# Electronic sun journal versus self-report sun diary: A comparison of recording personal sunlight exposure methods

Benjamin R. Dexter[a], Rachel King[a], Alfio V. Parisi[a,b], Simone L. Harrison[b],
Damien P. Igoe[a], Nathan J. Downs[a,b,*]

*[a]Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, Australia.*

*[b]School of Public Health, Medical and Veterinary Sciences, James Cook University,*

*Townsville, Australia.*

[*]To whom correspondence should be addressed.
email: nathan.downs@usq.edu.au
ORCID http://orcid.org/0000-0002-3191-6404

## Abstract

This research compared personal sunlight exposure times monitored electronically within suburban Australian environments against self-report paper journals for determining the timing and total duration of individual exposure to daily solar radiation. A total of 90 Electronic Sun Journal (ESJ) daily readings and self-report timing and duration estimates of exposure for weekend and weekdays were compared. A Wilcoxon ranked sign test showed a significant difference ($V$ = 157, $p$ < 0.001) between the duration of exposure recorded electronically and the duration of exposure that was self-reported in a diary. There was also found to be a statistically significant difference between total exposure time measured using both methods for weekends ($V = 10$, $p < 0.001$) and weekdays ($V = 87$, $p < 0.001$). General trends in outdoor exposure timing confirmed that the most frequent daily exposures received over the weekend occurred between one and two hours earlier than the most frequent exposures received on weekdays. This preliminary research found that exposure durations as recorded by the ESJ were longer on the weekends compared to weekdays ($W = 402$, $p < 0.001$) and confirmed that the ESJ is a viable alternative to self-reporting diaries.

## 1. Introduction

Duration and timing of exposure to solar radiation is of critical importance to a range of research applications. The amount of time spent outdoors and exposed to solar radiation is a major contributing factor to many health issues, positive and negative. Humans require exposure to solar ultraviolet radiation (UVR) to function healthily. In particular, exposure to solar UVR is important for the synthesis of Vitamin D [1]. Some exposure to bright light, including sunlight can also have a positive influence on mood [2,3], while a lack of exposure, particularly at high latitudes is associated with seasonal affective disorder [4,5]. A number of new studies have recently reported on the importance of individuals gaining sufficient personal outdoor exposure time within green spaces to improve and maintain overall well-being and mental health [6,7]. Urban design studies have also highlighted that access to tree canopies can benefit the mental well-being of local Australian communities [8].

However, whilst humans can benefit from exposure to solar radiation in the outdoor environment, there are recognized harmful effects that arise when exposure is excessive. This includes exposure to solar short wavelength UVR but also the potential blue light hazard [9,10]. Short wavelength blue light represents the ‘blue’ visible range in the optical solar spectrum. Solar blue light radiation can accelerate age-related macular degeneration in older populations and has recently been implicated as a causative factor for the cellular damage of skin in mice [11]. Recently, much research effort has been dedicated to understanding the relationship of solar radiation and the early onset of myopia in human populations [12,13,14]. However, keratinocyte and melanoma skin cancers, and eye conditions including cortical cataract have had well established causative links to hazardous solar UVR exposure for decades [1,15,16]. Unsurprisingly, given the vast majority of studies completed to date have concentrated on skin cancer, much focus remains on monitoring and improving solar UVR exposure in population groups during leisure activities, sports and at work [17,18,19].

The amount of solar UVR exposure received by an individual is dependent on duration and timing of exposure [20]. Personal solar exposure over a period of time is relatively easy to determine through the usage of polysulphone badges [21,22], electronic dosimeters [23,24], using records of timing based on self-reporting [25,26] and/or estimates of available ambient UVR for a given location [27]. Whilst accurate for determining personal UVR exposure, dosimetry requires access to seasonally calibrated equipment which can be cost prohibitive for some applications. Studies have been conducted to assess the validity of self-reported outdoor exposure compared to UVR dosimeter readings. A correlation of 0.57 was the strongest relationship found between self-report diaries and dosimeters [28]. Furthermore, participants may only be required to record outdoor exposures in hour long increments [28]. While useful in some situations, participant surveys may miss subtle variations in behavior including the timing and duration of incidental outdoor exposures that may occur during recreation or employment. Solar UVR dosimetry also requires strong participant compliance to be effective [29].

The Electronic Sun Journal (ESJ), based on an infrared photodiode can provide a personal sunlight exposure record, for each second, of whether a person is fully or partially exposed to sunlight [30]. Radiant exposures cannot be directly derived from ESJ records, rather the ESJ is a low-cost device that enables detailed monitoring of individual outdoor exposure patterns [30]. The ESJ does not rely on participant memory to record periods of outdoor exposure and can potentially help minimize the impact of recall bias found in previous studies that used paper or online surveys. Due to its ease of use the ESJ may be able to remove issues of non-compliance by study volunteers. As a new technology the ESJ has been used previously in the field [31]. The ESJ is used in this study to monitor the outdoor exposure behavior of three participants over 90 days compared to paper based sun-diaries recorded by the same participants during the same period. Improvements in outdoor exposure timing are presented showing differences in exposure behavior exist in this small sample between working weekday and weekend exposure habits.

## 2. Methods

### 2.1 Participant reporting of sunlight exposure

Three study participants recorded periods of exposure to sunlight during their normal everyday activities in paper diaries between 7:00 am and 6:00 pm. ESJs, attached to the wrist of each participant recorded the sunlight exposure and duration simultaneously. In this study, two participants recorded data in Toowoomba, Queensland (27.56°S, 151.97°E) and one was in Sydney, New South Wales (33.87°S, 151.21°E). A total of 90 daily records were taken between 14 February 2020 and 11 May 2020. Participants recorded their time spent outside in direct sunlight in self-report diaries corresponding to days they wore the ESJ.

Instructions were given to study participants to report the timing and duration they believed they were outside and exposed to direct sunlight. The qualification of ‘outdoor exposure’ was defined as any period outside of a building. This may have included periods in direct sunshine, or periods outdoors under shade. Paper diaries, distributed to each study participant were divided in the period 7:00 am to 6:00 pm into 5-minute intervals, of which participants we instructed to write their total time outdoors within each interval to the nearest minute. Participants were instructed that intermittent outdoor exposures of less than one minute were not to be recorded in the paper diaries.

