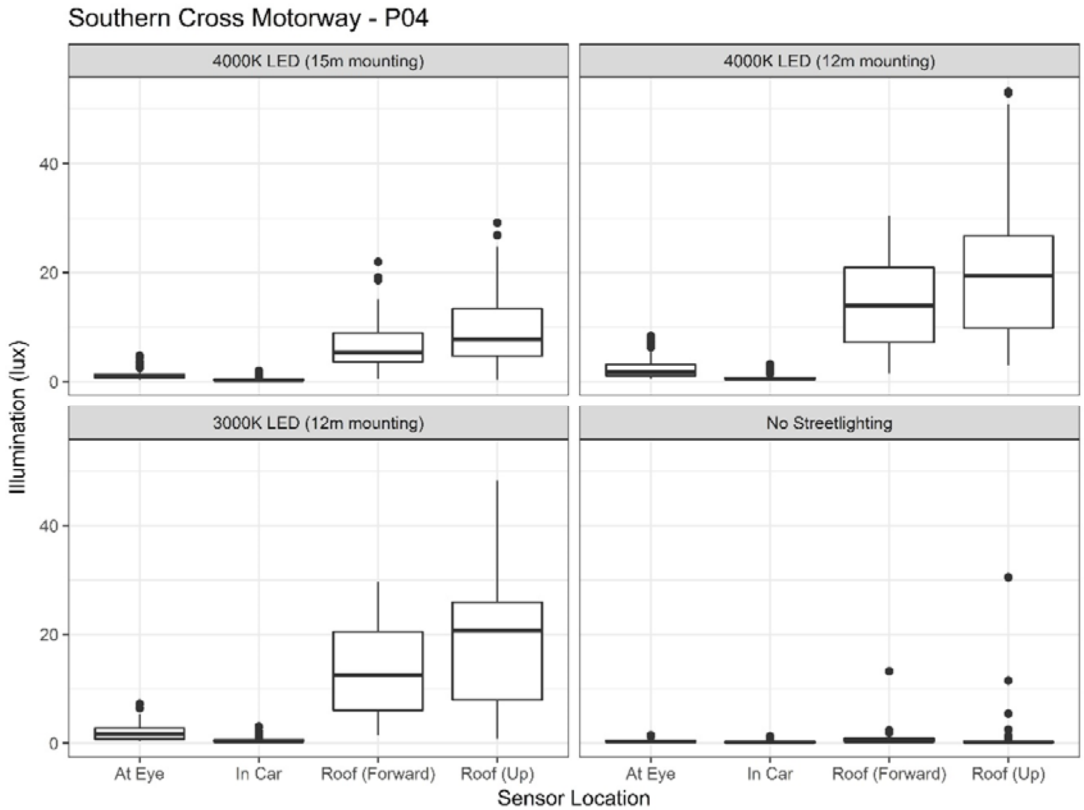


Figure 5-7: Boxplots of the illuminance (lux) in the various streetlighting zones, for the five participants in the pilot drives.

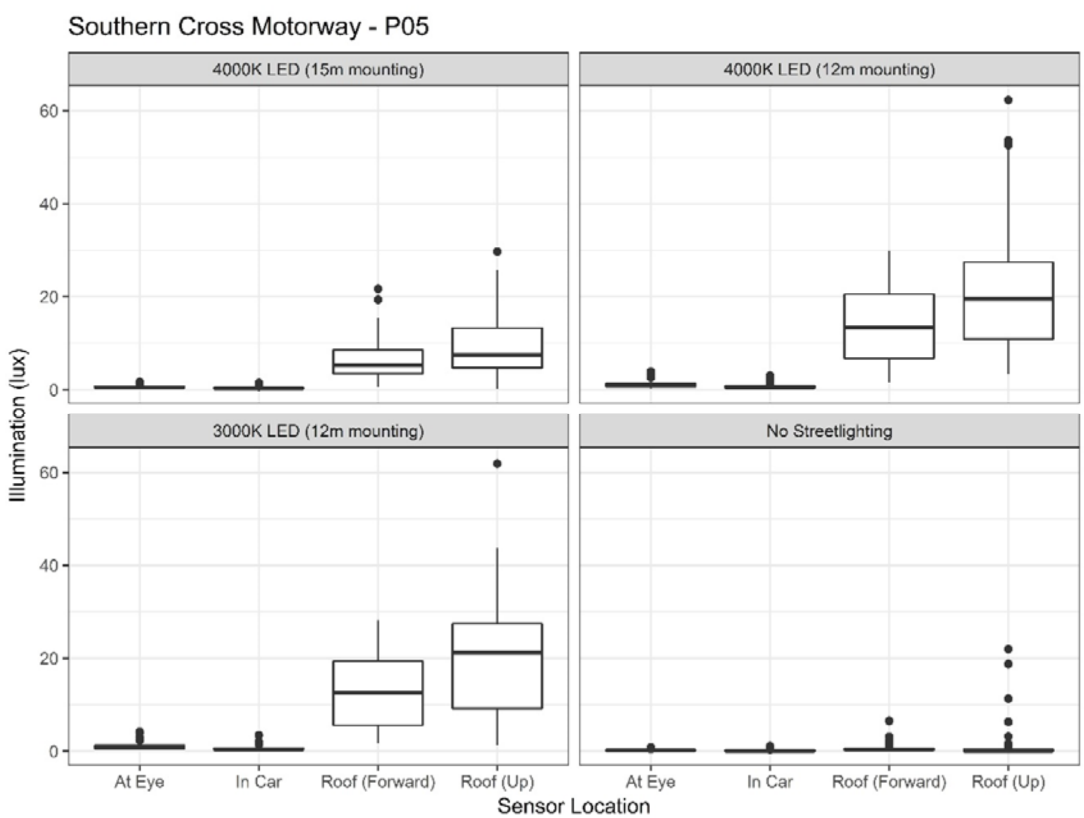



Southern Cross Motorway - P02
4000K LED (15m mounting)
4000K LED (12m mounting)
3000K LED (12m mounting)
No Streetlighting
Illumination (lux)
0
20
40
60
At Eye
In Car
Roof (Forward)
Roof (Up)
Sensor Location


