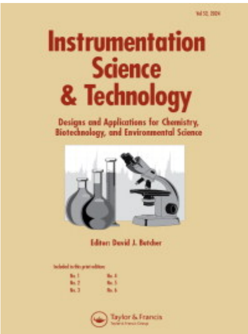

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Electronic sun journal as an evaluation tool for measuring sunflecks while walking through urban forests

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ABSTRACT

Fluctuations in direct sunlight intensities (or sunflecks) are experienced in urban forest parklands. A novel application of an electronic sun journal (ESJ) was developed providing accessible, objective detection and analysis of sunflecks sampled at 50 Hz while walking through urban parkland forests in Toowoomba (27.57°S 151.95°E), Australia. A total of 654 sunflecks were detected during 12 walks. Sunfleck durations (SFD) ranged from 0.02 s to 102.5 s, with a median of 0.10 s and interquartile range of 0.04-0.28 s. The sunfleck intervals (SFI) ranged from 0.02 s to 115 s, with a median of 0.16 s and interquartile range of 0.06-0.62 s. Of the 10,983 sunfleck clusters, approximately 90% included two or four sunflecks per second, with the highest frequency cluster reaching eight. The distribution of the sunfleck clusters changed with different sun angles and azimuth as the sunlight passed through different parts of urban parklands. The developed method with the ESJ may be employed in the evaluation of sunfleck durations, intervals and clusters at eye level in other urban forest environments, adding to the developing interest as greenspaces play an increasing role in urban studies.

KEYWORDS
Electronic sun journal; flickering sunlight; shade; sunflecks; urban forests; urban greenspaces

Introduction

There is a strong body of research linking vegetation in greenspaces, such as urban forests and parks with maintaining and improving human health, including encouraging participation in recreational activities.[1–4] A significant feature of these environments is the dappling of sunlight through leaves, which is identified as a pleasing visual feature of any park,[2] "Komorebi", a directly untranslatable Japanese term that describes this

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esthetically pleasing effect of sunlight flickering through the leaves of tree canopies.[5] Recent research has also analyzed the effects of intermittent sunlight on photosynthesis in agriculture.[6–8]

Tree canopies are not opaque immovable objects[3], resulting in solar irradiance randomly fluctuating in intensity and time.[3,6,9] Additionally, wind and seasonal variations in canopy density contribute to these fluctuations, generating patchy and dynamic environments consisting of real and perceived shade, partial shade, and direct sunlight.[8] This has led to varying terminology for this dynamic phenomenon, such as sunflecks, windflecks, shadeflecks, or more simply 'flecks'.[6–8,10] In this research, the fluctuations are just termed 'sunflecks' which describe the measured oscillations in sunlight intensities.

Rapid intermittent changes in sunlight intensities, such as direct sunlight flickering through the canopy (sunflecks), can lead to irritation, distraction and even, in more extreme cases, temporary visual disabilities.[11,12] There is some suggestion that sunlight flickering through the forest canopy could result in photosensitive epileptic seizures[13]. Photosensitivity is considered to be an important public health issue.[14] During incidences of bright light such as direct sunlight, humans tend to protectively squint or look away when their eyes are exposed to bright sources of light[15,16] which in the case of the sun, can become damaging in under a second.[15]

Tree canopy observations and measurements are often conducted using accessible and no-cost remote sensing tools such as Google Street View[3] in addition to employing complex and expensive equipment;[6–8] however, these methods do not provide a realistic interpretation of the collective canopy shade profile or sunfleck occurrences that people experience while walking outdoors within urban forests, which in this paper is the term to describe areas with significant tree cover such as walking tracks in parks. These aspects are better studied by means of eye-level observations.[3] Previous research by Durand and Robson,[6] Burgess et al.[7] and Durand et al.[8] used a CCD array spectrometer to collect sunfleck data from crops, such as oats, barley, broad bean and wheat, measuring up to under a meter in height. LiDAR is also used in some studies.[3] The measurements of sunflecks within crops is immobile at fixed points. A mobile technique at eye-level is required for the measurement of sunflecks observed by parkgoers utilizing urban forests for recreation or exercise. The type of instrumentation employed for crops is costly and cumbersome for human subjects to wear in urban forests.[3]

The Electronic Sun Journal (ESJ) provides an objective, wearable and customizable low-cost sensor that can observe shade and sunfleck patterns at eye level, ESJ operation and design is described in detail by Downs et al.[17] This preliminary study assesses the effectiveness of the Electronic

Sun Journal (ESJ) in measuring sunfleck duration and frequency at eye level during outdoor activities in urban forests, as precise measurement is imperative in addressing the documented potential impact of sunflecks on human health. These measurements are also a useful measure of partial shade duration and frequency, experienced by park users utilizing tree lined pathways.

