Mitigating Light Pollution: LED street lighting and public demonstration

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Light pollution is a worsening environmental issue with wide-ranging effects on human health, animal habitat, and observational power. Methods to reduce skyglow caused by widely used LED street lighting are investigated. Optimal LED parameters to reduce skyglow are found based on illuminance: warm white or orange light and a large hood covering ~80% of the source. With LED sources, a public demonstration of light pollution on a projected dark sky image was conducted, with 89% of participants finding it effective and engaging. It is recommended for future studies to conduct larger-scale investigations for the same parameters, finding ways to implement light pollution reduction measures in street lighting. Use of similar public demonstration methods is suggested to supplement educational material and awareness-raising.

Introduction and Background

Since the Industrial Revolution, the natural rhythm of day and night has been insufficient for human activity, with 10% annual global increase observed in artificial light in recent years [2, 8]. According to the World Atlas of Light Pollution, skies above the largest UK cities have estimated Light Pollution Index values up to 46.77 [4] meaning they are almost 50 times brighter than an unpolluted dark sky. While LED street lighting in the UK is energy efficient, it contributes large amounts of ALAN (Artificial Light At Night), which disrupts human circadian rhythms and animal habitats [8]. Astronomical observatories, situated far from urban areas to avoid contaminated skies, now cannot escape them [2].

While number of scientific publications referring to light pollution is increasing [6], decisions regarding mitigation do not lie in the hands of researchers. Differences in perspective mean there is lack of holistic understanding causing stagnation instead of change [6]. Clanton [1] recommends employing the lowest illuminance possible and minimizing light dispersion horizontally or above light sources. Dispersion like this causes skyglow: light escaping upwards into the atmosphere, which results in increased night sky brightness when reflected by atmospheric particles [3].

The research is split into two parts. In Part 1, LED illuminance was measured to find an optimal model for street lighting which reduces light dispersion and skyglow, based on light color and shape of model hoods placed over the source. Illuminance is a photometric measure: it is adjusted for human vision. Human eye sensitivity peaks at 555nm; this curve (the spectral luminous efficiency function) is applied to radiometric measurements converting them into photometric [10].

Part 2 aims to develop an effective method for demonstrating light pollution to the public and raising awareness, as recommended in [8]. Studies like Lyytimäki's [5] indicate a high level of awareness and concern among educated groups interested in astronomy, but layman opinions are not addressed. The combination of quantitative and qualitative methods in this report aims to address the discrepancy between light pollution research and public awareness.

PART 1

Methodology

Equipment used:

- IS instruments miniature spectrometer MSP1000
- Precision Gold Light & Lux Meter N76CC sensor diameter 40mm
- Sylvania E27 LED Smart Lightbulb with SylSmart Home app
- QAZCA E27 lamp stand.

Experiment was set up as shown in Fig.1. Spectrometer fiber was placed adjacent to LED and digital markers used to locate peak wavelengths. The spectrum was recorded in a screen capture. LED color (white) and brightness were kept constant throughout. Illuminance measurements were taken at various distances, and heights parallel to and above source. Figs. 2-3 show the laboratory setup.

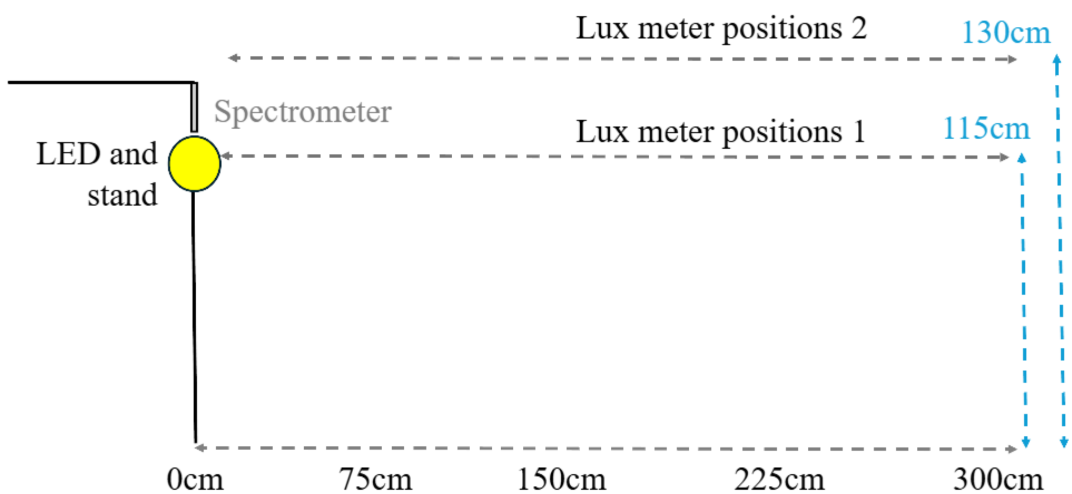

Fig.1 Experimental set-up.

