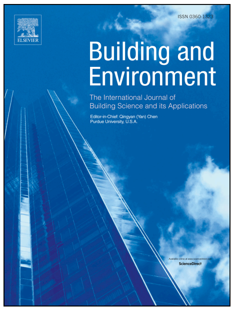
Journal Pre-proof



Evaluation of shade profiles while walking in urban environments: A case study from inner suburban Sydney, Australia

Damien P. Igoe, Nathan J. Downs, Alfio V. Parisi, Abdurazaq Amar

PII: S0360-1323(20)30232-8

DOI: https://doi.org/10.1016/j.buildenv.2020.106873

Reference: BAE 106873

To appear in: *Building and Environment*

Received Date: 3 February 2020

Revised Date: 17 March 2020

Accepted Date: 1 April 2020

Please cite this article as: Igoe DP, Downs NJ, Parisi AV, Amar A, Evaluation of shade profiles while walking in urban environments: A case study from inner suburban Sydney, Australia, *Building and Environment* (2020), doi: https://doi.org/10.1016/j.buildenv.2020.106873.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier Ltd.

Journal Pre-proof

Evaluation of Shade Profiles while Walking in Urban Environments: A case study from inner suburban Sydney, Australia

Damien P. Igoe[*1], Nathan J. Downs[1,2], Alfio V. Parisi[1,2], Abdurazaq Amar[1]

[1]Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia, 4350

[2]Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia, 4350

*Corresponding author

Damien.Igoe@usq.edu.au

Journal Pre-proof

Journal Pre-proof

Abstract

Precise shade distributions at the street level are an area of research of increasing importance to provide complete and high spatial and temporal resolutions of the amount and effectiveness of shade. Temporal shade distributions and profiles were evaluated for an inner Sydney tree-lined suburban street at different times of the day using an electronic sun journal (ESJ), providing detailed profiles of shade availability for various times of the day to provide very detailed street-level shade profiles and distributions that are often not included in shade audit methods and models. Further profiles were developed of streets adjoining shopfronts and public parks. Distributions of dense, light and no shade areas were calculated, revealing that tree canopy shade area during the middle of the day is considerably less effective and more prone to gaps than at other times. Distributions calculated using the ESJ were compatible with the paper-based shade auditing with less than 10% variation, whilst the ESJ has revealed a greater resolution of detail of gaps in the shade, thus records a higher amount of areas of no shade. The ESJ is a robust, low cost and portable tool that can efficiently and quickly produce shade profiles during walks in an urban environment, such as streetscapes.

Journal Pre-proof

Keywords

Shade profiles, shade distributions, urban greenspaces, shade audit, urban environment, smart devices.

Journal Pre-proof

1. Introduction

Tree-lined streets, alongside suburban parks or 'greenspaces', are included in a broad definition of natural environments [1] that are beneficial for human well-being [2]. In terms of physical well-being, urban treescapes can provide relief to pedestrians by improving thermal comfort and mitigating, on a local level, the urban heat island effect [3][4]. However, measurements of shade at street level is still imprecise, particularly when it comes to tree shade and effects of diffuse reflected light from street structures [2][5].

Rates of physical inactivity are significantly higher for residents of urban populations [6]. Access to transport and proximity to readily accessible services contribute toward a limited necessity to walk. When able to walk, urban populations are often restricted to sidewalks or street verges which are included in the definition of greenspaces [7][8], in some places these urban features are known as 'nature strips'.

It is well established that exposure to the sun provides benefits, such as promotion of vitamin D synthesis and general improvements in overall well-being, but a balance is needed as too much exposure can lead to harmful consequences such as skin cancers, eye conditions and photoaging [9][10]. Shade from objects such as trees and buildings can improve desirability to use an urban environment [11]. The use of tree shade can increase urban walkability, which has previously been measured using derived indices [12] and also can contribute toward reducing personal sun exposure risk [4][9][10].

There has been some research performed in the efficacy of urban greenspaces in reducing the exposure to direct and diffuse solar radiation and perceived thermal comfort. Factors such as canopy foliage density, tree species, season, solar zenith angle (SZA), cloud cover and proximity to artificial structures are cited as important parameters in influencing the protective quality of urban greenspaces [4][13][14]. As opposed to utilising motorised transport, accessible greenspaces that provide a comfortable and aesthetically pleasing environment can encourage ambulatory activity [15]. This, in turn is associated with reduced risk to diabetes, cardio-vascular and respiratory disease rates, improved social cohesion and mental health [16][17][18].

Ground based shade audits sometimes examine the 'greenness' or canopy density from aerial or satellite imagery [2]. Shade audits are an important aspect for assessing the photobiological risk amelioration capabilities of natural and artificial structures. Such assessments provide valuable information for informed shade planning and design [4][10][19]. The effectiveness of tree shade is often measured using the sky view factor (SVF), usually by measurements based on photographs of tree canopies, GPS based measurements, and simulations [13][20]. Recently, the Shade Protection Index (SPI) has been developed for observations of solar radiation [9][21]. Online tools such as the SunSmart 'Shade Comparison Check' tool and the use of Google Street View have also been employed in recent years [2][5][22].

