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A concise review of the impact of LED streetlighting on human sleep

Prepared for Waka Kotahi NZ Transport Agency

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1 Introduction

This report reviews the impact of streetlighting on human sleep patterns. The human body has a 24 hour circadian rhythm, the characteristics of which are largely determined by the light environment. The light which controls the circadian rhythm also powerfully impacts the body's endocrine system which results in behavioural impacts and health impacts when the normal functioning of the endocrine system is disturbed. .. One of these impacts can be sleep disturbance.

Melatonin is a hormone produced by the body and is intimately related to circadian rhythms. These rhythms impact the levels of melatonin in the blood and saliva.. Saliva or plasma Melatonin levels compared with the normal range of melatonin levels at different times of the day are often used a s a surrogate for sleep and circadian rhythm disturbance.

An important determinant of the circadian rhythm is light stimulation of the cells of the retina. It is known that bluer light preferentially stimulates these cells so excessive blue light is an important causative factor in these disturbances.. Too much lighting at night can suppress melatonin production which may indicate disturbed sleep patterns. and circadian rhythms. The amount of light necessary to disturb the daily melatonin rhythm is considerably higher than that required to merely change melatonin levels.

This review looks at three sources of information:

- Field measurement of circadian impact metrics near streetlighting sources
- Naturalistic measurements of human melatonin levels near streetlighting
- Measurements of human melatonin levels after exposure to LED light in a variety of situations.

Conclusions are then made regarding the likely impact of LED streetlighting on human sleep based on circadian impact metrics and night melatonin levels as a surrogate for the impact of the lighting on sleep...

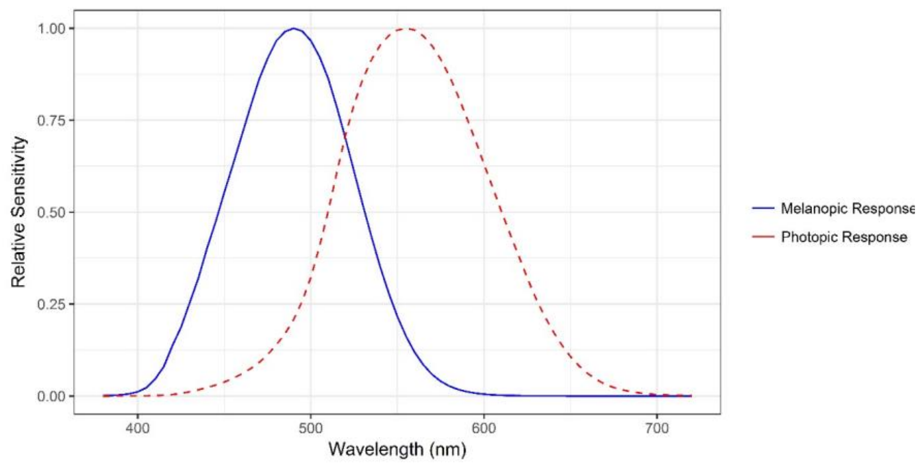
2 Field circadian impact measurements near streetlighting sources

Wood et al (2019) studied the potential circadian impact of streetlighting by measuring metrics related to that impact. The measurements were made at positions beneath the lights and also at the boundaries of residential properties adjacent to the lights.

2.1 Metrics used by Wood et al (2019)

According to Wood et al (2019) the release of melatonin is controlled via responses of specific cells in the retina called the melanopic retinal ganglion cells (mRGCs).. The spectral sensitivity of the mRGCs is measured by a metric known as the Equivalent Melanopic Lux (EML). This allows provision of an action spectrum for the circadian response . *Figure 2-1* depicts the mRGC action spectrum with the photopic curve V(λ) for reference,

Figure 2-1: The mRGC action spectrum and the photopic curve V(λ) (From Wood et al (2019),



It is apparent that the melanopic response is considerably biased towards the bluer wavelengths compared to the Photopic Response.

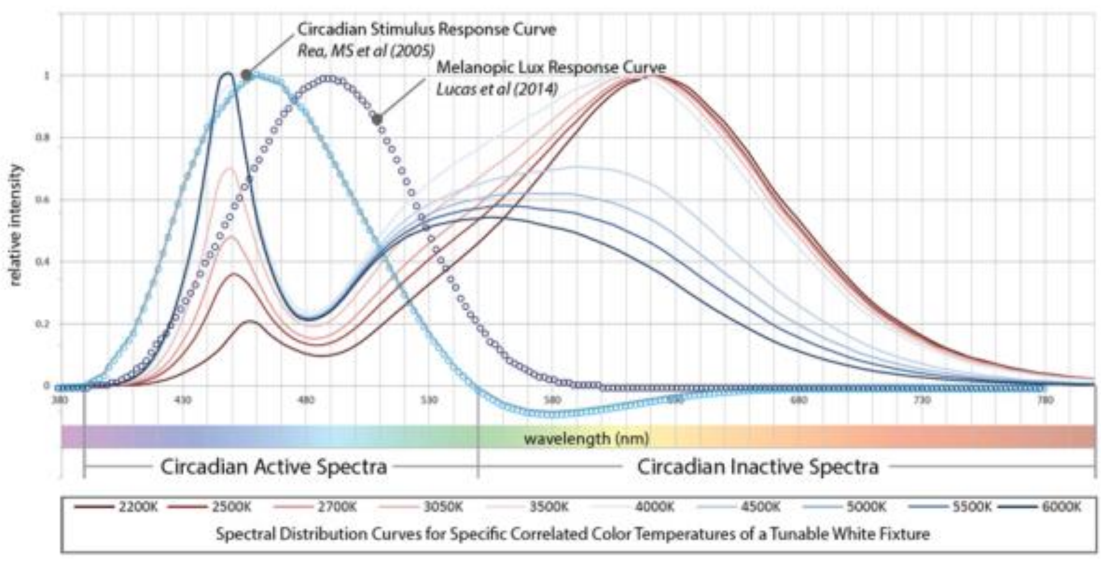
Some researchers (e.g., Rea, Figueiro et al. (2005) and Figueiro, Gonzales et al. (2016)). believe that the mRGCs are not the only retinal cells influencing circadian rhythms. Accordingly different metrics based on empirical measurement. have also been used by Wood et al (2019) to provide greater robustness.

One metric named Circadian Stimulus (CS) is described in the US Department of Energy Building Energy Data Exchange Specification (BEDES)[1] thus:

This metric indicates how well a one-hour exposure to a light source producing a certain light level and wavelength of light stimulates the circadian system, based on its ability to suppress the hormone melatonin. It ranges from 0.1, the threshold for circadian activation, to 0.7, which represents saturation.

Figure 2-2 from Wood et al (2019) quoting Clark and Lesniak (2017) depicts Melanopic and Circadian stimulus response curves for lighting of different colour temperatures.