Personal sunlight exposure data recorded in paper sun diaries was later transferred to spreadsheet for analysis. Study participants were assumed to be indoors any time outdoor exposure information was not self-reported in a daily paper diary record. The self-report process did not require participants to identify periods when in partial shading. Paper based records indicated only personal periods of outdoor and indoor activity.

## 2.2 Verification of Electronic Sun Journals

The ESJ uses an infrared diode that is sensitive to the infrared A waveband; between 870 – 1050 nm, with a peak response at 950 nm [30]. The diode operates in a reverse biased state and when exposed to sunlight the diode response saturates. Inversely, when in dense shade or indoor lighting which represents limited infrared environments, the diode response is minimized [30]. The ESJ logs the diode output voltage every second with a maximum voltage of 2.5 V representing full shade, a minimum of 0 V representing direct exposure to sunlight, and partial shade ranging between these two extremes (Table 1) [30]. These readings are stored on a mini SD card as a text file. The output recorded each second was stored as a numeric 10-bit entry ranging from 0 (direct sunlight exposure) to 1023 (fully shaded – indoor condition), and from 1 – 1022 in partially shaded environments with higher numbers indicating greater shade density. The partially exposed sunlight readings were split into either dense or light shading periods as defined by Downs et al. [30] and Igoe et al. [31]. Dense shading provided ESJ values that were between 512 to 1022, and light shading provided values between 1 to 511 [30,31]. Consequently, the ESJ was able to provide in time increments of one second, information regarding duration and timing for each of the following states: direct sunlight exposure, no exposure (indoor condition), and dense or light shade (Table 1).

**<Table 1>**

The classification of outdoor exposure time primarily focused on two levels of exposure to sunlight as recorded by the ESJ: exposure to direct sunlight, and combined direct sunlight exposure with light shade (Table 1). Direct exposure was investigated and compared against the self-report exposure periods as these periods were also periods where participants believed they were fully exposed to direct sunlight. Periods of light shade and direct sunlight exposure were combined into a separate outdoor exposure category because periods of light shade do not diminish the energy received by the sun significantly [32]. Due to the variation found in shading [30,31] and protection from solar radiation during periods of light shade [32] these periods of exposure were also chosen to compare against self-reported periods of outdoor exposure as participants may have believed they were fully exposed to sunlight when self-reporting but may have been going through brief and fluctuating periods of light shade.

The ESJ was tested to confirm its accuracy with respect to the angle of incidence of the available solar radiation and the position of the ESJ wrist site. To evaluate the potential influence of solar zenith angle (SZA), the ESJ was placed in an open unshaded environment on a horizontal plane for a full day on 30 September 2020 from 7:00 am to 6:00 pm. The conditions on this day were overcast (8/8 octas). The diurnal signal response test confirmed the signal output did not record a false indoor condition due to the direct sunlight angle, which on this day varied from SZA $71^o$ at 7:00 am, $25^o$ at solar noon (11:40 am) and $90^o$ at sunset at 5:50 pm. The ESJ digital output for each second over the 11 hour test period, reached a maximum digital level of 1021 at 6:00 pm. This pre-test reasonably confirmed that participants wearing ESJs at a wrist site would be logged as being outdoors in direct sunlight or partially shaded conditions irrespective of the SZA and the prevailing cloud cover for the 14 February to 11 May 2020 participant trials.

Comparison of ESJ data logs to personal paper based sun diaries under direct sunlight exposure conditions, and direct and partially shaded exposure conditions are dependent on the outdoor environment, the activity of the study participant, and the orientation of the wrist with respect to the body at the time of measurement. To quantify the accuracy of the ESJ used by human participants, the output of two ESJs attached to the left and right wrist of a human mannequin placed on a rotating stand was also examined. The mannequin and stand assembly was placed in an open unshaded, and a tree shaded environment completing a total of five full revolutions at approximately 35 seconds per revolution with the right wrist placed in an outstretched orientation and the left wrist placed close to the body (Figure 1).

**<Figure 1>**

Figure 2 shows the simultaneous output of the left (vertical orientation) and right (horizontal orientation) mannequin wrist ESJs for both the open environment and the environment shaded by a large tree. For an open environment, the outstretched right arm shows no change in ESJ signal as the mannequin rotated through each full revolution. For the left wrist placed close to the body, periodic intervals in increasing signal output are evident when the ESJ moved through the mannequin's shadow. Under the moving canopy of a large tree, regular patterns in signal output were also observed for the rotating mannequin. In this case, both the outstretched right arm and left wrist placed close to the body showed that brief intervals of direct sunlight could saturate the signal output (0 Volts), correctly logging intermittent periods of direct sunlight exposure. For a human study participant, this preliminary work showed that the ESJ output is independent of wrist orientation, recording partial shading only when protected from direct sunlight by the body or the physical shade of the local environment.

**<Figure 2>**

### *2.3 Participant Analysis*

All analysis and plotting were conducted in R [33] using packages: ggplot2 [34]; lubridate [35]; scales [36]; and gridExtra [37]. Summary statistics were produced for the durations spent in full sun, light and dense shade generated by the ESJ, and full exposure duration as indicated by self-report. All durations of exposure states are expressed in minutes. Histograms were created to identify the distribution of exposure duration for full sunlight exposure, both ESJ and self-report, and the periods of dense and light shade and full shade as recorded by the ESJ on each study participant. All exposure state durations (Table 1) were tested for skewness.

As the data was highly skewed a non-parametric Wilcoxon signed rank test was used to identify any differences between direct sunlight exposure periods as recorded by the ESJ and self-report using the data from weekdays and weekends combined. This analysis was then repeated with the ESJ direct exposure and light shade data combined. These two tests were then again repeated for weekday and weekend data separately. Therefore, in total six Wilcoxon signed rank tests were performed. In addition, a Wilcoxon rank sum test was used to identify differences between weekday and weekend direct sunlight exposure durations as recorded by the ESJ. This analysis was repeated on the combined direct exposure and light shade durations, again to determine differences between weekdays and weekends.

### 2.3.1 Timing of personal exposure

Participant ESJ records were collated and summarized according to exposure category. Again, these categories included time indoors (maximum ESJ voltage – digital level 1023); time in direct sunlight (saturated diode condition – digital level 0); and time outdoors but in a partially shaded condition (ESJ digital levels 1 to 511). The frequency distribution of each of the 90 daily ESJ records returned by the study participants was plotted with respect to time of day beginning at 7:00 am and ending at 6:00 pm. Frequency plots were sub-divided according to indoor, outdoor and partially shaded conditions for weekdays (*n* = 64 (71%)) and weekends (*n* = 26, (29%)). Thus, the effective activity index for the study cohort was derived to show the most frequent times of day participants spent outdoors in direct sunlight, outdoors in partially shaded environments, and indoors for the study period 14 February to 11 May 2020.

