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The Calculated Circadian Effects of Light Exposure from Commuting

Yihan Lu *, Wenye Hu and Wendy Davis

School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW 2006, Australia; wenye.hu@sydney.edu.au (W.H.); wendy.davis@sydney.edu.au (W.D.)
* Correspondence: yilu5201@uni.sydney.edu.au

Abstract: Light entrains human circadian rhythms, but increased time spent indoors and decreased daylight exposure may disrupt human circadian regulation and cause health problems. Much research is focused on improving indoor lighting conditions to minimize the adverse circadian impact of electric lights, and few studies investigate the circadian impact of daylight during the incidental time that people spend outdoors. For instance, when people commute from home to work, they are exposed to daylight. The purpose of this study is to investigate daylight's impact on commuters' circadian rhythms. Measurements of the illuminance and the spectral irradiance distribution (SID) of daylight were taken for three modes of commuting: driving, riding on trains, and walking; and under different weather conditions, on different days, and at different locations throughout the summer and autumn in the Sydney metropolitan region in Australia. With the SID data, three metrics were calculated to estimate the circadian impacts: α-opic irradiance, circadian stimulus (*CS*), and equivalent melanopic lux (*EML*). The results suggest that driving or walking on sunny or cloudy days and riding trains on sunny days are beneficial for the commuters' circadian synchronization.

Keywords: circadian impact; daytime light exposure; commuters

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1. Introduction

Light entrains human circadian rhythms [1–3], with studies showing that both light exposure history and timing can influence circadian rhythms. The master clock tends to phase early when exposed to light in the morning, and the clock phases late when exposed to light at night [4]. Research has shown that at least four hours of daylight exposure (or electric light exposure of equivalent intensity) during daytime for seven days decreased the subjects' sensitivity to subsequent light exposure, compared with dim light exposure during the day [5]. Despite using a variety of methodologies, several studies have consistently found that bright light exposure dampens the impact of subsequent light exposure on the circadian systems [6–8].

Disruption of circadian regulation has been associated with many health issues [9]. As many people spend a substantial portion of their time indoors [10], concerns have been raised that limited daylight exposure may disrupt the human circadian cycles [11], and some suggest that indoor lighting conditions should be changed to compensate for this reduced exposure to daylight [12].

A recent study showed that nighttime exterior lighting can have a circadian effect on people [13]. However, a human's light exposure is not limited to the electric lighting in indoor spaces or outdoor lighting at night—many people travel between their home and workplace on a regular basis. In Australia, the primary commuting modes are driving (79%), taking public transportation (14%), and walking or cycling (5.2%) [14], during which they are incidentally exposed to daylight. In 2017, the average commuting time of employed Australians was one hour [14]. A survey conducted in the United States shows that people spend about an average of 6% of their time in vehicles [15], which is approximately consistent with the Australian commuting time. There have been no studies on the effect of this light exposure on the circadian systems of commuters. This research aims to evaluate the circadian effect of daylight from commuting.

In this study, the illuminance and the spectral irradiance distribution (SID) of daylight were measured for three different commuting modes: driving, riding on trains, and walking, in two types of weather conditions (sunny and cloudy). The measurements were repeated during different times and days at various locations in the Sydney metropolitan area. The SID data were used to calculate three metrics: α-opic irradiance [16], circadian stimulus (*CS*) [17,18], and equivalent melanopic lux (*EML*) [19], in order to estimate the circadian effects of the different commuting modes. The average α-opic irradiance for each mode of commuting in both sunny and cloudy weather conditions is reported in this study. The average *CS* and *EML* values are compared to their recommended minimum values.

2. Materials and Methods

2.1. Light Exposure Measurements

A calibrated Everfine SPIC-300 spectral irradiance meter was used to measure the illuminance and SID. The sensor of the spectral irradiance meter can be separated from the rest of the instrument, which it communicates with via Bluetooth. In order to estimate the corneal illuminance and SID while traveling safely, the sensor was mounted on a modified helmet. When the operator wore the helmet to conduct the measurements, the sensor was, therefore, in the center of the operator's forehead, just above the eyes (Figure 1). After initiating the instrument, the equipment recorded the first measurement and automatically measured the subsequent light. The time taken for each measurement varied. The average measurement frequency during the trips was 1.4 recordings per minute. The measurements ceased when the operator manually stopped the equipment. A series of measurements were automatically and continuously recorded while the operator traveled.

Figure 1. Photo of the operator wearing the modified helmet with the sensor attached on it.

The mounting position of the sensor on a helmet was used to ensure the safety of the operator. However, comparisons were made between the measurements of the light striking the sensor when mounted on the helmet and when placed in front of the cornea, and very little difference was found. The same instrument was used for this comparison, with the same operator (Figure 1). The operator stood outdoors, measured the light once when the sensor was on the helmet, and then immediately moved the sensor onto her right eye and recorded another measurement. This process was repeated three times. The percentage difference of the measured irradiance was calculated as the difference between the irradiance at the helmet position and the irradiance at the eye position divided by the irradiance at the eye. The three percentages were 1.2%, −0.5% and 1.3%, which are all less than the measurement uncertainty of the instrument.