Southern Cross Motorway - P03
4000K LED (15m mounting)
4000K LED (12m mounting)
3000K LED (12m mounting)
No Streetlighting
Illumination (lux)
0
20
40
60
At Eye
In Car
Roof (Forward)
Roof (Up)
Sensor Location



Southern Cross Motorway - P04
4000K LED (15m mounting)
4000K LED (12m mounting)
3000K LED (12m mounting)
No Streetlighting
Illumination (lux)
0
20
40
At Eye
In Car
Roof (Forward)
Roof (Up)
Sensor Location



Southern Cross Motorway - P05
4000K LED (15m mounting)
4000K LED (12m mounting)
3000K LED (12m mounting)
No Streetlighting
Illumination (lux)
0
20
40
60
At Eye
In Car
Roof (Forward)
Roof (Up)
Sensor Location

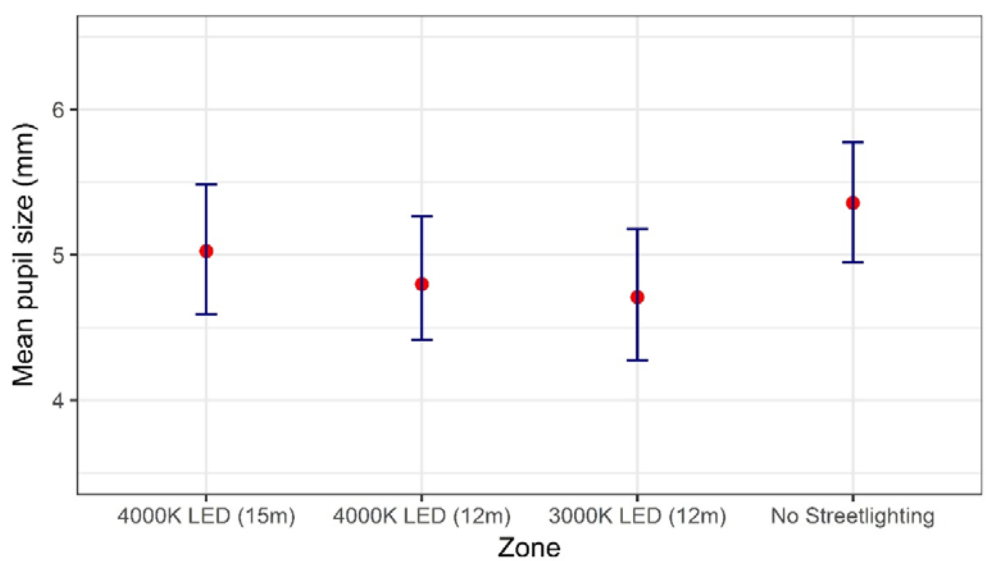
5.3.2 Pupil Data

Table 5-2 presents the pupil data obtained by the eye tracker for the four drivers (P02 to P05). Importantly, while the level of streetlighting will influence pupil size, it should be noted that pupil size will also vary due to other factors when driving, such as constriction in the presence of oncoming headlights, and constriction due to accommodation (focussing) on the speedometer. In general, all participants demonstrated the largest pupil diameters on average in the No Streetlighting zone, which would be expected in the lower lighting environment Figure 5-8. Further data is required to make more informed inferences about the variations in pupil size according to the lighting levels in the different streetlight zones.

Table 5-2: Pupil diameter data within the various streetlighting zones, for 4 drivers (P02 to P05).

	Pupil Diameter (mm), mean (standard deviation)				
	P02	**P03**	**P04**	**P05**	**MEAN**
4000K LED (15m mounting)	3.42 (0.23)	5.86 (0.16)	3.93 (0.28)	6.90 (0.39)	**5.03 (0.26)**
4000K LED (12m mounting)	3.30 (0.23)	5.69 (0.23)	3.73 (0.27)	6.49 (0.33)	**4.80 (0.26)**
3000K LED (12m mounting)	3.14 (0.22)	5.52 (0.26)	3.68 (0.29)	6.49 (0.30)	**4.71 (0.27)**
No Streetlighting	3.58 (0.28)	6.38 (0.21)	4.29 (0.31)	7.21 (0.25)	**5.36 (0.26)**

Figure 5-8: Mean pupil size of all participants across the various streetlighting zones



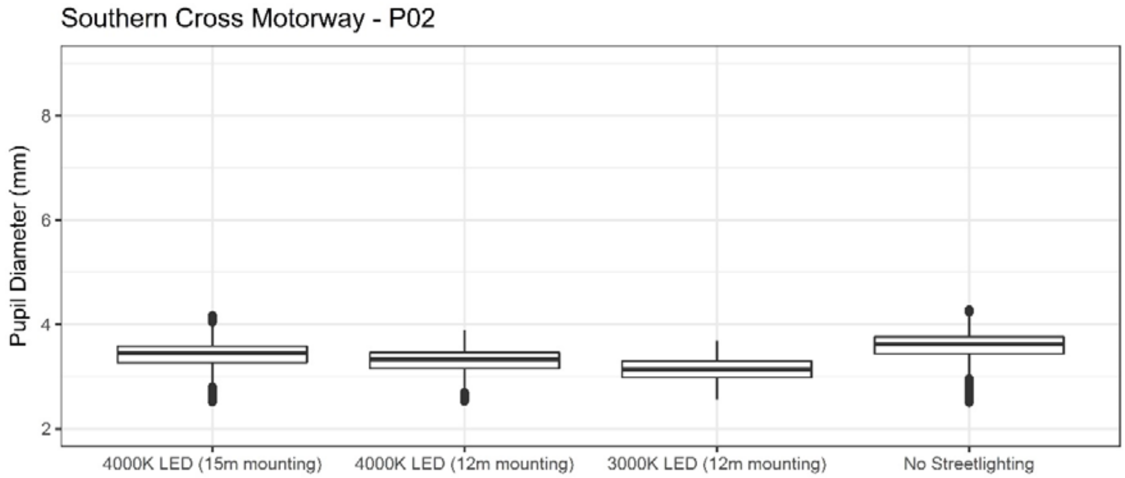
Generalised estimating equations were used to assess for statistical differences between the pupil sizes of drivers across the streetlighting zones. These models account for the repeated measurements of participants between zones. Results confirmed that there were significant differences between the four streetlighting zones (χ^2=168.3, $p<0.001$). In the post-hoc pairwise comparisons adjusted for Bonferroni correction, there was no significant difference in pupil size between the 4000K (15m mounting) and the 4000K (12m mounting) ($p=0.07$), but all other pairwise comparisons were significantly different ($p<0.001$).