## 3. Results and Discussion

### 3.1 Comparison of ESJ and self-report exposure durations

There were 90 series of observations collected during the Southern hemisphere late summer and early autumn where there were ESJ and self-report data that matched. Some of the data were collected by the three participants on the same day meaning there were sometimes readings for the same day. Of the ESJ data collected, there was a minimum of 10 minutes and a maximum of 749 minutes (12.5 hrs) recorded using the ESJ in a single day. The average continuous recording time each day using the ESJ was 475.3 minutes (7.9 hrs).

**<Table 2>**

The ESJ recorded the minimum time a participant was in direct sunlight for both weekdays and weekends to be 0 minutes (Table 2). The minimum time of self-reporting of full sunlight exposure was also 0 minutes for weekdays but 2 minutes on weekends. For weekdays, a maximum self-report of 173 minutes in full sunlight was recorded, approximately three times what was recorded by the ESJ direct sunlight condition on weekdays, at 61 minutes. Similarly, the self-reported full sunlight exposure duration for weekends was over twice that recorded by the ESJ (Table 2). Potentially, the difference between the direct sunlight exposure recorded by the ESJ and the exposure self-reported could be attributed to the ability of the ESJ to register periods of partial shading while the self-report considers those same periods to be full sunlight exposure. However, when the periods of light shading and full sunlight exposure recorded by the ESJ were combined and compared against the self-reported full sunlight exposure, the self-reported exposure duration (173 minutes) was still twice as large as the combined ESJ data (98 minutes) for weekdays. Similarly, the self-reported exposure (312 minutes) was still 50 % longer than the combined ESJ direct sunlight exposure and light shaded duration (190 minutes) for weekends. On weekdays, the average period of full sunlight exposure as recorded by the ESJ was 12 minutes whilst it was self-reported that 39 minutes were spent in direct sunlight. On weekends it was self-reported that 93 minutes on average was spent in direct sunlight, where the ESJ recorded on average 37 minutes. Regardless of day type or adding periods of light shade to periods of direct sunlight exposure recorded by the ESJ, self-reported exposure durations tended to be longer than recorded by the ESJ.

Figure 3 shows the distribution of the duration of sunlight exposure for all exposure states recorded electronically and by self-report. For weekend and weekdays combined, all results are highly positively skewed except for the periods of dense shade (Table 1) which were normally distributed. When considering all days combined there were 28 days where participants spent 0 – 5 minutes in direct sunlight (Figure 3) as recorded by the ESJ. The self-reported data (Figure 3b) showed that participants self-reported only 11 of these days where 0 – 5 minutes were spent in direct sunlight during the entire day. This indicates that the self-report data tended to under report the periods of 0 to 5 minutes of direct intermittent sunlight exposure. It was also found that the ESJ recorded only three days where participants were exposed to 100 or more minutes to direct sunlight where the self-report data showed that there were 12 days of more than 100 minutes of direct sunlight exposure (Figure 3).

Self-report exposure to solar radiation when compared to the ESJ showed participants were likely to record longer periods of direct sunlight exposure but often neglected to report brief periods of short outdoor exposure duration between 0 and 5 minutes. These self-report estimations may effectively misreport the potential impacts of incidental exposures, whether caused by intermittent shading or direct exposure to sunlight in studies that rely on the efficacy of participants to accurately recall total exposure durations [38].

**< Figure 3>**

## 3.2 Differences in weekend and weekday exposures

When considering weekend and weekdays separately (Figure 4 and Figure 5), the distributions of sunlight exposure duration were still all highly positively skewed except for periods of dense shade which were normally distributed (Table 2). The ESJ recorded 24 weekdays where direct sunlight exposure periods were between 0 to 5 minutes. In contrast, the self-reporting data showed that participants reported only 10 weekdays where 0 to 5 minutes were spent in direct sunlight (Figure 4). For weekdays there was only one day where the ESJ recorded direct sunlight exposure greater than 60 minutes, where there were 16 days self-reported outdoors at greater than 60 minutes.

For weekdays when the light shade periods were combined with the direct sunlight exposure periods according to the ESJ there were three days with exposure periods longer than 60 minutes. On weekends there were only four days where direct outdoor sunlight exposure was recorded between 0 to 5 minutes by the ESJ. Self-reporting for direct sunlight exposure on weekends only recorded one day where 0 to 5 minutes was spent outdoors. For weekends (Figure 5), the ESJ recorded no direct sunlight exposure periods greater than 145 minutes, however it was self-reported that three days were spent in direct sunshine for longer than 145 minutes.

**< Figure 4 >**

**< Figure 5 >**

With weekend and weekdays combined there was found to be a significant difference between the duration of direct sunlight exposure recorded by the ESJ and self-reported exposure ($V = 157$, $p < 0.001$). A significant difference between exposures recorded by ESJ and self-reporting was also found when looking at weekdays ($V = 87$, $p < 0.001$) and weekends ($V = 10$, $p < 0.001$) separately.

When the periods of light shade exposure were included with the direct sunlight exposure durations recorded by the ESJ and compared against the self-reported durations there were still significant differences found for all days combined ($V = 460$, $p < 0.001$), weekdays ($V = 233$, $p < 0.001$) and weekends ($V = 38$, $p < 0.001$). There was also a significant difference between levels of direct sunlight duration as recorded by the ESJ for weekdays versus weekends ($W = 402$, $p < 0.001$). This difference between weekend and weekday exposure continued when periods of light shade (Table 1) were added to the direct sunlight outdoor exposure periods ($W = 1830$, $p < 0.001$).

The results showed that regardless of weekend or weekday the self-reported duration of full sunlight exposure was longer than what was being recorded by the ESJ. This suggests that current estimates of personal exposures measured outdoors that rely on self-reporting and recall may be overestimating the amount of time people are spending in the sun. However, the results also indicate that periods of intermittent direct sunlight exposure between 0 and 5 minutes are often not recorded on paper by participants for either weekends or weekdays. According to the participant ESJ wrist measurements, there is a measureable difference in the amount of sunlight exposure received on weekdays and weekends.