Figure 2-2: Melanopic and Circadian stimulus response curves [from Clark and Lesniak (2017)]

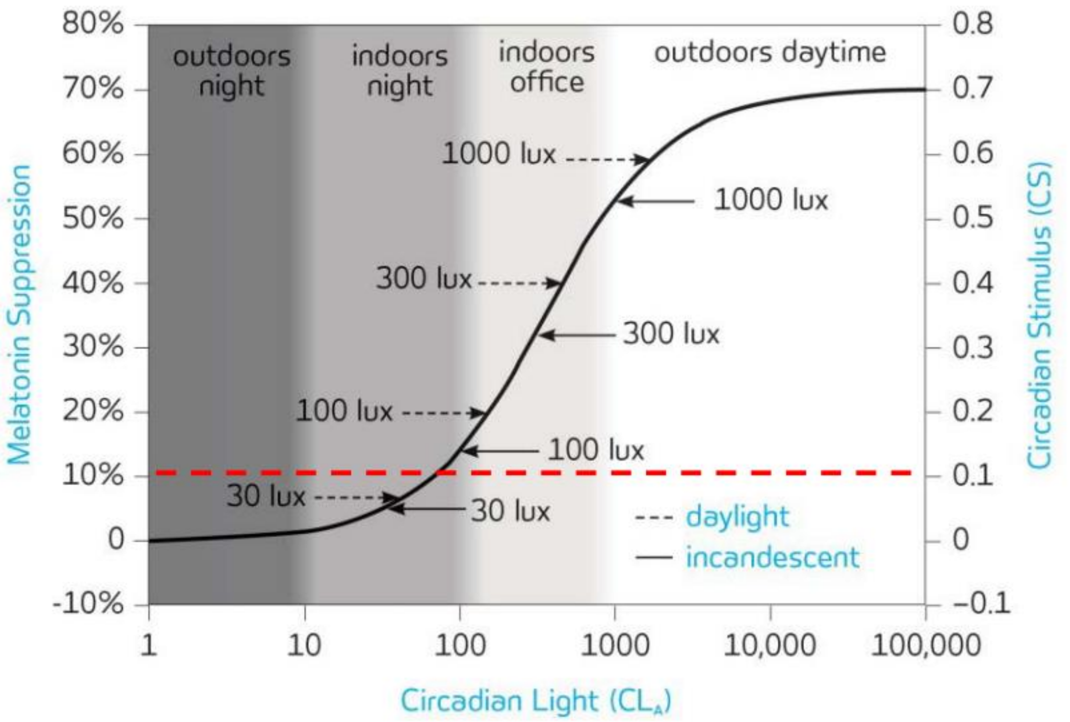


[1] Building Energy Data Exchange Specification (BEDES) | BEDES (lbl.gov)

It is apparent that both the CS curve and the EML curve peak in the bluer, circadian active, part of the spectrum and that the portion of a light's spectrum in that area decreases with decreasing CCT.

Circadian Light (CLA)is another metric related to CS used by Wood et al (2019) According to Wood et al (2019), :CLA measures the spectral irradiance of a source, weighted by the spectral sensitivity of the circadian system "assessed by acute melatonin suppression after one hour of exposure" (Page 43). Figure 2-3 Illustrates the relationship between CLA, CS and melatonin suppression.. The red dashed line represents the threshold below which melatonin suppression is less than 10%.

Figure 2-3: Graph of acute melatonin suppression at one-hour exposure according to Circadian Light (CLA) and Circadian Stimulus (CS) measures, from Figueiro and Gonzales et al.(2016), as quoted by Wood et al (2019).



2.2 The field measurements of streetlights made by Wood et al (2019)

Wood et al(2019) evaluated the impact on the circadian system of streetlighting using irradiance measurements at the eye. These irradiance measurements were weighted using the photopic response curve, the CS response curve and the EML response curve to achieve a high level of robustness. Calculations were made at 1 nm intervals, using the calculators from the research groups that developed the metrics: These were:

- Melanopic Lux Toolbox from Lucas Group at University of Manchester[2] ·
- Circadian Stimulus Calculator from Lighting Research Center at Rensselaer Polytechnic institute[3]

Field readings were taken of horizontal irradiance directly under the luminaire at 1.5 m above the road surface. This simulated a person standing under the streetlight looking up at it. This is useful as a 'worst case' scenario situation. Table 2:1 depicts the maximum measurements taken in this position for CS, CLA, EML and illuminance.

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[2] http://lucasgroup.lab.manchester.ac.uk/measuringmelanopicilluminance/
[3] CS Calculator (rpi.edu)

Table 2:1:Maximum irradiance-based measures from street lighting scenarios (directly below light source).(Adapted from Wood er al(2019)

	3200K LED	4000K LED	5900K LED	HPS
Illuminance (lux)	9	13	5	23
Circadian Light (CLA)	9	9	6	8
Circadian Stimulus (CS)	0.0118	0.0114	0.0075	0.0106
Equivalent Melanopic Lux ,	5	9	4	5

None of the lights used reached the CS threshold for melatonin suppression of 0..1. with the values in Table 2:1 being consistent with 'outdoors night' light (Figueiro, and Gonzales et al. (2016).

The above CS thresholds were also not met by assessments of light at residential boundaries adjacent to the streetlights

Table 2:2 depicts maximum values measured for spill light at the property boundary (vertical illuminance at 3 m above the ground) and equivalent circadian measures compared to some other relevant light sources.

Table 2:2: Maximum values measured for spill light at the property boundary (vertical illuminance at 3 m above the ground) and equivalent circadian measures compared to some other relevant light sources (Adapted from Wood et al., 2019).

	Illuminance (lux)	Circadian Light (CLA)	Circadian Stimulus (CS)	Equivalent Melanopic Lux (EML)
Exterior Sources Streetlighting, max reading at residential boundary @ 3 m height				
3200K LED 18W	3.0	2.8	0.0034	1.6
4000K LED 20W	3.4	2.2	0.0026	2.3
5900K LED 17W	3.6	4.1	0.0051	2.8
HPS 70W	4.8	1.7	0.0019	0.9
Interior Sources Room Lighting, Standing Activity				
Fluorescent 3500K 36W	78	80.3	0.114	42
LED 4000K 9W	150	87.5	0.123	100
LED 3000K 9W	85	82.5	0.116	45
Technology Devices, Seated Activity				
TV @ 3.5m	5	8.4	0.011	5.1
Computer @ 0.7m	49	87.5	0.112	47
Laptop, Max Brightness @ 0.5m	5ti	61.2	0.088	49
Smartphone, Max Brightness @0.3m	45	87.5	0.112	44

This spill light relates to that traveling towards windows of the nearest residences. As illuminance decreases with the inverse square of the distance from the light source these property boundary measurements will consistently exceed actual values at the residence itself.

2.3 Conclusions

It can be seen that the readings of the streetlighting sources for all the measures are well below those of room lighting sources and technology devices and according to Figure 2-3 the CLA and CS values correspond to very little, if any, melatonin suppression. This was irrespective of the CCT of the light source, indicating that even a 5900K LED is unlikely to be a source of sleep disturbance.