Measurements were obtained for a total of 21 trips, representative of those undertaken by the commuters. All trips were taken in the summer and autumn (from December 2019 to March 2020) in the Sydney metropolitan region in Australia. Seven trips were taken for each commuting mode: driving, riding trains, and walking. Additionally, all trips were taken during the morning peak hours (within the time range of 07:30 to 10:00). For driving, the average starting time was 08:54 a.m. and the average ending time was 09:22 a.m. For riding trains, the average starting time was 08:38 a.m. and the average ending time was 08:59 a.m. For walking, the average starting time was 08:28 a.m. and the average ending time was 09:00 a.m. The duration of the trips varied from 12 min to 41 min. The average duration of all trips was 27 min. For driving and walking, the direction of travel included all four directions (north, south, west, and east, approximately) for each mode of commuting. For train rides, the trips include one railway line which is a loop, as well as three other railway lines, for which measurements were collected in both directions of travel. All the measurements were conducted by the same operator (Figure 1).

When driving, the operator wore the modified helmet with the attached sensor and initiated the spectral irradiance meter before she started to drive. The equipment automatically recorded the measurements as she drove. The primary light source was the daylight coming through the front windshield and the windows of the vehicle. The operator was free to perform any necessary movements for safe driving, such as checking the GPS, adjusting the side-view mirrors, monitoring traffic conditions, etc. The seven trips that were taken for the driving mode started at different locations and ended at different destinations. The measurements were conducted inside of the same vehicle (model: 2018 Toyota, CH-R) with tinted side windows.

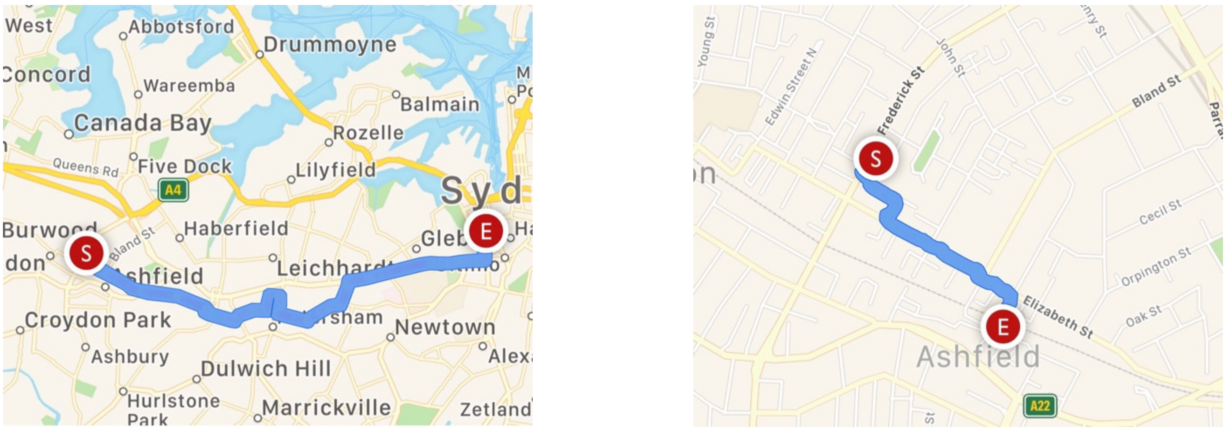
When riding on the commuter trains, the operator wore the modified helmet with the attached sensor and initiated the spectral irradiance meter just before she boarded the train. The operator sat near the windows in a seat either facing forward or backward, relative to the direction of travel, and on either the upper or lower level of the train. The operator was exposed to the daylight coming through the windows of the train and the electric lights in the train. The measurements captured the contributions of both light sources. The operator was free to perform any typical movements associated with riding trains, such as looking at the views outside the windows, reading a book, navigating through the train car, etc. The seven trips that were taken for the mode of riding trains started and ended at different stations. Between some stations, the train travelled underground, during which times daylight was blocked and the electric lights were the only light source. During this period, the measurements were continued, and the data for these sections were included in the calculation to reflect real-life commuting situations.

When walking, the measurement procedure was similar to the other two commuting modes. The operator wore the modified helmet with the attached sensor and initiated the spectral irradiance meter when she started to walk. The seven trips that were taken for the mode of walking started at different locations and ended at various destinations. The operator walked through a variety of areas, including places where tall buildings or trees partially blocked the daylight. The walking routes also included areas with more open space, where the operator was fully exposed to daylight. The operator was free to perform any necessary movements for safe walking, such as monitoring the environment, checking traffic conditions, waiting for traffic lights, etc.

A weather application on a smartphone was used to monitor and record the weather conditions. The weather was recorded twice for each trip—once when the trip started and again when the trip ended. The light measurements were taken when the weather was relatively steady throughout the trips. They were not just taken on sunny days, when the daylight was intense, but also on cloudy days, when the daylight was weaker. Table 1 gives detailed information about examples of the trip itineraries for each commuting mode. The majority of the areas where the measurements were conducted have high-rise buildings, in which 36–82% of the dwellings are high density [20,21]. The GPS route was captured for driving and walking by a smartphone GPS application. Figure 2 shows examples of the GPS route for driving and walking.

Table 1. Examples of trip itineraries for three commuting modes.