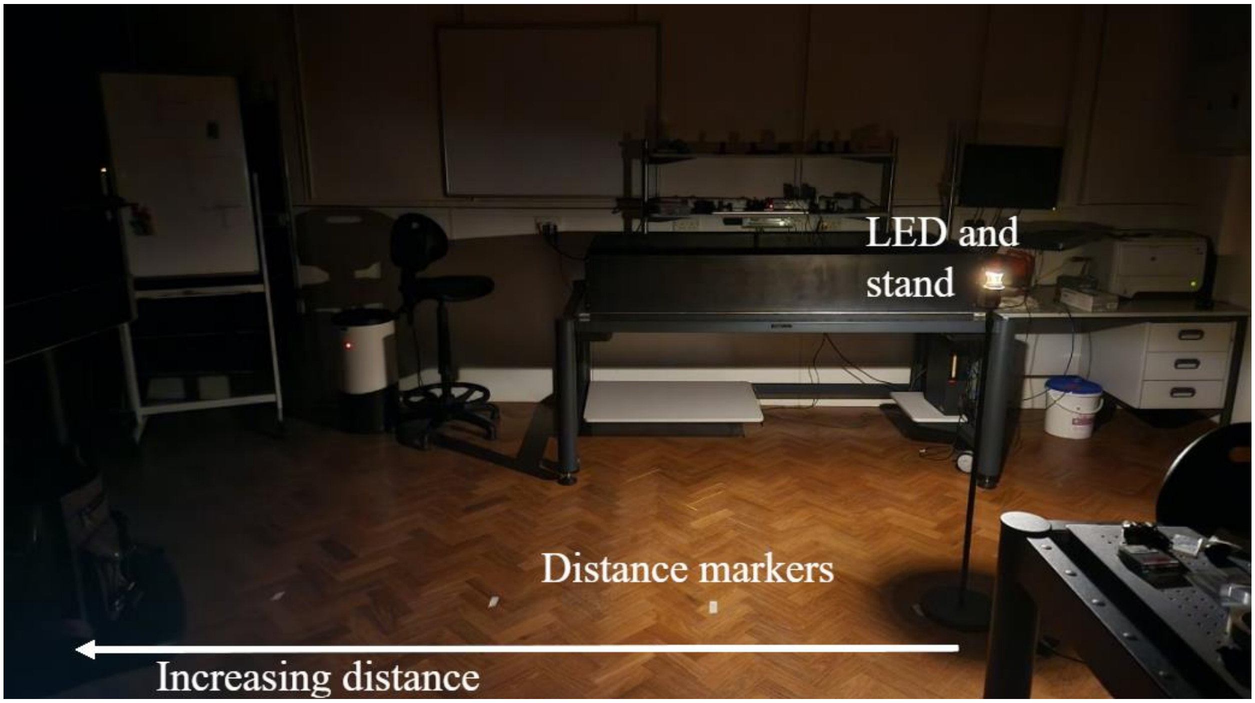

Fig.2: Laboratory set-up with LED stand placed at fixed position.

Fig.3: Photograph in well-lit conditions, showing lux meter position at 0cm.

Distance-dependent illuminance readings were taken with no hood, denoted as Hood 0 subsequently, then repeated with 8 black plastic hoods (Figs.4-5) placed over the source. Hood dimensions are detailed in Table 1.

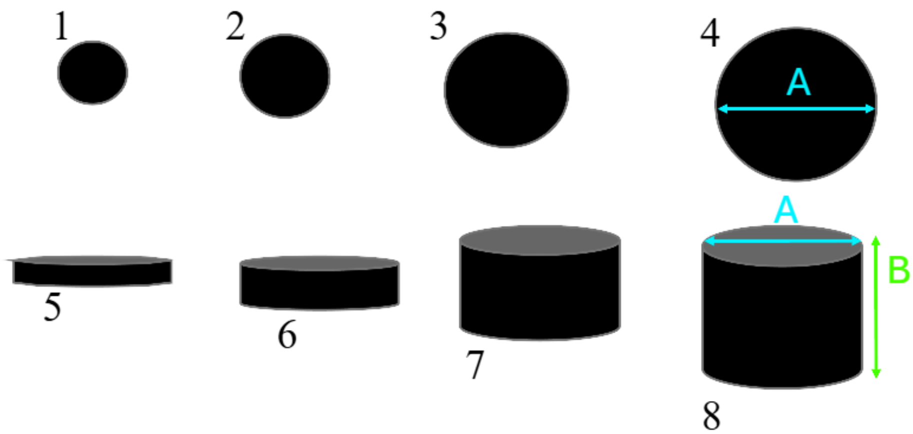

Fig.4: Hoods used to cover LED in Fig.1; diameter A and height B are varied.