The ESJ was employed to build upon prior methodologies and findings in sunfleck measurements, allowing for the objective recording of eye-level observations of duration and the intervals of sunlight fluctuations while walking through an urban forest. Furthermore, changes in sunfleck frequency during movement are explored as an objective method of evaluating shade profiles during different times of the day, providing an additional tool for conducting mobile sunfleck observations which can be beneficial for urban planning decisions regarding urban forests and other greenspaces.

Methodology

The approach for the methodology in this research was to employ the ESJ on 12 walks on paths through treed urban parks. A data analysis algorithm, written using Python (version 3.11) was developed to quantify sunfleck duration (SFD), sunfleck interval (SFI) and sunfleck clustering (SFC), adapted from Durand et al.[8] and Durand and Robson,[6] as described in the following sections.

Data collection

Data was collected by the authors from 12 walks taken at a range of sun elevations (29° to 86°) during the mornings, midday and evenings, on paths through treed urban forests in Toowoomba, Queensland, Australia (27.57°S, 151.95°E) such as West Creek Reserve (Figure 1). The tree lined paths were selected to allow up to three minutes of brisk walking, predominantly in a straight line and within approximately 30° of a northerly direction.

The ESJ employs an infrared diode, with a sensitivity range of 870–1,050 nm and operating in reverse bias mode.[17] An output of 0 V occurs in an unshaded sunny location, 2.5 V when in full shade and a value between these two extremes when in partial shade.[17] The voltage output is converted and logged by the ESJ as an integer value between 0 (full sunlight) to 1023 (full shade). Based on observations in previous research by Downs et al.,[17] Dexter et al.[18] and Igoe et al.,[19] the voltage increases as the wearer moves from full sun to a light shade and to a dense shade environment. ESJ values between 1 and 511 represent light shade, while dense

Figure 1. Examples of the shade profiles of tree-lined environments in the (a) late morning and (b) mid-afternoon. Images taken by A. Parisi and A. Amar, West Creek Reserve, Toowoomba, Australia.

shade is represented by the values from 512 to 1023. An advantage of the ESJ is that factors such as sun angle and direction, and cloudiness do not affect its output,[9,18] meaning that data could be collected at any time during dry conditions and not having to wait for a cloud-free day.

The ESJ was set to record data at a frequency of 50 Hz ($t = 0.02$ s), consistent with human perception of flickering.[20] The ESJ was fixed with clips on the shirt or collar, positioned approximately at eye level, and facing forward (Figure 2). This ensures that the occurrence of flickering is measured from an observer's perspective.[3]

Data analysis

The raw 8-bit ESJ data (ESJ_{signal}) was recorded as integer values between 0 to 1023. These values have been converted into $\log_2$ format (ESJ_2) according to:

$$ESJ_2 = \log_2\left(ESJ_{signal} + 1\right) \tag{1}$$

This transforms the total 8-bit ESJ_{signal} range from 0-1023 to a new range of 0-10, with the boundary between light and dense shade earlier being defined as occurring at $ESJ_{signal} = 511$[18] indicated by $ESJ_2 = 9$ (Table 1). The transformation in Equation (1) provides a better base for analyzing smaller changes in illuminance due to factors such as the wind.

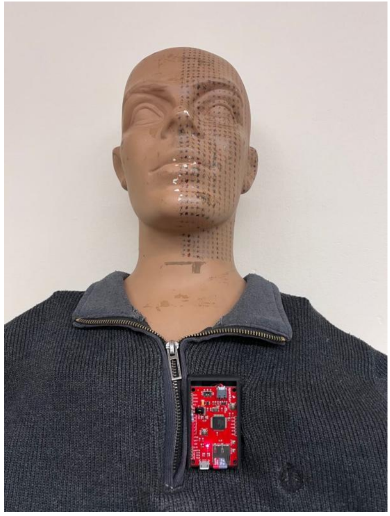

Figure 2. Position on the body that the Electronic Sun Journal was attached to clothing.

