

The Properties of our Everyday Spectral Microclimate

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Abstract

The CIE illuminant D65 is widely adopted as defining the standard spectral power distribution (SPD) for 'average' daylight. Thus daylight indoors is generally assumed to approximate the SPD for D65. The weight of research on the non-visual effects of light now suggests that a key consideration for the long-term health and well-being of occupants should be the amount, duration, timing and, importantly, the spectral profile of illumination received at the eye. Measurements of the SPD of illumination were made at a number of locations outdoor and indoors. In an outdoor environment, the spectral properties of the visible sky dictate the resultant SPD largely irrespective of the surrounding built environment. Only those indoor locations with close proximity to windows exhibit a spectral microclimate comparable to daylight, while all others are dominated by the artificial light sources. Early findings indicate the need to carry out further research to more clearly understand the experienced spectral microclimate.

Keywords Daylight, spectral profile distribution (SPD), circadian entrainment, standard illuminants, spectrometry.

1 Introduction

Today, the daylight design of buildings must not only consider energy performance and visual task but also matters of health and well-being. The discovery of the intrinsically photosensitive Retina Ganglion Cell (ipRGC) and subsequent findings suggest a much wider role for daylight in delivering healthy buildings than simply providing, say, illuminance for task. An often quoted fact is that people today can spend up to 90% of the lives indoors (1). It is therefore imperative that their health and well-being is a priority equal to considerations of energy performance, economics, etc. The role of daylight in building design is now multifaceted and trans-disciplinary. As such, new metrics, methods and measures of analysis based on proven research findings must be developed to support the design of healthy spaces. Metrics and supporting tools based on, for example, the daylight factor no longer suffice (2).

A considerable body of research has begun to provide insights to the many potential implications of good and bad daylight design decisions, but much of this has focused on visual physiology and non-image forming (NIF) issues. What is less often considered is the nature of the spectral microclimate (a particular environment whose specific properties resolve to directly influence the spectral properties of light) of everyday surroundings and the implications for design and the health of occupants. In other words, what is the circadian entrainment potential of a typical microclimate, inside or out.

The human circadian system is known to be responsible for the temporal regulation, over approximately 24 hours, of a range of physiological processes and drives the rhythms of body temperature, hormone secretion and metabolism. The light and dark cycles, or the sleep/wake cycle, is also recognised as important in circadian regula-

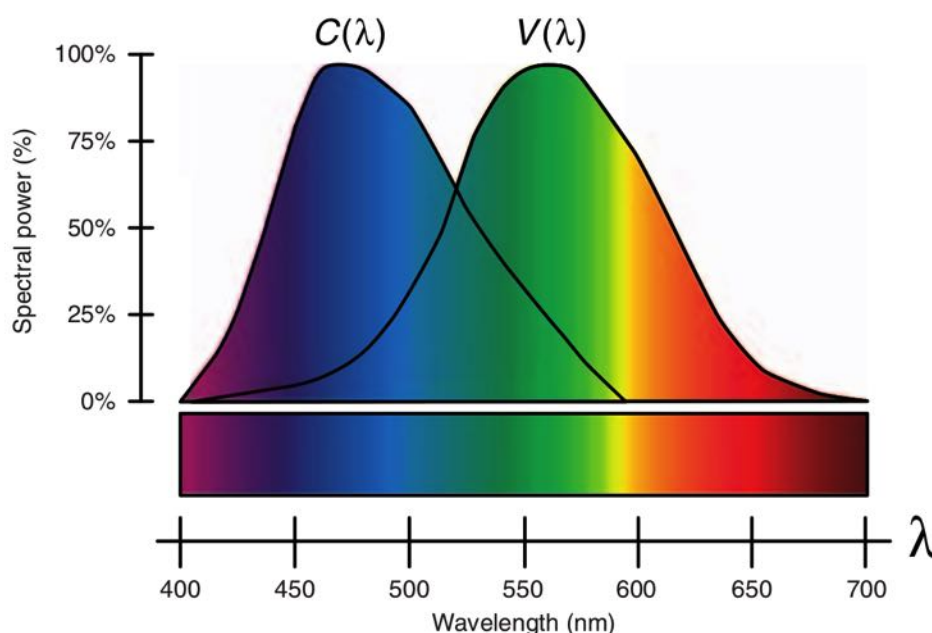


Figure 1: Spectral response of the visual system (photopic curve $V(\lambda)$) and the circadian system (melanopsin action spectrum $C(\lambda)$), after Andersen et al. (9)

tion (3). The primary environmental stimulus to this human circadian system is light exposure to the eye. Other organs and tissues have also been found to have peripheral oscillators that respond to the signalling of the central circadian regulator, or pacemaker as it is often called. As a result of this important role in regulating temporal physiological processes, imbalances in the circadian system have noticeable health and well-being consequences (4).

Published research on circadian physiology has demonstrated that the impact of light on the human circadian system depends on its intensity, spectrum, spatial distribution, timing, duration, pattern and photic history (5). The internal human body clock requires environmental cues to synchronise to this time cycle on a regular basis. Deviations can result in delay or advance in the 'internal' clock (6).

While there is much research yet to be undertaken to mature this field of knowledge, it has been observed, for example, that the circadian response to light approaches maximum levels after between 0.5 and 1.5 hours exposure under 'white' light at 300 lux (7) while longer durations of approximately 6.5 hours saturate the circadian response at 200 lux. Research also suggests that 100 lux at the cornea can initiate a 50% response, whereas 600-1000 lux can saturate the system (8).

