buildings

MDPI

Article

The Application of Human-Centric Lighting in Response to Working from Home Post-COVID-19

Frank Roberts [1], Michael White [1], Saim Memon [2,3,4], Bao-Jie He [5,6,7,8] and Siliang Yang [1,*]

1 School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds LS2 8AG, UK; m.j.white@leedsbeckeatt.ac.uk (M.W.)
2 Jiangsu Sanyou Dior Energy-Saving New Materials Co., Ltd., Changzhou 213149, China; memonsaim@gmail.com
3 School of Engineering and the Built Environment, Birmingham City University, Birmingham B4 7XG, UK
4 London Centre for Energy Engineering, School of Engineering, London South Bank University, London SE1 0AA, UK
5 Centre for Climate-Resilient and Low-Carbon Cities, School of Architecture and Urban Planning, Chongqing University, Chongqing 400030, China; baojie.he@cqu.edu.cn
6 Network for Education and Research on Peace and Sustainability (NERPS), Hiroshima University, Hiroshima 739-8530, Japan
7 Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing 400044, China
8 State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China
* Correspondence: s.yang@leedsbeckett.ac.uk

check for updates

Citation: Roberts, F.; White, M.; Memon, S.; He, B.-J.; Yang, S. The Application of Human-Centric Lighting in Response to Working from Home Post-COVID-19. *Buildings* **2023**, *13*, 2532. https://doi.org/10.3390/buildings13102532

Academic Editors: Chi-Chung Lee, Kin Wai Tsang, Asiri Umenga Weerasuriya, Yaohan Li and Xuelin Zhang

Received: 4 August 2023
Revised: 27 September 2023
Accepted: 4 October 2023
Published: 6 October 2023

Abstract: COVID-19 has caused a considerable proportion of the public to work from home, either part- or full-time, in unregulated domestic conditions, which have not been designed for commercial activities. This study determined what existing lighting conditions were present in a selection of work-from-home (WFH) environments (Objective One) through quantitative lux level and equivalent melanopic lux (EML) readings by evaluating them against regulatory standards, where further study is required to validate the results with a larger dataset. This study also investigated the social demand for human-centric lighting (HCL) installations within WFH environments (Objective Two) through qualitative questionnaires by considering key parameters: sustainability, practicality, and cost. The results of Objective One showed that compliance with general safety lighting requirements was achieved by 80% of the installations. The mean lux level recorded was 452.4 lux and 0.729 uniformity, which fell below commercial requirements defined for commonly performed WFH activities; 34.3% of recorded EML dropped below the regulatory requirements under daylight conditions. When isolated to artificial lighting, only 7.5% of the required EML was achieved. The results of Objective Two showed that generally participants did not feel that their WFH installations were unsuitably lit, however, 46.2% of participants identified noticeable headaches or eye strain when working from home. A total of 80% of participants highlighted that HCL task lighting would be preferable. It was also found that participants were willing to invest in circadian lighting for health, where 63.2% of them would not accept a reduction in efficiency of over 10% compared to non HCL. Wellbeing was found to be participants' key preference for their lighting systems, followed by efficiency, home impact, and cost.

Keywords: circadian lighting; biological potency; melanopic lux; lux level; uniformity

1. Introduction

Human beings have evolved to live under the earth's natural lighting conditions since the dawn of humankind [1]. The daily sun cycle, creating the sunrise and sunset phenomenon, emits varying light intensities and colour temperatures, which directly influence human psychology through a circadian rhythm [2]. The circadian rhythm is the human brain's internal 24-h clock, which regulates various states of sleepiness and alertness, as well as responding to light changes within the environment [3]. Humans would historically spend 90% of their time exposed to direct daylight, whereas the modern human is typically only exposed 10% of the time [4]. Within a short period of time, humans have become heavily exposed to indoor artificial lighting sources [5]. Consequently, this has led to a risk of breast cancer, metabolic disorders, and behavioural disorders [6].

Traditional installations of light consider a singular correlated colour temperature (CCT), which defines the colour appearance of light sources in degree Kelvin (K) [7]. Colour temperature is defined by the light wavelength adsorbed by human eyes [8]. Traditionally, either high or low CCT products were specified for light installations based on designer specification, so the colour temperature emitted would be fixed in traditional installations [9]. However, fixed CCT lighting is the fundamental problem with modern lighting, as it delivers poor colour rendering for users [10] and thus influences their mood and productivity [11]. Fixed CCT light installations are the most common type of installation throughout the United Kingdom (UK), where only a small proportion of commercial buildings have explored alternatives. A solution to the fixed CCT installations is known as human-centric lighting (HCL) [12]. HCL is described as a lighting solution that optimises human vision (the scotopic/photopic ratio), concentration, mood, alertness, wellbeing, and performance [9]. HCL recognises the effect on human psychology in relation to light intensity and CCT emission, which is designed to match the daily sun cycle and harmonise with the circadian rhythm [13].

Houser et al. [14] report an overview of the HCL on its pros and cons. It was defined that the term "Human-Centric Lighting" can mean different things, from a simple sales technique or health wash phrase to promote products or to signify a genuinely useful lighting solution that can benefit society in the next wave of artificial lighting. At its best, as described by Houser et al. [14], HCL is demarcated as "human-centric lighting is lighting designed to deliver a specified set of visual, biological and behavioural responses identified as appropriate for the users of that lighting". On the other hand, they demonstrated limitations of the ability to design lighting with the current technology that influences the physiological and psychophysical functionality of human beings. For example, it was described that the relationship between lighting levels and non-visual responses were non-linear, and therefore the precise biological potency levels to produce exact biological reactions was simply unknown at this point of the technology development.

A key metric of HCL is the biological potency received by an observer [13]. Schlangen and Price [15] introduced a concept of measuring biological potency based upon spectral responses within the intrinsically photosensitive retinal ganglion cells (ipRGCs) of the cone and rod receptors as well as the measurement of the reduction in melatonin. The CIE (International Commission on Illumination) endorses a combined method of quantifying biological potency based on photometric equivalence [16]. Through this methodology, the principles associated with providing high biological potency, described as the light intensity and spectrum in the earlier hours of the day, and lower biological potency in the evening, as per Figure 1, which shows a correlation with the existing research around how HCL should be designed to mirror the circadian rhythm [14].

Figueiro [17] discussed how light receptors interact with the pineal gland by affecting melatonin secretion under conditions of darkness. Melatonin is a key hormone that provides the human body with time cues by influencing the circadian rhythm directly. Sufficiently bright light (as shown in the hours of 6:00 to 16:00 in Figure 1) will cease melatonin production causing more alertness. Body temperature has an inverse relationship to melatonin, reaching maximum levels in the afternoon and minimum levels in the early hours of the morning. If true, these findings provide significant evidence for natural circadian regulation. Figueiro [17] also reported how long-term health deterioration, from sleep disorders to cancer, may be influenced by artificial lighting conditions. The link to serious illnesses such as cancer does have limitations, where the study claims that the respectively high reports of breast cancer within industrial settings may be caused by the reduction in melatonin due to artificial lighting sources. This hypothesis suggests that the melatonin suppression caused excess oestrogen production, stimulating the turnover of breast epithelial stem cells, thus increasing the cancer probability. Despite animal testing and human research, high-level connections between biological functions have been made to draw this conclusion, which is unproven at the moment. It was also noted that the study considered people at the extremes of circadian rhythm disruption (for example, night shift workers and teenagers), so it was not accurate to conclude that 9 am–5 pm workers would experience such a high risk of serious health deficiencies. However, static CCT lighting installations that do not consider circadian rhythm have been proven to have negative influences on hormone secretion. Furthermore, Figueiro [17] demonstrated how different light sources, with various CCTs, can cause melatonin suppression at different lux levels. For example, daylight provides 25% and 50% suppression at 138 lux and 524 lux, respectively, whereas a 2700 K luminaire will provide the same suppression at 313 lux and 1223 lux, respectively. Therefore, it can be concluded that it is important to consider not only the illuminance but also the type of luminaires and how the luminaires deliver light, as this has a significant effect on melatonin secretion.

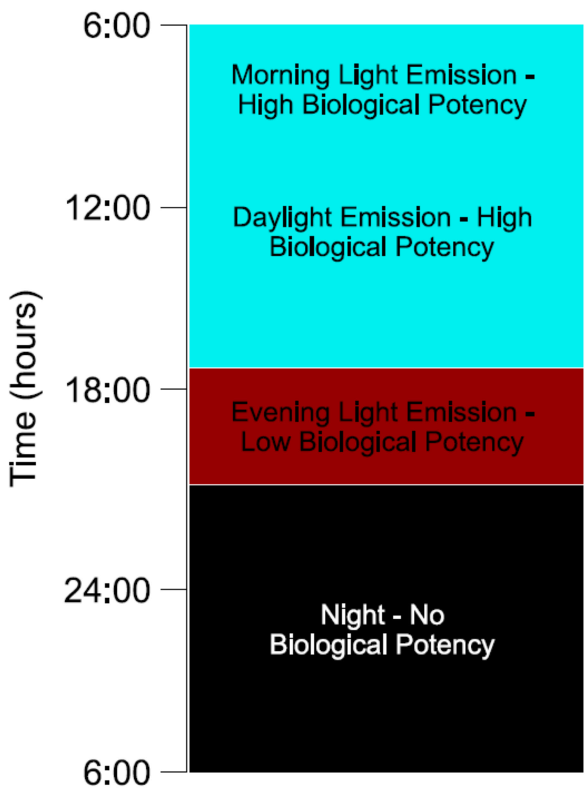


Figure 1. Recommended biological potency [14].

In summary, existing research studies have focused on proving the physical and psychological effects of human-centric lighting and lighting in general, whereas little research has been produced to reveal the real qualitative effects on users' operating under the lighting conditions in commercial applications. On the other hand, COVID-19 has changed the modern working environment to a hybrid system, where employees have shifted their working patterns between working from home (WFH) and attending a place of work [18]. According to a Gartner survey [19], about 74% of employers intend to move some on-site employees to remote positions permanently post-COVID-19. Within residential properties, illuminance levels and CCTs have not been designed to meet basic lighting standards, which potentially causes long-term deterioration of wellbeing, health and performance [20]. In the UK context, it is unclear whether the typical "home office" complies even with basic lighting requirements defined in the CIBSE (Chartered Institution of Building Services Engineers) standards and Health and Safety Guidance (HSG); this would potentially cause serious performance restrictions where lighting conditions may not be sufficient for facilitating desired outcomes as well as introducing visual safety risks [21].