Mode	Date	Weather		GPS Coordinates/ Train Stations		Time		Note
		Start	End	Start	End	Start	End	
Driving	12 Dec. 2019	Mostly cloudy	Mostly cloudy	(−33.882898, 151.121124)	(−33.879560, 151.198464)	8:40	9:11	Heavy traffic, medium to high-density housing areas
Train	18 Dec. 2019	Sunny	Sunny	Ashfield railway station	Parramatta railway station	7:39	8:10	facing direction of travel, lower level, no tunnel
Walking	19 Mar. 2020	Sunny	Sunny	(−33.922654, 151.190095)	(−33.922073, 151.190443)	8:08	8:34	High-density housing areas



(**a**) (**b**)

Figure 2. Examples of the GPS route for driving and walking: (**a**) driving from S point to E point; (**b**) walking from S point to E point.

2.2. *Calculations of the Circadian Effects of Lights*

The three metrics, α-opic irradiance, *CS*, and *EML*, were used to estimate the circadian effects of the light exposure experienced during a typical commute. The calculations were based on the following methods.

2.2.1. α-Opic Irradiance

The first method is recommended by the International Commission on Illumination (CIE) in CIE S 026/E:2018 [16]. This international standard provides the spectral sensitivity functions (action spectra), which describe the extent to which radiation stimulates each of the five photoreceptor types that contribute to the non-visual effects of light in humans [16]. The sensitivity function for the intrinsically-photosensitive retinal ganglion cells (ipRGCs) is based on the work of Lucas et al. [22]. The cone sensitivity function and rod sensitivity function recommended in CIE S 026/E:2018 are based on a previous CIE publication [16]. With the SID and spectral sensitivity functions, the weighted irradiance (α-opic irradiance) for each human photoreceptor type can be calculated with Equation (1):

$$E_{e,\,\alpha} = \int E_{e,\,\lambda}(\lambda) S_{\alpha}(\lambda) d\lambda \tag{1}$$

where $E_{e,\,\alpha}$ is the α-opic irradiance, $E_{e,\,\lambda}(\lambda)$ is the spectral irradiance, and $S_{\alpha}(\lambda)$ is the α-opic action spectrum [16]. A toolbox to support the use of this metric has been developed and is available on the CIE website [23].

2.2.2. Circadian Stimulus

Another method for quantifying the circadian impact of light is through the circadian stimulus (CS) [17,18]. CS represents the percentage of melatonin suppression evoked by light [24]. The non-linear model was initially developed based on spectral sensitivity data published by several researchers [25,26], and the model has been modified multiple times since it was initially proposed [18]. Instead of modeling the five different spectral sensitivity functions—one for each photoreceptor type—CS quantifies the total circadian effect from light. Given the SID, CS can be calculated with Equations (2) and (3):

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}} \tag{2}$$

$$CL_A = \begin{cases} 1548\left[\int M_{C\lambda} E_\lambda d\lambda + \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\right)\right)\right], \\ \quad if \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda \geq 0 \\ 1548 \int M_{C\lambda} E_\lambda d\lambda \ , \ if \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda < 0 \end{cases} \tag{3}$$

where CL_A is circadian light, CS is circadian stimulus, E_λ is the SID of the incident light, $M_{C\lambda}$ is melanopsin (corrected for crystalline lens transmittance) sensitivity [27], S_λ is the S-cone fundamental [28], mp_λ is macular pigment transmittance [29], V_λ is the photopic luminous efficiency function [30], V'_λ is the scotopic luminous efficiency function [30], $RodSat$ is the half-saturation constant for bleaching rods, equal to 6.5 W/m^2 [31], k equals 0.2616 [32], a_{b-y} equals 0.7 [32], and a_{rod} equals 3.3 [32]. Due to the non-linear structure of the model, there are slight differences in the intensity of the narrowband light of ~507 nm [18], which can lead to massive differences in the output of the CS. This discontinuity can cause inaccuracies when predicting circadian effects with this model. More details about the CS metric and its limitations are reported in the publications by Rea et al. [18,32,33].

2.2.3. Equivalent Melanopic Lux

The third method used here is the equivalent melanopic lux (EML), which characterizes the light's impact on the circadian system in the unit of melanopic lux [19]. It does not reflect modifications of the ipRGCs by the rods or cones [22,31]. With the retinal illuminance and SID, EML can be simply calculated by Equations (4) and (5):

$$EML = R \times L \tag{4}$$

$$R = \frac{Melanopic\ irradiance}{Photopic\ irradiance} \times 1.218 \tag{5}$$

where EML is equivalent melanopic lux and L is illuminance. The 1.218 constant is also called the $equal\ energy\ constant$. R is the ratio of the irradiance weighted by the circadian spectral sensitivity function and the irradiance weighted by the photopic spectral sensitivity function, multiplied by a constant. The constant ensures that the melanopic illuminance is equivalent to the photopic illuminance for a theoretical equal energy radiator [19]. The circadian spectral sensitivity function used in this equation is also from the work of Lucas et al. [22].

3. Results

In total, 21 commuting trips were taken to measure the illuminance and SIDs, with seven trips taken for each mode of commuting. The seven trips were then categorized into two groups based on their weather conditions, sunny or cloudy. The sunny group includes trips that were taken when the weather conditions were sunny, mostly sunny, or partly cloudy—i.e., when the daylight was intense. The cloudy group includes trips that were taken when the weather conditions were cloudy or mostly cloudy—i.e., when the daylight was relatively weak. Table 2 shows the number of trips categorized in the sunny group, the cloudy group, and the total for each commuting mode. In total, 732 SID measurements were collected during these 21 trips. Table 3 shows the number of SID measurements that were taken for each commuting mode in the different weather conditions, reflecting the uneven sample size of each group. Figure 3 shows the representative relative spectral power distributions measured for each of the three commuting modes for the two weather conditions. It is clear that the interior lighting in the trains dominates daylight, as the spectral power distributions for the train trips predominately correspond to those of white light-emitting diodes (LEDs).