Recent research pertaining to techniques and models related to the observation and measurement of shade details in urban streets, while attaining enhanced accuracy overall, are still prone to inaccuracies in regard to the shade distributions of urban trees and diffuse reflections of other surfaces [2][5]. An electronic sun journal (ESJ) was developed by Downs et al. [23] as a tool to complement and provide enhanced street-level precision to existing shade assessment methods. The ESJ is a low-cost, portable instrument that uses a reverse-bias infrared photodiode to assess the effectiveness of shade by recording the effective photovoltaic solar diode voltage every second.

This research expands on preliminary outdoor testing of the ESJ [23] to demonstrate an effective and accessible method to accurately measure high-precision urban street shade

Journal Pre-proof

details and to determine the effective shade in an urban environment from the ambulatory perspective of a typical pedestrian. The relative simplicity and potability of the ESJ as both a data collection and retrieval method provide a tool for anyone involved with research concerning shade audits and related applications, including those involved with urban sun protection research and policy making. The methods used are a means to provide high temporal resolution shade profiles encountered during walks through urban residential locales, with a focus on the 'green' infrastructure - tree-lined roads in comparison to streets dominated by buildings and suburban parks.

Journal Pre-proof

2. Methodology

A key tenet of the methodology and choice of equipment for this research is based on portability and simplicity to facilitate the replicability for all members of the community. The intended assessment method is expected to provide another tool for the community's custodianship of the local environment, research about environmental solar hazard, and potential increased participation in Citizen Science.

2.1. Equipment

The equipment used was kept to a minimum for the ease of movement along the walking transects. An electronic sun journal (ESJ) set to a sampling resolution of one second was secured to a small clipboard with enough space to write down observations of shade, direction changes and any other changes in conditions for the purposes of the ambulatory shade assessments. Photodiode output voltage data recorded from each walking transect was stored as a text file on a micro SD card and plotted against transect distance. Qualitative shade assessment data was also noted during each walking transect. The maximum photodiode output of 2.5 V represents the photodiode response in the full shade. The output falls to 0 V when the photodiode is exposed in an open unshaded environment [23] and records a voltage between 0 and 2.5 V depending on the shade density.

Journal Pre-proof

2.2. Locations

Walking transects were completed along streets and parks that were found to have significant amounts of shade in the inner eastern suburbs of Sydney of Kensington, Rushcutters Bay, Edgecliff and Darling Point, Australia (33° 54' S 151° 15' E). These represent examples of inner suburban settings complete with suburban parks, tree-lined streets and high set buildings and retaining walls.

2.2.1. Main location

The focus of the research was to assess the shade quality of a suburban tree-lined street in Darling Point. The street had a slight incline (approximately 3°), where the entire walking path was continuous without crossroads to allow for a reasonable consistent walking pace without interruption. This street is designated as 'Mona'. An example of part of the tree-lined street focus is presented in Figure 1.

Figure 1: Sample image of the focus tree-lined street in an inner Sydney suburb – the walking path is on the right. Image taken on a hazy day by the author at 2:00pm local time, 21st November 2019 at a solar zenith angle of 22.5°.

Pre-proof

For consistency, the street was walked in a general northerly direction for all transects. The street was approximately 400 m (1312 ft) long, with a section of 135 m (443 ft) in an almost direct north orientation (S1), turning to N 53° E for the remainder (S2). The street consists of older buildings and retaining walls, most were several levels high, and a mixture of mature and young trees with the walking path placed in between the retaining walls and tree line sidewalk. Transects along this road were completed at different times of the day to develop a temporal shade profile (transects A-D). Transects were timed to provide a range of shade profiles at different SZA. Two transects were made when the sun was at a low, midday solar zenith angle (SZA) preventing significant shadows from buildings and retaining walls, and two were made in the early morning and late afternoon when the sun had a high SZA and was positioned behind built structures. The high SZA transects are also useful to model similar wintertime shade conditions.

2.2.2. Validation locations

A further four validation transects (V1-V4) were completed along similar tree and building lined streets in all locations. These locations were assessed and selected using the *Google Map* satellite view function. All validation transects varied in length from 185 m to 500 m, and all had a significant proportion of trees of varying maturity alongside the walking path. Transects V2 and V3 were orientated roughly north-south, and V1 and V4 were roughly east-west. Built structures were also prominent in V1 and V4. Similar to the Mona transects, two validation transects were made at relatively low SZA (near midday) and two at a much higher SZA when the sun was nearer to the horizon (morning and afternoon) to further simulate wintertime shade conditions.

Journal Pre-proof

Journal Pre-proof

2.3. Times and conditions

All transect walks were completed in local late Spring and early Summer (Table 1). All times are local at UTC +11 (Australian Eastern Daylight Time), as local Daylight Savings is in effect. All walks had a duration of 5 minutes or less, the time taken to comfortably walk each of the streets. It is possible for the ESJ to be used for up to 4.5 hours [23].

The conditions varied between cloud free, partly cloudy and hazy (smoke and dust-affected) skies resulting from persistent forest fires and strong winds across the region [24]. Transect V4 was completed twice at approximately the same SZA to ascertain the effect of severe smoke haze compared to haze-free conditions.