Therefore, this study aims to understand what lighting conditions are currently present within the WFH environments in terms of safety and visual clarity. A further review will highlight if HCL is socially accepted within domestic WFH environments and what limitations could be expected with the implementation of this technology. Specifically, there were two objectives implemented through this study, which can be concluded as follows:

- To understand what lighting conditions are present in a selection of work-from-home applications by evaluating them in terms of lighting circadian functionality, visual comfort, and safety;
- To investigate whether there is a social acceptance for HCL within domestic homes by considering the impacts of sustainability, practicality, and cost associated with the installation.

2. Methodology

2.1. Methods for Objective One

A quantitative approach is an appropriate method to produce reputable data for analysis through experimental measurements to understand lux levels within a space. The quantitative data collection utilised a sampling method maximising generalisation, gathering a variety of results from different WFH environments (the participants). It is recognised that, even by using a sampling technique as broad as simple random, this will not generate results that represent all work-from-home installations due to significant non-standardisation of domestic dwellings. The nature of quantitative data requires a statistical analysis method to interpret the data and draw conclusions [10]. The initial approach of descriptive statistics shall be implied on the data collected to present mathematically recognised formats for further analysis. Descriptive statistics analyses a sample of the population only, determining the following parameters [22].

$$\text{Sample mean}: \ \overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

$$\text{Sample variance}: \ S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2 \tag{2}$$

$$\text{Standard deviation}: \ S = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2\right)} \tag{3}$$

where i is the item, x_i is the item observed, and n is the total count of item x_i.

2.1.1. Functional and Safety Lighting

To understand the functional and safety lighting conditions of existing work-from-home environments, measurements of lux levels shall be taken from various WFH environments and then analysed quantitatively in reflection against commercial regulatory standards. To achieve this, the following assumptions/limitations are highlighted:

- The Society of Light and Lighting [21] defines the key parameters to consider for conventional lighting as Average Lux Level ($\bar{E}_m$), Glare (U_{GRL}), Uniformity (U_o) and Colour Rendering (R_a). U_{GRL} and R_a are immeasurable with equipment accessible to participants of this study. Therefore, $\bar{E}_m$ and U_o are the two aspects of lighting conditions assessed in this study.
- Ipsen et al. [23] discuss that COVID-19 has caused most industries to promote working from home, where primarily office-related businesses have encouraged staff to work from home on a more regular basis. Lighting parameters from The Society of Light and Lighting [21] have been used as a commercial lighting benchmark for comparison

purposes. Safety lighting requirements have been considered from the guidance—Lighting at Work [24].

- Due to ethical limitations, access to various participants' properties to take lux readings was not permitted. To mitigate this, participants were asked to download a lux reading application on their smartphone device.

To determine the quantity of lux level measurements to be made by each participant, Equation (4) has been used to determine the grid size and precise measurement locations.

$$p = 0.2 \times 5^{Logd} \quad (4)$$

where p is the maximum distance between lux level reading points, and d is the longest distance of the working plane measured.

In this study, the working plane of a typical desk size of 1200 mm (W) $\times$ 800 mm (D) $\times$ 720 mm (H) was considered (as shown in Figure 2), and the following measurement points, as shown in Figure 3, have been applied in association with Equation (4) (that is, $p = 0.2 \times 5^{Log1.2} = 0.227$).

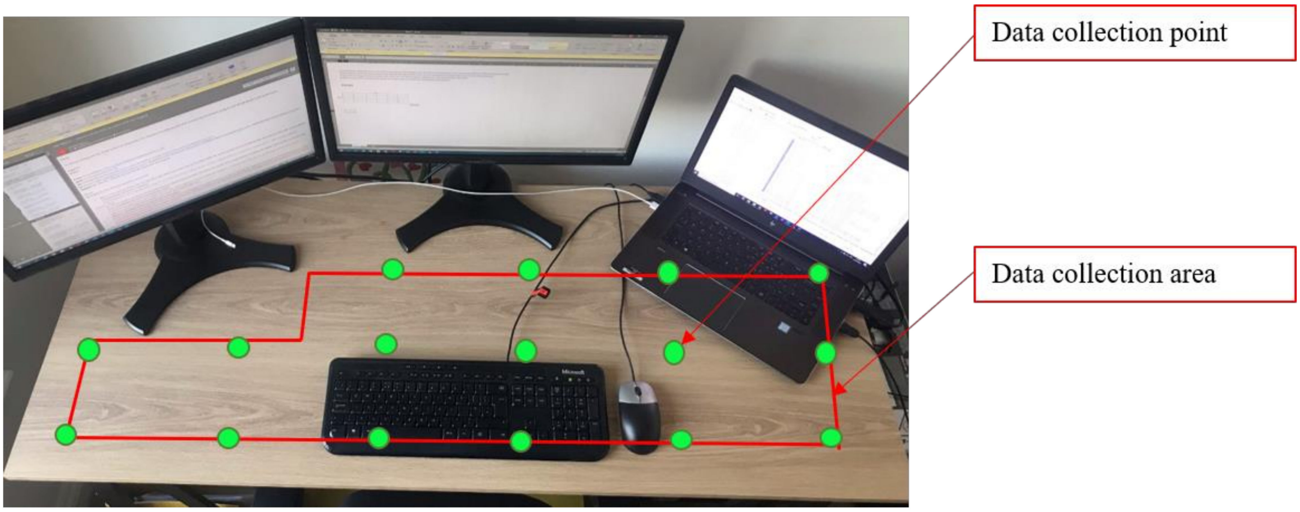


Figure 2. Typical desk used for the study.

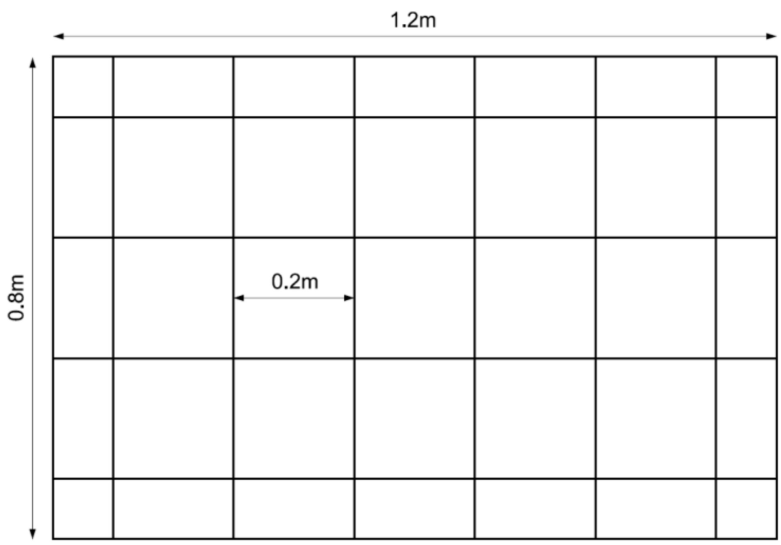


Figure 3. Working plane data collection points.

Therefore, 1.2 ÷ 0.227 = 5.28 (to be rounded up to 6 horizontal data points), and maximum spacing = 1.2 ÷ 6 = 0.2 (m), while 0.8 ÷ 0.2 = 4 (vertical data points).

Although desk heights vary, they cannot be controlled and therefore no mitigation measures to standardise this were proposed. Uniformity shall be determined for each participant via Equation (5):

$$Uniformity\ (U_o) = \frac{E(\min)}{E(\text{ave})} \quad (5)$$

where E(min) is the minimum lux level and E(ave) is the average lux level.

Various reliability issues may arise through user error, participant changes, and environmental changes. To mitigate this, the test–retest reliability strategy was implemented, where participants provided readings two days apart. Also, detailed instructions for participants reduced user error during the data collection phase.

2.1.2. Circadian Lighting

To understand the circadian lighting conditions of existing work-from-home environments, testing in line with IWBI (International Well Building Institute) [25] requirements was performed and analysed quantitatively using the following methodology. International WELL Building Institute [25] discusses the requirement for the assessment of the equivalent melanopic lux (*EML*) within working spaces for the benefit of the ipRGCs rods [17], while the *EML* can be determined from Equation (6). Table 1 describes the requirements.

$$EML = L \times R \quad (6)$$

where L is the visual lux (traditional lux calculated on a vertical plane) and R is the melanopic ratio.

Table 1. EML lighting requirement for work areas.

	Melanopic Light Intensity for Work Areas [25]
a.	For 75% or more of workstations, at least 200 equivalent melanopic lux is present, measured on the vertical plane facing forward, 1.2 m above finished floor (to simulate the view of the occupant). This light level may incorporate daylight and is present for at least the hours between 9:00 am and 1:00 pm for every day of the year.
b.	For all workstations, electric lights provide maintained illuminance on the vertical plane facing forward (to simulate the view of the occupant) of 150 equivalent melanopic lux or greater.

International WELL Building Institute [25] presents typical melanopic lux, as shown in Table 2, for various types of lighting sources. To determine the exact ratio for each project for more accurate results, a calculation should be performed based on the luminaire properties. To achieve this, the following equation is presented.

$$R = \frac{MR}{TVR} \times 1.218 \quad (7)$$

where *MR* is the product of the luminaire wavelength output and the melanopic curve and *TVR* is the product of the luminaire wavelength output and visual curve.

Table 2. Typical melanopic ratio [25].

CCT (K)	Light Source	Ratio
2700	LED	0.45
3000	Fluorescent	0.45
2800	Incandescent	0.54
4000	Fluorescent	0.58
4000	LED	0.76
5450	CIE E (equal energy)	1.00
6500	Fluorescent	1.02
6500	Daylight	1.10
7500	Fluorescent	1.11

2.1.3. EML Testing Validation

Vertical plane lux level measurements need to be attained for *EML* calculations in accordance with IWBI guidance [25]. The varying *EML* ratios described in Table 2 mean that participants would be required to isolate their light sources (for example, daylight and artificial lighting), take measurement readings, and identify the light source for that particular reading. This is deemed impractical, creating confusion and invalidity from untrained participants. Therefore, the recording of *EML* was limited to various rooms within one domestic property for validity purposes, and it is recognised that this is not a full representation of the population's *EML* conditions. A calibrated lux meter (Kimo Luxmeter LX50) was used to maximise accuracy. Both points a and b from Table 1. were assessed by taking readings at 1.2 m finished floor level (FFL) at 30° intervals from 0° to 180° (facing forward) towards the working direction. Generally, all commercially produced light meters contain three main photometric components for light measurements (Table 3). Lux meters are also calibrated yearly, provided with ISO calibration certificates as well as being designed and maintained to European standards, such as 2011/65/EU RoHS II, 2012/19/UE DEEE, 2014/30 UE EMC, and 2014/35/EU Low Voltage [26].

Table 3. Calibrated lux meter components.

Lux Meter Components	Functions
Photodiode	The photodiode converts the spectral range of visible colours, infrared light, and ultraviolet light to analogue signals for the light meter to measure.
Luminosity function filter	Filters or stops different wavelengths based on how interactive they are with human photopic vision.
Cosine corrected lens	Allows accurate measurements of light radiation on a flat surface considering all angles of incidence.