Hood	A (mm)	B (mm)
1	30	See caption
2	40	See caption
3	50	See caption
4	62	See caption
5	62	10
6	62	20
7	62	40
8	62	50

Table 1: Hood measurements. A *denotes diameter,* B *denotes height of hoods 5-8; 1-4 are flat discs with no height measurement. Each has an error of 1mm.*

Fig.5: Hoods 1, 5, 8 covering source.

An inverse square model is used for data fitting with illuminance *I*, luminous flux *L*, distance *r* and background offset parameter *i,* with assumptions of a spherical wavefront and zero surface reflection [3, 7]:

$$I = \frac{L}{r^2} + i \tag{1}$$

For wavelength-dependent illuminance measurements, LED was switched on at constant maximum brightness. Illuminance readings were taken at fixed height 115cm and fixed distance 75cm. LED color changes of 8 white and 10 RGB shades were carried out using the Sylvania app. Spectra were recorded with spectrometer as previously; each was assigned a color name and number for ease of quoting results.

Results

For the fixed white spectrum, wavelength peaks are 610±10 nm and 456±10nm. Illuminance against distance was plotted on a logarithmic scale for better data visualization. An offset of 3cm was appended to each distance value to include LED bulb radius. The data were fitted to inverse-square model Eq.1.

At height 115cm (Fig.6), points corresponding to distance 0cm are omitted because the point-source assumption for the inverse-square law is invalid at small distances [10]. L, i, and reduced chi-squared values χ_ν are calculated as set out in the error appendix and recorded in Table 2.

Hood	L	i	χ_ν
0	$3.89 \times 10^5 \pm 1.54 \times 10^3$	2.92 ± 0.05	176
1	$3.68 \times 10^5 \pm 1.54 \times 10^3$	3.12 ± 0.05	73.8
2	$3.70 \times 10^5 \pm 1.54 \times 10^3$	2.88 ± 0.05	78.0
3	$3.55 \times 10^5 \pm 1.52 \times 10^3$	3.04 ± 0.05	217
4	$3.59 \times 10^5 \pm 1.52 \times 10^3$	2.70 ± 0.05	77.2
5	$3.54 \times 10^5 \pm 1.52 \times 10^3$	2.55 ± 0.05	152
6	$2.89 \times 10^5 \pm 4.60 \times 10^2$	1.91 ± 0.04	126
7	$1.08 \times 10^5 \pm 4.56 \times 10^2$	0.79 ± 0.04	9.54
8	$1.51 \times 10^4 \pm 3.40 \times 10^2$	0.91 ± 0.04	631

Table 2: Fit parameters and χ_ν values (see Eq.1 and Eq.4-5) for measurements at 115cm.