3 Naturalistic measurements of the impact of streetlighting on human melatonin level

3.1 The work of Gibbons et al (2022)

3.1.1 Background to the work

Gibbons et al (2022) is a contribution to a continuing debate about the impact of street lighting on sleep disturbance, using the human production of Melatonin as a surrogate measure The impact of specific sources of light on Melatonin production is hard to judge in a naturalistic setting. That is because there are many sources of light which can influence melatonin levels, like vehicle headlights, billboards, industrial lighting. which would confound any attempt to isolate out the streetlight related impact. Gibbons et al (2022) attempted to step around this problem by carrying out a set of naturalistic experiments on a relatively isolated test track (Figure 3-1) to avoid as much as possible other light sources. The study involved three groups of subjects: vehicle drivers, pedestrians, and people in a room containing a bed near the roadway, to simulate occupants of roadside homes.

Figure 3-1: The test track used in the study (Room containing a bed is to the right)

3.1.2 Hypotheses tested.

The following two hypotheses (Gibbons et al, 2022, p. 634) were tested:

- *that saliva melatonin levels will be suppressed due to the exposure to light from typical roadway lighting levels as experienced in separate cohorts of vehicle drivers, pedestrians and individuals experiencing light trespass in their homes.* I
- *that light sources with higher blue content will suppress the saliva melatonin levels more than sources with lower blue content.*

3.1.3 Study participants

The Study participants were as follows.

- *Drivers: 5* males (M = 27.2 years, SD = 3.49 years) and 5 females (M = 26.2 years, SD = 2.59 years).
- *The light trespass group*: 5 males (M = 24.2 years, SD = 3.11 years) and 5 females (M = 23.61 years, SD = 3.71 years)
- Pedestrians: 5 males (M = 24.4 years, SD = 4.15 years) and 4 females (M = 21.5 years, SD = 4.72 years)

3.1.4 Sampling of melatonin

Saliva melatonin was used rather than blood plasm melatonin for the field study as the taking of blood in the field could not be justified for health and safety reasons nor by the Virginia Tech Institutional Review Board. Both types of testing were able to be used in the laboratory-based control study.

3.1.5 Preconditioning

Previous exposure to light may impact melatonin levels. To partially control for this the participants sat in a light conditioning space lit to 200 lux by a 4000k luminaire before engaging in the experimental sessions. The paper does not state how long they had to stay in the space. To represent an office or residential environment 200lux was chosen. This makes comparisons with other studies more problematic as most controlled laboratory studies on the impact of light on Melatonin levels precondition participants in a dim[4] or dark background.

3.1.6 Baseline control sessions

The experimental sessions included indoor control sessions and on-road sessions The indoor sessions included measurement of participants' plasma and saliva melatonin concentrations. The on-road sessions measured only saliva melatonin concentrations. This was for health and safety as well as ethical reasons. The control sessions were to check that:

- the participants demonstrated a normal melatonin rise in darkness.
- a normal melatonin suppression under bright light exposure
- and to verify the relationship between saliva melatonin concentrations and blood melatonin concentrations.

3.1.7 Participants' melatonin responses to changes in lighting level

Each participant took part in the control sessions during the two weeks prior to the experimental session which happened in booths where the lighting could be varied. The time periods of exposure of the participants to the control conditions were the same as in the experimental conditions. Both a lit "positive control" where a melatonin suppression was expected and a dark

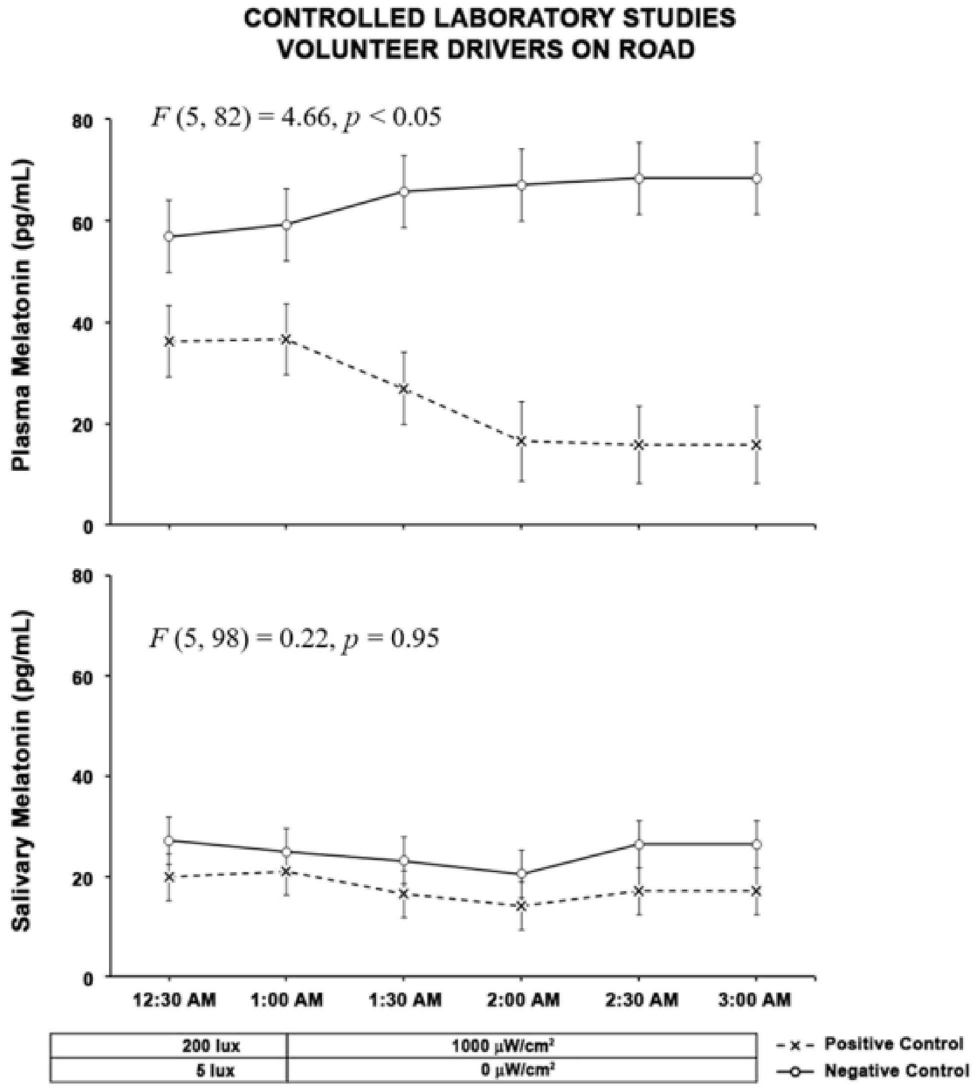
[4] Dim lighting has no universal definition and levels used in the literature vary.

"negative control" where a normal rise in melatonin was expected were used. The control sessions verified that the participants showed the expected melatonin responses to light.