Mobile devices recognise light using a different methodology. Glass screens on the front face of the mobile device distort incoming light radiation, where no cosine correction is provided on standard mobile devices. The specular glass face of a mobile camera results in light entering the sensor differently depending on the angle of incidence from the light source. Therefore, the larger the angle of incidence, the less accurate the readings become. The field of view obtained from a mobile camera is generally 50–70%, therefore a large majority of the low-angle light is missed by default [27].

The net result was that without the angle of incidence information from each light source of each participant, it was impossible to assign an accurate correction factor for each device to increase accuracy. In this study, the option of asking participants to hold their mobile devices perpendicular to the light source was considered. However, it was apparent that participants generally had more than one light source (for example, daylight and artificial light), so this could not be achieved.

Two typical WFH environments/rooms were selected to understand the 'real world' accuracy of the mobile application. Room 1 conditions (Figure 4) include a 2.55 m^2 clear glazed window facing 313° NW. Both daylight only and daylight plus artificial lighting conditions were assessed, where the artificial lighting includes a single pendant-shaded LED bulb in the centre of the room. In this case, the angle of incidence from the artificial light source was approximately 45°, whereas the clear glazing offered natural light from 0° to approximately 65°. On the day of measurement, there was a clear blue sky. The lux meter and mobile device were placed on a desk with a working plane approximately 700 mm above the FFL. Room 2 conditions (Figure 5) included a 2.4 m^2 clear glazed window facing 155° SE. In this case, the artificial lighting included a single pendant-shaded LED bulb in the centre of the room, and the angle of incidence from the artificial light source was approximately 70°, whereas the clear glazing offered natural light from 30° to approximately 70°. The lux meter and mobile device were placed on a desk with a working plane approximately 700 mm above the FFL.

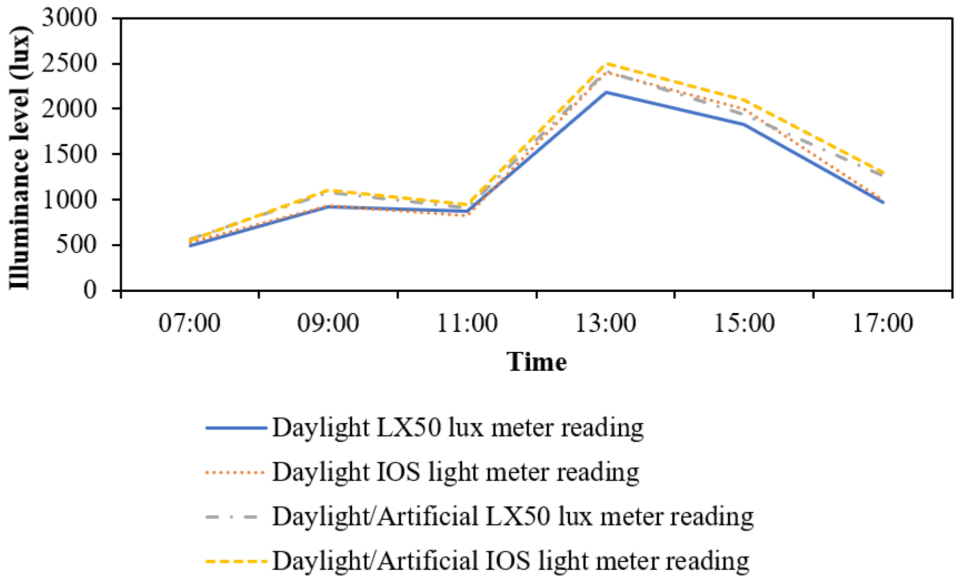


Figure 4. Lux level accuracy comparison—Room 1.

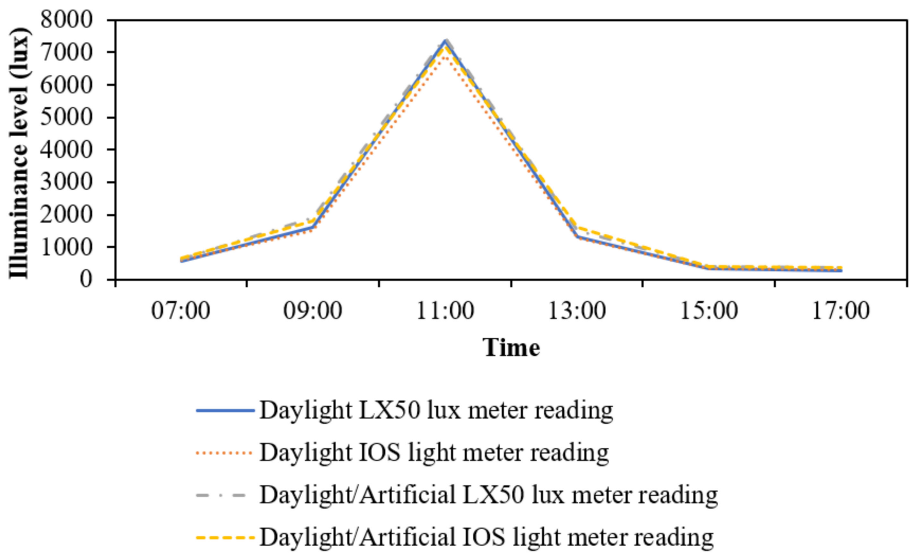


Figure 5. Lux level accuracy comparison—Room 2.

The mobile device used in the above test was an iPhone 7. The iPhone 7 was considered a worst-case accuracy comparison test due to the device's age and reduced technological performance. The worst variance achieved was 10.1%, while the best-case variance was 0.08%; both figures show a tightly grouped correlation between both the application and the calibrated lux meter. Therefore, the use of the application was considered acceptable for understanding general lighting conditions within the WFH environments.

2.2. Methods for Objective Two

HCL within domestic WFH environments is a topic that has had little to no research, so the goal of this study was to understand and explore social opinions and acceptance of the subject, therefore a qualitative approach was implemented [28]. A qualitative survey has been identified as the most appropriate method of data collection for Objective Two to offer the most time-efficient data collection process both for the researchers and the participants [29]. The qualitative data collection method followed a sampling method that maximised exposure to the majority of the public to mitigate the risk of bias from a particular group of participants. Purposive sampling, followed by probability simple random sampling, was used. The survey was advertised through LinkedIn as this provides data collection from an appropriate professional social network whilst maximising exposure to large data collection groups. The survey was issued using Jotform, an online survey/questionnaire platform.

Thematic analysis provides an appropriate analysis technique for the qualitative data collection. Coding the segments allows researchers to capture a range of meanings from the data, from obvious semantic meaning to conceptual or more latent ideas [30]. Deductive thematic analysis was applied to discover results beyond the obvious meanings within the data collected, thus allowing unforeseen varying theories to arise throughout data analysis. Any quantitative questions making up the research questions were assessed using statistical analyses.

3. Data Analysis and Interpretation

The data of both qualitative and quantitative research within this study are presented and analysed in this section. The primary data collected has been designed to answer the two objectives; a detailed discussion of the analysis is provided in Section 4.

3.1. Data for Objective One

3.1.1. Functional and Safety Lighting—Traditional Lux Level Readings

The quantitative data collection for lux levels within WFH environments has gathered a reasonable sample of illumination levels for analysis. A total of 24 data readings were submitted using the lux level collection methods specified in Appendix A via the use of the "Light Meter" application on the mobile device. Participants took their readings in their WFH environments on two separate days for validity, where each participant was located in a geographically different location allowing the study to obtain a wide breadth of information for analysis. The results are summarised in Table 4.

Table 4. Compliance with "Society of Light and Lighting".

Activity	Pass Requirement	Lux Level Pass Rate	Uniformity Pass Rate	Full Pass Rate
Computer-based writing, typing, reading, and data processing	500 lux 0.6 U_o	32%	96%	32%
Technical drawing (paper/by hand)	750 lux 0.7 U_o	12%	52%	8%
Computer-based CAD/BIM works	500 lux 0.6 U_o	32%	96%	32%
Online conference calls (MS Teams, Skype, etc.)	500 lux 0.6 U_o	32%	96%	32%
Admin work (either on or not on computer)	300 lux 0.4 U_o	72%	100%	72%
Lighting at work	200 lux 0.5 U_o	80%	100%	80%

3.1.2. Circadian Lighting—EML Readings

EML readings were taken using the calibrated LX50 lux meter, where the points for the readings are indicated in Figure 6 and the *EML* recordings are summarised in Table 5. The EML ratio applied was 1.10 as per Table 2, as the light source was isolated to daylight only measured on the vertical plane as per the requirements defined by the IWBI [25]. For artificial light sources, the *EML* ratio applied was 0.45, as per Table 2, as the light source was isolated to electric artificial LED 2700 K bulbs. *EML* requirements define a minimum of 200 EML facing forward. Room 1 conditions include a 2.55 m^2 clear glazed window facing 313° NW, while Room 2 conditions include a 0.93 m^2 clear glazed window facing 313° NW.

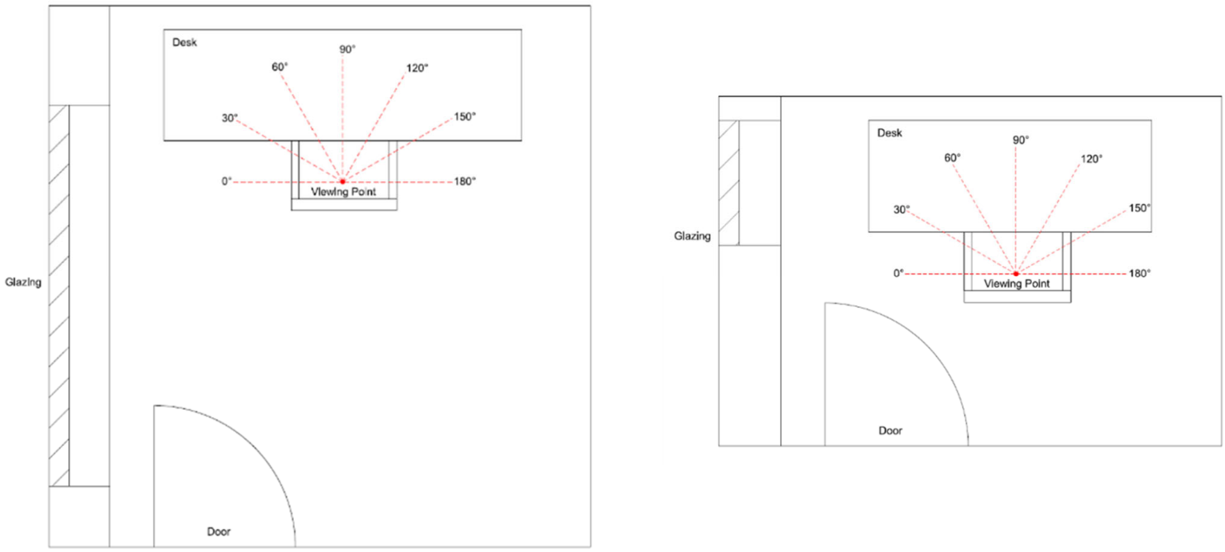


Figure 6. EML measurements 2D plan—Room 1 (**left**) and Room 2 (**right**).