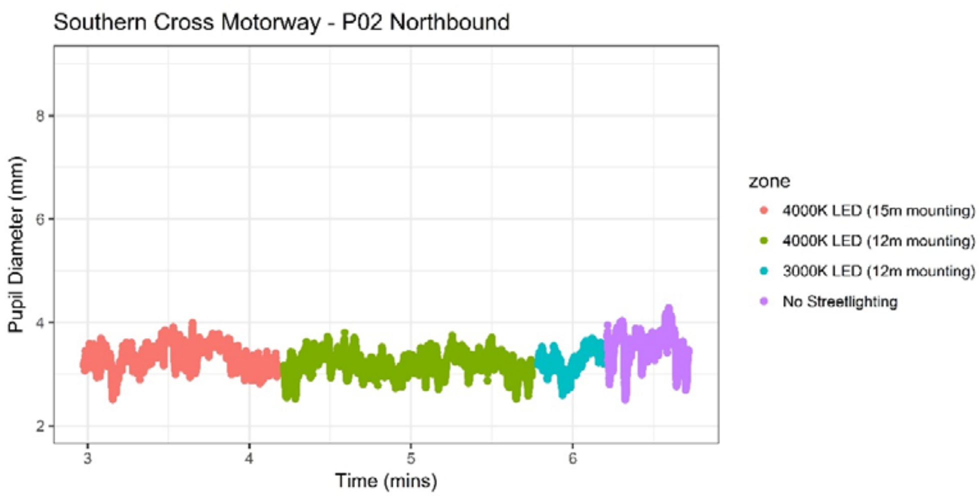
Boxplots of the average pupil sizes, as well as variations in pupil size within these zones for the northbound and southbound drives for each of the four participants are presented in the next section.

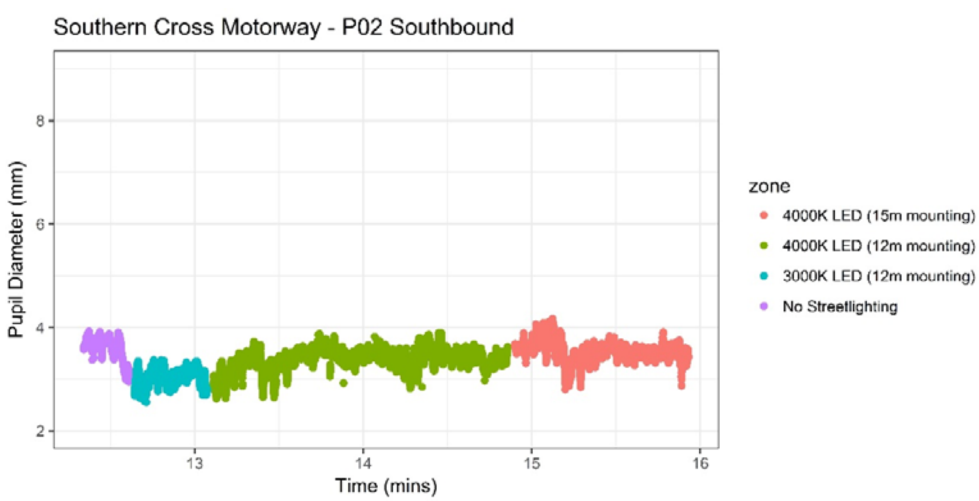
Collectively, these findings confirm that pupil size is sensitive to the effects of streetlighting of different levels and CCT, regardless of the effects of the headlights of oncoming vehicles and other sources of illumination within the road environment. Future studies will be undertaken to further explore these effects on a wider range of participants as well as for different streetlight dimming conditions, in order to better understand the impact that these pupil size differences might have on visual performance while driving at night.

5.3.3 Pupil Data – P02

The following figures present the average pupil diameter for P02 under the various streetlighting zones, and during the north and southbound drives.