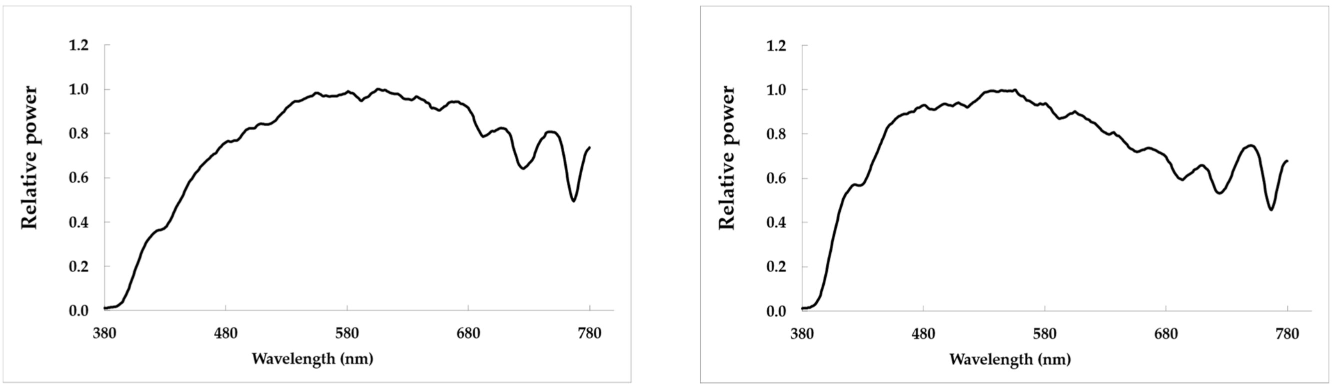
Table 2. The number of trips for each commuting mode in different weather conditions.

	Driving	Train	Walking
Sunny	5	4	5
Cloudy	2	3	2
Total	7	7	7

Table 3. The number of SID measurements for each commuting mode in different weather conditions.

	Driving	Train	Walking
Sunny	222	69	116
Cloudy	97	195	33
Total	319	264	149

The average values and standard deviations for the illuminance, the five α-opic irradiances (S-cone, M-cone, L-cone, rhodopic, and melanopic), CS, and EML for each of the three commuting modes are shown in Table 4. The table also distinguishes the results for the sunny and cloudy weather conditions. Box plots of the measured corneal illuminances and the five calculated α-opic irradiance values are shown in Figure 4. One-way analysis of variance (ANOVA) tests ($p < 0.05$) of the illuminance and the five α-opic irradiances were performed in MATLAB to determine whether there are statistically significant differences between the different modes of commuting in different weather conditions. Any significant differences ($p < 0.05$) are denoted with asterisks in Figure 4. The average illuminances and the average α-opic irradiances are higher for the sunny weather conditions than the cloudy conditions for each mode of commuting. The average illuminances and average α-opic irradiances are highest for the walking mode of commuting, while driving resulted in the lowest light exposure.



(a) (b)