Table 5. EML lux level recordings.

Room 1—EML Recordings (Natural Light)							
	0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**
9:00	1075.1	820.1	626.4	269.7	210.9	232.6	257.7
10:00	1667.6	1152.8	907.6	452.6	294.2	346.3	382.4
11:00	1937.1	1518	1145.1	609.9	326.8	399.1	441.9
12:00	2262.7	1657.7	1017.0	482.0	404.5	455.6	526.7
13:00	2006.4	1326.6	935.8	504.3	400.7	409.3	466.4
Room 1—EML Recordings (Artificial Light)							
	0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**
-	3.65	4.41	4.95	6.17	7.02	9.05	11.39
Room 2—EML Recordings (Natural Light)							
	0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**
9:00	592.13	405.79	241.56	128.04	116.16	106.15	97.13
10:00	866.25	737.33	467.94	344.96	314.82	186.89	85.58
11:00	1119.8	873.4	465.41	210.21	185.24	156.53	117.04
12:00	1215.5	983.4	438.46	237.6	216.15	111.65	103.62
13:00	1485	1125.3	515.13	471.02	322.19	208.538	156.53
Room 2—EML recordings (Artificial Light)							
	0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**
-	4.64	5.04	6.21	7.16	6.53	5.67	5.18

3.2. Data for Objective Two

A qualitative survey was produced to understand the four main categories for analysis, including the existing WFH lighting conditions of participants, social acceptance for having HCL installed, acceptable cost implications for the installation, sustainability impacts, and the participant's lighting priorities. A total of 30 participants responded to this survey from a single engineering business. Appendix B and Appendix C show the details of the survey, which demonstrate the statistical and thematic analysis, respectively, for participants' existing WFH environments.

4. Results and Discussion

4.1. Objective One—Functional and Safety Lighting

The requirement for functional lighting in terms of perception of detail is integral to commercial building design and covered extensively within BS EN 12,464 [31] and the Society of Light and Lighting [21]. From a safety perspective, the HSG 38 [24] details a separate simplified set of requirements. This section demonstrates whether domestic WFH installations meet the commercial requirements. Figure 7 shows the variety of lux levels and equating uniformity recorded, with a mean result of 452.4 lux and 0.73 U_o.

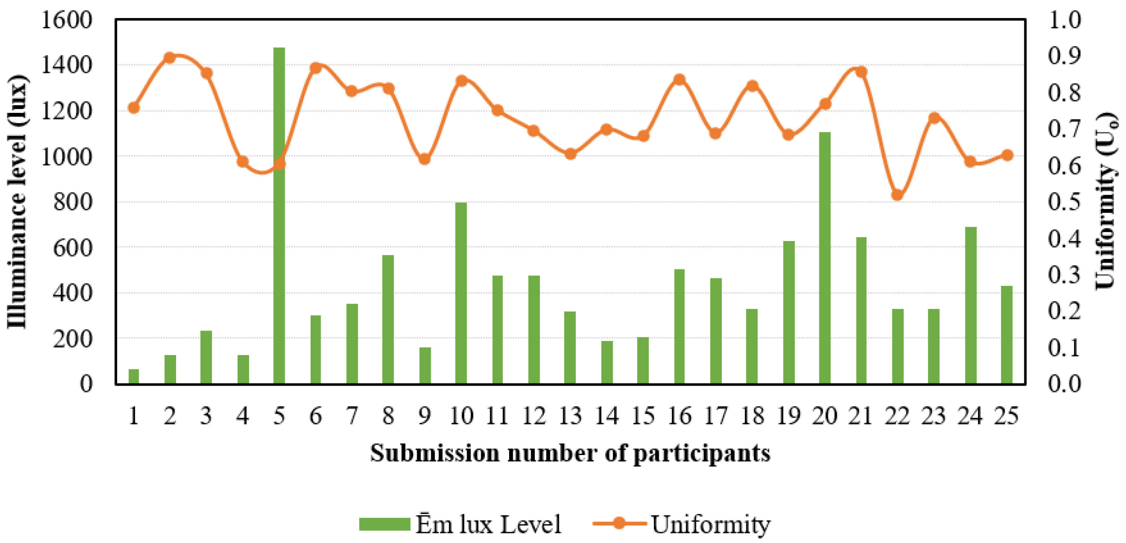


Figure 7. Ēm lux level and uniformity (U_o) results.

A comparison against the specification within the Society of Light and Lighting [21] shows that 72% of WFH installations provided sufficient functional lighting conditions above 300 lux and 0.4 U_o for admin work, which corresponds to 36.6% of the public's partial job role. For more detailed work, such as online conference calls or computer-aided design (CAD), only 32% of WFH installations achieved the full requirements of 500 lux and 0.6 U_o, where 96.7% and 56.6% of participants reported performing online conference calls and CAD work, respectively. For those 23.3% of participants undertaking technical drawings, only 8% of WFH installations achieved the 750 lux and 0.7 U_o requirements.

Full compliance with commercial lighting requirements defined by the Society of Light and Lighting [21] was generally not achieved for optimal functionality and visual comfort when performing the most common tasks reported within the qualitative survey. However, when assessing lux levels in terms of safety in line with the HSG 38 [24], it can be seen that 80% of all WFH environments met the safety requirements of HSG 38. Generally, uniformity values performed reasonably, where 96% of recorded U_o achieved at least 0.6. A total of 48% of the installations failed to achieve 0.7 U_o or higher, showing a generalised limitation to the domestic lighting distribution. Moreover, the standard deviation was relatively small compared to that of the recorded lux levels.

Although it is proven that only 32% of WFH environments achieved the lux levels defined for the most commonly performed commercial activities (that is, online conference calls or CAD), the qualitative survey showed that participants generally agreed that their WFH conditions are adequate for performing their job role. On a Likert scale, participants gave a mean value of 7.43 when queried about the adequacy of their existing installation. There was no correlation between participants who had little daylight interference and participants responding less than 7 on this Likert scale, therefore, daylight was not the sole factor causing unsatisfactory lighting.

4.2. Objective One—Circadian Lighting

Figure 8 shows the EML for daylight recorded in Room 1. With the position of the glazing relative to the viewing point shown in Figure 6, Room 1 saw the highest EML through the time 9:00–13:00 at 0° from the viewing point facing forward. This is due to the direct view towards the glazing, where EML reduces as the measurement angles pan away from the glazing. *EML* rises at 150° and 180° due to the high reflectance of the white walls opposite the glazing. The highest recorded *EML* was 2262 lux, and the lowest achieved was 210.9 lux. As a result, compliance with the IWBI was achieved in isolated daylighting conditions. It should be noted that the IWBI states that a minimum *EML* of 200 lux needs to be achieved year-round; further measurements would be required to demonstrate full compliance. The weather during this measurement was a clear sky condition. With a window size of 2.55 m^2, Room 1 has a considerably larger glazing area than the mean of 1.80 m^2 recorded within Objective Two's survey, meaning it is likely that most WFH scenarios would present a reduced *EML* in comparison.

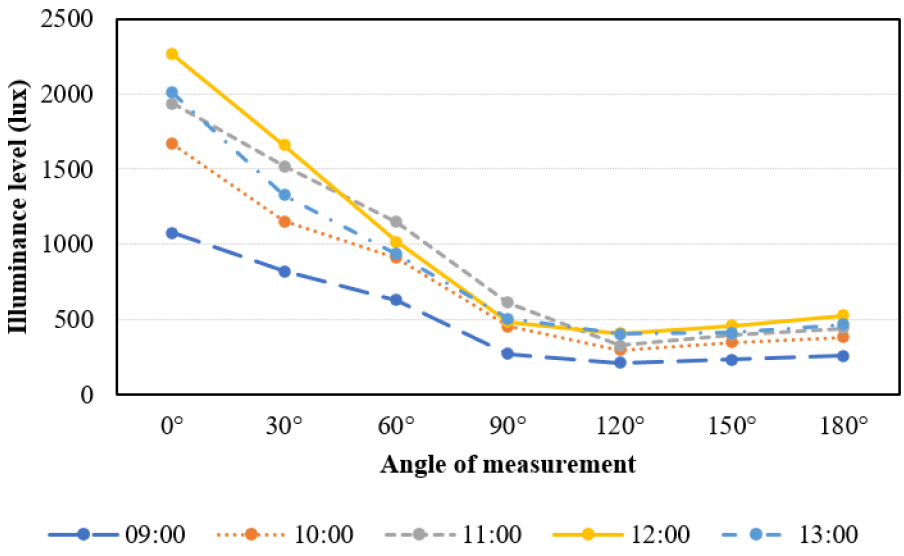


Figure 8. EML for daylighting—Room 1.

As shown in Figure 9, Room 2 followed a similar pattern as Room 1, where 0° respective to the viewing point saw the greatest yield of *EML* between 9:00 and 13:00. The maximum *EML* recorded was 1485 lux and the minimum was 85.58 lux, primarily due to the reduced glazing size compared to Room 1. With a glazing size of 0.93 m^2, this is approximately half that of the mean recorded in the qualitative survey. Room 2 conditions fell below the *EML* of 200 lux threshold defined by the IWBI for 34.3% of its recorded values despite the weather conditions being a clear sky. Therefore, supplementary lighting offering circadian facilities could provide an enhanced working environment for occupants.

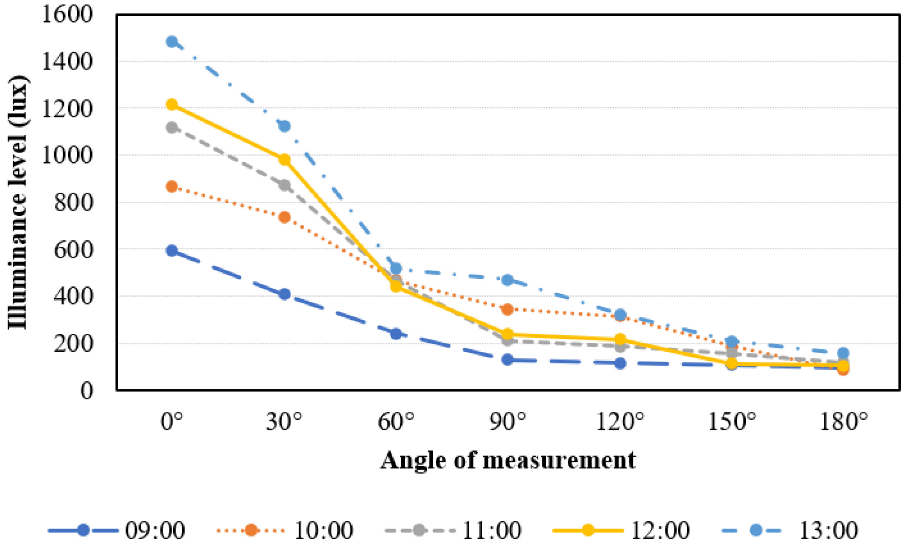


Figure 9. EML for daylighting—Room 2.