Table 1: Local times and conditions for transects for the temporal 'Mona' shade profile (A-D) and used for validation (V1-V4). Transect V4 was completed twice for comparison between severe smoke haze and haze-free conditions.

Transect	Local time	Conditions
A	8:52 – 8:57 AM 20 October 2019	Cloud free
B	11:45 – 11:50 AM 7 October 2019	Partly cloudy
C	3:13 – 3:18 PM 13 November 2019	Cloud free
D	5:08 – 5:13 PM 15 November 2019	Light smoke haze
V1	8:28 – 8:33 AM 7 December 2019	Partly cloudy / smoke haze
V2	11:31 – 11:36 AM 8 December 2019	Bright overcast
V3	8:29 – 8:34 AM 14 December 2019	Mostly cloudy
V4	*11:38 – 11:40 AM* *5 December 2019*	*Severe smoke haze*
	11:30 – 11:32 AM 14 December 2019	Mostly clear

Journal Pre-proof

2.4. Data collection and analysis

Raw data (*D*) from the ESJ was converted from the 10-bit output signal value to the corresponding proportion of the 2.5 V maximum output voltage (equation 1).

$$V_{output} = 2.5 \times \left[\frac{D}{1024}\right] \quad [1]$$

The output voltage recorded at each second from the ESJ was normalised to the length of the transect, where transect length was determined using the 'measure distance' tool in *Google Maps*. This was to convert the time-based ESJ data to the known transect distance, accounting for any variations in walking speed between transects, thus providing a reasonably consistent means of temporal shade profile comparison. Variations in walking (or gait) speed within each transect were assumed to be minor [25]. The position of shade structures was verified using the satellite view of *Google Maps.* Shade profile morphologies were validated in transects V1-V4 by comparing with shade profiles observed in transects A-D.

An overall shade distribution for each transect was calculated based on earlier preliminary observations of ESJ output voltage boundaries for light and dense shade of static objects [23], with the boundary between light and dense shade being estimated at approximately 1.25 V. The category numbers 1 and 2 were given for light shade and dense shade, respectively. Areas with no shade observed, 0 V reading from the ESJ, are designated category number 0: 'no shade' (Table 2).

Journal Pre-proof

Table 2: ESJ voltage output boundaries and category numbers for light and dense shade categories, based on preliminary observations by Downs et al. (2017).

Shade category	Category number	ESJ output V_{output} (V)	Description
No shade	0	0	Insignificant to no measurable shade. This category includes sparsely foliated canopies, particularly those experiencing wind during a transect.
Light shade	1	0-1.25	Persistent broken or weak shade. This category can experience significant variability during a transect due to wind.
Dense shade	2	>1.25	Persistent and continuous shade. This category is visibly darker, and the shade profile is generally not affected by wind. Built structures are usually within this category.

Recorded observations on the printed maps using the corresponding category numbers were employed in the validation transects. For the purposes of comparison, ESJ data were grouped into the same discrete category numbers as recorded on the printed maps. This grouping provides a comparison between the more commonly used qualitative 'shade diary' and the ESJ for shorter walks. Shade profiles were further validated by visually confirming the position of shade distributions.

Cloud cover was observed while walking to ensure that it is not a contributing factor in the signal recorded by the ESJ [23]. Solar azimuth and altitude data were collected from Geoscience Australia's online sun and moon position calculator [26]. Similar databases exist for other international locations. Alternatively, these parameters can be calculated from details of the position and times of observations using algorithms such as Michalsky [27] or similar. A relative azimuth angle (Az_R) represents the relative sun position. This angle is

Journal Pre-proof

Journal Pre-proof

measured as the clockwise angle from the transect, calculated from the solar azimuth (*Az*) and expressed relative to the transect orientation (*S*). Visual examples are provided in Figure 2.

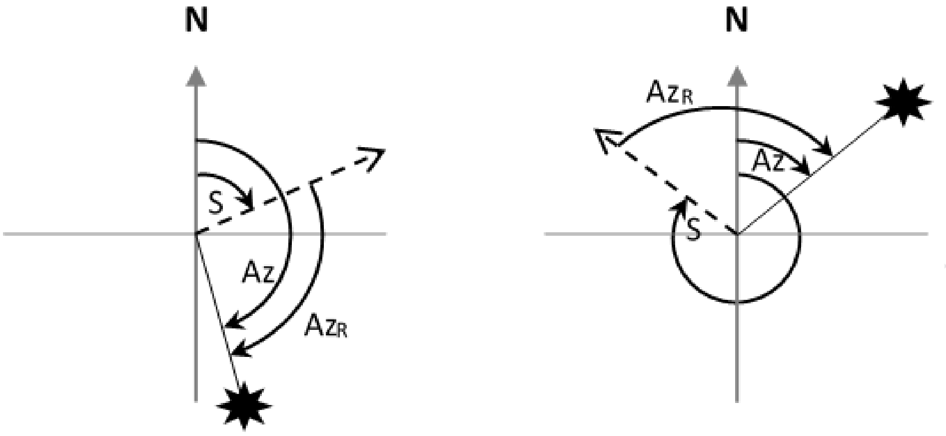


Figure 2: Examples of how the relative azimuth (Az_R) is measured from the sun's azimuth (Az) and the transect orientation (S). The sample transect direction is shown as a dashed arrow and the sun's azimuth by a solid line.