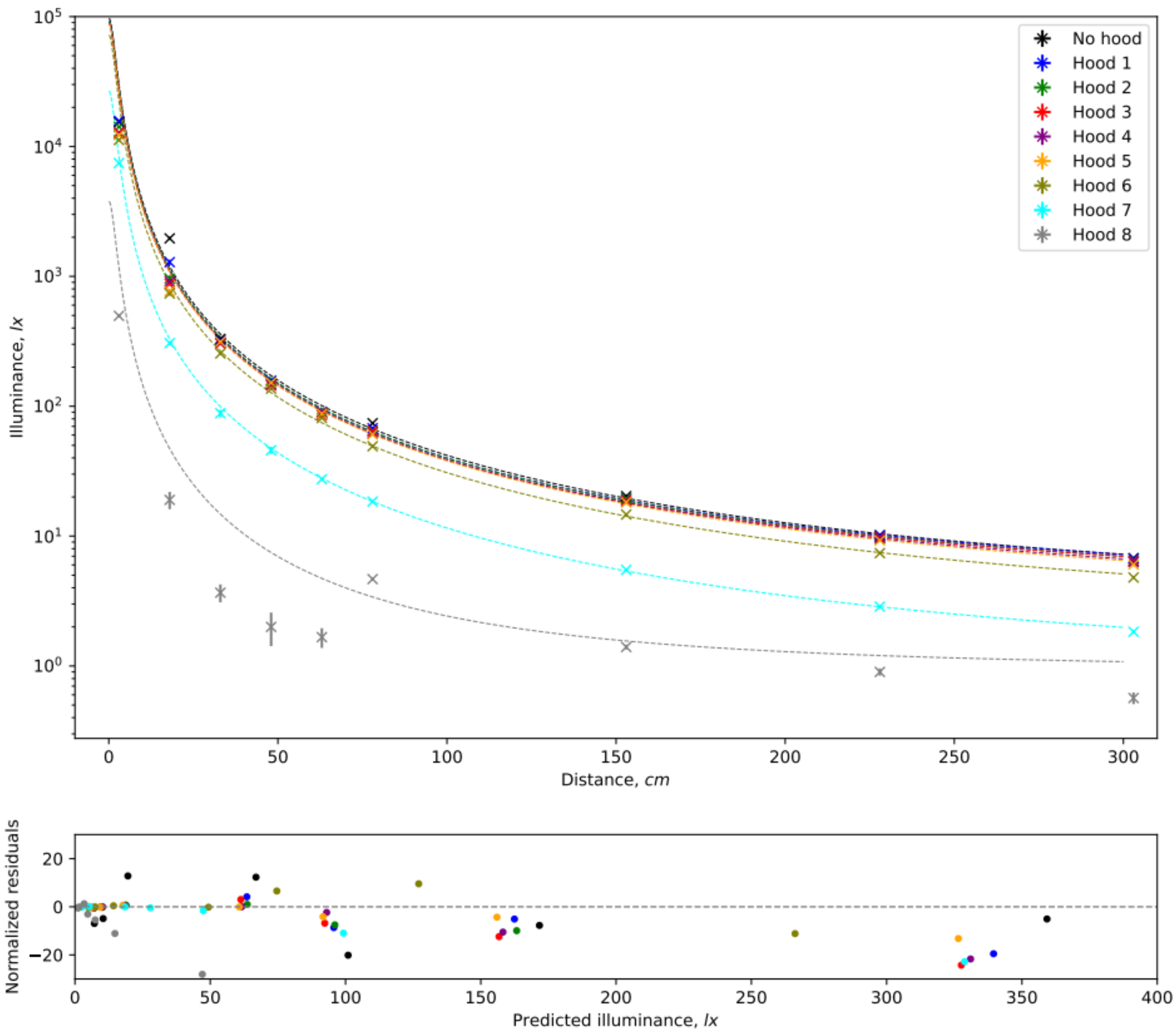

Fig.6: Illuminance against sensor-source distance plotted for height 115cm, for each hood. Majority of error bars are too small to be seen. Normalized residuals are plotted below.

At height 130cm (Fig.7), an identical fit was employed, except distance values below 75cm were deliberately excluded, enabling investigation of the hoods' effect on upward light dispersion. This is shown in points below 75cm deviating from the determined fit. Plotted sensor-source distances *D* are calculated using Eq.2, with horizontal distance *d* and sensor-source height difference *h*, 15cm:

$$D = \sqrt{d^2 + h^2} \tag{2}$$

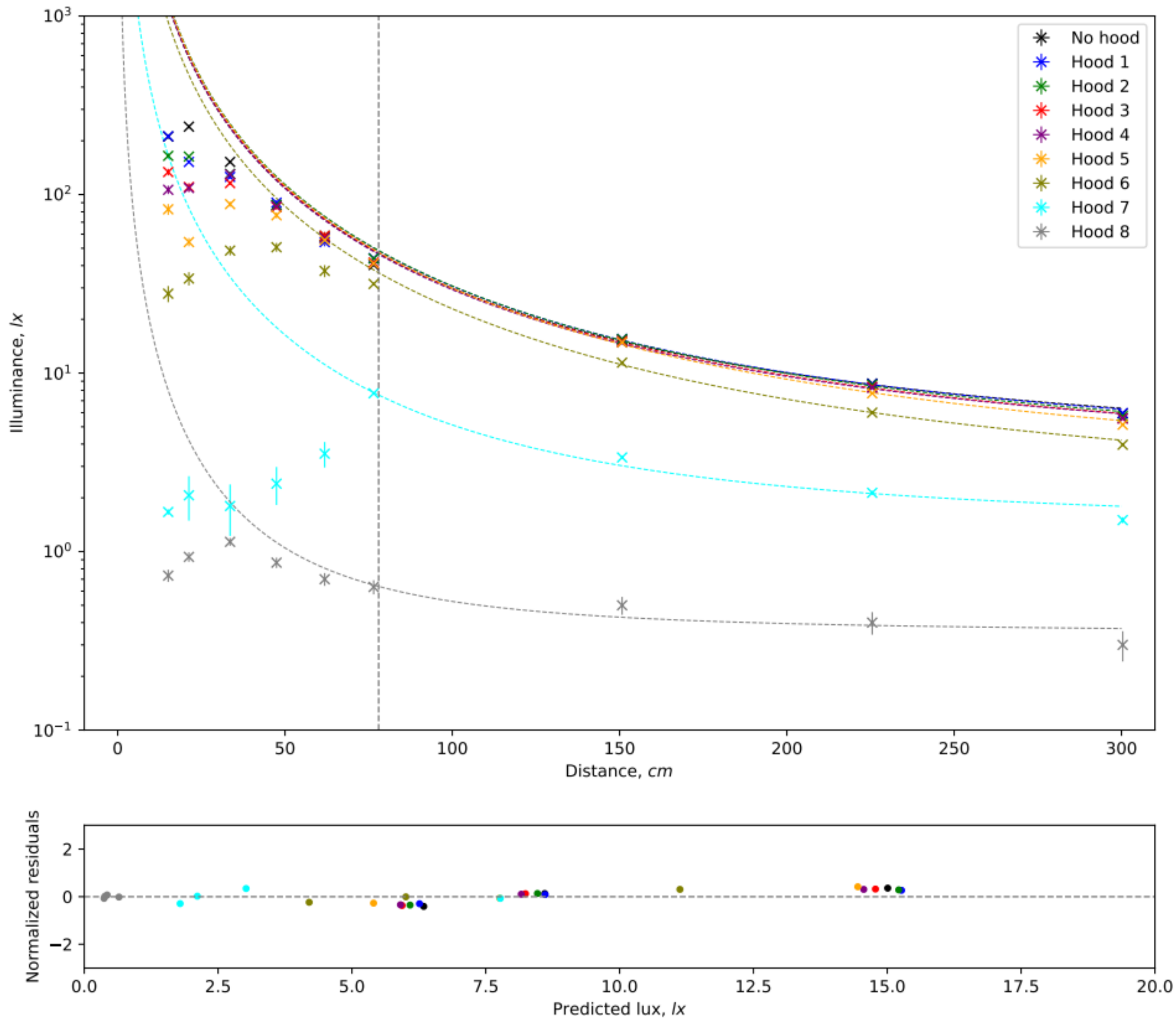

Fig.7: Illuminance plotted against source-sensor distance, height 130cm. All values left of the vertical dotted line are omitted from the fit. Majority of error bars are too small to be seen.

Spectral data is recorded in tables 3-4. The white light spectrum features a sharp peak in the blue area and a shallower peak in the red-green area due to LED composition [9]. An example is shown in Fig.8.

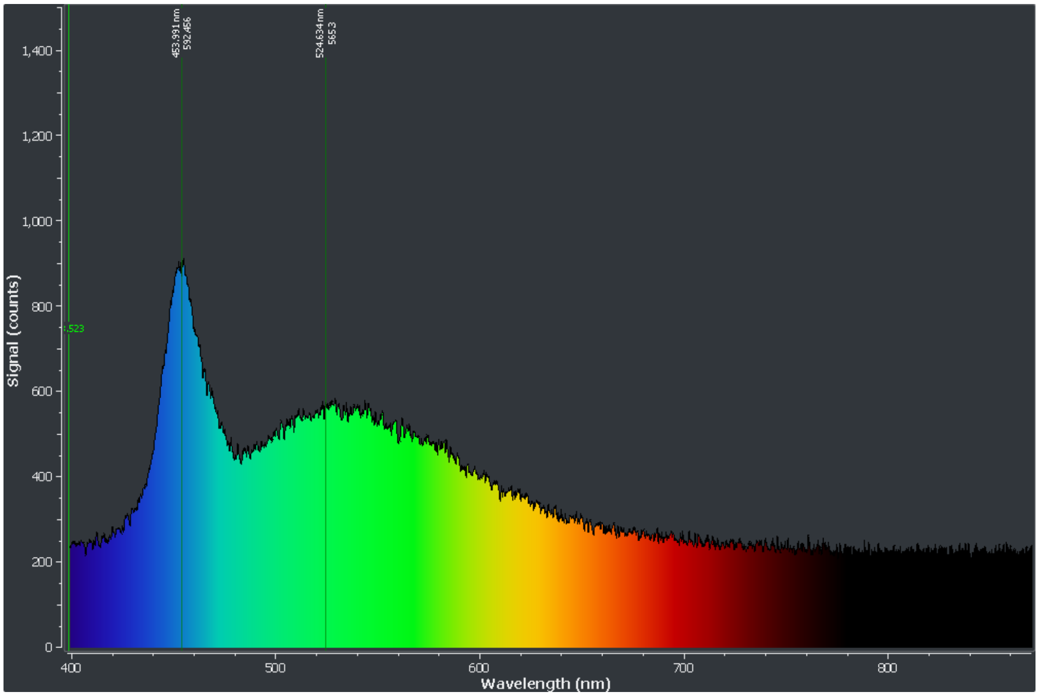

Fig.8: Blue-white spectrum featuring 2 peaks (see Table 3).

Color name	Number	Peak 1 (nm)	Peak 2 (nm)
Yellow-white	1	586 ± 10	456 ± 10
Warmest white	2	585 ± 10	455± 10
Warm white	3	581 ± 10	456 ± 10
Neutral white	4	579 ± 10	453 ± 10
Cool white	5	570 ± 10	454 ± 10
Coolest white	6	538 ± 10	451 ± 10
Blue-white	7	526 ± 10	454 ± 10
Pale blue	8	531 ± 10	453 ± 10

Table 3: Spectral data, white light, with ascribed number. Due to color composition of the LED two peaks are fitted.