Table 1. The $\log_2$ transformed ESJ signal boundaries for the shade types.

Shade category	ESJ signal value (ESJ_{signal})	$\log_2$ transform (ESJ_2)
No shade	0	0
Light shade	1	1
	511	9
Dense shade	>511	>9
	1023	10

For analysis, sunflecks are defined as instances when the ESJ signal drops to zero (direct sunlight) between non-zero signals. Raw ESJ data was analyzed to determine the prevalence and magnitude of the sunfleck duration (*SFD*) and intervals between sunflecks (*SFI*), using an algorithm adapted from Durand et al.[8] and defined as the number (n) of contiguous ESJ_{signal} meeting conditions in:

$$SFD = 0.02n_{\left(ESJ_{signal}=0\right)} \text{ seconds} \tag{2}$$

$$SFI = 0.02n_{\left(ESJ_{signal}>0\right)} \text{ seconds} \tag{3}$$

The overall distributions of SFD and SFI times from the walks are represented in boxplots.

For each walk, sunfleck clustering (*SFC*), adapted from Durand and Robson,[6] was measured as a unitless moving frequency of sunflecks ($\sum n_{SFD}$) that occur in a moving time interval ($\sum T$):

$$SFC = \frac{\sum n_{SFD}}{\sum T} \tag{4}$$

The summation provides the total number of sunflecks recorded within the time interval over the total time interval. A moving frequency of 50 signals were recorded giving a time interval of 1.0 s.

Analysis algorithm

A Python script was used in this paper to detect and quantify SFD and SFI based on detection of diagnostic features according to the definitions described for Equations (2) and (3); however, it should be noted that any programming language could be used to perform this analysis. The process is outlined below.

For this research, the raw text file from the ESJ was saved as a CSV (comma-separated values) file allowing for increased portability, giving a ESJ_{signal} dataset. Transformation of the data into ESJ_2 could be performed on the raw data in any spreadsheet program, such as Microsoft Excel, but either the ESJ_{signal} or ESJ_2 datasets can be used for the following process:

1. The data set CSV file is opened as an array.
2. Data is binarized such that any zero signal remains as zero, otherwise it is given the value of 1.
3. A moving frequency of 50 signals is taken (Figure 3), each centered at the middle of each interval. This results in sunflecks being counted in multiple moving frequency intervals. Additionally, intervals may start and end with a sunfleck that started in an earlier count.
4. For each moving frequency, the 'falling' and 'rising' edges to where $ESJ_{signal} = 0$ are detected and counted.

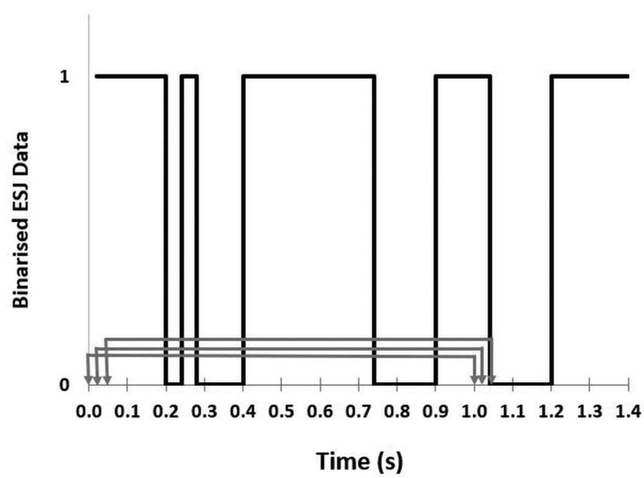

Figure 3. Stylized rendition of the moving frequency of 50 ESJ signals, equaling 1.0 s intervals. The number of sunflecks would be counted at the middle of each interval.

a. Falling edges signify when a sunfleck begins, occurring when a non-zero ESJ signal is followed by a zero signal. Rising edges are the opposite.
b. A count of the contiguous $ESJ_{signal} = 0$ is multiplied by 0.02 to provide the magnitude of SFD in seconds. Whereas the count of contiguous $ESJ_{signal} > 0$ multiplied by 0.02 represents SFI.
c. Additionally, sunflecks that occur at the start and end of the time interval, with only a falling or rising edge, are detected and included.