Journal Pre-proof

3. Results

3.1. Mona transects

3.1.1. Shade distributions

Mona transect walking speeds were calculated as 1.40 ± 0.05 ms^{-1}, consistent with the likely range of walking speeds determined by Bohannan [28] with only minor variation. Table 3 summarises the SZA and relative azimuth (for S1 and S2), averaged from the duration of each transect. Minimal variation in sun position occurred during each walk as the transects are of short duration (approximately 5 minutes). The shade distribution for the Mona transects as recorded by the ESJ is included for comparison.

Table 3: Summary of the average SZA, relative sun position, and ESJ shade distribution for each Mona transect.

Transect	Average SZA	Average relative azimuth		No shade	Light shade	Dense shade
		S1	S2			
A	57°	79°	26°	23.5%	12.6%	63.9%
B	31°	27°	334°	61.2%	34.6%	4.2%
C	37°	285°	232°	53.5%	34.7%	11.8%
D	62°	266°	213°	35.3%	28.7%	36.0%

Two trends are observed with the shade distributions depending on the sun’s position relative to shade structures:

1. Low SZA as in transect B and C, where the sun is ‘above’ shade structures creating relatively short shadows. At this orientation, the shade is primarily from the tree

canopies. A striking feature is the relative lack of dense shade, with the greatest distribution being in the 'no shade' category.

2. High SZA as in transect A and D, where, coupled with the relative azimuth, the sun is 'behind' shade structures resulting in long shadows, particularly from built structures. There is a definite increase in the distribution of dense shade, increasing with the proximity of built structures, where the structures in transect A are immediately adjacent the walking path, and those in transect D being on the opposite side of the walking path.

3.1.2. Shade profiles

The effects of each shading element of the streetscape relative to the sun were well defined. Changes of shade profile throughout the day were very clear and are visible in Figure 3. No evidence of significant effects of cloud and haze were observed in the ESJ output. The changing output voltages were, therefore, a result of the changing shade profile and not the local atmospheric conditions.

Journal Pre-proof

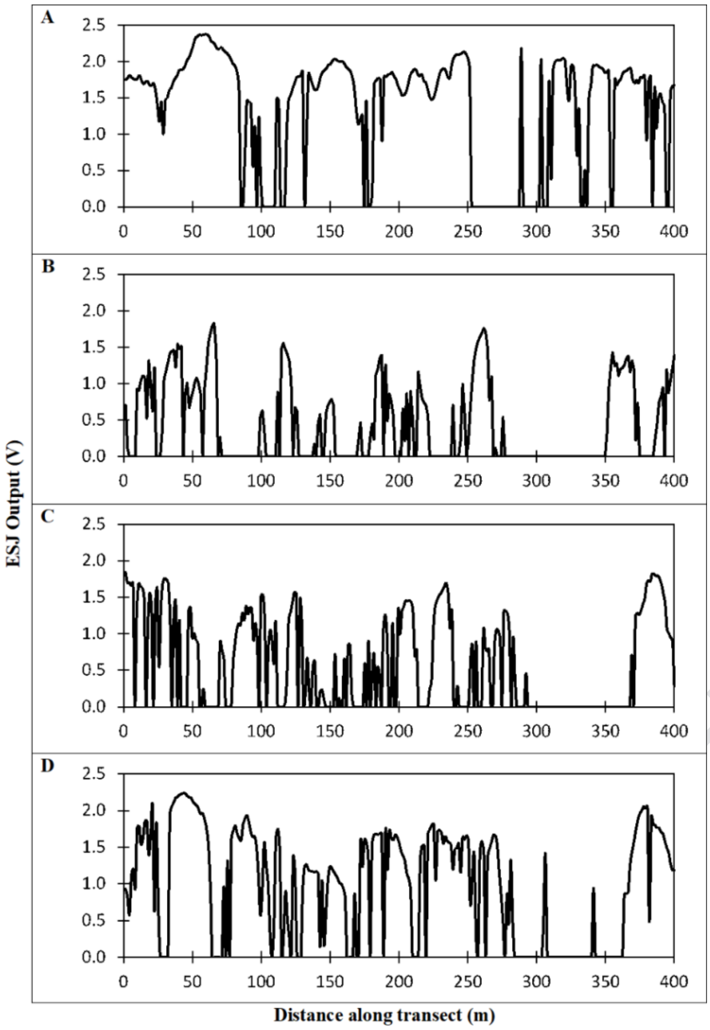


Figure 3: Comparison of four transects along Mona. The solar zenith angles and local times for each transect were 57°, 8:52-8:57 AM (A), 31°, 11:45-11:50 AM (B), 37°, 3:13-3:18 PM (C) and 62°, 5:08-5:13 PM (D). Shade was primarily provided by tree canopies in (B) and (C), and by built structures and trees in (A) and (D), the latter being from opposite street directions.

Change in shade profiles along a suburban street can clearly be observed over time, particularly depending on the position of the shade structures relative to the sun's position. The distinct shade morphologies can be identified, even when the observer is moving, allowing a shade profile of the street to be evaluated for different times of the day.