Some RGB spectra showed 2 peaks due to some colors being composites of red, green and blue. Were applicable, both are recorded. Fig.9 shows an example of a composite color with two peaks.

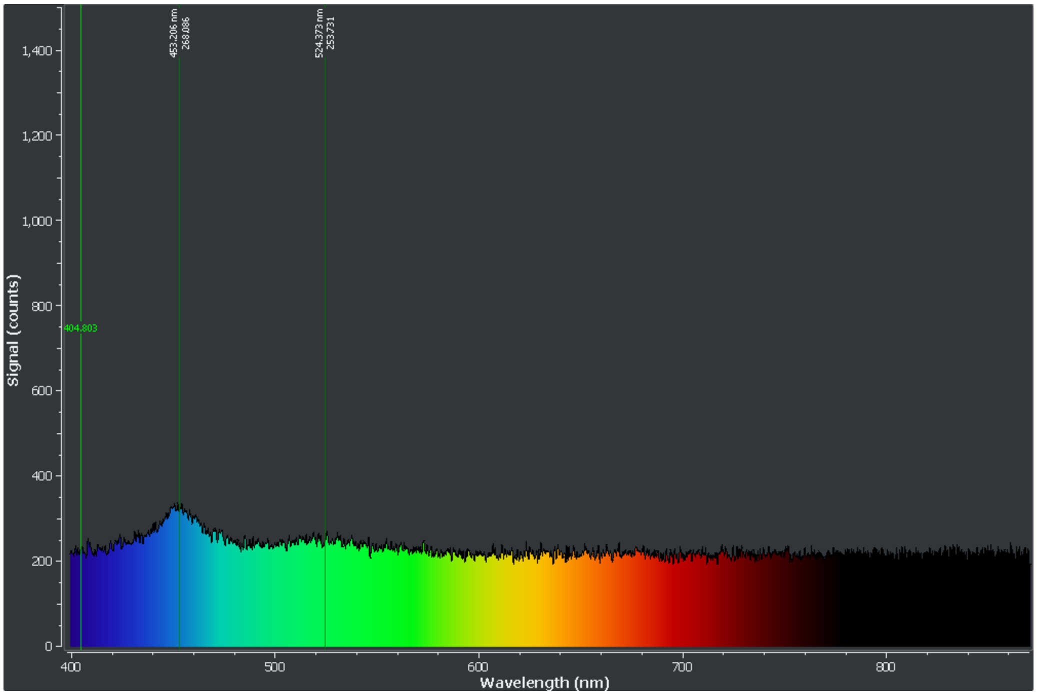

Fig.9: Cyan spectrum, with two shallow peaks in blue and green areas due to cyan being a composite blue-green color; see Table 4.

Color name	Number	Peak 1 (nm)	Peak 2 (nm)
Red	1	643 ± 10	n/a
Orange	2	641 ± 10	n/a
Yellow	3	637 ± 50	532 ± 10
Yellow-green	4	528 ± 50	650 ± 50
Green	5	524 ± 10	n/a
Green-blue	6	520 ± 10	460 ± 50
Cyan	7	524 ± 10	453 ± 10
Blue	8	454 ± 10	520 ± 50
Deep blue	9	451 ± 10	n/a
Indigo	10	451 ± 10	n/a

Table 4: Spectral data, RGB light. Errors of 50nm indicate shallow peaks with large visual uncertainty.

Figs.10-12 show illuminance plotted against assigned numbers for white and RGB light, then illuminance against peak wavelengths for RGB light.