Figure 3. *Cont.*

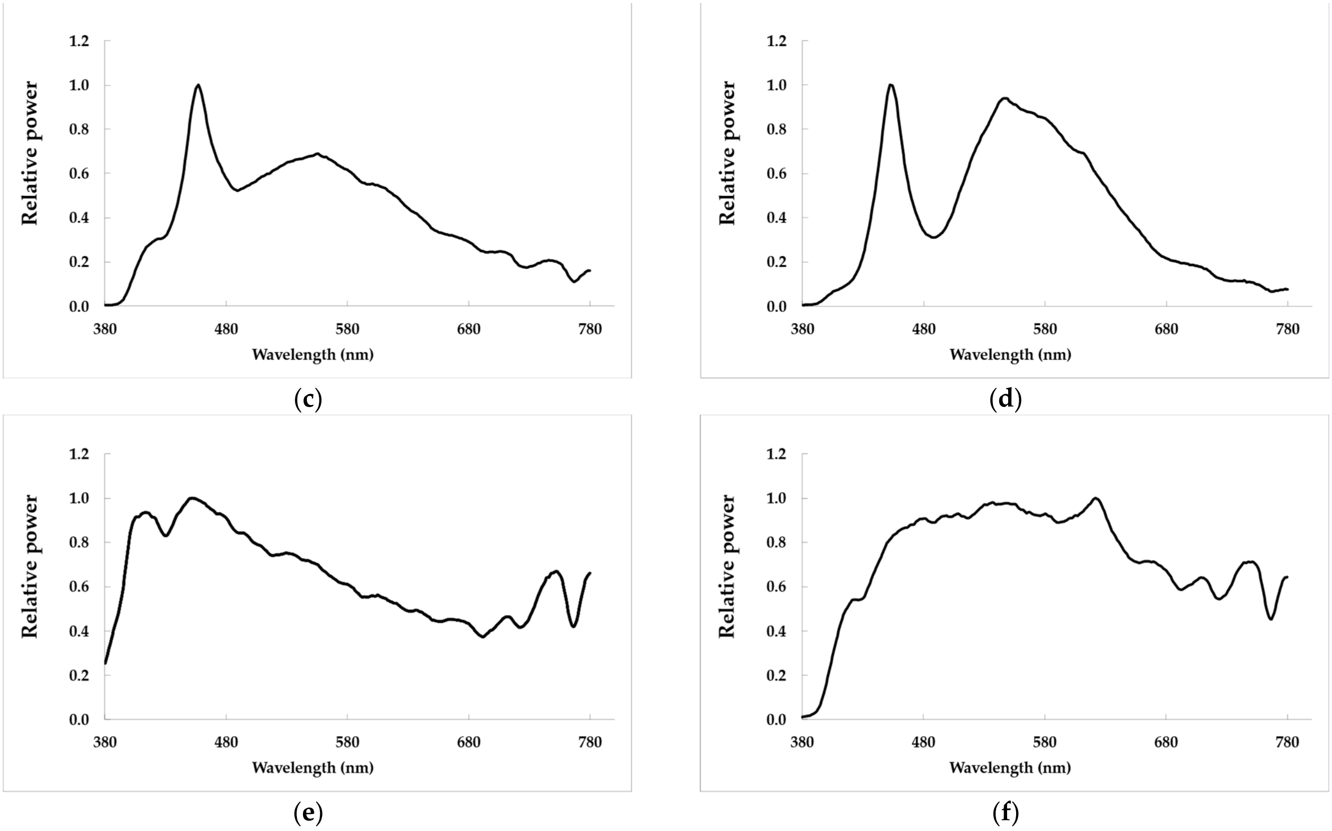


Figure 3. Representative relative spectral power distributions for the three commuting modes, for the two weather conditions (sunny and cloudy): (**a**) driving sunny; (**b**) driving cloudy; (**c**) train sunny; (**d**) train cloudy; (**e**) walking sunny; (**f**) walking cloudy.

Table 4. The average values and standard deviations (SD) of illuminance, S-cone-opic irradiance, M-cone-opic irradiance, L-cone-opic irradiance, rhodopic irradiance, melanopic irradiance, circadian stimulus (CS), and equivalent melanopic lux (EML) for the three commuting modes, for the two weather conditions (sunny and cloudy).

	Illuminance (Lux)		α-Opic Irradiance (W/m^2)										Circadian Stimulus (Unitless)		Equivalent Melanopic Lux (Melanopic Lux)	
			S-Cone		M-Cone		L-Cone		Rhodopic		Melanopic					
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Driving																
Sunny	819	711	0.52	0.44	1.17	1.01	1.33	1.15	1.07	0.92	0.97	0.83	0.40	0.25	817	702
Cloudy	733	382	0.47	0.25	1.04	0.55	1.19	0.62	0.96	0.50	0.87	0.46	0.50	0.06	734	388
Total	793	630	0.51	0.40	1.13	0.90	1.28	1.02	1.03	0.82	0.94	0.74	0.43	0.21	792	624
Train																
Sunny	2639	2344	1.93	1.66	3.77	3.33	4.29	3.82	3.52	3.08	3.23	2.83	0.59	0.09	2722	2380
Cloudy	336	272	0.19	0.21	0.45	0.39	0.54	0.44	0.36	0.35	0.31	0.32	0.25	0.16	260	270
Total	938	1582	0.64	1.15	1.32	2.26	1.52	2.58	1.19	2.12	1.07	1.95	0.34	0.21	903	1641
Walking																
Sunny	3339	4427	2.51	3.03	4.80	6.25	5.44	7.22	4.55	5.77	4.21	5.28	0.60	0.09	3542	4449
Cloudy	1313	894	1.11	0.76	1.93	1.31	2.14	1.46	1.90	1.28	1.78	1.20	0.56	0.12	1496	1014
Total	2891	4014	2.20	2.76	4.16	5.67	4.71	6.55	3.96	5.24	3.67	4.80	0.59	0.10	3089	4041