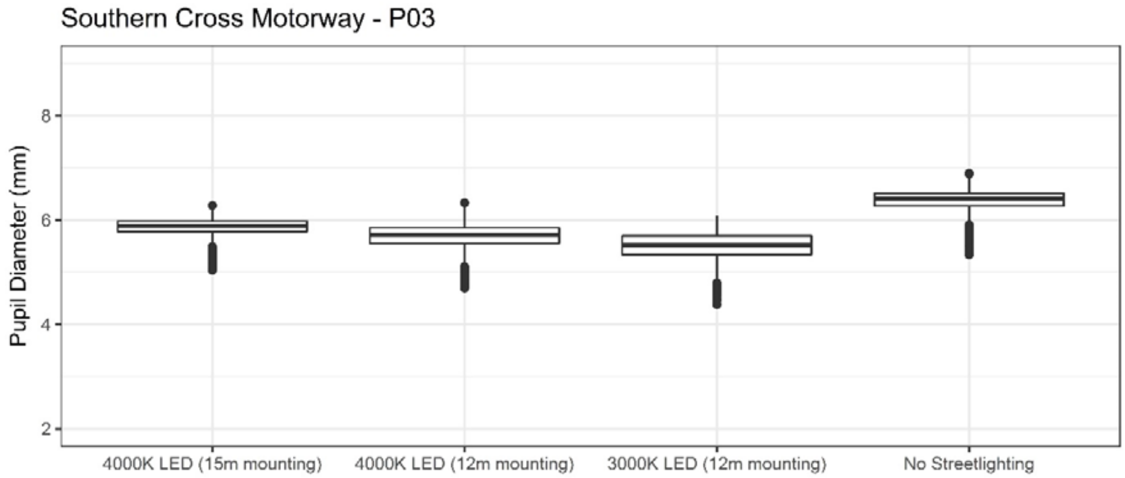


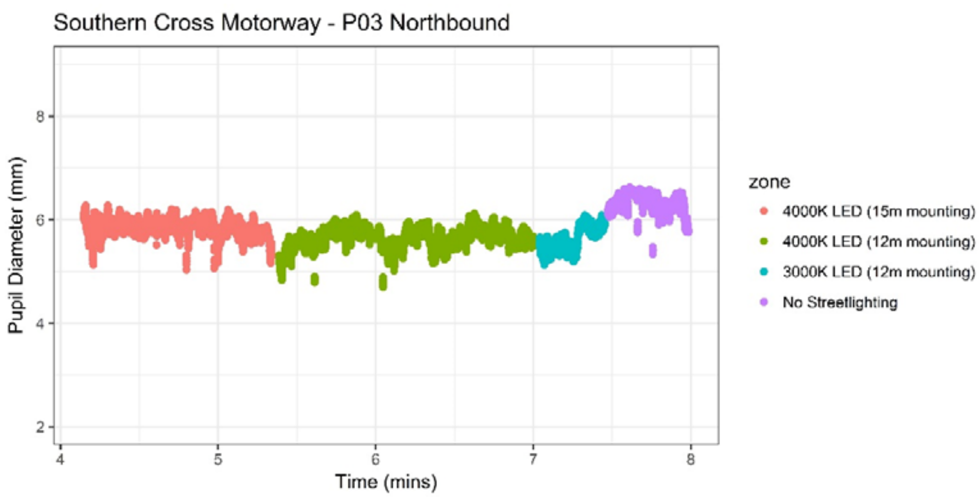


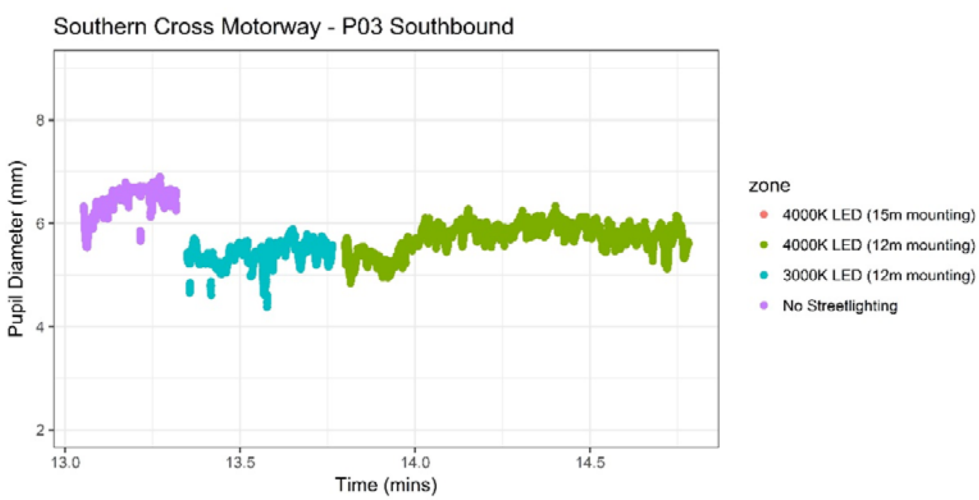


5.3.4 Pupil Data – P03

The following figures present the average pupil diameter for P03 under the various streetlighting zones, and during the north and southbound drives.