Moreover, it can be seen from Figure 10 that in both rooms *EML* recorded based on isolated pendant lighting fell well below the minimum EML (150 lux) defined by the IWBI. In both Rooms 1 and 2, the single-source pendant lighting was located behind the user, therefore when measuring the lux on the vertical plane facing forward, very little lux was present. A total of 53.3% of users within Objective Two's survey identified that pendant lighting is their primary source of lighting, so those with little daylight would suffer from very little *EML*; and this supports the need for supplementary lighting in those scenarios.

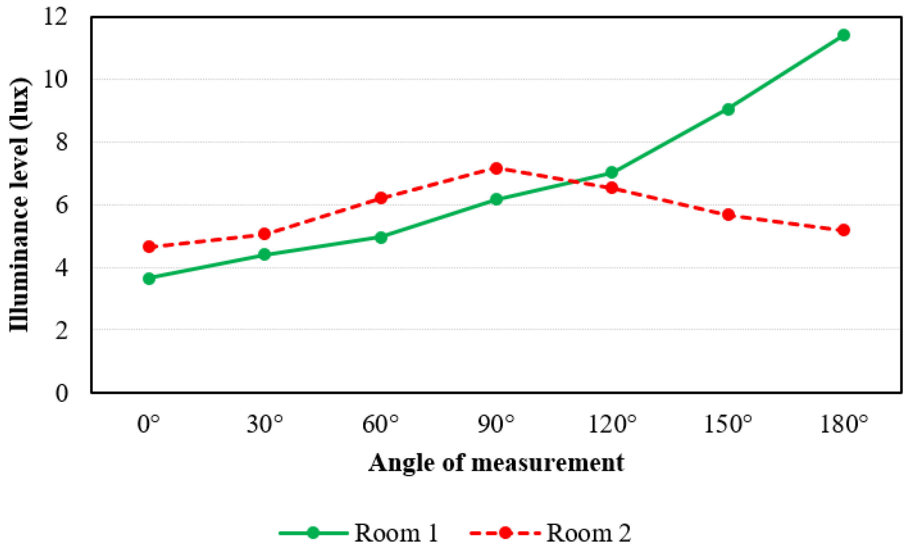


Figure 10. EML recorded for artificial lighting.

4.3. Objective Two—Existing Work from Home Environments

On average, participants now spend 78% of their working week at home post-COVID-19, therefore the long-term risks associated with insufficient lighting [17] will be present for a majority share of participants' weekly working hours unless mitigated. It is clear that participants perform a range of tasks when working at home, with the most common amongst all job roles being online conference calling (about 96%), then subsequent individual roles demanding specific lux requirements defined by The Society of Light and Lighting [21]. Each participant had a varying interface with daylight, with a mean glazing area of 1.8 m^2, demonstrating a large standard deviation due to the lack of standardisation amongst domestic dwelling construction methodology. A range of glazing directions has been accounted for, where no correlation regarding glazing direction can be identified with user satisfaction, although 3% of users identified shading methods—blinds/shutters—were utilised to mitigate glare where glazing matched that of the low morning or evening solar azimuth angles.

A thematic analysis was used to understand the existing lighting conditions within each WFH environment. A total of 53% of participants identified that their primary lighting source consisted of a centralised pendant lighting system, whereas 13.3% reported their primary light source was via flush spot lighting systems. A total of 46.6% of participants identified that they utilised supplementary desk lighting in addition to their primary lighting source. It is assumed that, since lighting levels were recorded at 12 pm, the desk lighting was not activated where lux levels were considerably less than the mean values recorded, although this was not made clear by the participants. A total of 20% of participants recorded that their natural light source via glazing was their primary light source.

The specific lighting technology deployed was predominantly LED, where 60% of participants reported LED use and only 10% reported Halogen bulb use within their primary lighting sources. A total of 46.6% of participants reported a warmer lighting colour with low biological potency with a CCT (approximately 3000 K). A total of 23.3% of participants described their lighting environment as having high biological potency and CCT (approximately 4000–5000 K). No correlation between the artificial lighting type and colour could be found within the respondents' responses to lighting adequacy. A total of 33% of participants recognised that the commercial office lighting they work under was considerably brighter and more intense than that of their WFH environment.

An initial 36.6% of participants reported no change to health, however, an equal portion of 36.6% of participants highlighted additional eye strain when working under domestic conditions. This was seen to significantly increase health issues such as headaches and eye strain among participants. A lack of compliance with the requirements of the Society of Light and Lighting [21] is likely the cause of increased eye strain from participants. A further 6% of participants reported headaches when working at home. It should be noted that health complaints cannot be purely attributed to the lighting system, although the correlation can be highlighted.

4.4. Objective Two—Social Acceptance for Domestic HCL Considering Sustainability, Practicality, and Cost

Participants initially provided a positive response to accepting a HCL system within their domestic environment on a 3.9 days WFH per week basis, providing a mean response of 7.37 on the Likert scale after an initial briefing on the scientific evidence provided by Houser et al. [14] and Figueiro [17] in supporting wellbeing, productivity, and performance. A total of 80% of participants recorded that localised task lighting would be best suited with circadian rhythm facilities. A total of 40% of participants suggested that HCL facilities integrated within their permanent system are preferred, whether that was spotlights or pendant lighting. A minority suggested bulkhead lighting or no further lighting.

Kwon et al. [32] conclude the current limitations around HCL lighting control and hardware from the perspective of capital cost to the end user. When considering the cost of cabling, framework, labour of installation, etc., it is considered unlikely at this specific time that manufacturers can produce domestic HCL systems within the price point identified by participants. The technology at this time is not yet manufactured and installed in the quantity required to drive down the price per unit to match that of current customer expectations. Participants recorded that they would be willing to invest in the circadian system, although the literature produced by Kwon et al. [32] suggests that this price point is unrealistic based on the current capital cost of hardware and the misalignment of business models presented by stakeholders of the lighting market. There may be an opportunity to increase this price point if employers agree to contribute to the lighting improvements for the benefit of productivity, although the logistics of this are currently unknown.

Most WFH environments fell afoul of legislative requirements, where 56.6% of participants suggested that employers should financially contribute to enhancing lighting systems as part of workstation assessments for display screen equipment (DSE) [24]. It has already been discussed that the coverage around lighting with the existing HSG DSE assessment guidelines is limited, therefore the data of this study is an initial indication that further assessment into WFH lighting needs to be considered throughout the legislation.

Furthermore, sustainability is an integral design aspect considered by lighting manufacturers for reducing the impact of energy consumption through artificial lighting systems [17]. A total of 26.6% of participants would not tolerate any reduction in efficiency if HCL systems were domestically installed, despite the inherited benefits of circadian lighting. There were about 36.6% of participants that would consider up to 10% reduced efficiency and 23.3% of participants would accept 10–15% reduced efficiency in pursuit of the benefits previously listed. A total of 63.2% of participants would not utilise a circadian product if a drop in efficiency greater than 10% was present, although this is not expected due to LED technology. It can be seen in the respondents ranking that cost, efficiency, and installation impact resulted in priority scores of 62, 69, and 62, respectively. In addition, wellbeing presented as the clear priority lighting function with a score of 97, indicating that there is a real demand for enhanced HCL lighting systems within domestic environments.

5. Conclusions

This paper presents a study focused on the lighting conditions within the WFH environments in terms of safety and visual clarity looking at the following two objectives:

(1) To investigate the lighting conditions of a WFH environment;
(2) To investigate the social acceptance of HCL within the WFH environment.

Objective One was investigated through the quantitative data collection of lux levels within domestic WFH environments through the use of an IOS mobile application "light meter". A preliminary review showed that the application was able to record lux levels reasonably and accurately, ranging from 0.08 to 10.1% accuracy, determining that the collection method was sufficiently precise for this study. Lux levels were quantitatively recorded on the horizontal plane at 12 pm by 25 participants in different locations and on various days representing a variety of conditions. The results showed that compliance with general safety lighting requirements defined by the HSG 38 was achieved by 80% of the installations. As lux level requirements increased for tasks requiring more visual clarity, the majority of installations fell below the requirements, where only 2% of installations achieved compliance for technical drawing activities requiring 750 lux or greater. This concludes that the majority of installations were considered to be safe, however, most installations do not provide the visual clarity recommended by The Society of Light and Lighting for the most commonly performed activities within WFH environments. It was concluded that there is a generalised need to supplement lighting within most WFH environments to improve functionality. For accuracy and response rates, EML results were undertaken in a single domestic dwelling in two separate rooms. Following the guidance provided by the IWBI, it was seen that the angle of measurement relative to the light source as well as the glazing area were the two key factors contributing to a drop in EML within both rooms, where 34.3% of recorded EML dropped below the 200 EML requirement in Room 2, which housed a below-average glazing area. When isolated to artificial lighting, the highest recorded EML in Room 1 or 2 was 11.39 lux, just 7.5% of the 150 EML requirement. Therefore, it is concluded that smaller glazed rooms would benefit from an artificial circadian lighting system to maintain EML > 200 throughout the year, or EML > 150 where the majority of lighting is artificial.

Objective Two sought to understand whether there was social acceptance around improving WFH lighting systems through circadian lighting, considering key impacts of sustainability, practicality, and cost. A qualitative survey (including quantitative questions) initially investigated the role of each participant, and their opinions associated with their existing WFH environment. Subsequently, participants were asked about the implications of introducing circadian lighting systems, considering the type of system, the cost, sustainability impacts, and their lighting priorities. The results demonstrated responses from a large range of WFH applications including varying job roles, geographical locations, lighting types, and glazing areas. Participants reported working from home 3.9 days per week on average, where the general responses suggested that their existing lighting levels were sufficient for their job role, opposing the results recorded in Objective One. The conclusion of this objective is therefore that although participants generally find their current environment acceptable, there is a demand for manufacturers to provide a low-cost lighting system with circadian functionality to enhance wellbeing within domestic WFH environments, as participants have highlighted with relative confidence that lighting enhancements would be welcomed.