From Figure 3b and 3c it was noted that self-report tends to overestimate daily periods of exposure that are greater than 3 hours. However, by comparing the same two histograms it can also been seen that the ESJ measures more days when participants receive little or no exposure to sunlight than self reported. This effect is increased if only periods of direct ESJ exposure are considered (comparing Figure 3b and Figure 3a). These results show that differences between monitored electronic records and self-report are largely dependent on how ‘outdoor exposure‘ is defined, including for example the definition of direct sunlight, or direct sunlight and light shade. Such definitions may not necessarily be clearly defined by participants of similar studies using paper diaries. This is an avenue for future research.

### *3.3 Timing of exposure to sunlight*

When considering the timing of direct sunlight exposure received as recorded by the ESJ, Figure 6a displays that on weekdays there was a steady increase in the likelihood of exposure up until 10:00 am. After this point, the frequency of records indicating exposure to direct sunlight plateaus out until 12:00 pm when the likelihood of outdoor exposure began to increase again with a sharp increase from 1:00 pm peaking at 2:00 pm. These results indicate that most outdoor exposure during the weekdays was received between 12:30 pm and 1:30 pm. There was a sharp decline in exposure from 2:00 pm onwards gradually declining through to the end of the day.

When considering timing of full sunlight exposure recorded by the ESJ on weekends, Figure 6b shows that there is minimal exposure up until 9:00 am whereupon there was a sharp increase in outdoor activity peaking at 12:00 pm. The tendency to be outdoors can then be seen to decrease until 1:30 pm. There was found to be another small peak of exposure at 2:00 pm dropping sharply at 3:00 pm. On weekends the frequency of participants had another brief increase at 4:00 pm, which declined steadily thereafter.

**< Figure 6 >**

The results shown in Figure 6 indicate the likelihood of a participant being exposed to sunlight on weekdays was more evenly spread throughout the day than weekends, where there was a clear peak in the frequency of outdoor exposure. Participants were more likely to be exposed to the sun earlier on weekends compared to weekdays. Irrespective of day type, outdoor exposure was less likely after 3:00 pm.

### 3.4 General observations and limitations

This research has shown that the ESJ is a viable method for recording individual sun exposure duration and timing. When comparing the average direct sunlight exposure recorded by the ESJ for weekdays and weekends (Table 2) against those reported by Diffey [20], it was found that the outdoor exposure durations were comparable. However, the ESJ measurements reported here found that exposure durations for both weekends and weekdays were less than those found by Diffey [20]. These differences highlight the ability of the ESJ to accurately identify any periods of direct sun exposure as opposed to the techniques of paper-based diaries. Another advantage of the ESJ compared to past research [20,39,40] was the ability to determine the timing of an individual's solar exposure. Due to the cost of electronic UVR dosimeters, the sample size of studies that utilize calibrated electronic dosimeters to accurately measure exposure timing are often small. This is a disadvantage when trying to generate meaningful estimates of population exposure patterns.

The use of the ESJ to determine accurate sun exposure timing and duration will improve models that attempt to derive estimated total sunshine fraction in larger populations. In future work, the ESJ could be a useful tool in research that aims to help minimize the negative impacts of solar UVR exposure including skin cancer, photo aging, and eye damage such as pterygium and cortical cataract [1,15]. This is of critical importance to Australians due to the high levels of UVR expected year-round and high national skin cancer rates [41,42]. The ESJ could similarly be used to help understand how outdoor exposure patterns could improve the quality of life in urban settings [8] or for those suffering psychological conditions such as Seasonal Affective Disorder [5], and Schizophrenia [1].

## 4 Conclusion

This research has shown that the ESJ is a viable method to determine individual and potentially a specific population’s exposure timing and outdoor sunlight duration and behavior. There remains opportunity to quantify what the ESJ readings mean in terms of specific shade level and total sunlight exposure received in a number of urban and regional settings. These may include future assessments of sun exposure behavior under tree groves, urban canyons, parks, sporting environments, or a range of occupational settings. Compared to self-reporting in a diary, the ESJ provides an improved quantification of the times and durations that population groups spend outdoors. Currently, the ESJ provides a measurable indication of individual outdoor behavior to a resolution of one second along with information on the time spent in light shade and dense shade. These new measures improve upon and extend the utility of self-reporting sun diary methods that may be used across a variety of different study settings.

## 5 Acknowledgements

The authors acknowledge the support of the University of Southern Queensland and James Cook University.

## 6 References

1. Lucas, R. M., McMichael, A. J., Armstrong, B. K. & Smith, W. T. (2008), ‘Estimating the global disease burden due to ultraviolet radiation exposure’, International Journal of Epidemiology 37(3), 654–667.
2. An, M., Colarelli, S.M., O’Brien, K. & Boyajian, M.E. 2016, ‘Why we need more nature at work: Effects of natural elements and sunlight on employee mental health and work attitudes ’, PLoS One, 11(5): e0155614.
3. Gonçalves, G., Sousa, A., Sousa, C., Jesus, F. & Afonso, E. 2019, ‘Effects of sunlight on psychological well-being, job satisfaction and confinement perception of workplace: The case of shopkeepers and marketers,’ in Occupational and Environmental Safety and Health, P.M. Arezes, J.S. Baptista, M.P. Barrso, P. Carneiro, P. Cordeiro, N. Costa, R.B. Melo, A.S. Miguel, G. Perestrlo (eds), pp. 573-580, Springer, Studies in Systems, Decision and Control, vol. 202.