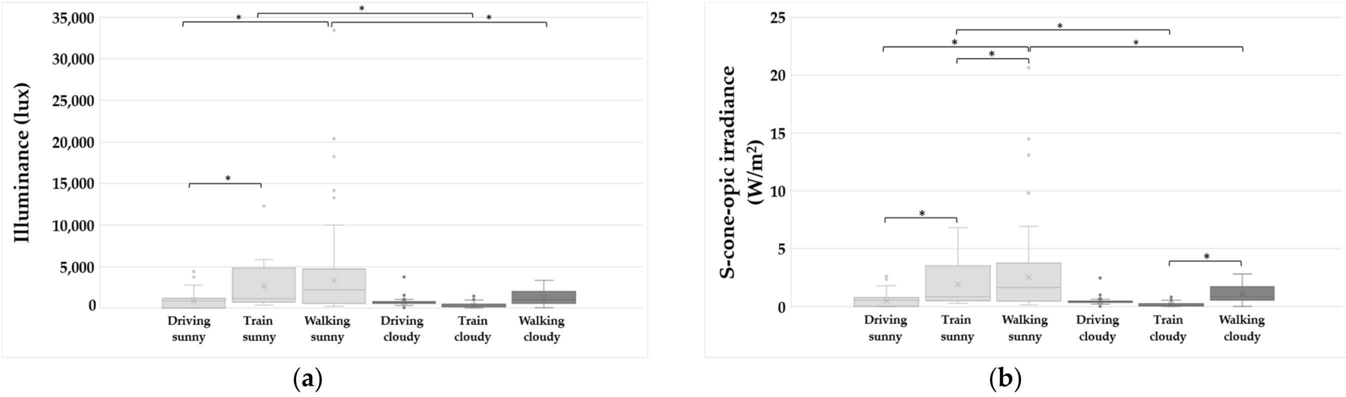


Figure 4. *Cont.*

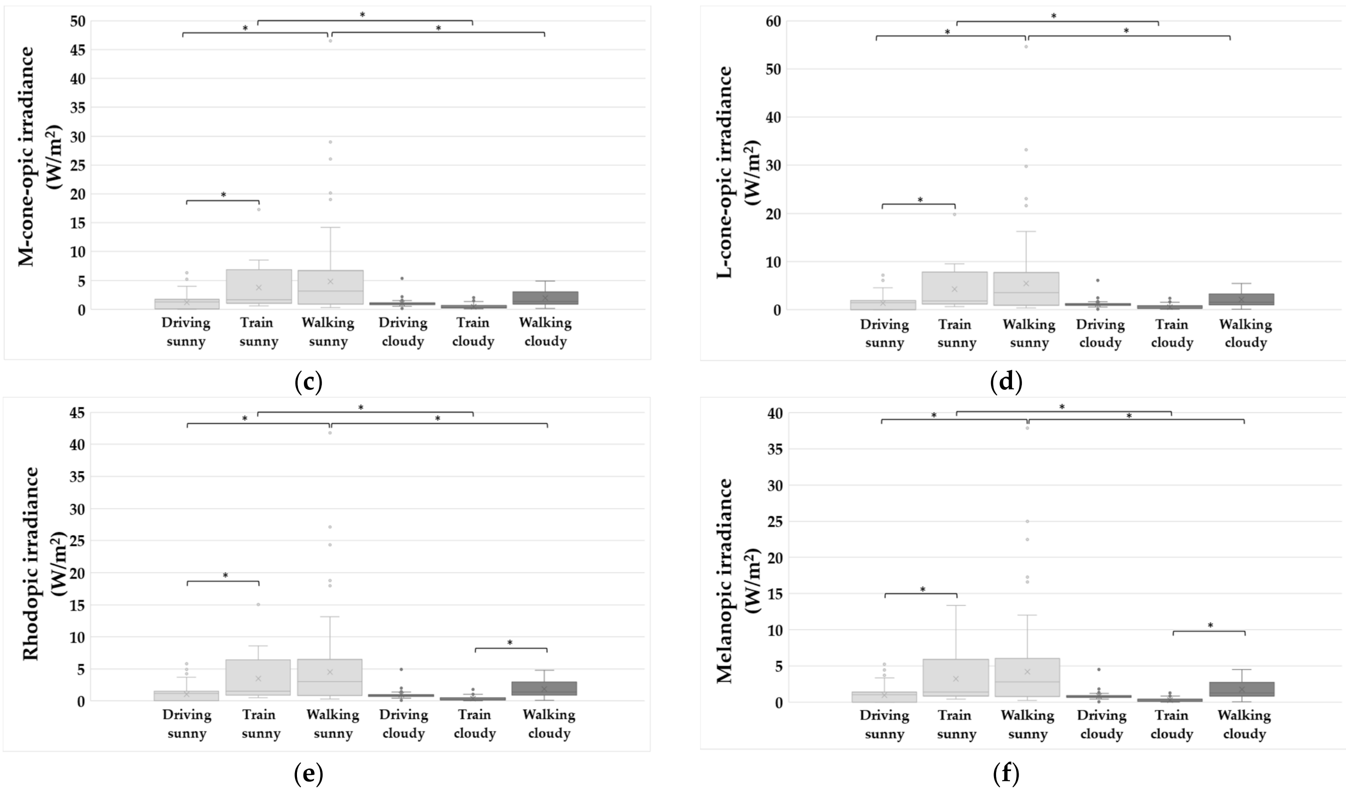


Figure 4. Box plots of the measured corneal illuminance and the five calculated α-opic irradiance values for the three modes of commuting under the two weather conditions (sunny and cloudy): (**a**) illuminance; (**b**) S-cone-opic irradiance; (**c**) M-cone-opic irradiance; (**d**) L-cone-opic irradiance; (**e**) rhodopic irradiance; (**f**) melanopic irradiance. The horizontal lines that divide the boxes into two parts denote the median (middle quartile). The boxes represent the inter-quartile range (the middle 50%), and the upper and lower whiskers show the highest and the lowest non-outliers. The individual points outside the boxes show the outliers. The cross in each box represents the mean. Asterisks indicate statistically significant differences between groups with a p-value < 0.05.