5. SFD and SFI magnitudes are saved as arrays.
6. SFC is determined by a count of SFD occurrences within a moving frequency of the dataset, this count is then saved as an array. A relatively simple method was used to count the number of sunflecks is equal to the maximum number of rising or falling edges counted in each interval.

Examples of SFC calculations

Figure 4 has 4 falling edges (downward arrows) and 4 rising edges (upward arrows), which correspond to the 4 sunflecks (binarized ESJ data = 0).

Figure 5 is similar to the previous example but starts with a sunfleck that started earlier. In this case, there are 4 falling edges and 5 rising edges, the maximum of these two counts correspond to the 5 sunflecks. The same pattern also occurs if there is a sunfleck at the end of the interval and shade at the start.

A correction is needed when there is a sunfleck measured at the start and the end of a moving frequency interval. In Figure 6, where there is a sunfleck at the start and end of the moving frequency interval, the number

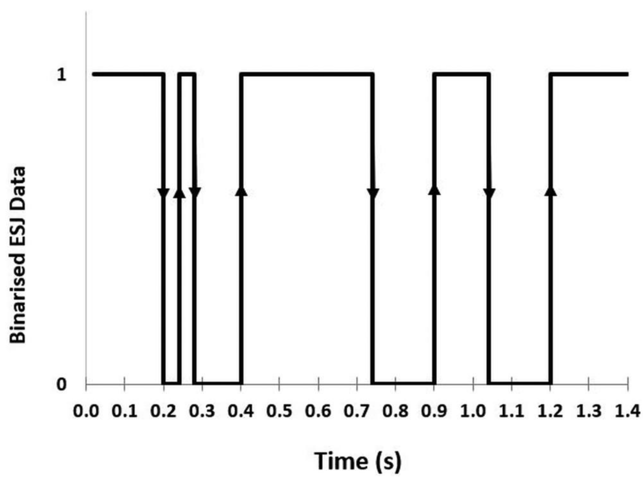

Figure 4. Case in which there is shade at the start and at the end of a moving frequency interval. The maximum number of rising (upward arrows) or falling edges (downward arrows) is equal to the number of sunflecks.

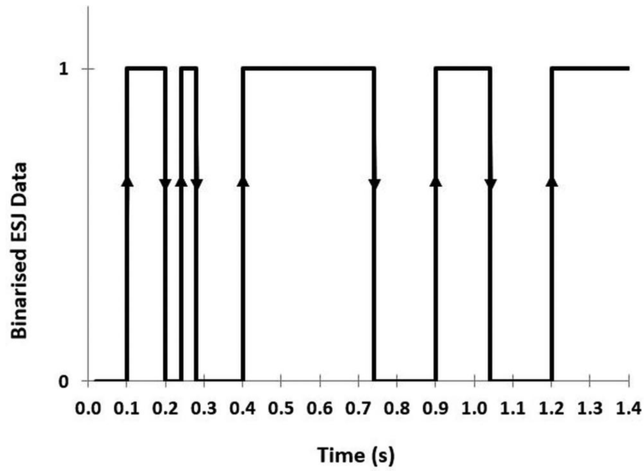

Figure 5. Case in which there is a sunfleck at the start and at the end of a moving frequency interval. The maximum number of rising (upward arrows) or falling edges (downward arrows) is equal to the number of sunflecks.

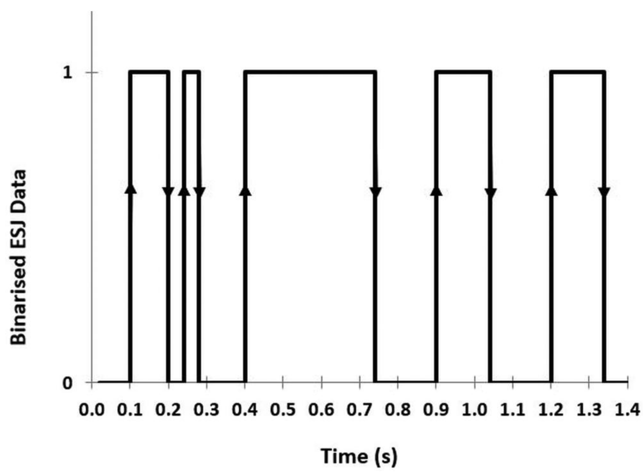

Figure 6. Case in which there is a sunfleck at both the start and at the end of a moving frequency interval. The maximum number of rising (upward arrows) or falling edges (downward arrows) is one less than the number of sunflecks, thus a correction is applied.

of rising and falling edges (5 each) is less than the 6 sunflecks, thus a correction is made by adding 1 to the maximum number of rising or falling edges.