The photopic visual response function $V(\lambda)$ peaks at 555 nm, however the circadian (melanopsin) response function is markedly different with a peak around 480 nm. This widely adopted circadian response function, $C(\lambda)$, seen in fig. 1, is based on a model proposed by Amundadottir et al. (10) and the findings of Cajochen et al. (7) and Zeitzer et al. (8). Much of the work defining the currently accepted melanopsin response of the human eye was published by Brainard (11) and Thapan (12). Its adoption has now become widespread among those looking to develop metrics and solutions in a building design context. But many also acknowledge that it is still too early to adopt such models in international standards without more research. Circadian entrainment is

also believed to be influenced by light wavelengths other than those of $C(\lambda)$. It would not be unreasonable to note that this area of daylight research is still in its infancy and dependent on the research findings of a much wider disciplinary range than ever before.

While CIE Standard Illuminants (13) have been widely used in building related research, their current adoption in spectral-based analysis does raise questions. There is a need to define the components of daylight by wavelength for use in spectrally-based simulation modelling. Most research published to date has looked to extend the functionality of the Radiance light simulation system (14). In doing so, most have adopted CIE D65 to define the spectral power distribution of daylight. But the D65 illuminant does not reflect all realities of daily occurring spectral distributions as will be seen in this exploratory study. It represents a typical overcast day at noon, not dissimilar to a CIE standard overcast sky (15). Being a static model, D65 naturally omits many of the variables relevant to circadian entrainment. It does not support considerations of duration or any specific spectral condition nor does it allow patterns of photic history to be accommodated. Recognising, and by implication, acknowledging that D65 may not be appropriate for use in indoor daylight design, the CIE adopted two further illuminants, ID65 and ID55 (16). In particular, while ID65 does address the issue of spectral interference by glazing systems, it suffers from the same shortcomings as does D65 in the context of circadian entrainment and responsive daylight design.

Circadian entrainment as a means to regulate human physiology has now become a part of the growing picture that is daylight design in buildings. More research is required before international standards can be delivered to research and practice. In the meantime, there is enough known to begin exploring the spectral microclimates of the built environment. In this paper, physical measurement of existing spaces under real skies was the chosen method of exploring the spectral characteristics of a range of both indoor and outdoor microclimates.

2 Method

The study reported in this paper takes a first step in exploring ‘real world’ spectral characteristics of a number of commonplace outdoor and indoor environments, or spectral microclimates. A series of spectral power distribution (SPD) measurements was taken within each selected environment. The location of the study was in Dublin, Ireland.

It is acknowledged that the cases studied represent a small sample of possibilities but within these, a range of environments have been chosen and presented as representative. In choosing these microclimates, composition of scene, function, etc. were considered. When choosing external environments, surface material types and colours together with a range of street width-to-height ratios were selected.

One of the questions addressed in the study was how to take SPD measurements in such a context. That is, in what direction should the measuring sensor be aimed. Typically, when taking illuminance readings within a space, the sensor is held away from the body and aimed towards the ceiling and less often vertically. This technique is typically used when assessing the visual or energy performance of the space and how light is falling on work and other horizontal activity planes (17). A review of literature has found no tested or recommended procedure describing a technique for using spectrometers in the field when studying outdoor or indoor spaces from a human perspective. As the study is concerned with human health as influenced by the spectral character of incident light and as the eye is the receptor of concern, all measurements were taken

using the spectrometer sensor as a proxy for the illumination received at the eye. In some situations this is as if the observer was standing while in others as if they were sitting.

When making external readings, the spectrometer was aimed horizontally to represent a normal human field-of-view (FOV) as well as vertically to capture the widest view of the sky component and so the maximum spectral intensity reading at each location. Internally a similar technique was used in the atria spaces studied while in retail, cafes, etc. readings were taken from a point within the space and aimed looking inside, outside and across the space.

Two sensor systems, manufactured by well known companies, were used to take readings in each location. Neither spectrometer used was specifically designed to take readings from a human perspective. One was designed with lighting designers in mind. From a review of available systems and the wider literature, there is no instrument currently on the market specifically designed to measure SPDs with respect to a human observer or indeed at low ambient illuminance levels. This relates to their sensory sensitivity and instrumentation functionality. Each was fitted with a cosine correction filter and so all measurements were taken over a targetted hemispherical range.

Where permitted, a calibrated professional DSLR camera with a 180° circular fisheye lens was used to capture HDR images to study the luminous environment. Seven frames separated by 1EV were taken, composed and analysed using the Photosphere software package (18). These images were subsequently used to support interpretation of the SPD readings at each location.

3 Results

A series of both external and internal studies were carried out to explore the SPDs of various microclimates. A representative selection of these are presented here with specific interpretations given. Overall conclusions are gathered and presented at the end of the paper. The results have been grouped into three categories: external, atria and internal. To accompany these studies and to provide a reference, measurements of each sky SPD were carried out.

3.1 Sky Spectral Measurements

External spectral conditions were recorded over a number of time intervals on both survey days. All spaces were studied within these respective time ranges to allow for comparative analysis where relevant. A representation of the spectral profiles of each of the days is illustrated in fig. 2. Readings were taken with the sensor aimed at the sky zenith and in wide open spaces with minimal surrounding obstructions. Those obstructions occupied less than 8° from the horizon within the hemispherical FOV.