Box plots of the calculated *CS* and *EML* values for the three modes of commuting under the two weather conditions are shown in Figure 5. One-way ANOVA tests ($p < 0.05$) of *CS* and *EML* were performed in MATLAB to determine whether there are statistically significant differences between the different modes of commuting in different weather conditions. Any significant differences ($p < 0.05$) are denoted with asterisks in Figure 5. The average *CS* and *EML* values are shown in Table 4. The suggested desired criterion of

CS is 0.3, with the condition that the light exposure is one hour in duration [12,32,34,35]. When the *CS* value is over 0.3, people who are exposed to such lighting conditions will have better daytime alertness and sleep quality [12,32,34,35]. As the average commuting time of employed Australians was one hour (66 min in mainland capital cities, and 48 min in others) [14], 0.3 is used here. As shown in Table 4, the average *CS* value for riding trains in cloudy conditions (0.25) is slightly below the desired criterion (0.3), but others are all above it. The suggested value of the *EML* depends on the space. For example, 200 melanopic lux is the recommended minimum level for a work area [19]. Although there is no recommended criterion for commuting, 200 melanopic lux is applied here, since the purpose of this study is to analyze daylight's impact on people while they are commuting, before they spend the rest of the day at their workplaces. As shown in Table 4, all average *EML* values exceed the *EML* recommended value (200 melanopic lux), including riding trains in cloudy conditions (260 melanopic lux).

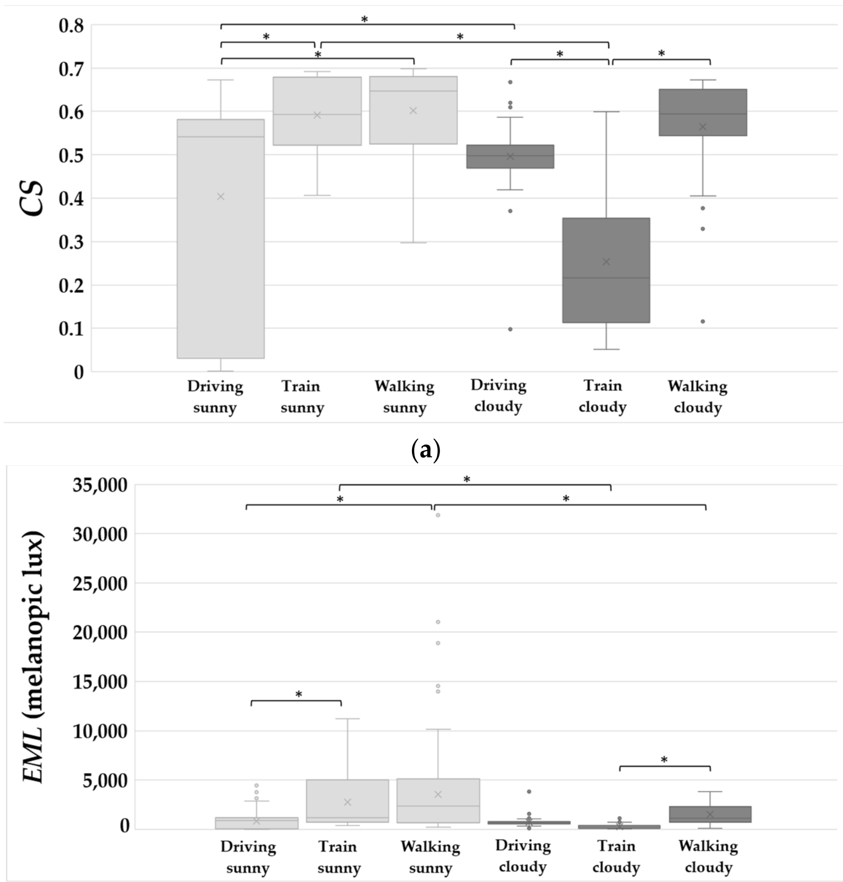


Figure 5. Box plots of calculated CS and EML values for the three modes of commuting in sunny and cloudy conditions: (**a**) CS; (**b**) EML. The horizontal lines that divide the boxes into two parts denote the median (middle quartile). The boxes represent the inter-quartile range (the middle 50%), and the upper and lower whiskers show the highest and the lowest non-outliers. The individual points outside the boxes show the outliers. The cross in each box represents the mean. Asterisks indicate statistically significant differences between groups with a p-value < 0.05.

As shown in Table 4, the calculation results for α-opic irradiance and *EML* show a consistent trend—the average values for sunny conditions are all higher than the average values for cloudy conditions, which suggests that commuting on sunny days results in greater circadian impacts than traveling on cloudy days. For walking and traveling by train, these differences were statistically significant, but the differences between driving in sunny conditions and cloudy conditions were not significant. Interestingly, the average *CS* is smaller for driving in sunny conditions (0.40) than in cloudy conditions (0.50), and this difference was statistically significant. Similarly, *CS* predicts that driving results in greater circadian stimulation than riding a train, which is contrary to the predictions of the other metrics. Driving has the lowest average α-opic irradiance and *EML* values, but the *CS* (0.43) for driving is not lower than riding trains. Riding trains has the lowest average *CS* value (0.34), but α-opic irradiance and *EML* are higher for riding trains than driving. The illuminance measurements are consistent with the α-opic irradiance and *EML* calculation results. The average illuminance when driving in sunny conditions are higher than in cloudy conditions, and the average illuminance when riding trains is higher than when driving. However, one cannot conclude that the α-opic irradiance and *EML* are more accurate than the *CS* based on the illuminance measurements, as a higher photopic intensity of light doesn't necessarily result in greater circadian effects. Several characteristics of light influence the circadian rhythms interactively: spectrum [2,36–38], intensity [39], duration [40], timing [5,6], and spatial distribution [41–44]. It is also unclear the extent to which the contribution of the electrical lighting in trains (i.e., the fact that the spectral power distributions largely correspond to LEDs) influences these findings. Further studies should be conducted to investigate the inconsistent predictions between these metrics.