Details of walks

Data was collected during 12 separate walks on six different paths, as illustrated in Table 2. Walks were replicated on three of these paths at different times of the day to investigate the impact of sun position. The walks,

Table 2. Details of walks employed in this study. All walks were taken in an approximate northerly direction in parks in the vicinity of West Creek Reserve 7, Kearneys Spring and Garnett Lehmann Park, Rangeville, Toowoomba, Australia. All times are in 24-h Australian Eastern Standard Time (UTC +10). All days had clear and partly cloudy conditions with little to no wind except one day (8th November 2022) experienced winds up to 28 km/h.

Date	Time	Peak solar angle (°)	Average solar azimuth (°)	Length of walk (m)	Location of walk
17th Sep 2022	10:48	57	27 (NE)	140	27.5918°S 151.9447°E
20th Sep 2022	12:28	60	339 (NW)	243	27.5977°S 151.9434°E
8th Nov 2022	07:15	29	94 (E)	248	27.5874°S 151.9731°E
27th Dec 2022	08:22	42	97 (E)	253	27.5755°S 151.9683°E
	11:22	82	61 (NE)	253	27.5755°S 151.9683°E
	15:23	43	263 (W)	253	27.5755°S 151.9683°E
28th Dec 2022	08:30	44	97 (E)	532	27.5728°S 151.9662°E
	11:50	86	11 (N)	532	27.5728°S 151.9662°E
	15:22	43	263 (W)	532	27.5728°S 151.9662°E
30th Dec 2022	08:25	43	97 (E)	182	27.5873°S 151.9455°E
	11:45	85	27 (NE)	182	27.5873°S 151.9455°E
	15:30	42	263 (W)	182	27.5873°S 151.9455°E

conducted at a brisk pace, took place in spring and summer (Southern Hemisphere), under varying weather conditions including clear and partly cloudy conditions with little to no wind on most days, except for one day with winds reaching up to 28 km/h (8th November 2022). The paths were generally covered by remnant Australian Eucalyptus trees, with the path on the 17th September 2022 covered by established planted palm species, predominantly, *P. canariensis*.

Results and discussion

The data obtained from the ESJ exhibits substantial fluctuations with no immediate noticeable pattern (Figure 7). This is as expected, as the data highlight the random and dynamic nature of shade patterns and sunflecks associated with the canopy of an urban tree lined path as observed by Downs et al.[17] and Igoe et al.[19] This contrasts with the well-defined boundaries observed for artificial structures, such as buildings and retaining walls, where changes are due only to the sun's relative position[17,19] An important observation from Figure 7 is that most of the data is in the light shade category. Transforming 8-bit ESJ_{signal} data (Figure 7a) to ESJ_2 format (Figure 7b) provides finer detail of the nature and fluctuations of sunlight exposure and shade that occur along the transect.

The raw data (Figure 7a) and $\log_2$ transformed data (Figure 7b) of the example walk demonstrate the variable and random nature of sunflecks that occur along a walk in an urban forest. For approximately the first 20 s, 55 to 80 s and 100 to 105 s, the observer would experience full sunlight, and mostly would perceive light shade from approximately 105 s with few instances of flickering (sunflecks) at about the 170, 190 and 205 s marks. Significantly, the intervals between approximately 20 to 55 s and 80 to 100 s