3.1.8 Relationship between the saliva melatonin of participants and their blood plasma melatonin

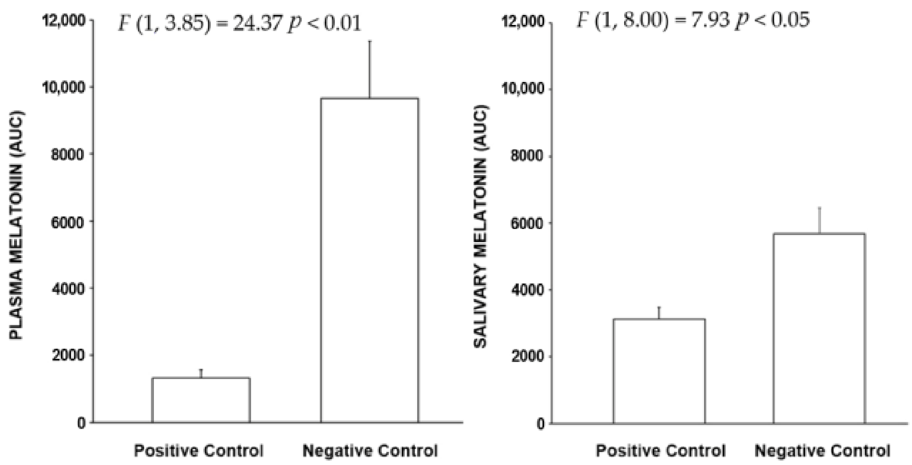
In the controlled lab tests the plasma melatonin response to light changes was much more pronounced than that of the saliva melatonin. This would indicate that had the experiment been able to be carried out with blood testing the inconclusive results (discussed later) may possibly have become conclusive. The relative lack of response of saliva melatonin change to light changes is illustrated in Figure 3-2

Figure 3-2:Laboratory changes in saliva and plasma melatonin during the study period of people in the sample of drivers.



The response is as expected for the plasma melatonin but is anomalous for the saliva melatonin as it as it shows a downward progression for the first 1.5 hours in both the lit and unlit cases with increases from 2am. However, when the AUC (Area under the curve) is examined, there is a difference between the lit and unlit conditions, and this is in the expected direction (see Figure 3-3). The AUC is a measure of the impact of melatonin on the blood plasma/ saliva over the exposure time.

Figure 3-3: AUC plasma and saliva melatonin levels for the lit and unlit conditions for the driver sample.



Similar exercises were completed for the people in the other samples, with broadly similar results.

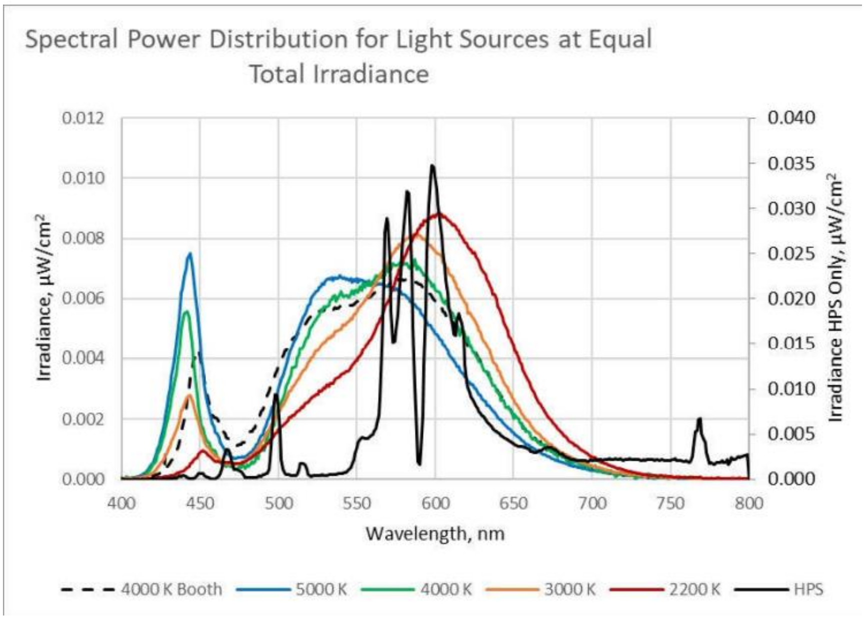
3.1.9 Experimental Sessions

3.1.9.1 The experimental conditions

The participants were exposed to five different LED light sources and the previously mentioned 200lux condition..

The Spectral Power Distributions (SPDs) of the sources are shown in Figure 3-4.

Figure 3-4: SPDs of the light sources



The exposure times were drivers 1 am to 3 am, pedestrians 10 pm to 2 am, and light trespass group 12 am to 2 am. The luminaires were set up to provide 1.0 cd/m2 average luminance on the roadway. This is a similar level to that provided on motorways/ expressways in New Zealand when they are lit.

3.1.9.2 Experimental results

The results for the three experimental groups are shown in **Error! Not a valid bookmark self-reference.**, Figure 3-6 and Figure 3-7.

Figure 3-5:Pedestrian AUC saliva melatonin levels for different light sources

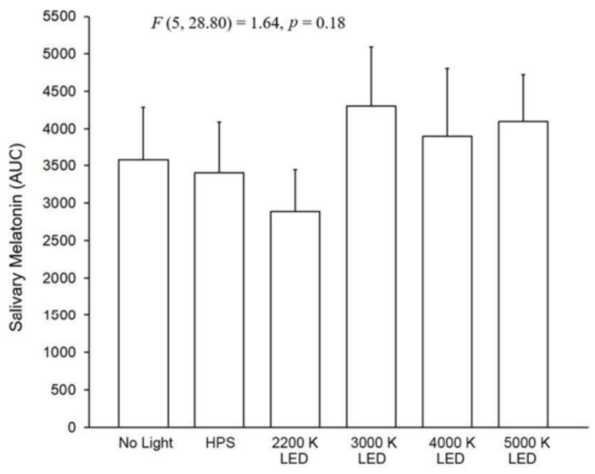


Figure 3-6: Light trespass group AUC saliva melatonin levels for different light sources