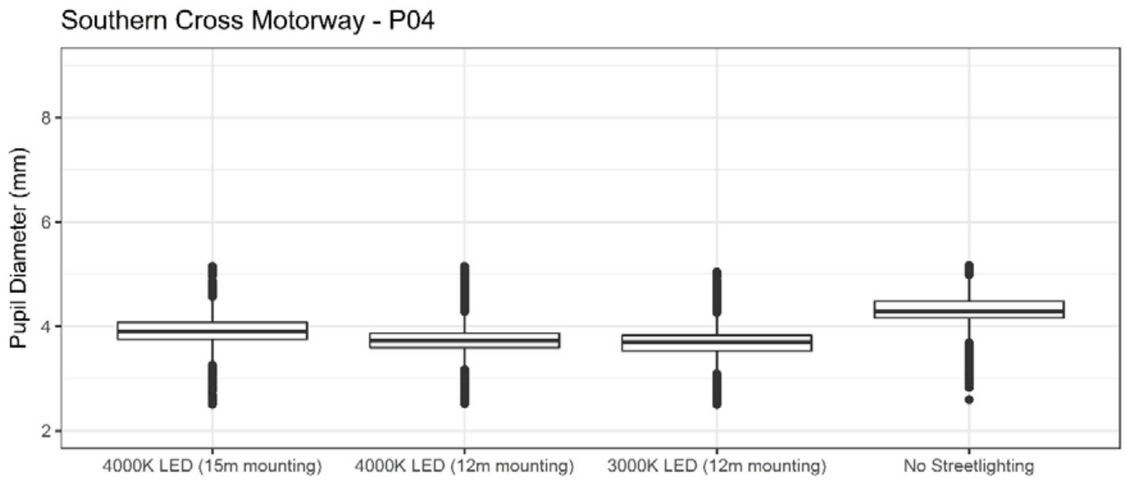


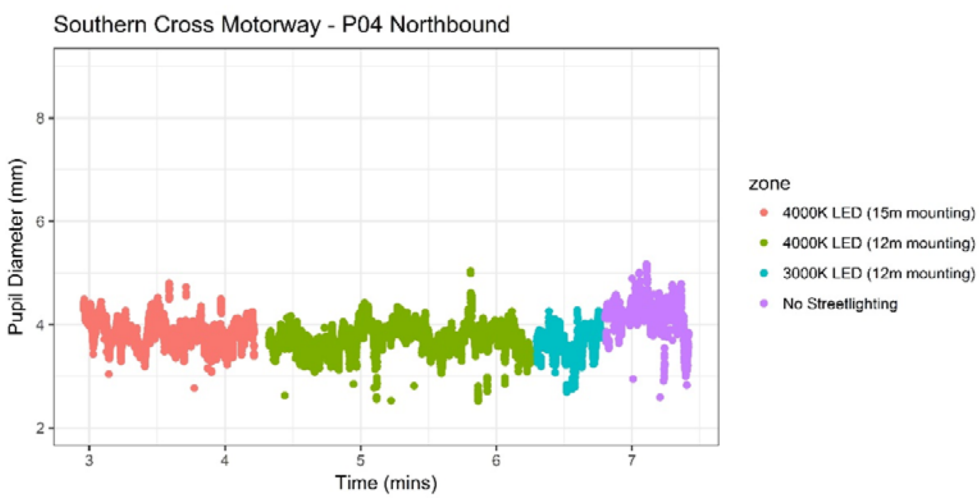


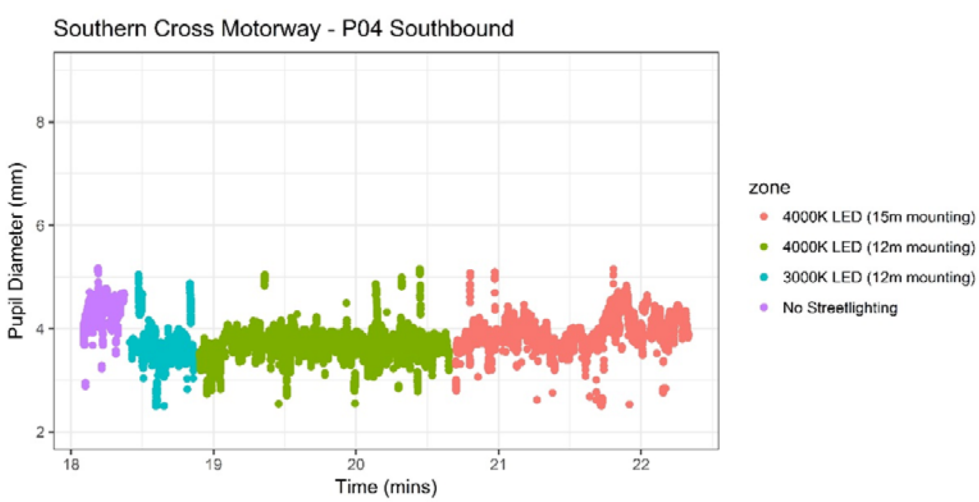


5.3.5 Pupil Data – P04

The following figures present the average pupil diameter for P04 under the various streetlighting zones, and during the north and southbound drives.