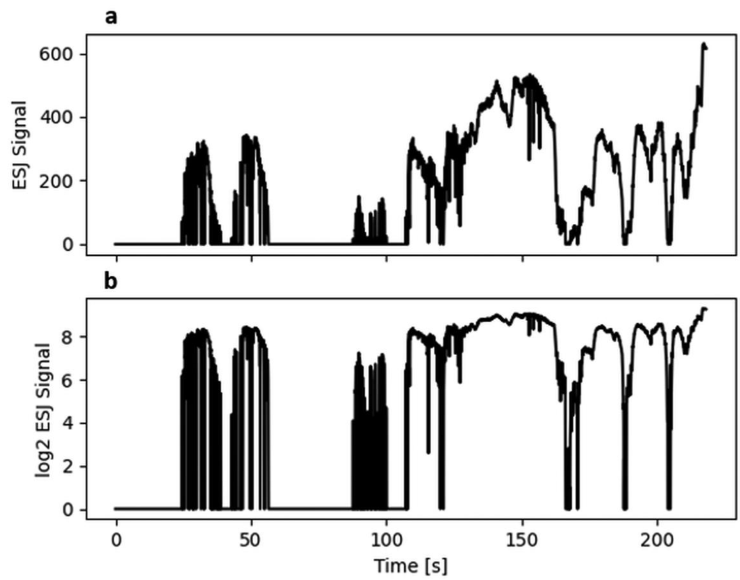

Figure 7. Example of (a) raw and (b) $\log_2$ transformed ESJ data from 7:15 am AEST 8th November 2022 at a peak solar angle of 29° and average solar azimuth of 94°. Sunflecks occur where the ESJ signal is zero in both cases.

indicate periods of rapidly occurring, short duration sunflecks which could be perceived as flickering sunlight.

A total of 654 sunflecks were observed from all 12 walks. Sunfleck durations (SFD) ranged from 0.02 s to 102.5 s, with a median of 0.10 s. The interquartile range was 0.04-0.28 s, resulting in approximately 15% of sunfleck durations being outliers (Figure 8). Similarly, the time intervals between sunflecks (SFI) were also heavily skewed, ranging from 0.02 s to 115 s, with a slightly higher median and interquartile range, of 0.16 and 0.06–0.62 s respectively and a similar proportion of outliers (Figure 8). The longer intervals are likely to be due to walking in direct sunlight between tree canopies. The trend in the data for all walks suggests that there is a prevalence of short duration sunflecks occurring at close intervals. These clusters can be seen occurring between approximately 20 to 55 and 80 to 100 s in the example in Figure 7 and are separated by periods of continuous longer duration direct sunlight or shade.

The sunfleck clusters calculated for a sample walk on a treed path from 7:15 am (AEST) 8th November 2022, with a peak solar angle of 29° and average solar azimuth of 94° shows five distinct sunfleck clusters, with the frequency peaking at six sunflecks per second (Figure 9). However, the predominant sunfleck clusters occurred in areas of light shade (Figure 9). An observation is that the light flickering as an observer moves through a treed environment occurs in clusters, consistent with observations made with an immobile sensor by Durand and Robson[6] and Burgess et al.[7] Future

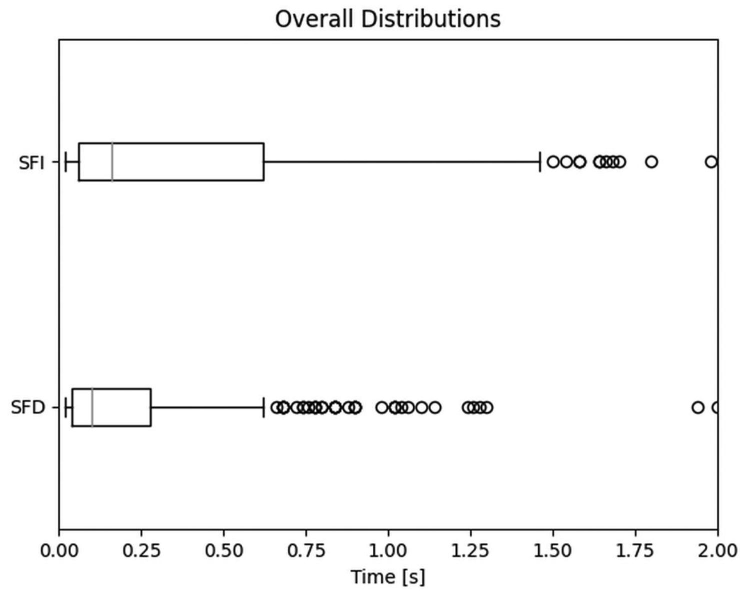

Figure 8. Distribution of sunfleck duration (SFD) and interval between sunflecks (SFI) for 654 sunflecks in all 12 walks with the median as the line within each box. The box represents the interquartile range with the circles representing the outliers. The distributions have been truncated to 2.0 s to make it easier to compare the median and interquartile ranges. The longer durations are likely due to walking between trees.

research, employing a GPS and the ESJ may make detailed analysis of tree canopy gaps possible by comparison to aerial images such as those publicly available in Google maps.