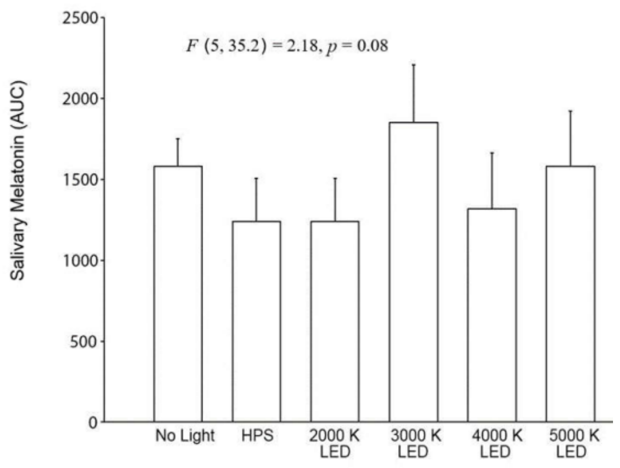
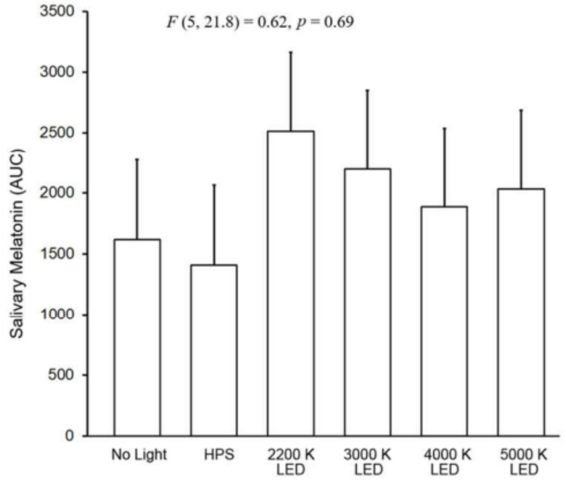


Figure 3-7:Driver AUC saliva melatonin levels for different light sources



The pedestrians under lit conditions generally had higher saliva melatonin levels than the other groups. This could be attributed to their exposure time being double that of the other groups.

However, they also had higher melatonin levels than the other groups without light. No explanation for this is attempted by the authors. As can be seen from the f values displayed there was no significant relationship found for any of the groups between saliva melatonin and the type of light source. There was no consistent increase as the SPDs from the luminaires increased..

3.1.10 Statistical method

The statistical method used was one where the mean levels for each group of participants were compared for the prior 200lux condition and for the different light sources. This type of method is less precise than a method where the individual differences of each participant are used. This could have been attempted by comparing the differences between the lit state and the unlit state for each source and the individuals in each group. That would have yielded a set of differences for each group based on the individuals in the groups and more precise paired sample tests could then have been used.

3.1.11 The statistical test results.

3.1.11.1 Discussion

The two null hypotheses of the study were:

> *that saliva melatonin levels will be suppressed due to the exposure to light from typical roadway lighting levels as experienced in separate cohorts of vehicle drivers, pedestrians and individuals experiencing light trespass in their homes.*
>
> *that light sources with higher blue content will suppress the saliva melatonin levels more than sources with lower blue content.*

In both cases the study yielded null results, which arguably could have been suspected as probable given the results of the prior laboratory study. In the prior laboratory study. the difference between dark and light was 0 lux to 200 lux and the AUCs were not significant for light trespass and significant for pedestrians and drivers.

In the experiments, the differences were between < 0.03 lux and 1.5 lux., a much smaller difference for the same numbers of participants as in the prior laboratory study.

Thus, the lack of a significant difference overall is not surprising.

What is surprising is the lack of difference between the impact of the different types of luminaires. This was obvious from inspection and did not really need a statistical test to be established.

3.1.11.2 In practical terms what do these results tell us?

They do not tell us a lot. This is because the practical question is whether the change is important from the point of view of sleep disturbance, rather than statistical significance. To tell us whether it is likely to be a sleep disturbing rise, we need to look at the wider literature. The charts showing maximum AUC[5] do not help with comparisons as all other literature unearthed looks at saliva levels rather than AUCs.

Also, the AUC units are not shown In Gibbon et al (2022), so if AUC levels were available from other literature, comparison would still be difficult. Therefore, it was necessary to read approximate maximum levels of saliva melatonin directly off the appropriate charts In Figure 7, page 641 of Gibbon et al (2022). These were read for the lit condition and the prior 200 lux condition.

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[5] Area under the curve - a measure of the impact of melatonin on the saliva over the exposure time

From the charts the maximum saliva melatonin levels over the experimental period were approximately as shown in *Table 3:1*.

Table 3:1 :Approximate maximum average saliva melatonin levels for each experimental group from Gibbons et al (2022) during the experimental period

	Drivers (Figure 7 of Gibbons et al (2022)	Pedestrians (Figure 9 of Gibbons et al (2022)	People subject to light trespass (Figure 11 of Gibbons et al (2022))
With light	. 21pg/ml)	15pg/ml	15pg/ml
200 lux prior condition	14pg/ml	20pg	12 Pg/ml

These differences are not large and in the case of the pedestrian, the melatonin levels reduced in the presence of the lights.

3.2 The work of Bhagavathula et al (2021).

3.2.1 Impact of streetlighting on driver alertness and sleep health

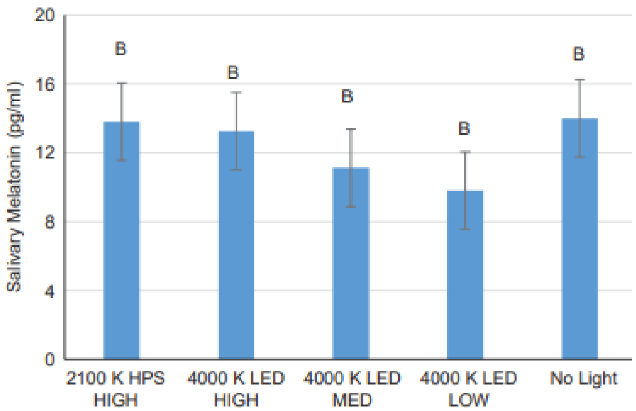
The same team as Gibbons et al (2022) carried out experimental work aimed at determining the impact of LEDs as an indicator of driver alertness and sleep health. This was published as Bhagavathula et al (2021). Sleep health was measured using saliva melatonin testing. . The study used 10 healthy participants between 18 and 30 years with steady sleep-wake cycles. The luminaire CCTs and lighting conditions used are as laid out in see *Table 3:2*. The exposure time for saliva melatonin was 1 am to 3 am and five saliva samples were collected at 30-minute intervals. The prior condition was no light while that in Gibbons(2022) was 200 lux.

Table 3:2 Luminaire CCTs and lighting conditions Bhagavathula et al (2021)

Luminaire CCT	Lighting conditions
2100 K HPS	High (1.5 cd/m^2)
4000 K LED	High (1.5 cd/ m^2)
4000 K LED	Medium (1.0 cd/ m^2)
4000 K LED	Low (0.7 cd/ m^2)
No luminaire	(Less than 0.05 cd/ m^2)

The results are shown in Figure 3-8.

Figure 3-8: Effect of light condition on mean saliva melatonin. Levels with standard errors (Derived from Bhagavathula et al, 2021, p 41).



It is apparent that the saliva melatonin is never raised compared with the no light condition.

3.2.2 Illuminance dose at eye from streetlighting and other light sources

Other results from Bhagavathula et al (2021) related to Illuminance dose at the eye from streetlighting and other light sources are represented in the form of charts in Bhagavathula (2022). Firstly, the illuminance dose at the eye from a 4000K LED was compared with that of electronic devices commonly used in the home in the evening hours leading up to sleep when they are in full brightness mode (Figure 3-9) and when they are in night /dark mode (Figure 3-10).