3.2. Validation

Four transects were completed to provide a shade distribution comparison between observations recorded on a printed map and the ESJ output (Table 4, Figure 4), and to validate the shade profiles observed in the Mona transects (Figure 5). Walking speeds for each transect were kept as consistent as possible, ranging from 1.21 ms^{-1} for V2 to 1.92 ms^{-1} for the second walk of V4.

Table 4: Summary of the average SZA, relative sun azimuth (Az_R), and shade distribution recorded by the ESJ and by using a printed map (in parentheses) for each validation transect. An additional shade distribution for V4 was made during the severe haze, affected transect is also provided (no printed map record was possible during the period of severe haze).

Transect	Average sun position		Shade distribution		
	Az_R	SZA	No shade	Light shade	Dense shade
V1	176°	56°	35.1% (29.4%)	55.1% (49.0%)	9.8% (21.6%)
V2	39°	19°	64.8% (47.6%)	23.8% (40.1%)	11.4% (12.3%)
V3	72°	56°	29.3% (20.3%)	47.3% (49.2%)	23.4% (30.5%)
V4	316°	18°	35.1% (27.8%)	64.9% (62.9%)	0.0% (9.3%)
V4 (severe haze)	*323°*	*20°*	*56.4%*	*43.6%*	*0.0%*

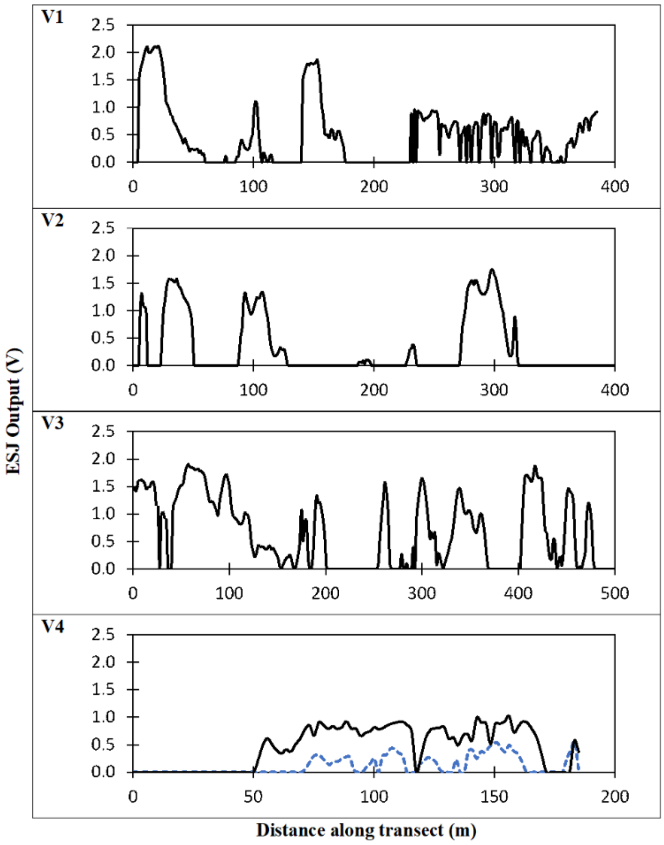


Figure 4: Validation shade profiles from the ESJ normalised to transect distance. The blue stippled line in V4 represents the ESJ output during the severe haze event in early December 2019.

The relative shade profile (Figure 4) for the buildings in the first 200 m of V1 contrast distinctly with the tree canopy shade in the second 200 m. However, they possess similar profiles to thick and overlapping canopy shade shown in the other validation transects, albeit with a higher relative output. When there was a lot of tree canopies overlapping as in V4, the shade profile resembles a continuous profile, only broken by features such as crossroads, as occurs at approximately 120 m. Combinations of adjacent tree canopies and canopies on the opposite side of the road, alongside with built structures also exhibit a continuous profile, as in the first 100 m of V3.

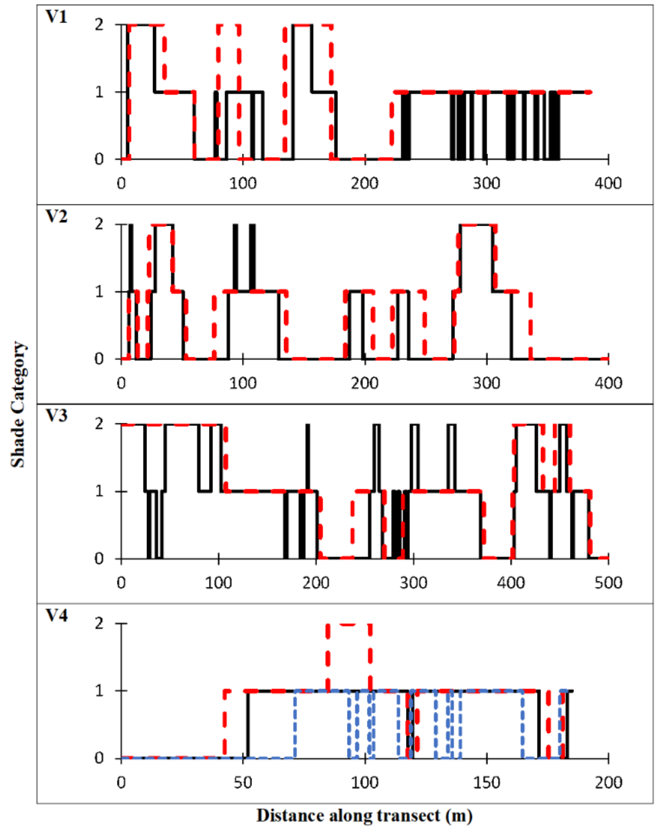


Figure 5: Validation of shade distributions. Categorised ESJ output (solid black lines) is compared with observations made on printed maps (red dashed lines). The blue stippled line in V4 is from the severe haze observation.