In Figure 9, there is a prevalence of SFC magnitudes of 0 and 1. These are time intervals of consistent shade and consistent sun exposure occurring in that timeframe respectively, these can be omitted as they are not sunflecks. Only values of SFC > 1 may be considered as indications of the fluctuating sunlight under the canopy in urban forests. Sunfleck clusters (SFC) were detected throughout all walks at different times, occurring at relatively low frequencies. Of the 10,983 sunfleck clusters with SFC > 1 for all 12 walks, approximately 90% were clusters of 2-4 sunflecks per second, with the highest frequency cluster reaching 8 sunflecks per second.

Sunfleck clusters can change with different sun angles and azimuth, particularly when the sunlight passes through different parts of the urban tree canopy or if it is directly above a canopy-free section of the walking path. Variable factors, such as wind can also affect the position of the shade but could be used in identifying the positions and magnitude of sunfleck clustering. An example of a time series observed on the 30th of December 2022 is shown in Figure 10. ESJ_2 transformed signals and the corresponding sunfleck clusters (*SFC*) were recorded at 8:25 am (Figures 10a and 10d), 11:45 am (Figures 10b and 10e) and 3:30 pm (Figures 10c and 10f).

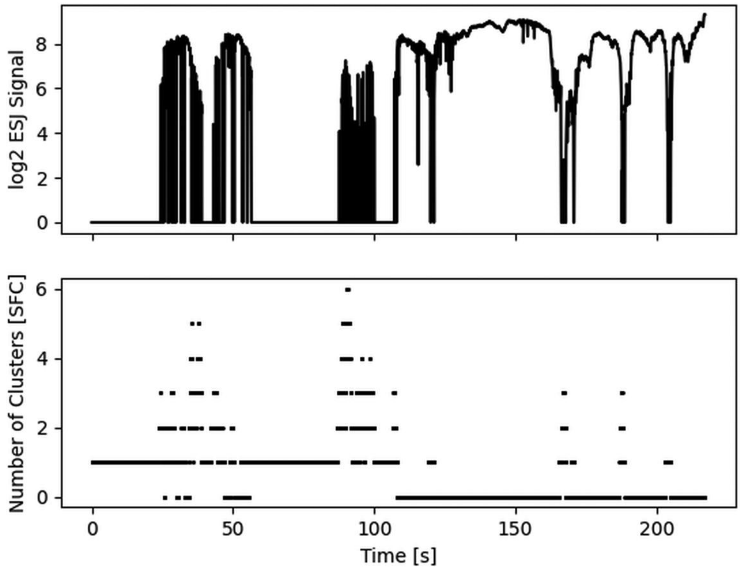

Figure 9. Sunfleck clusters (SFC) showing the number of sunflecks per second for the duration of the walk taken at 7:15 am (AEST) 8th November 2022 with a peak solar angle of 29° and average solar azimuth of 94°.

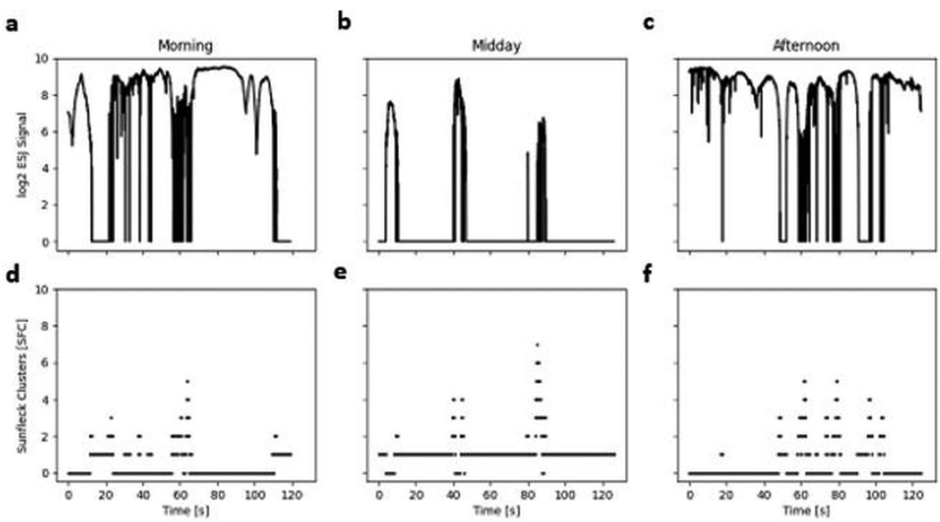

Figure 10. Time series along an approximately north direction walk on 30th of December 2022 underneath a canopy in an urban forest situated in Toowoomba, Australia. ESJ_2 transformed signals and the corresponding sunfleck clusters (*SFC*) recorded at 8:25 am (Figures 10a and 10d), 11:45 am (Figures 10b and 10e) and 3:30 pm (Figures 10c and 10f).