4. Van der Rhee, H., de Vries, E., Coomans, C., van de Velde, P. & Coebergh, J.W. 2016, 'Sunlight: For better or worse? A review of positive and negative effects', Cancer Research Frontiers, 2(2), 156-183.
5. Wirtz-Justice, A. 2018, 'Seasonality in affective disorders', General and Comparative Endocrinology, 258(1), 244-249.
6. Douglas, O., Lennon, M. &  Scott, M. 2017, 'Green space benefits for health and well-being: A life-course approach for urban planning, design and management', Cities, 66, 53-62.
7. Barton, J. & Rogerson, M. 2017, 'The importance of greenspace for mental health', BJPsych International, 14(4), 79-81.
8. Astell-Burt, T. & Feng, X. 2019, 'Association of Urban green space with mental health and general health among adults in Australia', JAMA Network Open, 2(7): e198209.
9. Okuno, T. 2008. 'Hazards of solar blue light', Applied Optics, 47, 2988-2992.
10. Parisi, A.V., Igoe, D.P., Amar, A., Downs, N.J. 2020. 'Solar blue light radiation enhancement during mid to low solar elevation periods under cloud affected skies', Sensors, 20(15): 4105.
11. Nakashima, Y., Ohta, S. & Wolf, A.M. 2017, 'Blue-light induced oxidative stress in live skin', Free Radical Biology, 108, 300-310.
12. Hobday, R. 2015. 'Myopia and daylight in schools: a neglected aspect of public health? ', Perspective in Public Health, 136(1), 50-55.
13. Dolgin, E. 2015, 'The myopia boom', Nature, 519(7543), 276-278.
14. Lanca, C., Teo, A., Vivaganden, A., Htoon, H.M., Najjar, R.P., Spiegel, D.P., Pu, S-H., Saw, S-M. 2019. 'The effects of different outdoor environments, sunglasses and hats

on light levels: Implication for myopia prevention', Translational Vision Science and Technology, 8(4): 7.

15. Garźon-Chavez, D. R., Quentin, E., Harrison, S. L., Parisi, A. V., Butler, H. J. & Downs, N. J. (2018), 'The geospatial relationship of pterygium and senile cataract with ambient solar ultraviolet in tropical Ecuador', Photochemical & Photobiological Sciences, 17(8), 1075–1083.
16. Gallagher, R.P., & Lee, T.K. 2006, 'Adverse effects of ultraviolet radiation: A brief review', Progress in Biophysics and Molecular Biology, 92(1), 119-131.
17. Modenese, A., Korpinen, L. & Gobba, F. 2018. 'Solar radiation exposure and outdoor work: an underestimated occupational risk', International Journal of Environmental Research and Public Health, 15(10): 2063.
18. Schmalwieser, A.W. & Siani, A.M. 2018. 'Review of nonoccupational personal solar UV exposure measurements', Photochemistry and Photobiology, 94(5), 900-915.
19. Snyder, A., Valdebran, M., Terrero, D., Amber, K.T. & Kelly, K.M. 2020. 'Solar ultraviolet exposure in individuals who perform outdoor sport activities', Sports Medicine Open, 6: 42.
20. Diffey, B. 2008. A behavioral model for estimating population exposure to solar ultraviolet radiation. Photochemistry and Photobiology, 84(2), pp.371-375.
21. Kimlin, M.G., Parisi, A.V. and Wong, J.C.F. 1998. Quantification of personal solar UV exposure of outdoor workers, indoor workers and adolescents at two locations in Southeast Queensland. Photodermatology, Photoimmunology & Photomedicine, 14(1), pp.7-11.

22. Diffey, B.L. 1989. Ultraviolet radiation dosimetry with polysulphone film. Radiation Measurement in Photobiology, in Radiation Measurement in Photobiology, B.L. Diffey (ed), pp.135-159, Academic Press, London.
23. Stratimirović, Đ., Blesić, S., Wright, C., Allen, M. and Ajtić, J. 2015. Wavelet analysis of personal solar UVR exposure. In Rad 2015: The Third International Conference on Radiation and Applications in Various Fields of Rese (pp. 443-446). RAD Association.
24. Køster, B., Søndergaard, J., Nielsen, J.B., Christensen, K.B., Allen, M., Olsen, A. and Bentzen, J. 2017. Knowledge deficit, attitude and behavior scales association to objective measures of sun exposure and sunburn in a Danish population based sample. Plos One, 12(5), p.e0178190.
25. Glanz, K. and Mayer, J.A. 2005. Reducing ultraviolet radiation exposure to prevent skin cancer: methodology and measurement. American Journal of Preventive Medicine, 29(2), pp.131-142.
26. Kimlin, M., Harrison, S., Nowak, M., Moore, M., Brodie, A. and Lang, C. 2007. Does a high UV environment ensure adequate vitamin D status? Journal of Photochemistry and Photobiology B: Biology, 89(2-3), pp.139-147.
27. Lin, S.W., Wheeler, D.C., Park, Y., Cahoon, E.K., Hollenbeck, A.R., Freedman, D.M. and Abnet, C.C. 2012. Prospective study of ultraviolet radiation exposure and risk of cancer in the United States. International Journal of Cancer, 131(6), pp.E1015-E1023.
28. Glanz, K., Gies, P., O'Riordan, D.L., Elliott, T., Nehl, E., McCarty, F. and Davis, E. 2010. Validity of self-reported solar UVR exposure compared with objectively measured UVR exposure. Cancer Epidemiology and Prevention Biomarkers, 19(12), pp.3005-3012.

29. Sun, J., Lucas, R.M., Harrison, S.L., van der Mei, I., Whiteman, D.C., Mason, R., Nowak, M., Brodie, A.M. and Kimlin, M.G. 2014. Measuring exposure to solar ultraviolet radiation using a dosimetric technique: understanding participant compliance issues. Photochemistry and Photobiology, 90(4), pp.919-924.
30. Downs, N.J., Parisi, A.V., Butler, H., Rawlings, A. and Elrahoumi, R.S. 2017. An inexpensive high-temporal resolution electronic sun journal for monitoring personal day to day sun exposure patterns. Frontiers in Public Health, 5, p.310.
31. Igoe, D.P., Downs, N.J., Parisi, A.V. and Amar, A. 2020. Evaluation of shade profiles while walking in urban environments: A case study from inner suburban Sydney, Australia. Building and Environment, 177:106873.
32. Parisi, A.V., Kimlin, M.G., Wong, J.C. and Wilson, M. 2001. Solar ultraviolet exposures at ground level in tree shade during summer in south east Queensland. International Journal of Environmental Health Research, 11(2), pp.117-127.
33. R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: http://www.R-project.org/
34. Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.
35. Grolemund, G., and Wickham, H. 2011. Dates and Times Made Easy with lubridate. Journal of Statistical Software, 40(3), 1-25. Available at: http://www.jstatsoft.org/v40/i03/.
36. Wickham, H., and Seidel, D. 2019. scales: Scale Functions for Visualization. R package version 1.1.0. Available at: https://CRAN.R-project.org/package=scales