4. Discussion

In this study, a total of 732 SID measurements were recorded during 21 trips for the three modes of commuting: driving, taking trains, and walking. The measurements were then categorized into two groups based on the weather conditions, sunny or cloudy. Three metrics (α-opic irradiance, *CS*, and *EML*) were used to quantify the circadian impact of light on commuters. The results of the *CS* and *EML* were compared to their recommended minimum values. The light exposure measured when riding trains in cloudy conditions was below the *CS* desired criterion, but above the *EML* recommended value. However, the *CS* and *EML* results for driving and walking in both sunny and cloudy conditions, as well as riding trains in sunny conditions, exceed the recommended values for both metrics. This suggests that riding trains on sunny days and driving or walking in all weather conditions can be beneficial for commuters' circadian synchronization to the local day–night cycle and is likely to improve commuters' daytime alertness and sleep quality [12,19,32,34,35,45].

Limitations

Although the results suggest a positive circadian impact of daylight on commuters, it should be noted that the measurements were conducted in a metropolitan environment in Sydney, Australia and this conclusion may not apply to all circumstances or age groups. For example, travelling in suburban areas may result in a higher circadian impact than travelling in a central business district, as suburban areas have fewer tall buildings that can block the light [10]. Travelling toward the light source (sun) will result in more circadian effects than travelling away from the light source. Older individuals may be impacted differently than younger people traveling on the same commute, as lens transmittances varies with age [46]. While people are commuting, many factors affect how much daylight people are exposed to, and not all these factors were reflected in these measurements. For example, wearing sunglasses will reduce the amount of light entering the eyes and, consequently, reduce the circadian impacts. Wearing a pair of prescription glasses with blue light filters may also reduce the circadian impacts compared with wearing glasses without filters, as the human circadian systems are most sensitive to blue light [2,36–38]. These measurements were taken in the summer and autumn and the effects of commuting on circadian entrainment may differ in the winter and spring. The Sydney peak morning commuting hours occur after the sun has risen [47] year-round and the sun angle is lower in winter [48], so it's possible that commuters' corneas would receive more light in winter than in summer, which would lead to a greater circadian impact.

In this research, no physiological measurements were made. The conclusions are based on the calculated results of the three metrics. When the *CS* value is over 0.3 and EML value is over 200 melanopic lux, the lighting conditions can be beneficial to people's circadian synchronization to the local day–night cycle, and are likely to improve one's daytime alertness and sleep quality [12,19,32,34,35,45]. However, the improvement of daytime alertness and sleep quality from daytime light exposure can be varied between different individuals. A recent literature review conducted by Lok et al. shows that the non-visual effects of light on subjective alertness and sleepiness are inconclusive [49]. Several studies also show inconclusive results [50–52]. There are also some inconsistencies between the results of the three metrics reported in this paper. The results of this study cannot conclude which metric is more accurate. Future research could investigate this inconsistency by measuring a circadian rhythm marker, such as melatonin suppression [7], pupil constriction [53], phase shifting [41], and/or changes in core body temperature [54], to identify the actual circadian effects of commuting on people.

Several studies have used the melanopic equivalent daylight (D65) illuminance (melanopic EDI) to quantify light's circadian impact [55–57]. In addition to the five α-opic irradiances, the melanopic EDI is defined as one of the five α-opic equivalent daylight (D65) illuminances (α-opic EDIs) by the CIE in CIE S 026/E:2018 [16]. It can be simply calculated as the melanopic irradiance divided by the melanopic efficacy of the luminous radiation for daylight (D65), which is 1.3262 (mW/lm) [16]. Compared with other types of cells, the melanopsin-based ipRGCs predominantly contribute to the non-visual effects, including circadian impacts [25,57–59]. However, the actual non-visual effects from light exposure rely on the combined responses of all photoreceptors [16,22]. It is necessary to report the response of each photoreceptor type [16]. As the five α-opic irradiances and five α-opic EDIs can be easily converted between each other, to avoid repetition, only irradiances are reported here. Readers who are interested in melanopic EDI values can calculate them from the α-opic irradiances.

A new version of the *CS* was published in 2021 [33] during the preparation of this paper. Two factors were introduced into the *CS* equation: a duration factor, which indicates the duration of light exposure (ranging from 0.5 h to 3.0 h), and a distribution factor, which is a variable equal to 2, 1, or 0.5 corresponding to three visual field conditions (full visual field, central visual field, and superior visual field) [33]. The older version of the *CS* requires the light duration to be one hour or more, and it doesn't take the distribution of light exposure across the retina into consideration. However, the new *CS* equation can be used to predict melatonin suppression for different light exposure durations and different distributions. Instead of applying the new version of the *CS*, this paper used the older version [17,18,32] to calculate the *CS* value, which has been validated [60–63] and used [12,13,45,60,64] in several papers. More details about the new version of the *CS* metric and its limitations are reported in Rea et al.'s publication [33].

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