Figure 3-9: At eye Illuminance dosage from electronic devices in bright mode devices compared to 4,000 K LED Bhagavathula (2022).page 28.

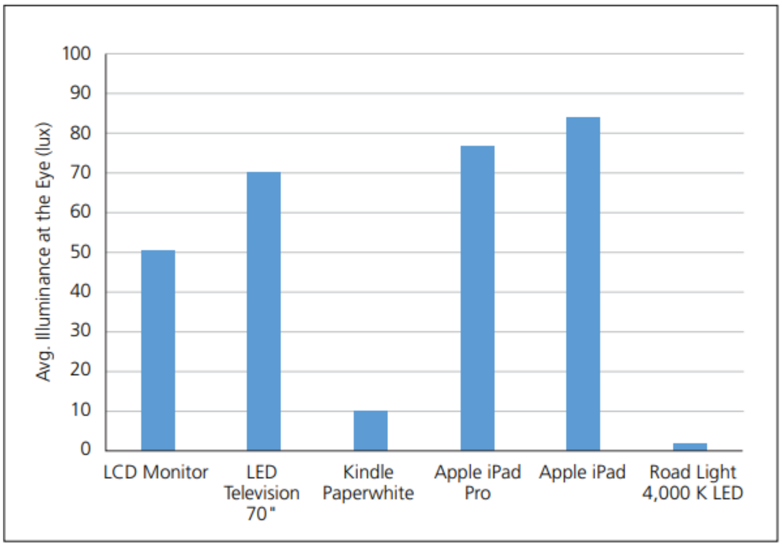
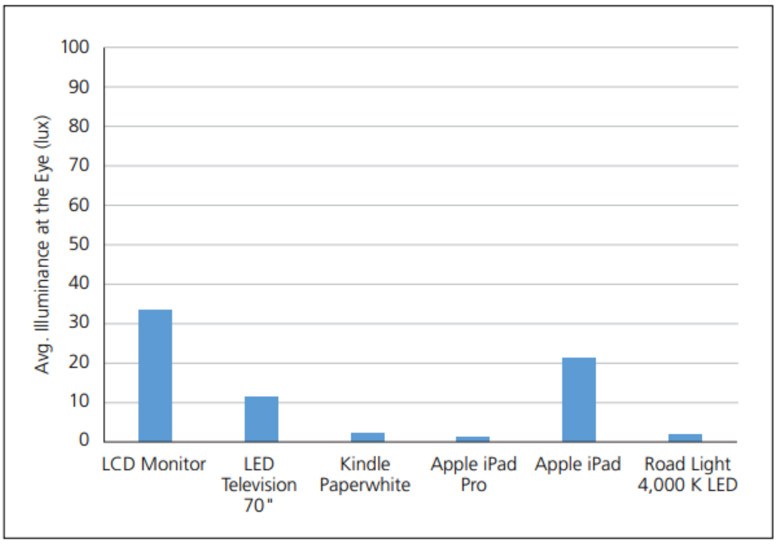


Figure 3-10: 3 At eye Illuminance dosage from electronic devices in dark/night mode compared to 4,000 K LED Bhagavathula (2022).page 28.



It is apparent that the impact of the 4000K LED is small compared to the devices in full brightness mode and comparable only to the Kindle and the iPad Pro when they are in night/dark mode. The exposures used were for a 2 hour duration.

Overall, the study results indicated that:

- LED roadway lighting at light levels up to a luminance of 1.5cd/m^2 does not significantly suppress saliva melatonin between 1:00 am to 3:00 am in healthy drivers.
- The impact of LED lighting on saliva melatonin suppression was not significantly different from HPS at similar lighting levels (1.5 cd/m^2) or from no lighting.

- No statistically significant differences between any of the roadway lighting conditions for detection distance and colour recognition distance.

- the impact of a 4000K LED is small compared common electronic devices in full brightness mode and comparable only to the Kindle and the iPad Pro in night/dark mode.

These findings are in accord with those of Gibbons et al (2022). The experimental conditions differed from those of Gibbons et al (2022) in that the roadway illuminance was 1.2 cd/m^2 rather than 1.0cd/m^2. Also, the saliva melatonin levels obtained were well within the range of variation of *such levels found in the literature.*

3.3 Conclusions

- The statistical results from Gibbons et al (2022) and Bhagavathula et al (2021). tell us that their tests of the impact of streetlighting on their participants could not detect any difference between the streetlighting condition and the prior conditions (200 lux for Gibbons et al (2022) and no light for Bhagavathula et al (2021).,. No differences were not found for lights of differing CCT.

- Comparisons of illuminance at the eye for LED streetlighting and common electronic devices found similarities only from the Kindle and the iPad Pro in night/dark mode.

- The lack of statistical significance of the results cannot be taken as an indication that melatonin levels were not disturbed. This is because of the small-scale nature of the experiment. and the relative insensitivity of saliva melatonin compared to plasma melatonin to circadian changes. Similar remarks may be made regarding the results of Bhagavathula et al, (2021) However, neither is there any evidence that they were disturbed.

4 Results of Gibbons et al (2022) and Bhagavathula et al (2021) compared to the wider literature.

It is useful to compare these results with unlit and dimly lit night melatonin levels from the wider literature. Much Information on night-time saliva melatonin levels in the literature is for people with medical conditions. This makes the information atypical and excludes it from this report. However, some information is available.

Ito et al (2013) sampled the bedtime saliva melatonin of 47 young Japanese women and compared it to their daytime melatonin levels. The daytime average was 2.46 pg/ml (SD 0.62) and the bedtime average was 29.6 pg/ml (SD 18.23). Gibbons' results are lower than these bedtime results… Gibbons' tests were done over a 4-hour and 2-hour periods in the night rather than bedtime so some difference from a bedtime level could be expected. The results of Ito et al (2013) also show that day and night-time melatonin in the sample varied widely between individuals.

Harada et al (2004) examined the impact of bright light (2000 lux) and dim light (60 lux) from fluorescent light bulbs for the three hours from 19:30 to 22:30 on saliva melatonin concentrations from 19.45 to 23:40 (see
Figure *4-1*). The bright light had a high but unspecified CCT and the dim light a lower but unspecified CCT.. Both the bright light and dim light participants comprised two females and three males aged 14–15 years. In the 60 lux dim light the saliva melatonin level increased rapidly from 3.00 pg/ml to 9.18 pg/ml in just under 2 hours (from 21:45 to 23:40). In bright light, saliva melatonin remained at less than 1.3 pg/ml. This work indicates that dim light at a higher lux level than street lights[6] may increase melatonin levels in 14-15 year old Japanese girls.