6. Limitations and Future Research

When exploring Objective One, it was found that a large proportion of WFH environments have glazing, where the weather condition influences the lux levels recorded to a considerable degree. Therefore, where non-compliances to commercial standards occur, this does not conclude that the environment is constantly non-compliant to commercial standards. User error cannot be defined in the data collection of Objective One, as it was unclear how accurately users were operating equipment to mitigate any shadowing effects. This was mitigated as much as possible through clear instructions.

Lux level mobile applications fluctuate in accuracy compared to calibrated lux meters due to correction and variations in the light processing software. The results of this study are to be used for generalisation only, and further investigation using calibrated light meters would be required before taking actions that may have financial implications for both employees and employers. Despite an early engagement and reminder communications, the response rate was relatively low and it is doubtful that any of the surveys in this study achieved saturation. A total of 25 participants responded with lux level readings, which were valid for this study, while a total of 30 responses were received from participants in Objective Two's survey. To increase the validity, a larger sample set should be pursued in a further study. In addition, time limitations associated with this study restricted further sampling to take place.

Due to the nature of the results recorded within this study, a selection of variables would affect the sensitivity of the results. A non-exhaustive list of those variables includes the bulb type and output, artificial light position, shadowing effects, reflectance of the environment, weather conditions, time of day, mobile device model and settings, user error, room air conditions, measurement positions, etc. Each variable's intensity, for each isolated user, will have an effect on the results, which is unquantifiable across the study. Therefore, a sensitivity analysis could not be accurately performed.

Based on the conclusions drawn in this study, these recommendations should direct future studies to further understand the need for additional lighting systems within WFH environments for staff working from home regularly. Whilst literature exists around the biological effects associated with light alterations, few studies exist where there is a combination of biological alterations (for example, hormone secretion and temperature fluctuations) and qualitative responses describing the feeling of circadian lighting systems. A study of this nature would bridge the gap between scientific knowledge and that of real-time participant reactions under circadian lighting. Further study around the isolated risks within WFH environments should be undertaken to determine a reasonable safety lux level requirement if existing commercial standards are not found to directly correlate.

As per the data found in Objective Two, it is recommended that manufacturers use this study as a baseline for understanding the customer demand for domestic circadian products, where a larger test group of WFH employees should be contacted in a similar study representing more of the public. It is also recommended that a range of industries participate in this study to further generalise the results. This way, a financial motive to create these products may be highlighted bringing more accessible products into the marketplace.

Author Contributions: Writing—original draft preparation, F.R.; methodology, F.R., M.W. and S.Y.; formal analysis, F.R.; data curation, F.R.; writing—review and editing, F.R., S.Y., M.W., S.M. and B.-J.H.; supervision, M.W. and S.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

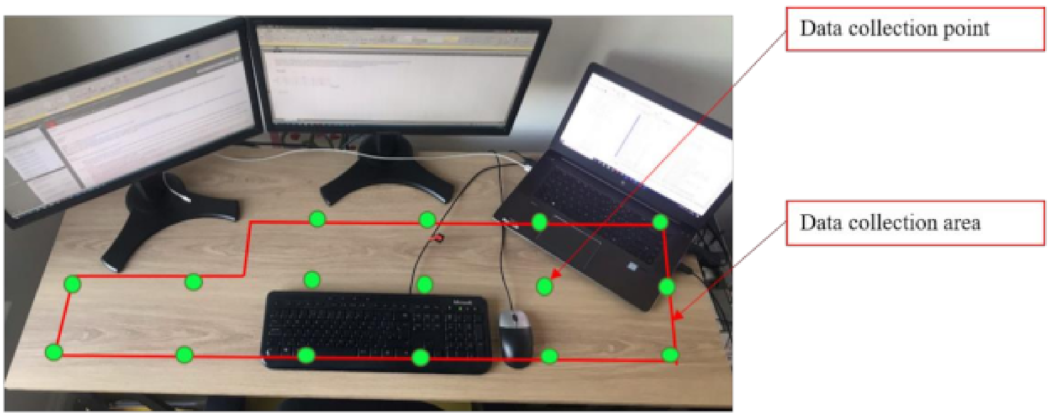
Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Lighting Data Collection

The instructions for data collection (for participants) are as follows:

(1) Data shall be collected in 0.2 m × 0.2 m grids. To standardise the readings, desks are assumed to be 1.2 m × 0.8 m, meaning there will be a maximum of 24 readings to note.
(2) If your desk is smaller than this, please only take the readings that fit on your desk size and leave the remaining boxes empty on the grid specified above.
(3) If your desk is bigger than this, please stick to the size defined above, making the 1.2 m × 0.8 m central on the desk.
(4) Where there is permanent equipment on your desk (for example, screens), please do not take readings under these as they will be producing shadows. Flat equipment such as keyboards are okay, and readings can be taken on top of them. This may mean you will record less than 24 data points, similar to the example below.
(5) There is no need to use a ruler to measure exactly 0.2 m grids, there will be negligible result changes by using approximations when measuring the readings.
(6) When taking measurements, please ensure your body is not causing any shadows over the device as this will reduce the light levels picked up and recorded.
(7) Pease take your readings at 12 pm (noon).



1.2 m

0.8 m						
			289	279	276	269
	310	305	295	285	279	275
	315	320	299	288	283	279

Left empty due to screens

Appendix B. Survey Analysis for Objective Two

Question: Post-COVID-19 caused a transition to working from home more often, how many days per week on average do you work from home?				
Responses:				
2 Days/Week	3 Days/Week	4 Days/Week	5 Days/Week	Weighted Mean
4 Participants (13.3%)	4 Participants (13.3%)	9 Participants (30%)	13 Participants (43.3%)	3.9 Days/Week
Question: What type of work do you perform when working at home? Please select multiple if necessary.				
Responses:				
Computer-based writing, typing, reading, data processing	Technical drawing (paper/by hand)	Computer-based CAD/BIM works	Online conference calls (Teams, Skype, etc.)	Admin work (either on computer or without)
29 Participants (96.7%)	7 Participants (23.3%)	17 Participants (56.6%)	29 Participants (96.7%)	11 Participants (36.6%)
Related Commercial Lux Levels, The Society of Light and Lighting [21]				
500 lux0.6 U_o	750 lux0.7 U_o	500 lux0.6 U_o	500 lux0.6 U_o	300 lux0.4 U_o
Question: Do you feel the lighting in your work-from-home working space is adequate for performing your current job role?				
Survey	Responses	Weighted Response (x_i)	Descriptive Analysis	
1–3	0 (0%)	N/A	Mean	7.433333333
4	1 (3.2%)	$1 \times 4 = 4$	Standard Error	0.305818417
5	3 (9.6%)	$3 \times 5 = 15$	Median	7.5
6	5 (16.1%)	$5 \times 6 = 30$	Mode	8
7	6 (19.4%)	$6 \times 7 = 42$	Standard Deviation	1.675036455
8	8 (25.8%)	$8 \times 8 = 64$	Sample Variance	2.805747126
9	2 (6.5%)	$2 \times 9 = 18$		
10	5 (16.1%)	$5 \times 10 = 50$		
Question: Does your work-from-home environment have a window allowing daylight? If you have more than one window, please specify how many and their area in the "other" selection.				
Survey	Responses	Weighted Response (x_i)	Descriptive Analysis	
No	1 (3.3%)	0 m^2	Mean	1.806034483
Yes (0.5–0.75 m^2)	1 (3.3%)	$1 \times 0.625 = 0.625$ m^2	Standard Error	0.342359548
Yes (0.75–1.0 m^2)	3 (10%)	$3 \times 0.875 = 2.625$ m^2	Median	1.375
Yes (1.0–1.25 m^2)	4 (13.3%)	$4 \times 1.125 = 4.5$ m^2	Mode	2
Yes (1.25–1.5 m^2)	6 (20%)	$6 \times 1.375 = 8.25$ m^2	Standard Deviation	
Yes (1.5–1.75 m^2)	1 (3.3%)	$1 \times 1.625 = 1.625$ m^2		
Yes (1.75–2.0 m^2)	2 (6.7%)	$2 \times 1.875 = 3.75$ m^2		
Yes (>2 m^2)	10 (33.3%)	$10 \times 2.0 = 20$ m^2		

"Other" 3 Windows	1 (3.3%)	Size unknown from response—dismissed from data.		
"Other" 11 m^2	1 (3.3%)	$1 \times 11 = 11\ m^1$		
Question: What direction is your workspace window facing? If you have more than one window, please specify how many and their direction in the "other" selection.				
Survey				Responses
North				5 (16.7%)
Northeast				6 (20%)
East				3 (10%)
Southeast				2 (6.7%)
South				4 (13.3%)
Southwest				1 (3.3%)
West				3 (10%)
Northwest				5 (16.7%)
"Other" three windows North, South, and West				1 (3.3%)
"Other" one South, one West				1 (3.3%)
No, window shutters kept closed for security obscuration. Room shared as a music studio facing road/public footpath				1 (3.3%)
Question: Would you be open to having human-centric lighting installed within your work-from-home environment to benefit from improved wellbeing, productivity, performance, and long-term health?				
Survey	Responses	Weighted response (x_i)	Descriptive Analysis	
1	2 (6.6%)	$2 \times 1 = 2$	Mean	7.366666667
2	0 (0%)	N/A	Standard Error	0.451009935
3	1 (3.3%)	$1 \times 3 = 3$	Median	8
4	0 (0%)	N/A	Mode	8
5	3 (9.6%)	$3 \times 5 = 15$	Standard Deviation	2.470283152
6	1 (3.3%)	$1 \times 6 = 6$		
7	5 (16.1%)	$5 \times 7 = 35$		
8	9 (30%)	$9 \times 8 = 64$		
9	2 (6.6%)	$2 \times 9 = 18$		
10	7 (23.3%)	$7 \times 10 = 70$		
Question: If you were to have human-centric lighting installed within your home to improve working conditions and bring your home environment up to commercial lighting conditions, what method of lighting system would you prefer?				
Responses:				
Task lighting (desk lamp)	Task lighting (floor lamp)	Permanent lighting, e.g., ceiling recessed luminaires	Bulkhead lighting on internal walls	No further lighting
15 Participants (50%)	9 Participants (30.0%)	12 Participants (40.0%)	1 Participant (3.3%)	2 Participants (6.6%)