Comparing the spatial extent of shade distributions in Figure 5 shows a significant proportion of shade over-estimation calculated in Table 4. This is due to either overestimating the extent of shade structures or missing finer shade features, such as the shade profile for tree canopies in the final 200 m of V1. It is quite difficult to discern the source of the shade based on the spatial distributions in Figure 4 as the morphologies can be almost identical. An example is the building shade in the first 200 m of V1 compared to the thick and overlapping canopies in V2 and V3.

4. Discussion

The research outcome provided a reliable evaluation of the ESJ ability to detect any changes in the shade profile while in motion. The ESJ shade-sensitivity is very apparent when, in all transects, there are sections where the signal is 0 V, indicating that it is experiencing direct sunlight. A distinct example of this output is the point centred at approximately 120 m in V4 (Figure 4), representing the time taken to cross the street at the intersection where there is no trees or buildings, and it obviously exists in both clear-sky and hazy conditions' data. Another example is noticed in the final 200 m of V1, where no shade areas due to the canopy gaps were clearly recorded. As evident in Figures 3 and 4, the ESJ can evaluate the shaded areas at a temporal resolution of 1 second, resulting in a measurable spatial resolution consistent with the observer's average walking speed.

There was a consistent overestimation, usually within 10%, in shade distributions when using a printed map compared to the ESJ output (Table 4). The discrepancy increased when conditions were bright overcast (V2) but not when conditions were mostly cloudy (V3). Bright overcast conditions increase the diffuse proportion of light depending on the cloud thickness and the relative position of the sun [29]. The overestimation could be attributed to some subjective factors including walking speed and observer concentration level and judgement, which may result in missing or generalizing some finer shade details, such as the gaps observed in the trees in V1 (Figure 4). The ESJ output is not affected by this subjectivity and provides a much finer resolution of small intermittent changes within shade features.

Trees, adjacent and to the left of the walking path on the street verge (Figure 1), are the prominent source of shade in the Mona transects B and C (Figure 3) and validation transects V2 and V4 (Figure 4) when the SZA was relatively low at midday. The observed shade profiles were dependent on the maturity of the tree, overlapping canopies and canopy extent,

Journal Pre-proof

as has been demonstrated by other research groups [9][13][21]. Most tree shade profiles were observed to have an irregular and discontinuous morphology, although can possess profiles like built structures, as in V2 and V3. The ESJ immediately defined the boundaries of areas where trees were either not present or too small to provide shade, as at the 300-350 m section (illustrated in Figure 3 parts B, C and D). Variations in the canopy shade profile could occur due to wind, as it was observed that even a slight breeze caused the light shade to shift rapidly. However, the effects of wind will generally be averaged out to allow determination of the shade along each transect. Dense and overlapping shade was not significantly affected by wind.

The shade profiles of artificial structures, such as buildings and retaining walls, were typically broader and possessed a relatively more regular signal output than trees, consistent with earlier observations [23]. When the sun is at a low SZA, tall retaining walls (Figure 6) and buildings provided no effective shade along the pathway. However, when the sun was at a high SZA and positioned with a relative azimuth placing it 'behind' built structures, their broad shadows became prominent in the shade profile, as in Mona transect A (Figure 3) and the first 200 m of V1 (Figure 4). In this situation, tall buildings were behind and above the retaining walls providing the combined shade and, therefore, the shading provision of any trees is negated [13].

Journal Pre-proof

Figure 6: An example of a tall retaining wall on the opposite side of the pathway to the street verge. Image taken on a hazy day at 2:00pm local time, 21st November 2019.

Journal Pre-proof

Similarity between some shade profiles can be noticed, such as the shade profile of the large and overlapping canopy trees at about 370 m to 400 m in transect C compared to the profile centred on 50 m in transect D of a multilevel apartment complex on the opposite side of the road casting a long shadow due to the high SZA and position of the sun behind it (Figure 3). A similar observation occurs in V3, where the source of the shade is a combination of large overlapping canopies from either side of the street, buildings only contribute to the first 100 m of this profile. These similarities highlight the importance of developing a temporal profile of a transect using the ESJ at different times of the day to ascertain the temporal extent of each structure's influence on the overall shade quality within a given streetscape.