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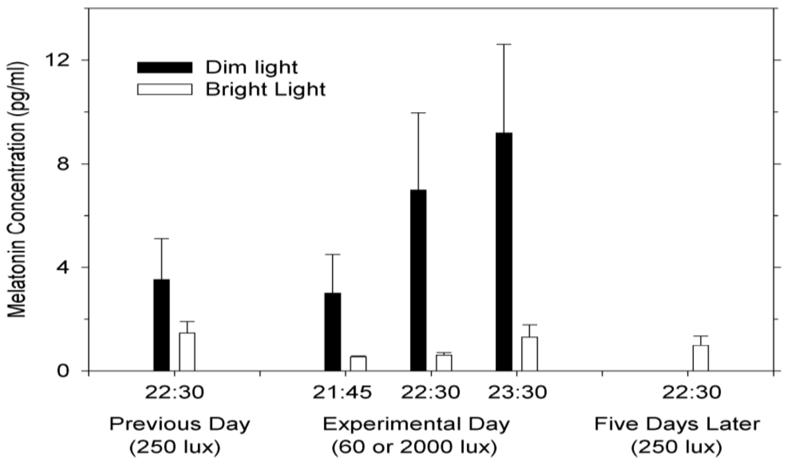
[6] According to [How many Lux is a street light? – Short-Question] streetlight lux can vary from 4 to 10 lux

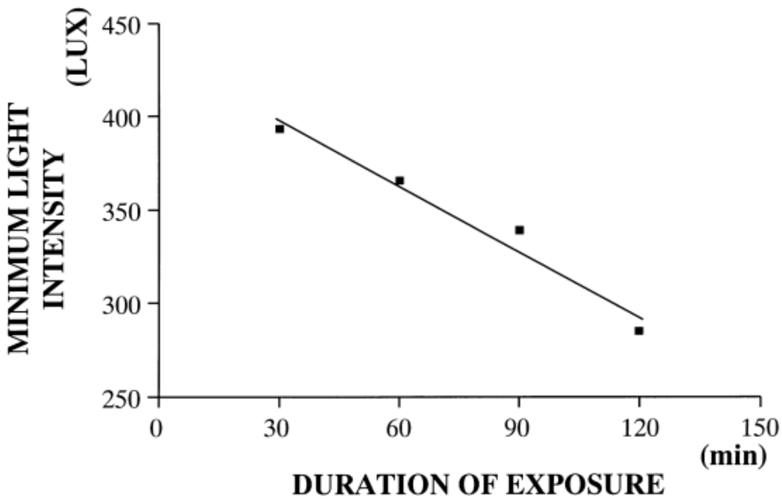
Figure 4-1: Mean impact of light condition on saliva melatonin concentration for groups of five 14–15-year-old Japanese girls.



Nagare et al (2019) examined the impact of exposure duration and light spectra on night-time melatonin suppression in adolescents and adults. The work also looked at possible lighting thresholds for melatonin suppression. They found that a longer exposure suppressed melatonin to a greater degree. Also, they found a significant impact of spectrum and a significant interaction between spectrum and participant age. They considered that a previously proposed melatonin suppression threshold of 30 lux for 30 min for white light, suggested by Bullough et al. (2008), Figueiro and Rea (2005); Figueiro et al.(2006) and Rea and Figueiro, (2013) appeared to be an acceptable, if conservative, recommendation. Safety -effective streetlighting is typically around 5 lux, 1/6 of the suggested threshold.

Aoki et al (1998) exposed 5 healthy male volunteers to light at different intensities (10, 500, 1000, 2500, and 5000 lux). Melatonin suppression depended on both light intensity and exposure. duration. Minimum light intensities to suppress nocturnal melatonin levels were 393, 366, 339, and 285 lux for exposures of 30, 60, 90, and 120 min, respectively. Minimum intensity and duration were linearly related with a negative slope (Figure 4-2). Dim light (<10lux) was used as a control.

Figure 4-2: Relationship between minimum intensity of light to supress melatonin and duration



The lux of safety-effective street lights is similar (5 lux) to the dim light (<10lux) used as a control.

In another paper out of Japan, which used young adult subjects, broadly similar results were found. Hashimoto et al (1996) had eight young male subjects spend 3 days in an experimental living facility with lighting below 200 lx. They were exposed to light for 3 hours in the early morning on the 2nd day. The same procedure was repeated five times in each subject with an interval of at least 3 weeks, and five light intensities were trialed.

The experiment found that nocturnal melatonin level was not suppressed by light of 200 lx but significantly suppressed by light of intensity > or = 500 lx. The circadian melatonin rhythm was not shifted by any light intensity up to 10,000 lx. It was concluded that the threshold of light intensity for suppressing the melatonin level is between 200 and 500 lx in young Japanese males, and the threshold shifting the circadian melatonin rhythm was much higher.

Again, these lux level thresholds are much greater than used in street lighting and the length of exposure was much longer than one would expect to be common for street lighting. The subjects were also too young to have yellowed lenses.

There have been a small number of studies specific to street lighting which have attempted to do assist our understanding of this area. Rea e t al, 2012 looked at the response of the human circadian system after one hour of exposure to outdoor LED lighting of different colour temperatures. The metric used was melatonin suppression. The 95 lux light sources used were:

- HPS CCT 2050K
- Metal Halide CCT 4000K
- Cool White LED 5200K
- Cool White LED 6900K

The subjects were 20 years old. The experiment was carried out under laboratory conditions and then modelling was used to better simulate 4 real road related conditions. The model used was that of Rea et al, 2004 and 2012. The approach was to determine whether sufficient light reached the subject's retina to stimulate the circadian system as measured by melatonin suppression. The pupil area of the subject was estimated using a method from Berman, 1998. The result of the experiment indicated no melatonin suppression within the 10% uncertainty level for assaying melatonin except for the 6900K LED source which reduced melatonin by 12% for one scenario and 15% for another, both being 1 hour exposures.

The authors emphasised that the human circadian system is relatively insensitive to light., compared to the visual system which responds very quickly. The circadian system needs a number of orders of magnitude more light for many minutes for a measurable response to be detected. According to Rea et al, 2012 this is because the circadian system is biased against false positives in the detection of light. It achieves this by setting high thresholds and by responding only to a narrow subpart of the entire spectrum.

The authors concluded no meaningful impact on the circadian system for any except the 6900 LED. This experiment would indicate that there is little of concern regarding circadian issues from the common 4000K and lower LEDs in use these days.

4.1 *Summary comparison* with Gibbons et al (2022) and Bhagavathula et al, (2021) results.

A summary comparison of Gibbons et al's (2022) results with literature results is displayed in

Table 4:1. The results indicate that saliva melatonin levels found by Gibbons et al (2023) and Bhagavathula et al, (2021) are well within the range of saliva melatonin levels experienced at night found in the literature.

Table 4:1 Summary comparison of literature information with Gibbons et al (2022) information

Author(s)	Subjects	Night-time saliva melatonin information
Ito et al (2013)	Young Japanese women	29.6(SD 18.23) pg/ml at bedtime
Harada et al (2004)	2 females and 3 males aged 14–15 years.	9.18 pg/ml in in 60 lux light
Aoki et al (1998)	Five healthy males	Minimum intensity of light to supress melatonin was around 280 lux for a 2 hour
Nagare et al (2019)	Adolescents and adults	Supported a melatonin suppression threshold of 30 lux for 30 min for white light
Bhagavathula et al, (2021)	healthy participants between 18 and 30	A maximum of just over 16 pg/ml which occurred for the no light condition for drivers
Gibbons et al (2022)[7]	Young males and females	Maximum of around 20ug/ml for drivers pedestrians and for light trespass victims

4.2 Conclusions

The saliva melatonin levels found by Gibbons et al (2023) and and Bhagavathula et al, (2021) are well within the range of saliva melatonin levels experienced at night found in the literature.