Question: If your existing domestic work from home environment was proved insufficient for your current job role, that is, it did not meet minimum regulatory requirements, would you expect your employer to fund a method of lighting to meet those requirements? Please state any opinions on this matter in the "other" selection if necessary.					
Survey					Responses
Agree					17 (56.6%)
Disagree					9 (30%)
Other "As I work as a Contractor, I would be expected to create my own suitable working environment". "Depends. If you have no other choice but to work from home, then yes I think the employer should pay. However, if you have the opportunity to work from office then there should only be a certain amount an employer can contribute to your costs." "Don't Know"					3 (10%)
Question: Please list which of the following lighting factors are most important to you from top (most important) to bottom (least important). (1) Wellbeing and productivity enhancement; (2) minimising the cost of installation; (3) maximising energy efficiency of the installation; and (4) minimising the impact on your home (installation works) via improving your lighting conditions.					
Responses	Rank 1 (4 Points)	Rank 2 (3 Points)	Rank 3 (2 Points)	Rank 4 (1 Points)	Total weighted result
(1) Wellbeing and productivity enhancement	22	0	2	5	97
(2) Minimising the cost of installation	2	8	11	8	62
(3) Maximising energy efficiency of the installation	3	11	9	6	69
(4) Minimising the impact on your home (installation works) via improving your lighting conditions	2	10	7	10	62
Question: If the human-centric lighting system proposed was less energy efficient than your existing lighting configuration, please indicate what level of reduced energy efficiency you would tolerate to improve your wellbeing, productivity, performance, and long-term health through a human-centric lighting installation.					
Survey					Responses
I would not tolerate any reduced efficiency					8 (26.6%)
0–5%					6 (20%)
5–10%					5 (16.6%)
10–15%					7 (23.3%)
15–20%					3 (10%)
Other "I would say that given the lighting would only impact 1 room in the house, 8 h a day, 5 days a week a greater inefficiency value may be acceptable (35%?) if a real positive benefit was realised"					1 (3.3%)

Appendix C. Thematic Analysis

Question: Please describe your work from home lighting conditions. For example, do you have LED lighting? Is your room lighting recessed in the ceiling or do you use a lamp? Does your ceiling lamp have a shade installed or are they spotlights? Do you have warm lighting (yellow colour, approx. 3000 K) or cool lighting (white/blue colour, approx. 5000 K). How does it compare with your usual office lighting conditions?		
Theme identification	Theme occurrence rate	Theme generalisation
Q6T1	3 (10%)	10% of participants have discussed the use of energy saving lightbulbs within their existing lighting setup.
Q6T2	7 (23.3%)	23.3% of participants have discussed having cool/white lighting primarily within their existing lighting setup.
Q6T3	16 (53.3%)	53.3% of participants have discussed pedant lighting as their primary light source.
Q6T4	14 (46.6%)	46.6% of participants have discussed using desk lamps for additional lighting.
Q6T5	6 (20%)	20% of participants have discussed having natural light as their primary light source.
Q6T6	1 (3%)	3% of participants have discussed using shutters/shading devices.
Q6T7	14 (46.6%)	46.6% of participants have discussed having warm lighting primarily within their existing lighting setup.
Q6T8	10 (33.3%)	33.3% of participants have suggested office lighting is brighter and more intense than their work-from-home conditions.
Q6T9	4 (13.3%)	13.3% of participants have discussed having recessed spotlights as their primary light source.
Q6T10	1 (3%)	3% of participants have noted that their work-from-home environment presents more shadowing than an office environment.
Q6T11	2 (6%)	6% of participants have already got lighting which allows customisation of colour temperature.
Q6T12	1 (3%)	3% of participants have discussed that office lighting is uncomfortable.
Q6T13	3 (10%)	10% of participants have stated they use halogen bulbs as their primary light source.
Q6T14	18 (60%)	60% of participants have stated they use LED bulbs as their primary light source.
Question: Have you noticed any change in your health since working from home more regularly which you think you can attribute to the lighting of your environment? For example, headaches, eye strain, etc.		
Theme Identification	Theme Occurrence Rate	Theme Generalisation
Q7T1	1 (3%)	10% of participants have reported tiredness in a poorly lit room (assumed to be their home environment).
Q7T2	11 (36.6%)	36.6% of participants have reported additional eye strain when working from home.

Q7T3	2 (6%)	6% of participants have reported noticeable headaches when working from home.
Q7T5	11 (36.6%)	36.6% of participants reported no noticeable change in health that they can associate with the lighting.
Q7T6	2 (6%)	6% of participants have reported a reduction in eye strain when working at home.
Q7T7	1 (3%)	3% of participants have reported additional tiredness when working from home.
Q7T8	1 (3%)	3% of participants have reported additional migraines when working from home.

Detailed Thematic Analysis	
Response	Theme and Code (QXTX defines the question and analysis theme number)
Central hanging standard white energy saving lightbulb within lampshade supported by a small desk lamp adjacent, again with a standard white energy saving lightbulb/lampshade. As I'm primarily working on screen and have the window wooden shutters closed for security reasons, I rarely use supporting artificial lighting unless I need them on for Teams Video calls (laptop camera struggles with poorly lit locations).	Q6T1: Energy saving lightbulb Q6T2: White light Q6T3: Single light bulb and lampshade Q6T4: Desk lamp Q6T5: Natural light Q6T6: Wooden Shutters Q6T14: LED
Standard singular bulb (not LED) with shade, warm lighting, it provides enough lighting as the room is only 3 × 2.5 m. In comparison the office lighting is LED lights, they are large ceiling spotlights that provide much more lighting than home working and are more of a cool white lighting.	Q6T7: Warm Light Q6T3: Standard singular bulb with shade Q6T8: Office provides more lighting than home working and cool white lighting
I have LED, cool lighting. The room lighting is recessed in the ceiling. Lighting at home is less intense than in the office.	Q6T2: LED Cool lighting. Q6T9: Lighting is recessed in the ceiling Q6T8: Home lighting is less intensive than in the office Q6T14: LED
4000 K LED pedant lighting, 4000 K LED desk lamp and undershelf LED tape lighting. Pendant lighting has a shade but has been removed (see below). I have considered human centric enabled LED tape controlled via an app but didn't complete the purchase, will consider further going forward.	Q6T2: 4000K LED pendant lighting Q6T4: 4000K LED desk lamp and Q6T14: LED
Ceiling light with shade	Q6T3: Ceiling light with shade
Warm ceiling lighting (yellow colour) central to room. Creates some shadowing to desk, in comparison to office lighting conditions	Q6T3: warm ceiling lighting Q6T7: warm lighting Q6T10: more shadowing compared to office
I have light coming from a ceiling light. It is a cool white light covered by shade. I also have light coming from the window throughout the day. Although my lighting from home is good, I'd say there's something about the office that feels better	Q6T3: I have light coming from a ceiling light Q6T5: Natural Light Q6T8: Something about the office that feels better
LED lamp positioned behind the two monitors to light the wall behind them (and my face for calls)—doesn't shine directly on my face. This is cool lighting.Behind me I have a pendant light (warm lighting) with a shade that directs most of the light down/up.Office lights are generally cool lighting from recessed tubes.	Q6T4: LED lamp Q6T2: Cool lighting Q6T3: Behind me I have a pendant light with shade Q6T7: warm lighting Q6T8: Office lights are generally cool lighting Q6T14: LED

Ceiling lamp with shade, yellow colour	Q6T3: Ceiling lamp with shade, yellow colour Q6T7: warm lighting
LED light suspended from the ceiling with a lamp shade.Warm lighting (approx. 3000 K). This lighting is very different from my office lighting conditions where there is a large amount of natural light (ceiling to floor windows) and where the artificial light is approx. 5000 K (unlike the warm lighting in my office room).	Q6T3: LED light suspended from the ceiling with a lamp shade. Q6T7: warm lighting Q6T14: LED
ceiling light and desk light. white lights	Q6T3: ceiling light Q6T4: Desk light Q6T2: white lights
LED lighting in living room with 4000 k lights,	Q6T2: LED lighting in living room with 4000 k lights Q6T14: LED
4no. recessed LED GU10 downlighters in ceiling.1no. bedside lamp on the desk, with a LED golf ball bulb	Q6T9: 4no. recessed LED GU10 downlighters in ceiling. Q6T4: Desk light Q6T14: LED
natural lightangle poise lamp above desk when it's dark	Q6T5: Natural light Q6T4: angle poise lamp above desk
Single pendant in ceiling, with bare bulb (we're in the process of renovating). Bulb is halogen, warm light.Desktop lamp on desk, with LED lights.	Q6T3: Single pendant in ceiling Q6T7: warm lighting Q6T4: Desktop lamp on desk, with LED lights. Q6T13: halogen bulbs Q6T14: LED
I have a LED light that is capable of changing colour temperatures. There are 3 settings that allow me to switch between 2700 K, 4000 K and 5000 K. This allows me to adjust the colour temperature to suit the conditions and to reduce eye strain and tiredness. The office is well lit however, at times the light can be uncomfortable. I like the option of being ab le to adjust the temperature.	Q6T4: LED desk light Q6T11: LED light that is capable of changing colour Q6 temperatures Q6T12: at times the office light can be uncomfortable. Q6T14: LED
Low level desk lamp with LED bulb, warm light. This is less than normal office lighting conditions.	Q6T4: level desk lamp with LED bulb Q6T7: warm lighting Q6T8: This is less than normal office lighting conditions. Q6T14: LED
I have 5 recessed lights in the ceiling which are a cool white LED estimated to be 5000 K. I have a large bar window which is south facing.	Q6T9: 5 recessed lights in the ceiling Q6T2: Cool lighting Q6T5: Natural light Q6T14: LED
Pendant light fitting with lamp shade and 5 watt LED warm light lamp. Comparison to office is that home lighting is not as intense.	Q6T3: Single pendant in ceiling Q6T7: warm lighting Q6T8: Comparison to office is that home lighting is not as intense. Q6T14: LED
I have a lamp that sits on a chest of drawers slightly behind my main monitor—warm lighting.	Q6T4: a lamp that sits on a chest of drawers Q6T7: warm lighting