Smoke haze became a significant influence during the first validation transect V4. Sydney experienced several days, during November and December 2019, of hazardous air quality due to surrounding forest fires, affecting human health and visibility [24]. Particulate matter from the forest fires tend to accumulate in the city, which lies in a natural basin [30]. The resultant increase in particulate matter results in Mie Scattering, causing a relative increase in the proportion of diffuse solar radiation [31] and a decrease in visible shade resolution. This was also observed in the ESJ output in the first V4 transect. However, the observed hazy conditions were very exceptional and there are enough days with lower haze conditions when the ESJ can be employed to determine street-side shade profiles.

Journal Pre-proof

Journal Pre-proof

5. Conclusion

The output of the ESJ is not affected by cloud cover in normal operating conditions, only becoming less reliable under more extreme circumstances where shade audits are not feasible, such as severe smoke haze events. The ESJ permits a greater level of precision for observing street-level shade details while the observer is in motion, at different sun angles. Thus, providing an inexpensive and accessible method performing shade audits for researchers and those involved with sun protection policies.

Generally, the ESJ can be used to observe very precise shade profiles along a walking path, identifying areas where shade is either lacking or broken. Although the shade distribution (no shade, light shade and dense shade) determined from the ESJ was in very good agreement with printed-map based observations, typically within 10%, the ESJ overestimated the no shade portion – not due to inaccuracy, but due to the device's ability to record small intermittent breaks in the shade that can be subjectively missed by the observer. As shade conditions during each day and across seasons, the ESJ also provides a means to capture high temporal resolution in street-level shade detail changes that would be very difficult if using satellite and online viewing tools.

Journal Pre-proof

A considerable limitation of the ESJ is a difficulty to discern the source of specific shade profile morphologies, particularly buildings and large overlapping canopies of trees; however, this can be simply overcome by repeating the transect to provide a temporal scope to the shade of any street. Nevertheless, the building shade is still part of the shade in an urban environment and it is detected by the ESJ. Using a printed map can aid in identifying larger structures which will impact upon shade, while the ESJ delineates the finer details, particularly the smaller gaps in shade, with higher resolution. Another limitation is to accurately measure variations in the observer's walking speed, additional equipment can be used, including pedometers to accurately log walking speeds during a transect, using GPS-enabled devices, or visual devices such as Go-Pro cameras, the use of which can greatly extend the distance that a shade audit can be performed.

In summary, the ESJ is a robust, low cost and portable tool that can be used in mobile auditing of shade in public spaces, such as streetscapes, providing an efficient method to establish shade profiles during walks in an urban environment.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Journal Pre-proof

References

[1] Silva, R. A., Rogers, K., & Buckley, T. J. (2018). Advancing environmental epidemiology to assess the beneficial influence of the natural environment on human health and well-being. *Environmental Science and Technology,* 52, 9545-9555.

[2] Du, K., Ning, J. & Yan, L. (2020). How long is the sun duration in a street canyon? – Analysis of the view factors of street canyons. *Building and Environment*, 172, 106680.

[3] Deng, J., Pickles, B. J., Smith, S. T. & Shao, L. (2020). Infrared radiative performance of urban trees: spatial distributions and interspecific comparison between ten species in the UK by in-situ spectroscopy. *Building and Environment*, 172, 106682.

[4] Holman, D. M., Kapelos, G. T., Shoemaker, M., & Watson, M. (2018). Shade as an environmental design tool for skin cancer protection. *American Journal of Public Health,* 108, 1607-1612.

[5] Gong, F-Y., Zeng, Z-C., Ng, E. & Norford, L. K. (2019). Spatiotemporal patterns of street-level solar radiation estimated using Google Street View in a high-density urban environment. *Building and Environment*, 148, 547-566.

[6] Guthold, R. Ono, T., Strong, K.L., Chatterji, S. & Morabia, A. (2008). Worldwide variability in physical inactivity: a 51-country survey. *American Journal of Preventive Medicine,* 34, 486-494.

[7] Taylor L., & Hochuli, D. F., (2017). Defining greenspace: multiple uses across multiple disciplines. *Landscape and Urban Planning*, 158, 25-38.

[8] Rupprecht, C. D. D., & Byrne, J. A. (2014). Informal urban green-space comparison of quantity and characteristics in Brisbane, Australia and Sapporo, Japan. *PLoS One*, 9(6), e99784.

[9] Downs, N. J., Baldwin, L., Parisi, A. V., Butler, H. J., Vanos, J., Beckman, M., & Harrison, S. (2019a). Comparing the annualised dynamic shade characteristics of twenty-one tree canopies across twenty-six municipalities in a high ambient UV climate, Queensland – Australia. *Applied Geography,* 108, 74-82.

[10] Parisi, A. V., & Turnbull D. J. (2014). Shade provision for UV minimisation: a review. *Photochemistry and Photobiology,* 90, 479-490.

Journal Pre-proof

[11] Tabatabaie, S., Litt, J. & Carrico, A. (2019) A study of perceived nature, shade and trees and self-reported physical activity in Denver. *International Journal of Environmental Research and Public Health*, 19, 3604.