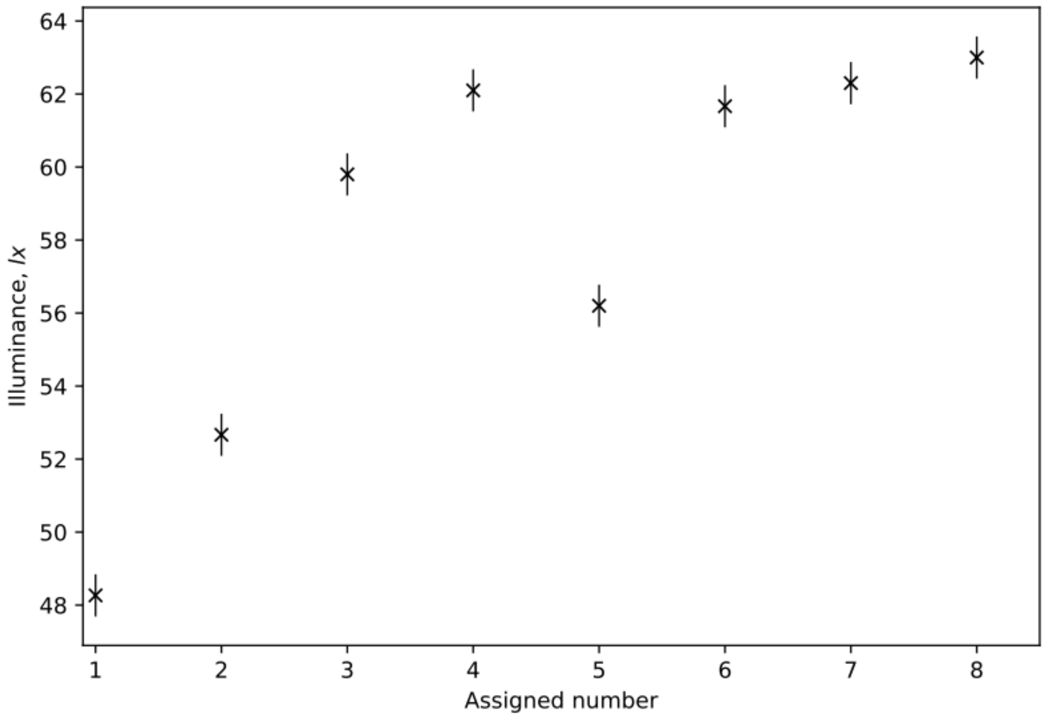

Fig.10: Illuminance against assigned number for white light shades. Labels 1-8 denote pale yellow to pale blue light.

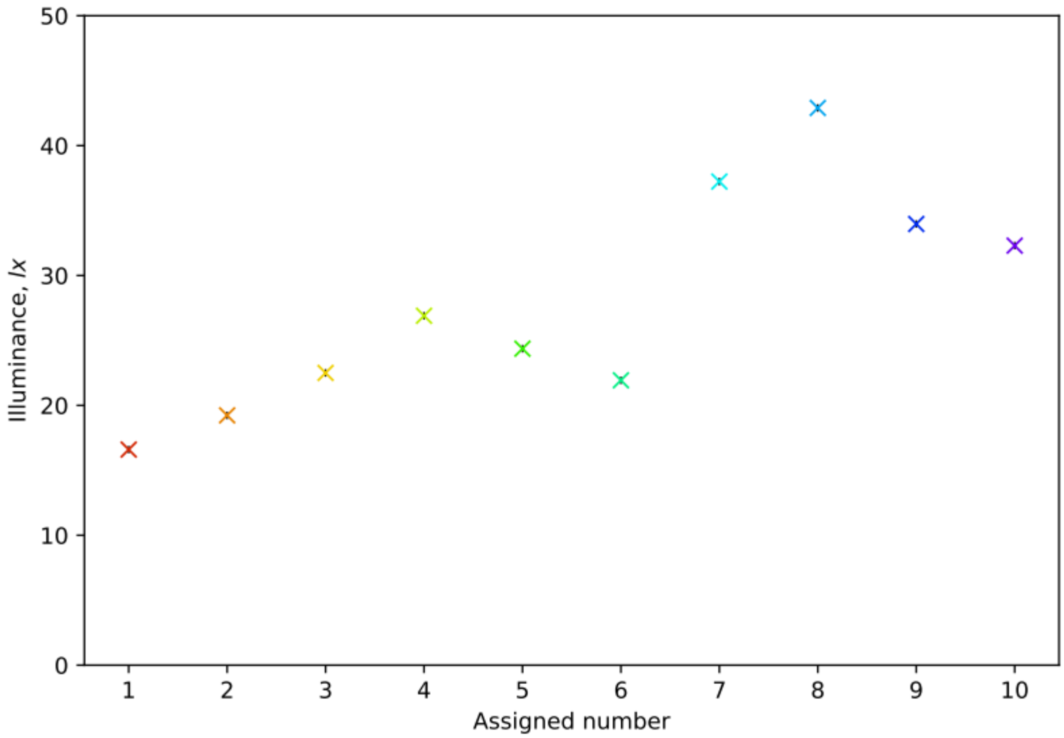

Fig.11: Illuminance against assigned number, RGB light. Vertical error bars are too small to be seen. Marker colors indicate light color.