As expected, at low sun angles during the morning and afternoon, when sunlight filters through the canopy, most of the clustering occurs at SFC = 0, or in some form of shade during that time interval (Figures 10a and 10c). This contrasts with high sun angles at around midday where most of the clustering occurs SFC = 1, and when direct sunlight is interrupted only by overhead branches (Figure 10b). However, an interesting observation from the time series is that the amount and magnitude of sunfleck clustering (Figures 10d, 10e, and 10f) is not necessarily predicated on there being denser and more consistent shade as observed in the morning and afternoon (Figures 10d and 10f) compared with the measured sunlight exposure observed at midday (Figure 10e).

Figure 11 is a Google Maps satellite image of the walk analyzed in Figure 10. From Table 2, the sun during the morning and afternoon walks was from the east and west respectively, passing through the trees either side of the path, and from the north-northeast at midday, passing almost directly over some of the path. However, it is not feasible to ascertain the perceived level of shade nor the sunlight flickering at different times of the day from

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Figure 11. Google Maps satellite image of the path taken on the 30th December 2022 for the time series in Figure 10. During the morning and afternoon walks was from the east and west respectively, passing through the trees either side of the path, and from the north-northeast at midday, passing almost directly over some of the path. SFC magnitudes cannot be ascertained from this satellite image due to insufficient spatial resolution.

this satellite imagery. As SFC observations can only be made at eye-level by walking along the path rather than the often-used Google Maps,[3] they provide a straight-forward and cost-effective method of quantifying the shade and sunlight flickering patterns observed and perceived by park users.

Conclusion

The novel application of the electronic sun journal has been proven to be highly effective at objectively sampling sunflecks at eye level while walking in urban forests. The data analysis algorithm a provides robust and repeatable quantification of sunfleck duration, interval and clustering, with the flexibility to be implemented in any programming language. Measurements of sunfleck duration and interval provide an objective measure of user movement underneath a partially shaded environment. The technique was applied to collect data on 12 walks on urban treed paths orientated in an approximate northerly direction.

There were substantial fluctuations in the analyzed data with no immediate noticeable pattern due to the random and dynamic nature of shade patterns associated with the canopies adjacent to the tree lined paths. The sporadic nature of the sunflecks is well suited to use of electronic sun journal. The developed application with the electronic sun journal presents a suitable and accessible method to evaluate sunfleck durations, intervals and clusters in various urban forests and environments where people engage in exercise and day-day activities within established parklands. How much shade is available along a designated pathway, the density of that shade and the frequency at which that shade is encountered are able to be measured objectively using the electronic sun journal. This research has presented a straightforward method for analysis of shade quality within a designated urban forest.

For designers of such environments, where shade is of primary importance, the outcomes of research conducted from shade measurements received by active park-users could enable objective comparison between different locations, park designs and pathways. This is an avenue for future research, where samples conducted across larger populations and environments may help to inform and guide future park and urban forestry design.

Further analysis can be performed by adapting the developed method in this preliminary study to detect contrast changes between dense and light shade. The ESJ can be employed to evaluate sunfleck duration, intervals and clusters in open sorting grounds, playgrounds, natural floristries and other outdoor urban environments. Additionally, higher detection frequencies may be employed, such as used for agricultural crops by Durand et al.[8] and Burgess et al.[7] to provide an accessible sampling method to determine finer temporal and spatial details in the observed shade profiles.

The techniques developed in this work can potentially be extended in future research to analyze further linkages between sunflecks, visual irritation and distraction, and possibly even monitoring for sunfleck frequencies that can affect perceptual discomfort, particularly related to photosensitivity,[11] including sunfleck clusters that could result in photosensitive epileptic seizures. Behavioral perceptions, studied in unison with objective measures of shade may inform future investigations that seek to examine relationships between environmental esthetics, human mood, psychology and connectedness to the urban environment.

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Disclosure statement

The authors declare that there are no competing interests to declare.

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