[12] Adams, M. A., Frank, L.D., Schipperjin, J., Smith, G., Chapman, J., Christiansen, L. B., Coffee, N., Salvo, D., du Toit, L., Dygrýn, J., Hino, A. A. F., Lai, P., Mavoa, S., Pinzón, J. D., Van de Weghe, N. Cerin, E., Davey, R., Macfarlane, D., Owen, N. & Sallis, F. F. (2014). International variation in neighbourhood walkability, transit, and recreation environments using geographic information systems: the IPEN adult study. *International Journal of Health Geographics*, 13, 43-59.

[13] Li, X., Ratti, C., & Seiferling, I. (2018). Quantifying the shade provision of street trees in urban landscape: a case study in Boston, USA, using Google Street View. *Landscape and Urban Planning*, 169, 81-91.

[14] Parisi, A.V**.**, Willey, A., Kimlin, M.G. & Wong, J.C.F. (1999), Penetration of solar erythemal UV radiation in the shade of two common Australian trees. *Health Physics*, 76(6), 682-686.

[15] Ball, K., Bauman, A., Leslie, E. & Owen, N. (2001), Perceived environmental aesthetics and convenience and company are associated with walking for exercise among Australian adults. *Preventive Medicine*, 33, 434-440.

[16] Ulmer, J.M., Wolf, K.L., Backman, D.R., Tretheway, R.L., Blin, C.J.A., O'Neil-Dunne, J.P.M. & Frank, L.D. 2016, Multiple health benefits of urban tree canopy: the mounting evidence for a green prescription. *Health & Place*, 42, 54-62.

[17] James, P., Banay, R. F., Hart, J. E., & Laden, F. (2015). A review of the health benefits of greenness. *Current Epidemiology Reports*, 2, 131-142.

[18] Bedimo-Rung, A. L., Mowen, A. J., & Cohen, D. A. (2005). The significance of parks to physical activity and public health. *American Journal of Preventative Medicine*, 28(2 suppl. 2), 159-168.

[19] Parisi, A. V., Amar, A., Downs, N. J., Igoe, D. P., Harrison, S. L., & Turner, J. (2019). Development of a model for calculating the solar ultraviolet protection factor of small to medium sized built shade structures. *Building and Environment*, 147, 415-421.

Journal Pre-proof

[20] Colter, K.R., Middel, A.C., Martine, C.A. (2019). Effects of natural and artificial shade on human thermal comfort in residential neighbourhood parks of Phoenix, Arizona, USA. *Urban Forestry and Urban Greening*, 44, 126429.

[21] Downs, N. J., Butler, H. J., Baldwin, L., Parisi, A. V., Amar, A.A., Vanos, J. & Harrison, S. (2019). A site-specific standard for comparing dynamic solar ultraviolet protection characteristics of established tree canopies. *MethodsX*, 6, 1683-1693.

[22] Gage, R., Wilson, N., Signal, L., Barr, M., Mackay, C., Reeder, A., & Thomson, G. (2018). Using Google Earth to assess shade for sun protection in urban recreation spaces: methods and results. *Journal of Community Health*, 43(6), 1061-1068.

[23] Downs, N. J., Parisi, A. V., Butler, H., Rawlings, A., & 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, 310.

[24] Nguyen, K. & Bullen, J. (2019). Sydney smoke three times worse this NSW bushfire season, but health effects from 'medium-term' exposure unclear. https://www.abc.net.au/news/2019-12-03/sydney-air-quality-smoke-haze-worse-this-bushfire-season/11755546 accessed 15th December 2019.

[25] Hausdorff, J. M. (2005). Gait variability: methods, modelling and meaning. *Journal of NeuroEngineering and Rehabilitation*, 2, 19.

[26] Geoscience Australia (2010). *Compute Sun and Moon Azimuth & Elevation*. http://www.ga.gov.au/geodesy/astro/smpos.jsp accessed 15 December 2019.

[27] Michalsky, J. J. (1988). The astronomical almanac's algorithm for approximate solar position (1950-2050). *Solar Energy*, 40(3), 227-235.

[28] Bohannon, R. W. (1997). Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. *Age and Aging*, 26, 15-19.

[29] Rossini, E. G., & Krenzinger, A. (2007). Maps of sky relative radiance and luminance distributions acquired with a monochromatic CCD camera. *Solar Energy*, 81(11), 1323-1332.

[30] Monk, K., Guérette, E-A., Paton-Walsh, C., Silver, J. D., Emmerson, K. M., Utembe, S. R., Zhang, Y., Griffiths, A. D., Chang, L. T-C., Duc, H. N., Trieu, T., Scorgie, Y., & Cope, M. E. (2019). Evaluation of regional air quality models over Sydney and Australia: Part 1 – Meteorological model comparison. *Atmosphere*, 10, 374.

Journal Pre-proof

[31] Nichol, J. (1997). Bioclimatic impacts of the 1994 smoke haze event in southeast Asia. *Atmospheric Environment*, 31(8), 1209-1219.

Journal Pre-proof

Journal Pre-proof

Highlights

- Enhanced temporal and spatial resolution for mobile shade distributions.
- Temporal urban shade profiles at different sun angles evaluated while walking.
- Inexpensive electronic sun journal used for mobile urban shade evaluation.
- Shade profiles and distributions modelled for distinct urban environments.
- Methodology allows for continuous high temporal resolution shade evaluation.

Journal Pre-proof

Journal Pre-proof

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Journal Pre-proof