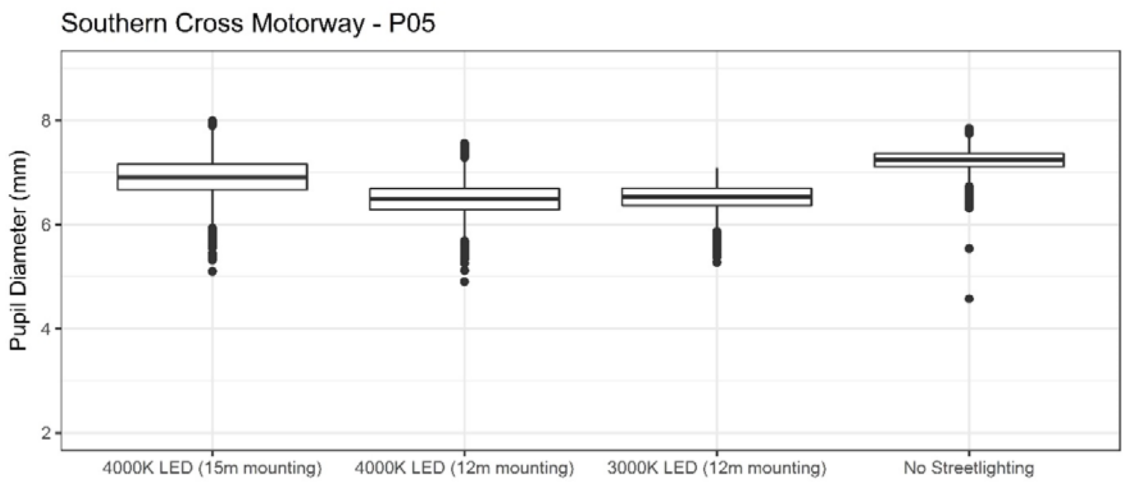


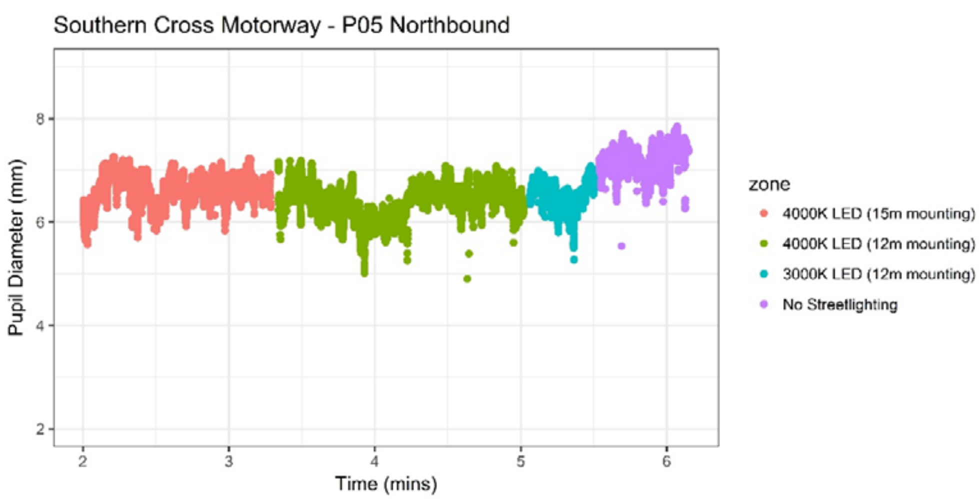


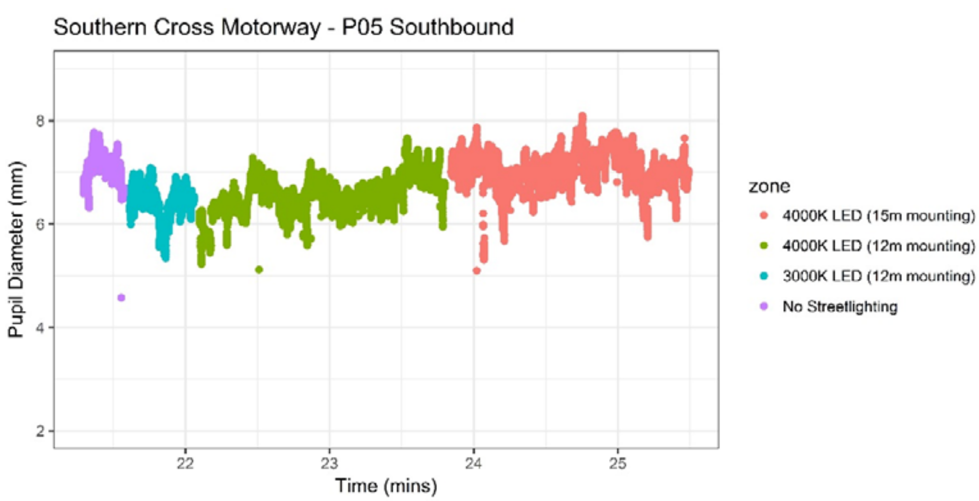


5.3.6 Pupil Data – P05

The following figures present the average pupil diameter for P05 under the various streetlighting zones, and during the north and southbound drives.







5.4 Visual Performance Assessment

Assessment of visual performance under LED streetlighting of different dimming levels has been explored to some extent in studies on a closed road circuit (Gibbons, Meyer et al. 2015, Wood, Isoardi et al. 2018), with targets including roadside pedestrians as well as moving and stationary, and road-based targets. However, this approach is not suitable when conducting such studies under open road conditions in the presence of traffic, where it is not safe to position targets at the side of the roadway. An alternative approach, which we have used in previous studies (Wood, Tyrrell et al. 2011), is to assess visual performance under field-based conditions, where drivers make judgements regarding a range of different targets while seated in a stationary rather than a moving vehicle. This requires access to locations where streetlight dimming is possible and which have pavement areas where targets can be safely positioned.

The pilot experiments involved determination of the configuration of targets required to assess visual performance under LED streetlights at different dimming levels and of different CCT, developing protocols to assess visual performance in the field using these targets and collection of pilot data on participants of a range of ages. A series of targets of different sizes and contrast levels were fabricated in a format suitable for single presentations in a field-based situation, that would enable assessment of visual acuity for high and low contrast targets (the ability to resolve fine detail) and measurement of contrast sensitivity (the ability to resolve low contrast, or faint objects against its background), when positioned at the road side in front of the vehicle.

A quiet street location was selected for the pilot studies, where we were able to undertake the field-based measurements and which provided adequate sighting distance. Participants were seated in the driver's seat of a stationary vehicle (the instrumented 2015 Toyota Camry), with the engine running and low beam headlights. The visual acuity and contrast sensitivity targets were presented by an experimenter located 30 m in front of the vehicle, at chest height which was outside the direct headlight beam of the car, but was illuminated by the overhead streetlighting, to evaluate visual performance relevant to detection of pedestrians and other road users not within the car headlight beam. Targets were presented using pre-determined sequences, from larger to smaller letters and from high to low contrast edges. For the contrast sensitivity measures the effect of reducing light levels using tinted lenses (representing streetlight dimming) was also evaluated to determine whether the targets presented sufficient dynamic range and sensitivity to detect differences in streetlight levels. All testing was conducted binocularly to replicate the effects of normal driving, with participants wearing their habitual refractive correction (spectacles or contact lenses), if any.

5.4.1 High and Low Contrast Visual Acuity

Targets comprised a series of large size, single 'E' targets at a contrast level of either 90% (high contrast or black) or 22% (low contrast or faint grey) (Figure 5-9). Targets were presented singly to the participants, with the orientation of the E being presented randomly by an experimenter (at 30 m from the participant seated in the stationary vehicle) in one of four directions: right, left, up or down.

Figure 5-9: Schematic representation of the high 90% contrast (left) and low 22% contrast (right) tumbling E letters.

For each letter size, five orientations of the target were presented randomly to participants who were required to identify the correct orientation of the E target. If participants correctly identified at least two of the target orientations for a given size, the next smallest size was selected and five orientations of the target presented. Participants were given three practise presentations at the largest target size and then testing commenced. Testing was finalised when participants correctly reported only one of the five target directions for a given size. This procedure was then repeated for the 22% contrast letter E targets.

5.4.2 Contrast Sensitivity (Melbourne Edge Test)

Targets consisted of a series of singly presented large circular targets (28.5cm, 5.4 degree of visual angle at 30 m testing distance), each of which contained an edge, which varied in contrast dependent on the level of contrast sensitivity being measured (Figure 5-10), as per the standard Melbourne Edge Test. Seven targets were created whose contrast levels spanned 10 dB (7, 8.5, 10, 11, 14, 16, 17 dB), which were found to provide sufficient dynamic range to assess participants of a range of ages (19-57 years). Participants were required to indicate at which of four possible orientations they could detect the edge in each of the circles (45 (oblique up and to the right), 90 (vertical), 135 (oblique up and to the left), or 180° (horizontal)).