On the first day of the survey the sky was of an intermediate type with almost equal thin cloud cover and with sunlight. The second day was under a completely clear sky with low turbidity (outdoor temperature was 2°C). In this case, two recordings were taken, the first with the sensor exposed to direct sunlight while the second was with the sensor shaded from direct sunlight. The CIE D65 (overcast) standard illuminant was added to both plots as reference while D55 (sunshine) was added to day two.

When considering the measurement profiles shown on the second day, that with a blue sky, there is, as expected, a distinct difference between the SPD with the sensor shaded and with it exposed to direct sunlight. At an unobstructed point this day might

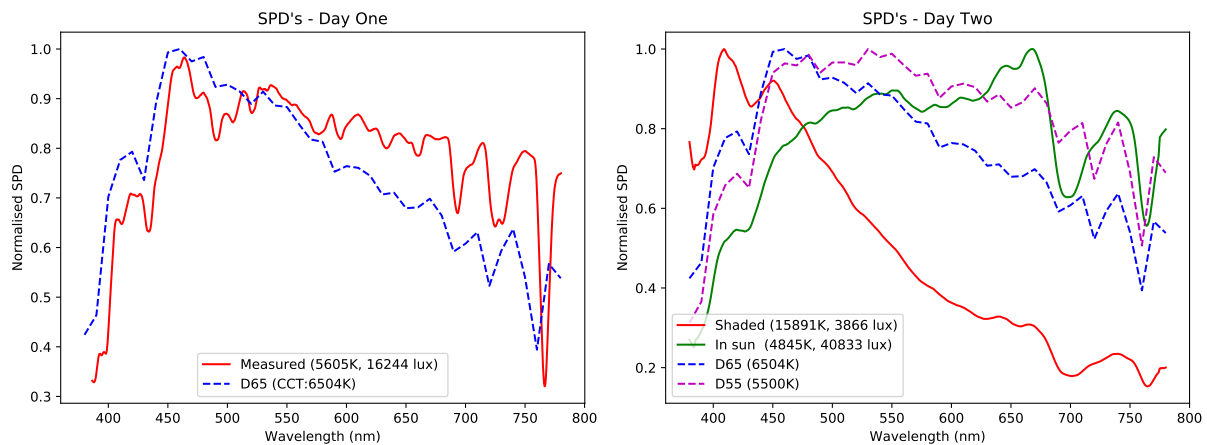


Figure 2: Spectral measurements taken on both survey days compared against CIE D65 and D55 and demonstrating variations typically experienced.

best be represented by CIE D55 but in real situations and particularly in an urban context, light would be received with the direct sun component or without, as in shade, and this is illustrated by the measured profiles. As such, no single CIE profile can be used to represent a single clear-sky day as circumstances at a point will vary.

3.2 External Spectral Studies

The potential effect of differing width-to-height ratios in urban street ‘canyons’ was then considered for width to height ratios of 1:1, 1:2 and 1:3. These were compared to the open sky measured at the same time with the results presented in fig. 3 which illustrates the SPDs weighted against the measured illuminance and then normalised. What is clear from the results is little or no difference in the spectral profile when compared with that of the measured open sky. Illuminance levels shown are as expected given the relative reduction in visible sky at each point. What was less expected was the independence of the SPD profile from different facades typically composed of old or new brick, concrete, painted walls, timbre of various shades and glass.

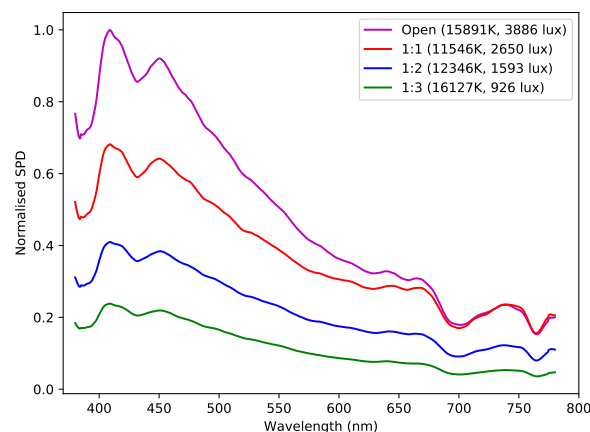


Figure 3: Normalised spectral power distributions of an open sky and on streets or 1:1, 1:2 and 1:3 width-to-height ratios, weighted by illuminance levels.