37. Baptiste Auguie. 2017. gridExtra: Miscellaneous Functions for "Grid" Graphics. R package version 2.3. Available at: https://CRAN.R-project.org/package=gridExtra
38. Kitchener, S. et al. 2011, ‘Ultraviolet radiation exposure and melanoma in Australian naval personnel’, Journal of Military and Veterans Health, 19(3), 50.
39. Godar, D.E. 2005. UV doses worldwide. Photochemistry and Photobiology, 81(4), pp.736-749.
40. Xiang, F., Harrison, S., Nowak, M., Kimlin, M., Van der Mei, I., Neale, R.E., Sinclair, C. and Lucas, R.M. 2015. Weekend personal ultraviolet radiation exposure in four cities in Australia: influence of temperature, humidity and ambient ultraviolet radiation. Journal of Photochemistry and Photobiology B: Biology, 143, pp.74-81.
41. Hille, D.M. 2019. Identifying changes in trends in the age standardized incidence of melanoma in Australia. SKIN The Journal of Cutaneous Medicine, 3(4), pp.250-252.
42. Gordon, L.G., Elliott, T.M., Olsen, C.M., Pandeya, N. & Whiteman, D.C. 2018. Multiplicity of skin cancers in Queensland and their cost burden to government and patients. Australian and New Zealand Journal of Public Health, 42(1), pp.86-91.

## 7 List of Tables

**Table 1:** Exposure state definitions, ESJ voltage and data output based on preliminary findings by Downs et al. [30] and Igoe et al. [31].

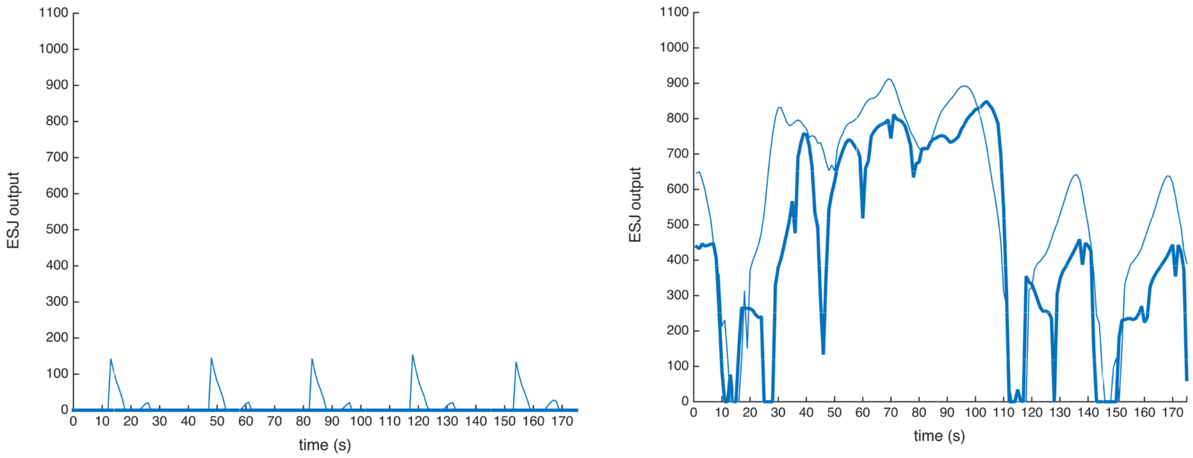
| Exposure state | ESJ voltage (V) | ESJ data output | Description |
|---|---|---|---|
| Direct exposure | 0 | 0 | No measurable shade between participant and sun. Unobstructed exposure to sunlight. |
| Light shade | 0.1 – 1.25 | 1 - 511 | Weak or broken shade. Serious variations to exposure due to environmental factors such as wind and clouds. |
| Dense shade | 1.26 – 2.4 | 512 - 1022 | Continuous and persistent shade. Shade not affected by environmental factors, with built structures falling into this category. |
| No exposure | 2.5 | 1023 | Completely shaded from sunlight. Indoor condition. |
| Direct exposure and light shade | 0 – 1.25 | 0 - 511 | Combination of both direct sunlight exposure and light shade exposure. Sunlight received during these periods may still have harmful and beneficial outcomes. |

**Table 2**: Summary statistics of ESJ total, light and dense shade, direct sunlight exposure, direct sunlight exposure and light shade combined, and self-report direct sunlight exposure minutes for weekend and weekdays in minutes.

| | | | Weekday (*n* = 64) | | | | | Weekend (*n* = 26) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Exposure state | ESJ Output (V) | Min | Mean (SD) | Median (IQR) | Max | Skew | Min | Mean (SD) | Median (IQR) | Max | Skew |
| ESJ | Total shade (No exposure) | 2.5 | 2 | 167 (172) | 106 (243) | 630 | 1.07 | 1 | 178 (148) | 156 (270) | 407 | 0.17 |
| | Dense shade | 1.25 – 2.4 | 0 | 294 (188) | 366 (350) | 630 | -0.33 | 2 | 226 (176) | 237 (154) | 544 | 0.08 |
| | Light shade | 0.1 – 1.24 | 0 | 9 (10) | 7 (8) | 57 | 2.44 | 0 | 19 (20) | 9 (23) | 85 | 1.56 |
| | Combined light shade and direct sunlight exposure | 0 – 1.24 | 0 | 21 (19) | 17 (11) | 98 | 1.66 | 1 | 56 (52) | 43 (47) | 190 | 1.19 |
| | direct sunlight exposure | 0 | 0 | 12 (12) | 8 (15) | 61 | 1.64 | 0 | 37 (39) | 27 (28) | 142 | 1.62 |
| Self report | direct sunlight exposure | - | 0 | 39 (34) | 35 (50) | 173 | 1.12 | 2 | 93 (77) | 78 (41) | 312 | 1.34 |

## 8 List of Figures

**Figure 1:** Experimental apparatus for testing ESJ signal output in two different wrist orientations (right wrist outstretched and horizontal, left wrist close to the body and vertical).



(a) (b)

**Figure 2:** ESJ signal output of the right wrist (solid line) and left wrist (light line) of a mannequin placed on a rotating stand completing five full revolutions in an open (a) and tree shaded (b) environment.