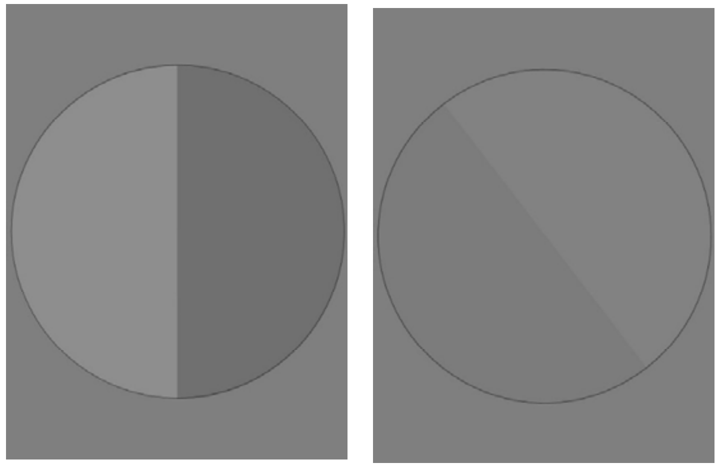


Figure 5-10: Two examples of the contrast sensitivity targets representing a target with a higher contrast edge (left) and a lower contrast edge (right).

For each contrast level, five orientations of the target were presented randomly. If participants correctly identified at least two of the target orientations for a given contrast level, the next contrast level was selected and five orientations of the target presented. Participants were given three practise presentations at the highest contrast level and then testing commenced. Testing was finalised when participants only correctly reported one out of five targets for a given contrast level. This was then repeated for participants viewing through the tinted lenses, to represent the effects of reduced ambient road lighting, as would be the case for streetlight dimming.

Figure 5-11 shows the visual acuity and contrast sensitivity targets being used under field-based road conditions, as per the pilot experimentation.

Figure 5-11: Single targets presented by an experimenter in the field-based pilot studies for contrast sensitivity (left) and a high contrast tumbling E target (right).

5.5 Results

5.5.1 Visual Acuity

The pilot experimentation involved collection of data for three participants (ages 19, 43 and 57 years) and demonstrated that the high and low contrast visual acuity tumbling E targets provided a good dynamic measurement range, with no ceiling or floor effects. Each participant took between 10-15 minutes to measure high and low contrast visual acuity.

As shown in Figure 5-12, mean high contrast visual acuity was -0.07 ± 0.09 logMAR, which was equivalent to 3-4 letters better than 6/6 (normal levels of visual acuity), while mean low contrast visual acuity was +0.24 ±0.11 logMAR, which represents 12 letters (greater than 2 lines) worse than 6/6. The difference between high and low contrast acuity was around three lines, which is in line with what would be expected given the level of contrast used for the low contrast targets.

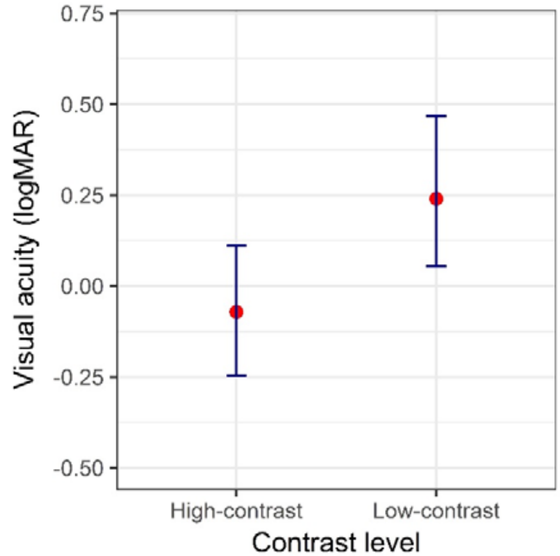


Figure 5-12: Group mean high and low contrast visual acuity measured under field-based road conditions.

5.5.2 Contrast Sensitivity

As for visual acuity measurements, pilot experimentation involved collection of data for three participants (ages 19, 43 and 57 years). The pilot studies demonstrated that the dimensions and the contrast levels provided adequate dynamic measurement range for both the normal streetlighting and dimmed viewing (through tinted lenses) and there were no ceiling or floor effects. Each participant took between 10-15 minutes to measure contrast sensitivity, dependent on the viewing conditions.

Contrast sensitivity data for the participants is presented in

Figure *5-13*, and demonstrates that as would be expected, as contrast levels are reduced the percentage of targets correctly detected reduces. This effect was age dependent, as would be expected, with the youngest participant (age 19 years) being able to detect lower contrast levels than either of the older participants (ages 43 and 57 years). All participants were able to detect 100% of targets, up to a contrast sensitivity level of 10 dB, whereas, for the two lowest contrast targets, correct recognition levels were at 50% or less and less than 25%, ie, at chance levels, for the lowest contrast level.

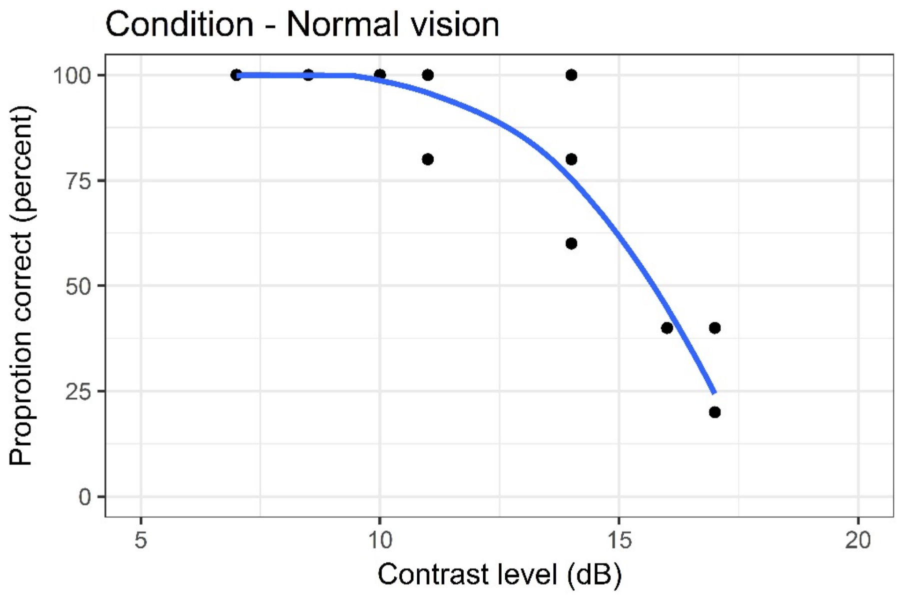


Figure 5-13: Contrast sensitivity measured under field-based conditions for three participants: data are presented as percentage of targets correct as a function of target contrast.