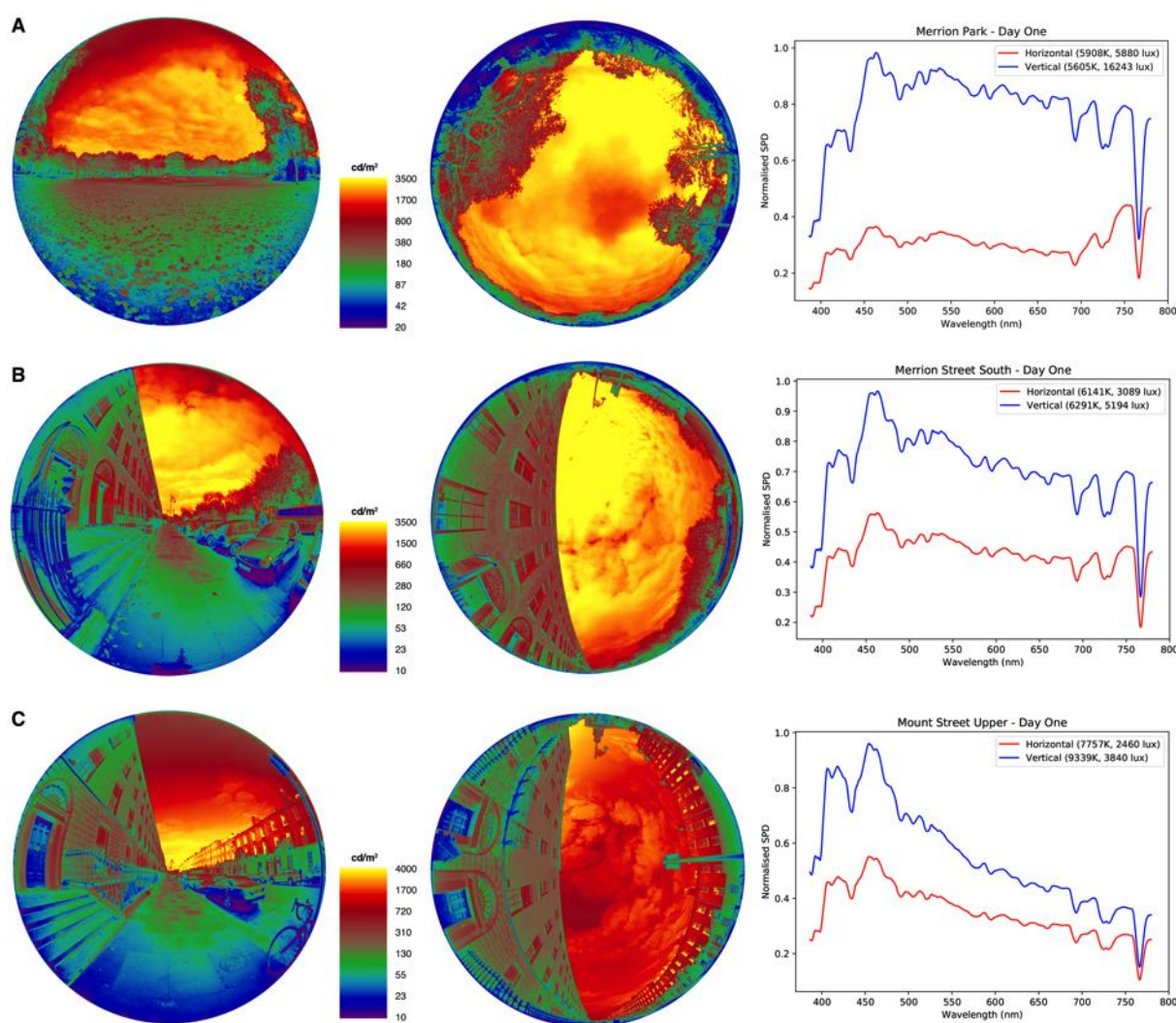


Figure 4: A study of historic georgian urban scape.

Dublin is fortunate to still have a substantial Georgian architectural heritage. Georgian streets typically follow a 1:1 width-to-height ratio and so the above conclusions with respect to this ratio were tested in this Georgian context with the addition of an adjacent park landscape. Results of the study are shown in fig. 4. These studies were conducted on day one of the survey.

As was seen in the street ratio study, the spectral profile of both vertical and horizontal views were virtually identical on Mount Street Upper with no vegetation. When considering Merrion Street South and the Merrion Park the respective spectral profiles changed, responding to the vegetation of the park. The fluorescence effect of vegetation is well known (19) and explains why within the red frequency range there is a notable change in behaviour. Also notable is that, as the area of vegetation increases, the blue range of frequencies proportionately decreases. This is likely due to absorption by vegetation as reflection from buildings and road surfaces appears to have little role in the resultant spectral profile.

A final external study was carried out within a range of building types that represented both new and old streets of ratios 1:1 and 1:2. The results of this study are represented in fig. 5. As observed in fig. 4C, the only variation would appear to be over illuminance