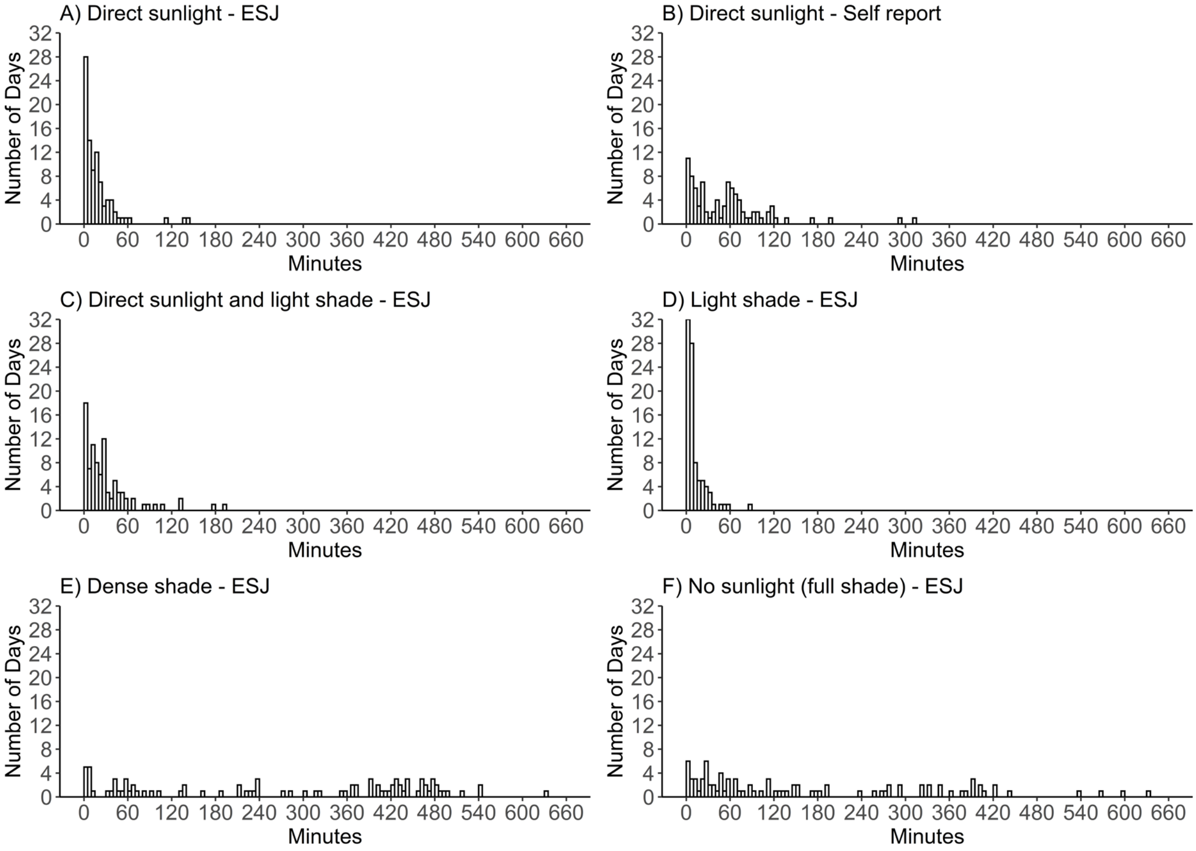


**Figure 3**: Frequency histograms for weekend and weekdays combined of duration spent in varied exposure states. Exposure states (Table 1) are: A) Direct sunlight – ESJ; B) Direct sunlight – Self report; C) Direct sunlight and light shade combined – ESJ; D) Light shade – ESJ; E) Dense shade – ESJ; and F) No sunlight (full shade) – ESJ. All bin increments are five minutes. *N* = 90.

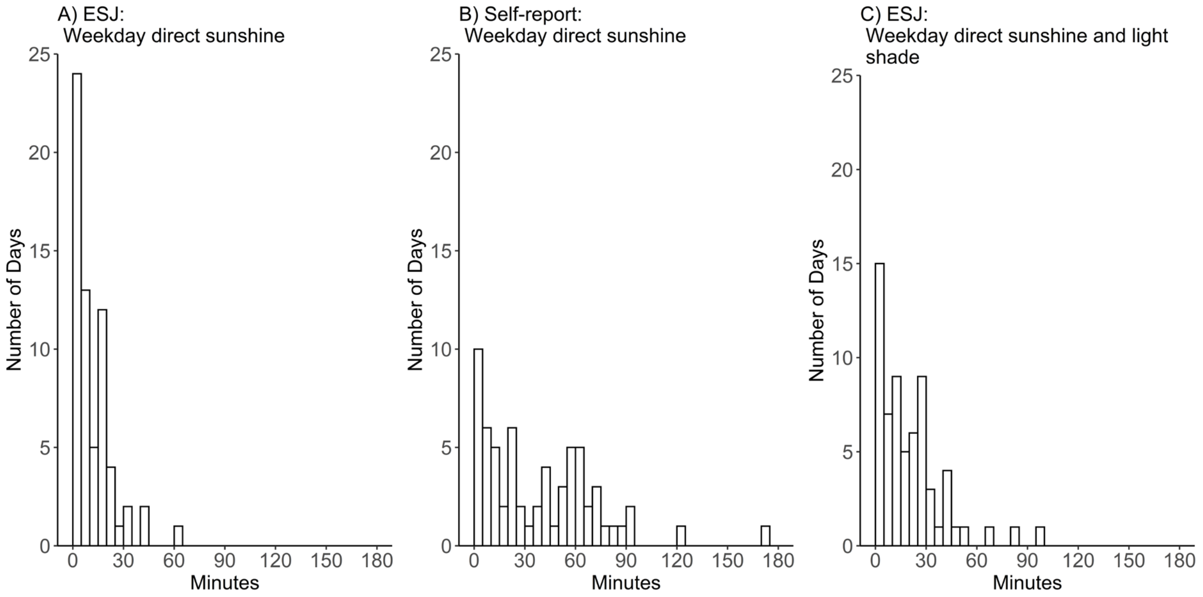


**Figure 4**: Frequency histograms of: A) weekday direct sunlight durations; B) weekday direct self-reported sunlight durations; and C) weekday direct sunlight exposure combined with periods of light shade as recorded by the ESJ. *N* = 64.