When light levels were dimmed by approximately 85% when viewing through the filter, contrast sensitivity was reduced for all participants, particularly for the lower contrast levels Figure 5-14. It was also evident that there was a greater spread of performance, indicating that at these lower road light levels, the effects of age were exacerbated, with participants either failing to identify the edge direction correctly or detection being only at chance level. Importantly, the range of contrast levels discriminated both between participants and between different levels of streetlighting.

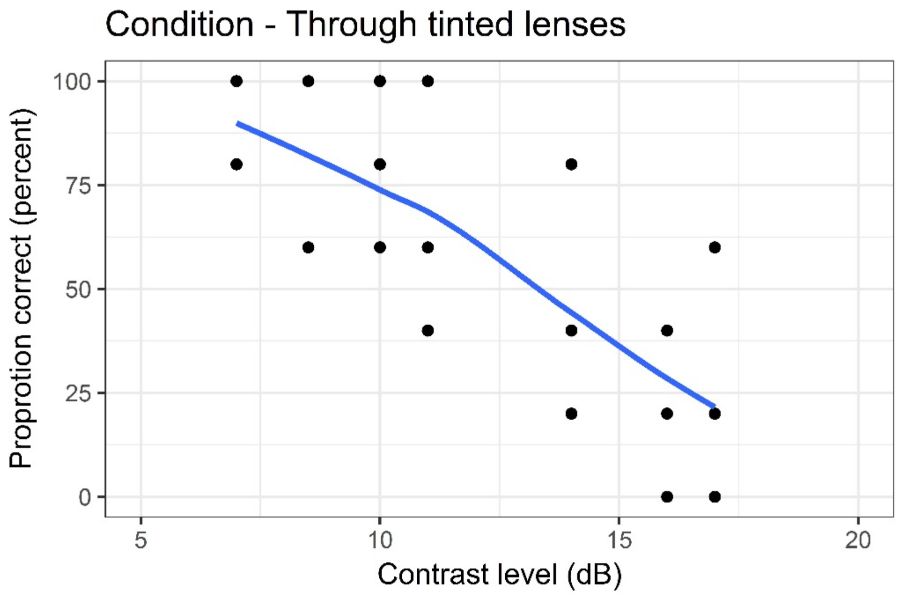


Figure 5-14: Contrast sensitivity measured under field-based conditions for three participants when viewed through tinted lenses to reflect dimmed streetlighting levels; data are presented as percentage of targets correct as a function of target contrast.

Collectively, these data on visual performance demonstrate that using the approaches developed as part of this research, visual resolution for both high and low contrast targets, as well as contrast sensitivity, can be measured within a practical time-frame and that the measures are sensitive to the effects of reduced streetlighting (as reflected by viewing through tinted lenses in our pilot studies). Future studies will explore these effects for a wider range of participants and for different streetlight dimming and CCT characteristics.

6 Qualitative Methodologies

6.1 Self-reported questionnaires

The lighting performance of different streetlighting installations can be measured using a range of quantitative approaches, some of which are outlined in this report. However, it is also important to record the subjective impressions of these different installations, as this can provide insight into the potential impact that these different lighting installations might have on aspects of human performance including vision and driving. Our aim was to incorporate an instrument into our ongoing research that can capture self-reported perceptions of drivers' visibility, glare and safety when driving under the various streetlight levels. Assessment of available literature suggested that available questionnaire instruments capture different aspects of self-reported perceptions that are not well-suited to our main purpose of evaluating perceptions of differences in LED streetlighting at different dimming levels and CCT.

The de Boer scale has been used in previous studies to assess the level of discomfort experienced at night-time from oncoming headlights (Theeuwes, Alferdinck et al. 2002, Fekete, Sik-Lanyi et al. 2010), rather than from streetlighting. The scale has five response options, ranging from "just noticeable" to "unbearable" in response to the questions "How disturbing do you find oncoming headlight glare?" A question regarding discomfort glare was included in our survey but the wording adapted, given that it became apparent, following the pilot drives along roadways illuminated by LED streetlighting, that the level of discomfort glare was very low, and would be even lower under dimmed LED streetlight conditions.

Other available questionnaires have been developed to evaluate different aspects of perception, including, for example, pedestrian reassurance (Fotios 2018) or subjective impressions of lighting quality (Djokic, Cabarkapa et al. 2017) of different streetlighting installations. Our approach involves a newly developed questionnaire instrument with a 5 point response scale, with questions based on group discussions within the research team as well as reference to the wider literature. The questionnaire, which was developed to include a series of eleven key statements, is given below in Figure 6-1.

Pilot data collection indicated that this response measure provides relevant information that can inform the research question and will be incorporated in future field-based research in this area.

	Response Category				
Please state your level of agreement to the following statements on a scale of 1=”Strongly disagree” to 5=”Strongly agree”	1 Strongly disagree	2	3	4	5 Strongly agree
The lighting on this roadway is noticeably uneven and patchy					
The lighting on this roadway is too bright					
The lighting on this roadway makes me feel comfortable to drive					
The lighting on this roadway makes it easy to see the lane markings					
The lighting on this roadway is too dim					
The lighting on this roadway made the road feel more expansive					
The lighting on this roadway made the colour of surrounding vegetation (i.e. roadside trees/bushes) more discernable					
The lighting on this roadway made detection of other road users easy					
The lighting on this roadway made visibility generally poorer					
The lighting on this roadway made everything look crisper/cleaner					
The lighting on this roadway was glarey and uncomfortable					

Figure 6-1: Questionnaire containing key statements relevant to driving in roads with streetlighting of different technologies, CCT and dimming levels.

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