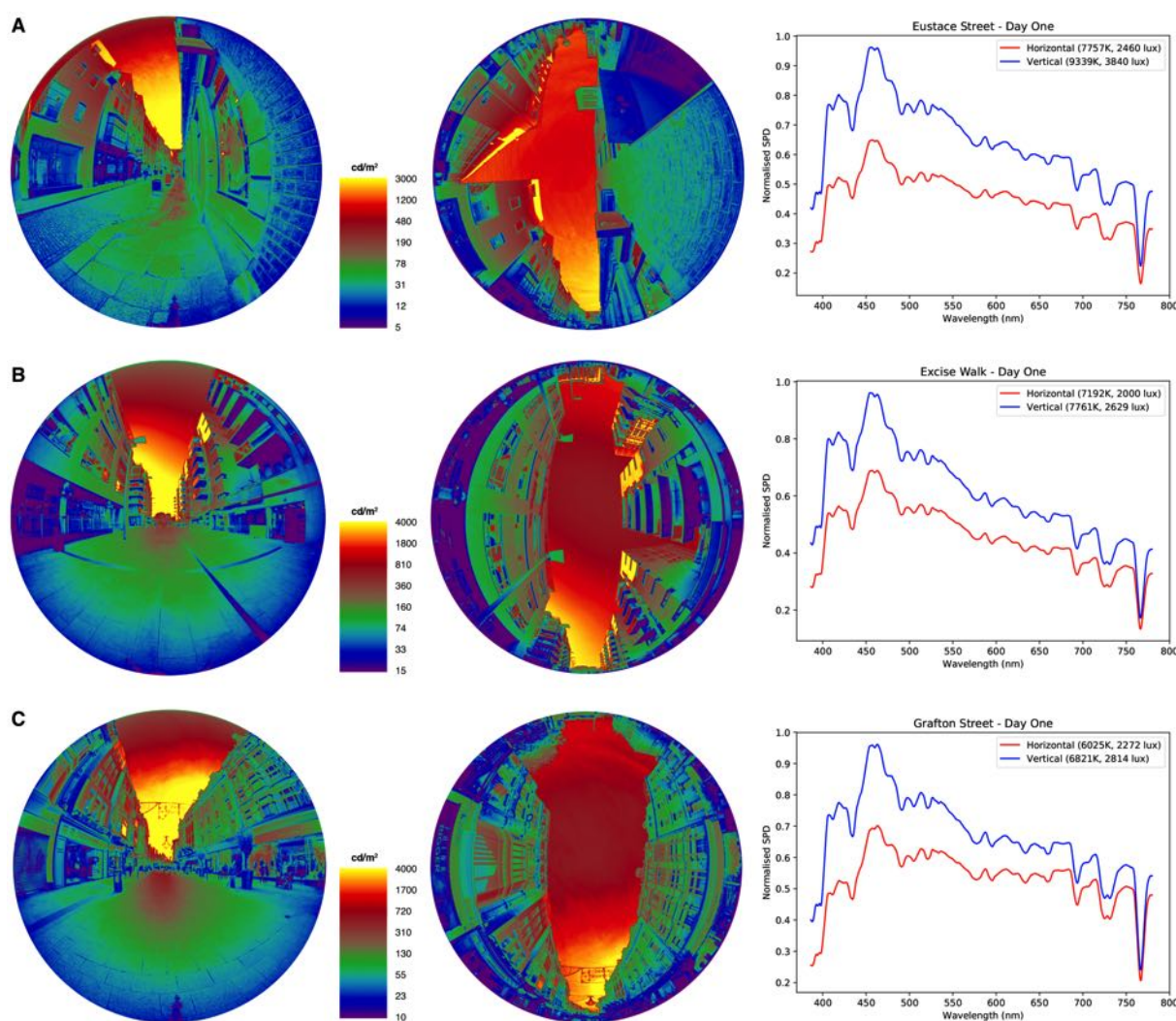


Figure 5: City streets.

levels and not a particularly noticeable change in spectral profile. This further supports the suggestion that facade treatments and ground surfaces only have a role in broadband illuminance and have little effect on the SPD at measurement points. It can also be observed that many of the readings were taken from footpaths and so the measurement points were close in proximity to building facades. Despite this, no noticeable change in SPD can be observed.

In summary, from the results of external studies, the only source of illuminance is the visible sky and its spectral profile is dominant in all readings presented with the exception of those where large areas of vegetation are present. What does change is the measured illuminance. Considering the HDR derived luminance maps, it is clear that the luminosity of the visible sky at each study point is significantly higher than that reflected from any surface. As such, the area-weighted average luminance of the sky versus the sum of all reflecting surfaces is dominant at each point. Therefore, with respect to the SPD at each point, the effect of a reflected component from buildings and ground surfaces can largely be ignored.