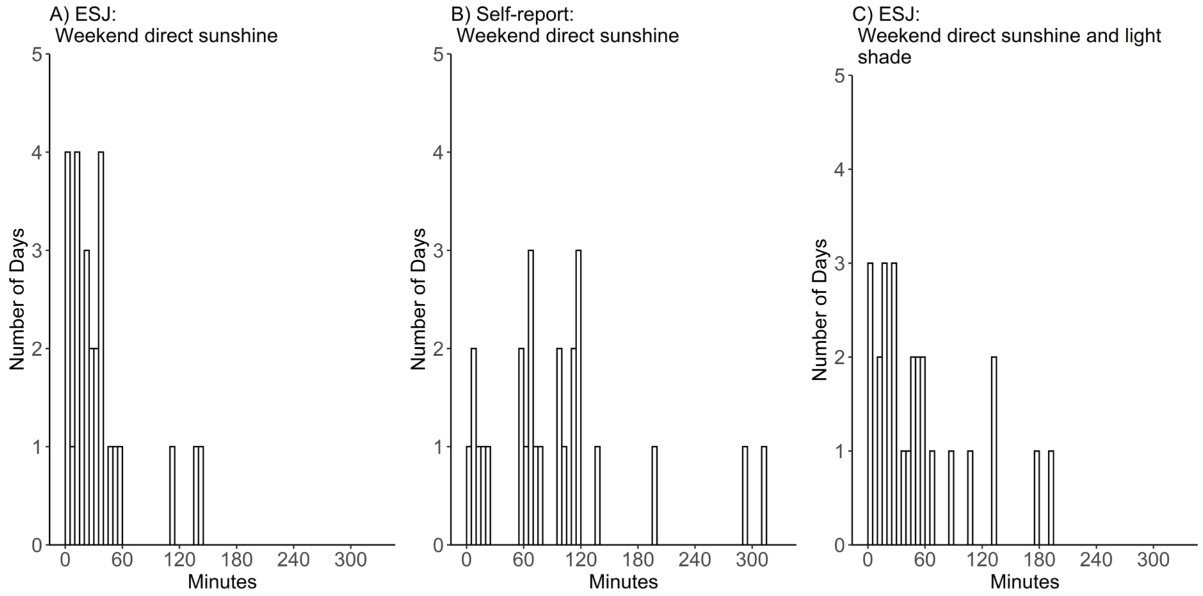
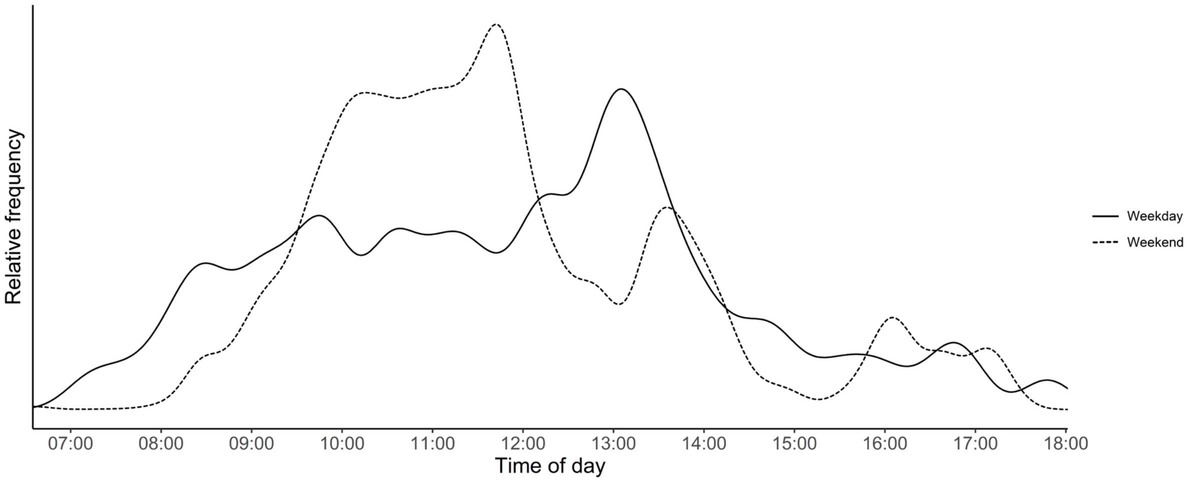


**Figure 5:** Frequency histograms of: A) weekend direct sunlight durations; B) weekend direct self-reported sunlight durations; and C) weekend direct sunlight exposure combined with periods of light shade as recorded by the ESJ. *N* = 26.

A) Direct sunshine



B) Direct sunshine and light shade combined

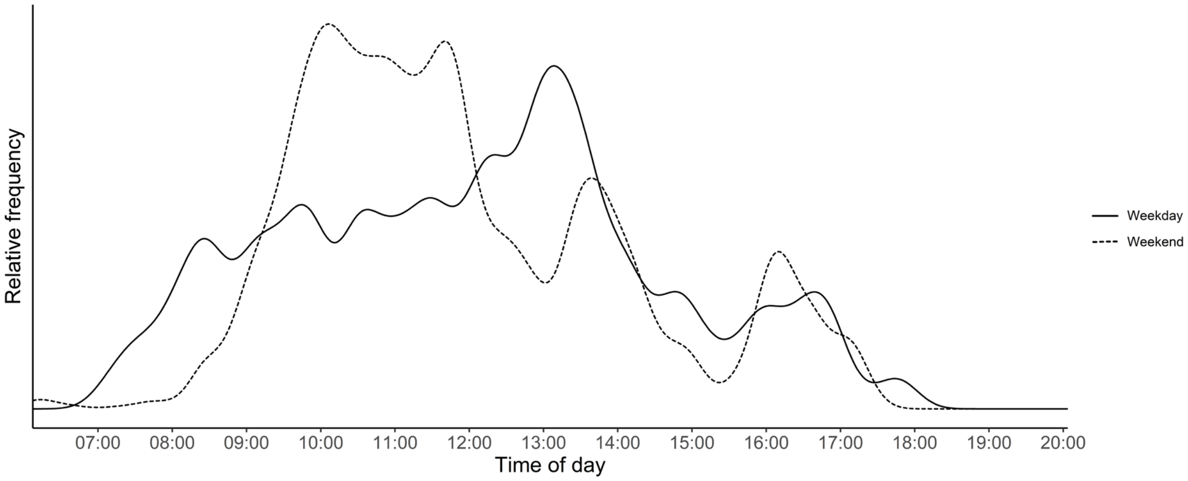


**Figure 6:** Relative frequency of timing for weekdays and weekends for: A) Direct sunlight exposure; and B) Direct sunshine and light shade exposure.