2 Ceiling lamps with shades energy saving bulbs	Q6T1: Energy saving lightbulb Q6T3: Single light bulb and lampshade
I have a ceiling light with five warm coloured halogen bulbs, used this is used only very rarely. I typically use a lamp with a white paper shade over the bulb that sits next to me on my desk. The bulb is LED but is yellow to mimic a halogen bulb. Typically, don't have any lights on in the day until approx. 3 pm when it starts getting darker in the room, at which point I turn the desk lamp on until I finish between around 4 pm and 6 pm.	Q6T13: halogen bulbs Q6T4: LED lamp with a white paper shade Q6T7: warm lighting Q6T5: do not have any lights on in the day Q6T14: LED
Ceiling lighting, 2 X GU10 Halogen lightbulbs, warm (yellow lighting).Slightly darker than the office lighting (Meridian House, York, 2nd floor).	Q6T13: halogen bulbs Q6T7: warm lighting Q6T8: Slightly darker than the office lighting
I sit beside the window which varies (based on winter) from providing glare first thing in the morning, to good amount of light to being too dark in the afternoon. I also use ceiling mounted low voltage energy saving lights with light shades. It is not as bright as office, and it is not as consistent through the days as office.	Q6T1: Energy saving lightbulb Q6T3: ceiling mounted low voltage energy saving lights Q6T8: not as bright as office and it is not as consistent through the days as office.
Standard Light fitting in room with desk light to supplement that has multiple settings for different light temperatures	Q6T3: ceiling mounted low voltage energy saving lights Q6T4: desk light to supplement Q6T11: multiple settings for different light temperatures
Daylight for most of the day, then either led small lamp or fluorescent strip light if working at night.	Q6T5: daylight for most of the day Q6T4: led small lamp Q6T14: LED
Just room lighting 5 bulbs in a centre pendant. warm white LED Bulbs. Not as harsh.	Q6T3: room lighting 5 bulbs in a centre pendant Q6T7: warm white LED Bulbs. Q6T8: not as bright as office and it is not as consistent through the days as office. Q6T14: LED
I have Warm LED Lighting	Q6T7: I have Warm LED Lighting Q6T14: LED
2 LED table lamps and one pendant LED, all with shades. All warm lighting. Less light than office.	Q6T4: 2 LED table lamps Q6T3: one pendant LED, all with shades Q6T7: All warm lighting Q6T8: Less light than office. Q6T14: LED
3 No. LED spotlights	Q6T9: 4no. recessed LED GU10 downlighters in ceiling. Q6T14: LED
Question: Have you noticed any change in your health since working from home more regularly which you think you can attribute to the lighting of your environment? For example, headaches, eye strain, etc.	
Survey	Responses
Can be mentally tiring and a strain on the eyes working all day on a laptop/monitor in a poorly lit room.	Q7T1: mentally tiring in a poorly lit room. Q7T2: strain on the eyes in a poorly lit room.
Definitely headaches and eye strain.	Q7T3: Headaches Q7T2: Eye strain

Yes, as the lighting is less intense it's helped me to spend more continuous hrs working and be more productive	Omitted as this does not answer the question.
Yes—eye strain in particular that prompted me to purchase a supplementary desk lamp and also remove the shade on my pendant light to increase lux levels in room.	Q7T2: Eye strain
I think my eyesight is worse	Q7T2: Eyesight is worse
eye strain increased very slightly	Q7T2: eye strain increased
no	Q7T5: No
No, main problem previously was the distance of monitors from my eyes—I have a comfortable position both at home and at work (usually).	Q7T5: No
No, I have not noticed any change in health which I think I can attribute to lighting	Q7T5: No
I sometimes suffer from headaches, but this could be caused by other factors as well as my lighting conditions.	Q7T3: Headaches
Strain has reduced as I have larger monitors at home than office	Q7T6: Eye strain reduction
No	Q7T5: No
No	Q7T5: No
probably healthier because I take breaks to go outside	Omitted as this does not answer the question.
No. General health has probably improved, but nothing relating to headaches or eye strain.	Q7T5: No
Prolonged usage of the lights, for example on a cloudy or rainy day and glare from the monitors can at times cause eye strain or tiredness.	Q7T2: eye strain Q7T7: tiredness
No	Q7T5: No
No negative effects on health. In fact, the complete opposite, I have been more active since working from home due to having additional time which would have been used to commute to work.	Omitted as this does not answer the question.
Less eye strain and headaches as office lighting is constantly the same level of brightness throughout the day. At home the light can be switched off, whereas in an open plan office it cannot, therefore, on days with very bright daylight the additional office lighting is probably higher than the recommended office lighting lux levels. Open plan offices with large window area should include a zonal control system to compensate for natural daylighting effect.	Q7T6: Eye strain reduction
Slight eyestrain	Q7T2: eye strain
Maybe eyestrain some of the time in an evening	Q7T2: eye strain
Since getting a new laptop from work that has the night light setting disabled (no idea why) I get noticeable eye strain when looking at the screen in the evening, especially if I use my own PC for a while (which has a night light setting on) then switch back to the laptop. Similarly, my eyes can be strained from using the screens in work if I don't change the brightness setting on them when I start the day.	Q7T2: eye strain
More migraines (unsure if this is related to lighting or something else though).	Q7T8: migraines
No	Q7T5: No
Eye strain when working from home is an issue. I try to follow the 20/20/20 rule but working from home this slips.	Q7T2: eye strain
Before I put up a glare shade, I was finding I didn't move around too much and would suffer from a sore shoulder. By putting a moveable blind in place so I can adjust through the day, it's now fine.	Omitted as this does not answer the question.
No	Q7T5: No
No	Q7T5: No
Eye strain on dark evenings	Q7T2: eye strain
No	Q7T5: No

References

1. Basalla, G. *The Evolution of Technology*; Cambridge University Press: Cambridge, UK, 1988.
2. Ghosh, A.; Kundu, P.K.; Sarkar, G. Internet of human centric lighting: A brief overview on Indian aspects. *Sci. Cult. J.* **2020**, *86*, 350–356. [CrossRef]
3. Reddy, S.; Reddy, V.; Sharma, S. *Physiology, Circadian Rhythm*; StatPearls Publishing: Treasure Island, FL, USA, 2018.
4. Walerczyk, S.; Hclpc, C.; Wizards, L.L. Human centric lighting. *Archit. SSl* **2012**, *23*, 20–22.
5. Roberts, F.; Yang, S.; Du, H.; Yang, R. Effect of semi-transparent a-Si PV glazing within double-skin façades on visual and energy performances under the UK climate condition. *Renew. Energy* **2023**, *207*, 601–610. [CrossRef]
6. Bedrosian, T.A.; Nelson, R.J. Timing of light exposure affects mood and brain circuits. *Transl. Psychiatry* **2017**, *7*, e1017. [CrossRef]
7. Borbély, Á.; Sámson, Á.; Schanda, J. The concept of correlated colour temperature revisited. *Color Res. Appl.* **2001**, *26*, 450–457. [CrossRef]
8. Cupkova, D.; Kajati, E.; Mocnej, J.; Papcun, P.; Koziorek, J.; Zolotova, I. Intelligent human-centric lighting for mental wellbeing improvement. *Int. J. Distrib. Sens. Netw.* **2019**, *15*, 450–457. [CrossRef]
9. Houser, K.W. Human Centric Lighting and Semantic Drift. *Leukos* **2018**, *14*, 213–214. [CrossRef]
10. Gilman, J.M.; Miller, M.E. 41.4: Daylight Matching with Blended-CCT LED Lamp. *SID Symp. Dig. Tech. Pap.* **2012**, *43*, 565–568. [CrossRef]
11. Kralikova, R. Influence of Lighting Quality on Productivity and Human Health. *J. Environ. Prot. Saf. Educ. Manag.* **2015**, *3*, 42–48.
12. Mathew, V.; Kurian, C.P. A Framework for the Selection of Tunable LED Luminaire for Human Centric Lighting Design. In Proceedings of the 2020 International Conference on Smart Technologies in Computing, Electrical and Electronics (ICSTCEE), Bengaluru, India, 9–10 October 2020; pp. 95–100.
13. Houser, K.W.; Esposito, T. Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process. *Front. Neurol.* **2021**, *12*, 630553. [CrossRef]
14. Houser, K.; Boyce, P.; Zeitzer, J.; Herf, M. Human-centric lighting: Myth, magic or metaphor? *Light. Res. Technol.* **2021**, *53*, 97–118. [CrossRef]
15. Schlangen, L.J.; Price, L.L. The lighting environment, its metrology, and non-visual responses. *Front. Neurol.* **2021**, *12*, 624861. [CrossRef]
16. Joblove, G.H. A Tutorial on Photometric Dimensions and Units. *SMPTE Motion Imaging J.* **2015**, *124*, 48–55. [CrossRef]
17. Figueiro, M.G. An overview of the effects of light on human circadian rhythms: Implications for new light sources and lighting systems design. *J. Light Vis. Environ.* **2013**, *37*, 51–61. [CrossRef]
18. Kwee, R.M.; Kwee, T.C. A New Working Paradigm for Radiologists in the Post-COVID-19 World. *J. Am. Coll. Radiol.* **2022**, *19*, 324–326. [CrossRef]
19. Gartner. Shift Some Employees to Remote Work Permanently. Available online: https://www.gartner.com/en/newsroom/press-releases/2020-04-03-gartner-cfo-surey-reveals-74-percent-of-organizations-to-shift-some-employees-to-remote-work-permanently2 (accessed on 9 October 2022).
20. Ticleanu, C. Impacts of home lighting on human health. *Light. Res. Technol.* **2021**, *53*, 453–475. [CrossRef]
21. The Society of Light and Lighting. *The SLL Code for Lighting*; Chartered Institution of Building Services Engineers: London, UK, 2012.
22. Sutanapong, C.; Louangrath, P. Descriptive and inferential statistics. *Int. J. Res. Methodol. Soc. Sci.* **2015**, *1*, 22–35.
23. Ipsen, C.; van Veldhoven, M.; Kirchner, K.; Hansen, J.P. Six Key Advantages and Disadvantages of Working from Home in Europe during COVID-19. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1826. [CrossRef]
24. Health and Safety Executive. *Lighting at Work*; The Office of Public Sector Information: Surrey, UK, 1997.
25. International Well Building Institute. Circadian Lighting Design. Available online: https://standard.wellcertified.com/light/circadian-lighting-design (accessed on 10 March 2023).
26. Emco Kimo. LX 50 Luxmeter. Available online: https://www.kimoinstruments.com/detail/lx-50-luxmeter (accessed on 10 March 2023).
27. Donson, J. Don't 'Phone It In': Why Smartphones are Poor Substitutes for Light Meters. Available online: https://kw-engineering.com/dont-phone-smartphones-poor-substitutes-light-meters/ (accessed on 3 February 2023).
28. Golafshani, N. Understanding reliability and validity in qualitative research. *Qual. Rep.* **2003**, *8*, 597–607. [CrossRef]
29. Wright, K.B. Researching Internet-based populations: Advantages and disadvantages of online survey research, online questionnaire authoring software packages, and web survey services. *J. Comput.-Mediat. Commun.* **2005**, *10*, JCMC1034. [CrossRef]
30. Willig, C.; Rogers, W.S. *The SAGE Handbook of Qualitative Research in Psychology*; SAGE: Thousand Oaks, CA, USA, 2017.
31. *BS EN 12464-1*; Light and Lighting. Lighting of Work Places—Indoor Work Places. British Standards Institution: London, UK, 2021.
32. Kwon, H.-I.; Baek, B.-H.; Jeon, Y.-S. A Study of the Business Model Development of Human Centric Lighting: Based on Eco-Science Methodology. *Energies* **2021**, *14*, 4868. [CrossRef]