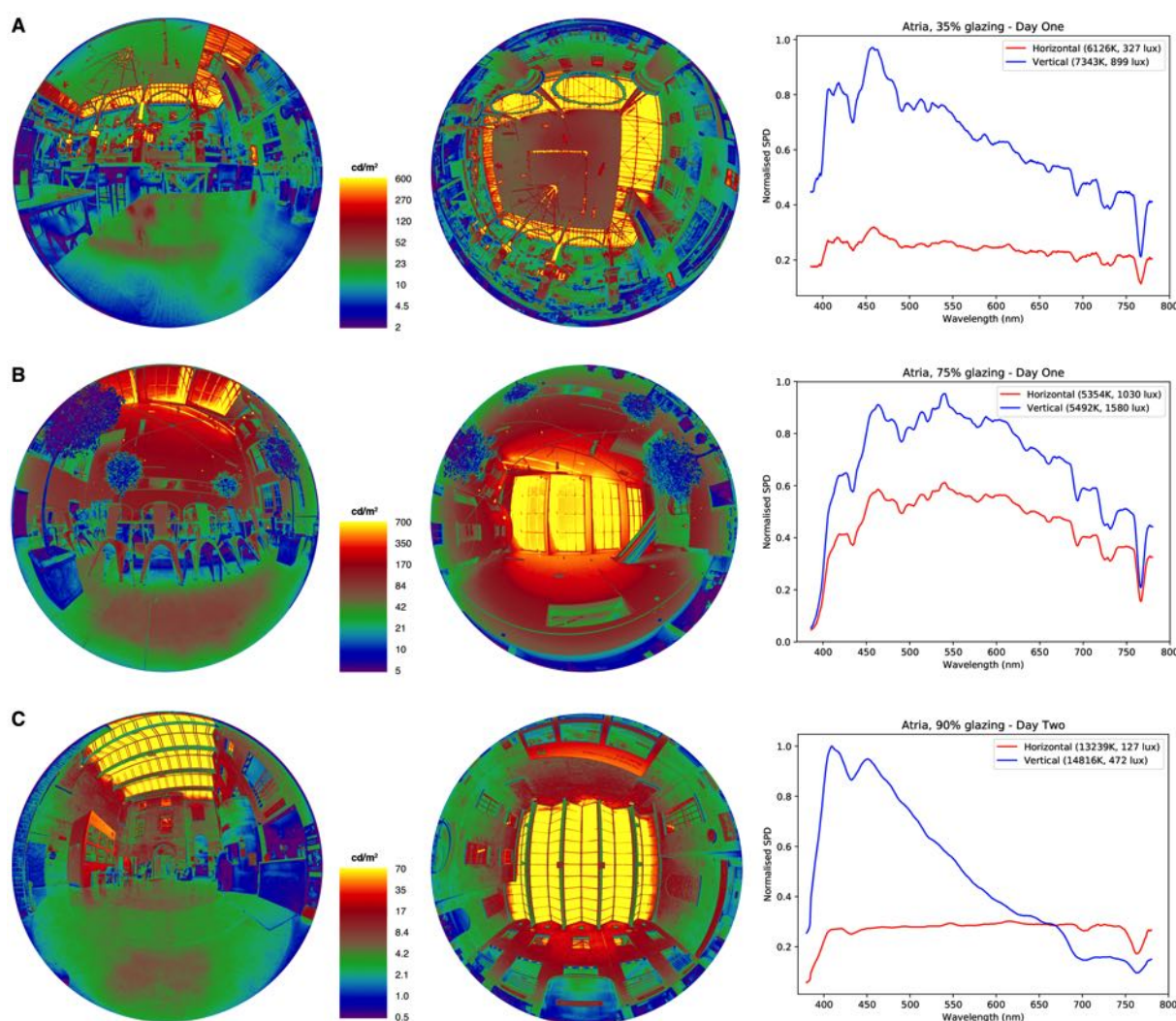


Figure 6: A study of three atria with roof glazing proportions of 35% (A), 75% (B) and 90% (C). The third study (C) was carried out on day two.

3.3 Internal Studies

Two types of internal study were conducted. The first was a consideration of three atria spaces with varying proportions of glazing in roofs. The second was a study of a range of retail, office and cafe spaces.

3.3.1 Atria studies

Three city centre atria were studied, each of which functions as a cafe with adjacent retail areas. The first two were visited on the first day of the survey, under the intermediate sky, while the third was visited on the second day, under a clear sky and shown in fig. 6.

In studies A and B, the measurements taken vertically demonstrate a close correlation to the measured outdoor spectral profile on day one. There is an expected reduction in illuminance but there is clearly a difference in SPD. In the case of A, there is a more dramatic reduction in the blue range of frequencies. This is explained by internal finishes. In case A, the proportion of glazing is considerably less than in B and, as such, daylight illuminance as a source is proportionately lower. The decorative finishes

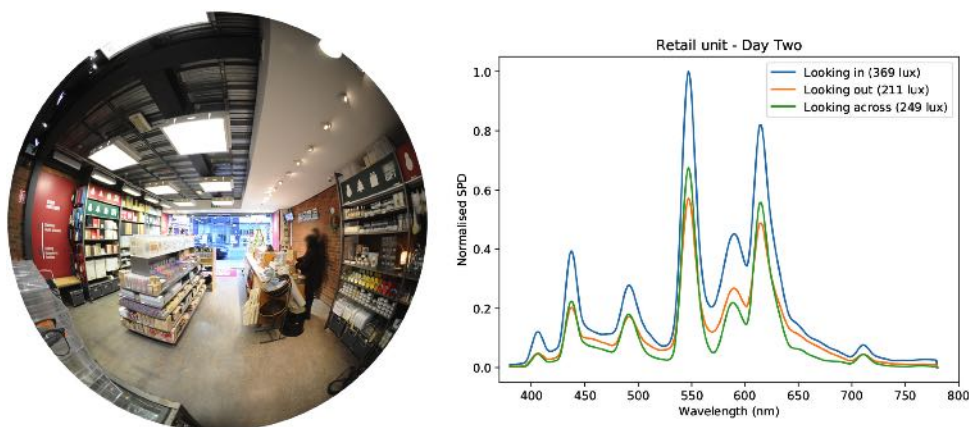


Figure 7: Mid-specification retail unit.

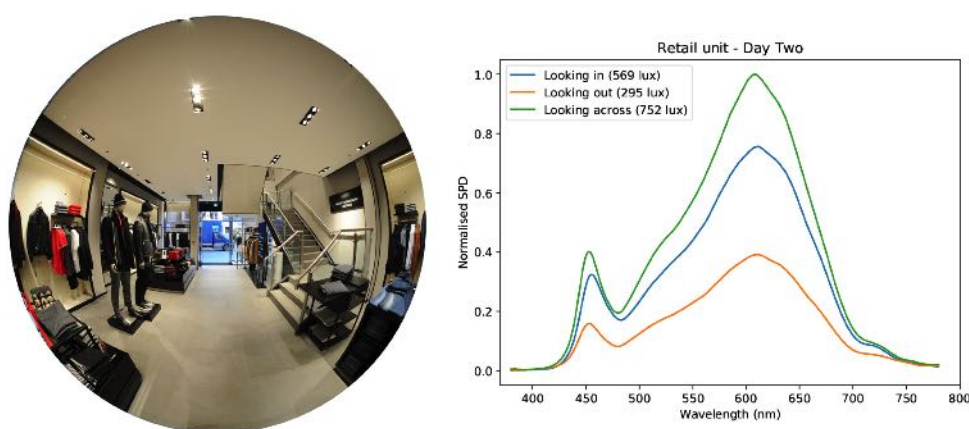


Figure 8: High-end clothing retail unit.

in A are of old red/brown brick, it having been an outdoor space before its covering, and of dark wood panelling and furniture. This is likely to absorb in the blue range of frequencies and thus the modified profile. Electric lighting consisted of halogens but these were sparse and did not contribute significantly to the overall illuminance at the point of measurement. In B, the old brick and stone walls have been rendered with a light sand-toned finish but not painted. This, having a higher reflectivity, together with a large vertically measured illuminance would suggest that sky sourced daylight and its SPD remains dominant and that the reflected component is proportionately lower in illuminance and less modified spectrally, resulting in an SPD resembling the vertical component and that of outside.