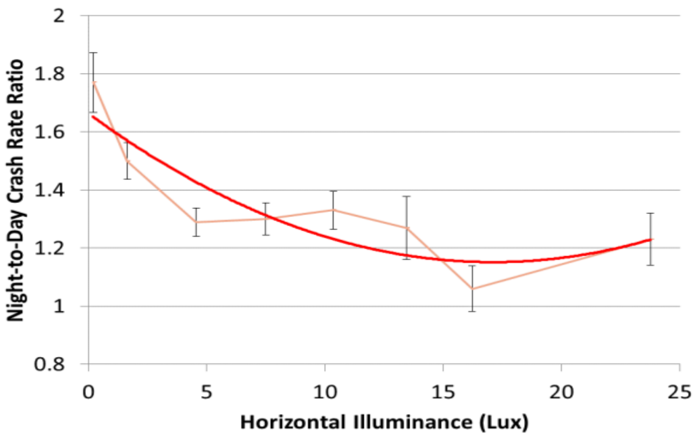
5 When lights provide good safety outcomes what impact do they have on Melatonin levels?

It would seem reasonable to use lighting levels which provide good safety outcomes as a benchmark for streel lighting and then relate these levels to melatonin levels. Safety has been related to both illuminance (Gibbons et al., 2014) and luminance (Jackett & Frith,2013; Frith & Jackett, 2015). Gibbons et al (2014) related horizontal illuminance to the night/day crash rate ratio on a road length.. The crash rate ratio used by Gibbons et al (2014) is the ratio of the rates per million vehicle kilometres travelled. . This reduces as night-time safety increases and therefore can be used as a surrogate for the impact of lighting on safety Their results are shown in Figure 5-1.

Figure 5-1:Relationship between mean horizontal illuminance and weighted night/ day crash rate ratio. Best fit line R2 = 0.794 (Gibbons et al, 2014)

[7] Note that Gibbons et al (2022) compared the results for the 3 different groups and lights of different SPDs using the AUC metric, which could not be compared with the pg /ml saliva melatonin metric from other literature.. Gibbons et al (2022) did graph the pg /ml results and the numbers in

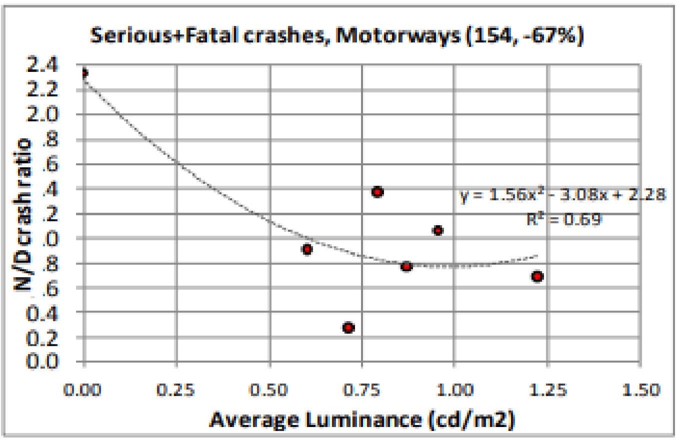
Table 4:1 are approximate values read off the charts in that paper.



This indicates that there is little change in safety once 5 lux is reached apart from a dip at around 16 lux. This dip can be discounted as Gibbons et al (2014) remark that the data point was based on a short length of road and was not significant.

Frith and Jackett (2015l looked at luminance for New Zealand Motorways, similar to the roads on which Gibbons et al (2022} based their luminance values of 1.0cd/m2. Frith and Jackett (2015)'s night/day crash ratio looked at crashes on a length rather than crash rate on a length.

Figure 5-2: Night to day crash ratio for DSI crashes on New Zealand Motorways vs Average luminance



Their chart (Frith and Jackett (2015l looked at luminance for New Zealand Motorways, similar to the roads on which Gibbons et al (2022} based their luminance values of 1.0cd/m2. Frith and Jackett (2015)'s night/day crash ratio looked at crashes on a length rather than crash rate on a length.

Figure 5-2) indicates a turning point upwards in the direction of unsafety at around that level. Therefore, putting together the results of Gibbons et al (2014) and Frith and Jackett (2015)' a reasonable assumption is that luminance of around 1-1.2 cd/m^2 and horizontal illuminance of 5 lux should provide good safety outcomes. Work by Gibbons et al (2014) also suggests that vertical illuminance should not exceed horizontal illuminance. Therefore, a value of 5 lux appears appropriate for vertical illuminance.

It can thus be construed that Gibbons' 1.0 cd/m^2 luminance paired with 5 lux for both vertical and horizontal illuminance should be associated with good safety outcomes. This means that the melatonin impacts of Gibbons et al (2022) are those that can be expected from a safe lighting installation.

Also, the lighting used by Gibbons et al (2022) did not take the participants beyond the range of saliva Melatonin expected among the participants given the ranges observed in the literature in dark conditions.

5.1 Conclusions

Safe road lighting is unlikely to elevate melatonin levels.

6 Summary of Conclusions

- Direct measurements of circadian metrics beneath streetlights and at residential property boundaries near streetlights indicate negligible melatonin suppression potential of the lights.

- The statistical results from Gibbons et al (2022) and Bhagavathula (2022). tell us that their tests of the impact of streetlighting on their participants could not detect any difference between the streetlighting condition and the prior conditions (200l lux for Gibbons et al (2022) and no light for Bhagavathula,. Differences were not found for lights of differing CCTs. nor lights of differing CCT.

- Comparisons of illuminance measurements at the eye for LED streetlighting and common electronic devices found similar results only from the Kindle and the iPad Pro in night/dark mode.

- The lack of statistical significance of the results cannot be taken as an indication that melatonin levels were not disturbed. This is because of the small-scale nature of the experiment. and the relative insensitivity of saliva melatonin compared to plasma melatonin to circadian changes. Similar remarks may be made regarding the results of Bhagavathula et al, (2021)

- The wider literature indicates that saliva melatonin levels associated with Gibbons et al (2022) and Bhagavathula et al, (2021) are well within the range of saliva melatonin levels experienced by sleeping humans or humans at bedtime indicating that lighting used by Gibbons et al (2022)and Bhagavathula et al, (2021is unlikely to disturb sleep..

- The lighting levels associated with safe street lighting in New Zealand are broadly similar to those used in Gibbons et al (2023) indicating that lighting at those levels is unlikely to elevate melatonin levels, and therefore unlikely to disturb sleep...

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