The final space, C, is a purpose built atrium with a similar brick finish to A but with a large dark grey polished concrete floor. It does have a proportionately larger percentage of roof glazing but as can be seen, the illuminance measured vertically and horizontally are low. This is largely due to the external sky as shown in fig. 2 and its relatively low luminosity typical of blue skies. When the vertical and horizontal profiles are compared there is a very clear absorption of the blue range of frequencies, due largely to internal surfaces which, in this case, given the low illuminance, do exhibit a role in the resultant SPD.

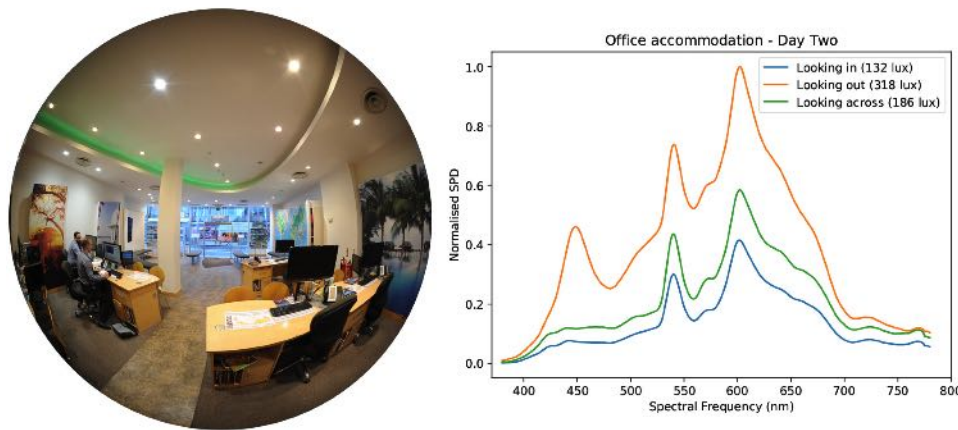


Figure 9: Office unit.

3.3.2 Retail

Two retail stores were studied on day two of the survey. Both companies are well known and to be found in major cities throughout Europe and globally. Additionally, in an effort to communicate uniformity of a corporate/company image, fit-out of these two 'brands' is similar in all stores internationally. This is not unusual.

The measurement technique changed in the study of these spaces. Typically, these and many other retail units visited had large or even floor-to-ceiling and wall-to-wall glazed store fronts which were largely used for product display. The result was that little available daylight was transmitted into the stores. In addition, with the exception of an area approximately 1-1.5m depth from this frontage, no sky was visible with the only daylight available being as a result of the externally reflected component. When its intensity is compared to that of internal electric lighting it is not surprising how little an effect it had. As such, the spectral microclimate of these spaces was dominated by the installed electric lighting systems with a minimal, if any, contribution by daylight at the front/entrance.

The measurement technique employed was from the perspective of an employee who will almost exclusively work in the interior of the space. Measurements were taken from a single point looking towards the outside, looking inside the unit and sideways. It was also noted from the retail units visited that only fluorescent and LED lighting was found and almost exclusively one or the other.

Figs. 7 and 8 are typical representatives of such retailers. The first might be described as mid-range, selling stationary, home products, etc. while the second is a high-end fashion outlet selling men's clothing. Fluorescent light was used in the first while LED was installed in the second. The second was fitted out in early 2017.

As can be seen in both cases, the SPD of the points measured clearly exhibit the profile of the installed lighting system. In the first case fluorescent and in the second LED. The only variation in either case is the broadband illuminance with the SPD holding its characteristic profile. In conversation with the manager of the second retailer, it is their policy to show products to customers under daylight at the door to ensure they achieve optimal colour rendering. Illuminance levels in this retailer were also significantly higher. Their variation was due to the focus of the recessed spotlights, clearly designed with product display in mind.

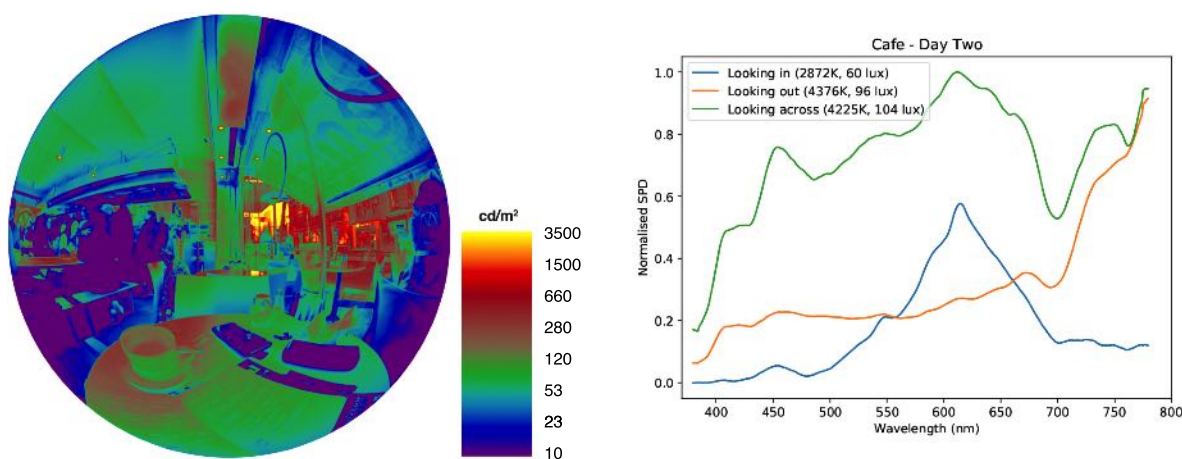


Figure 10: Cafe.

3.3.3 Office unit

The office unit chosen for the study was open to walk-in customers and so there is a public area to the front with a fully glazed wall at street level, as shown in fig. 9. The lighting installed consisted of CFLs as can be seen from the measured SPD profiles. The study was carried out on day two.

What made this example interesting was the change in profile when looking outside. Not only did the illuminance level increase from what was a surprising low level generally, so too does the SPD. It is not characteristic of daylight but the increases are not only at the peaks that are characteristic of CFLs but also in-between, suggesting that some daylight is having an effect at the point of measurement, at approximately 6 m from the window.

3.3.4 Cafe

Sample measurements taken in the cafe illustrate an important point. Fig. 10 shows a HDR luminance map and SPDs taken looking in three directions. What became noticeable is the very distinct change in profile when looking across the cafe. In this view, a very small patch of sky becomes visible. Illuminances measured looking into and outside the cafe were very low. Like most cafes considered for observation, this cafe had external awnings – in part to prevent glare on sunny days but also to act as promotional signage. Within the view looking across the cafe, this small patch of visible sky changed the profile quite significantly. Illuminance levels were still low but given a more favourable profile it is a matter of duration of exposure to secure a suitable dosage to contribute to circadian entrainment. Extrapolating from this particular example, one might speculate that what is most important in terms of experienced daylight SPD is view of open sky.

4 Conclusions and Further Research

As stated at the outset, these studies are of an exploratory nature – to look at issues with respect to the spectral properties of a range of representative microclimates. From these a number of indicative findings have been presented which support the need for further research. In summary, a number of observations can be made.

External findings show that at any point outside, the reflected component of light received is relatively low compared to that from open sky. The spectral profile of mea-

measurements shows that as a result, the spectral properties measured at a point are influenced almost exclusively by the SPD of the sky.

One noted exception to this is in an area where vegetation is present – trees, shrubs, grass – where chlorophyll fluorescence results in strong presence within the red frequency range of the spectrum. It can be reasonably assumed that such a phenomena would also be found in built scenarios where vegetation is used for shading. This is a method widely disseminated in recommended ‘passive design’ strategies.

The only indoor spaces studied where profiles resembled in any way that of outside daylight were atria. As outside, the internally reflected component played little role except where daylight from outside was relatively low compared to that measured internally.

Spectral profiles measured internally were almost entirely dictated by the dominant source of electric light installed. In urban areas (all ground floor), even with generous street width-to-height ratios, a spectral profile resembling one of daylight was only observed within 1–1.5 m of the window after which it was entirely overwhelmed by electric light. This correlates directly with the view of sky, or sky component.

The visible sky component, as in conventional daylight design, is the single most important factor in delivering a desirable SPD to indoor spaces. As such, room and window height are of particular importance as they will increase the likelihood of a sky view as well as increasing the depth of penetration of daylight and its associated SPD and intensity. Ground floors are obviously the most disadvantaged. This can be extrapolated to homes and, in particular, apartments which are, in part, aimed at increasing urban housing density but are at risk of depriving residence of this important spectral quality of light.

In retail, in which many work, even when windows were present and generally wall-to-wall and floor-to-ceiling, they were taken up by front-of-shop displays and products and so blocked almost all external daylight. Resultant SPDs were of the installed electric lighting exclusively.

Those working in such environments, especially in winter months, potentially received no daylight-like SPDs during the working week. Restricting the possibility to get daylight SPD exposure to the weekend. What might this mean for a person’s long-term well-being and productivity is emerging as a research question in photo-biology and related disciplines.

Atria, while somewhat of a design trend in the 1980’s and 1990’s, might still prove useful as an in-house space where staff might break and at the same time received a better spectral source of light than provided artificially.

With regard to the instrumentation used in the study, an integration time of 16 sec was often required as surprisingly low illuminances were often experienced. Manufacturers of future instrumentation, which is needed, should work towards enabling readings at lower illuminance levels, as low as 40 lux, with good signal to noise ratios and, at the same time, high resolution.

It is widely believed that there is no substitute for outside sourced illuminance with its associated ‘good’ spectral properties. This is not surprising given that human evolution took place outdoors: “we are all outdoor animals” (20). Contemporary lifestyles and work practices have led to a marked and unprecedented reduction in the time spent outdoors by humans in much of the developed world. With huge changes therefore in

the experienced spectral power distribution of illumination. Lighting design predicated on visual task and energy performance is no longer sufficient in building design. Much of the research needed to support a change towards a more balanced focus that includes health-based design is and will come from a wide range of disciplinary fields, and more is still required before such knowledge can form the basis of regulatory standards and practices. Characterisation of the experienced spectral power distribution will play a vital part in the formulation of future guidelines and recommendation for illumination in buildings. The evaluation of daylight design for buildings is once again experiencing considerable change, this time in support of the health and well-being of occupants.

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