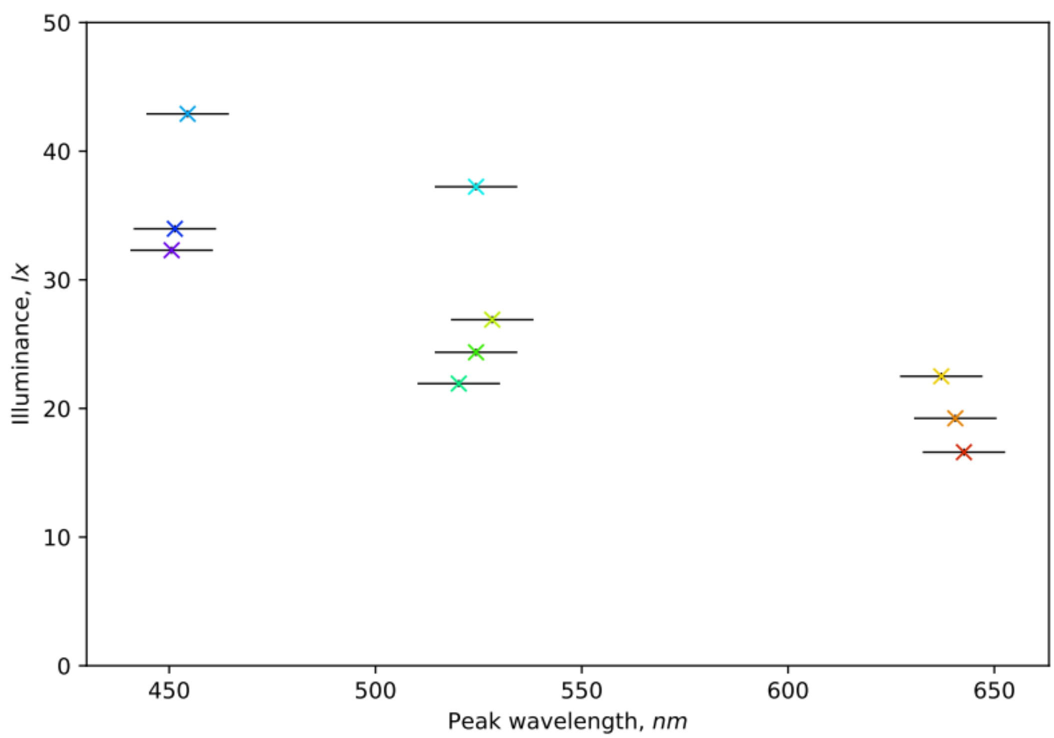

Fig.12: Illuminance against peak wavelength for RGB light. For spectra with two peaks, the higher and narrower of the two is chosen as dominant and plotted.

Discussion

Fig.6 shows illuminance readings at height 115cm. Though normalized residuals are in magnitude large, random fluctuation about 0 indicates some fit suitability. However, large χ_ν values indicate that a larger dataset is required to determine whether the fit is appropriate. Parameter i, ranging from 0.79lx to 3.12lx, indicates that small levels of background noise are present, but may only affect data at lower illuminances. Luminous flux L overall decreases with hood size as expected. Hoods 1-4 show negligible fit deviation, with Hood 0 at 18cm being a suspected anomaly. Average percentage decrease in illuminance from Hood 0, denoted $I_i - I_0$, ranges from ~5% (Hood 1) to ~12% (Hood 4). This indicates that they are insufficient reducers of light dispersion. Hoods 5-8 show significantly lower illuminance than hoods 1-4: $I_i - I_0$ ranges from ~15% (Hood 5) to ~96% (Hood 8). This suggests that Hood 8 is a suitable candidate for reducing light dispersion.

In Fig.7, showing readings above source at height 130cm, normalized residuals are low in magnitude and scattered about 0, confirming that the fit is appropriate for the distances used (>75cm), satisfying the inverse-square law assumption [10]. At excluded distances <75cm, deviation from the fit is observed. Illuminance decreases initially for Hoods 6 and 7, being less than half of that expected from the fit. However, illuminance increases around 50cm, showing they block upward dispersion closer to the LED but lose their effect as light propagates to further distances. Hood 8, covering ~80% of the source, is lowest in illuminance overall, remaining below 5lx. Its small peak indicates that it blocks significant amounts of upward dispersion with no loss of effect with distance. This makes it suitable to decrease skyglow. However, it may cause reduced brightness at ground level: further studies should make this a consideration. Though light color is kept constant, small variations due to the LED being variable color may cause discrepancies in illuminance readings.

Fig.10 shows an increase in illuminance with yellow- to blue-toned white light, though the point at label 5 may be omitted as a suspected anomaly. Light colors with lowest illuminance are 'Yellow-white' and 'Warmest white'. Due to illuminance being a photometric measure [10], it is concluded that warmer-toned or more yellow light appears less bright to humans and would decrease the contribution of street lighting to skyglow.

Fig.11.employs an interval scale of RGB assigned numbers for clarity, with illuminance increasing from red to blue shades. A possible linear correlation is seen from labels 1 to 4, with the illuminance peak at 4 (528±10 nm, 650±50 nm) roughly corresponding to the human eye's brightness peak at green light of wavelength 555nm [10]. Though points are scattered widely from labels 5-10, all blue shades 7-10 result in 5lx to 20lx higher illuminance than previous colors, confirming that bluer or cooler-toned light appears brighter.

Fig.12 uses a peak wavelength scale to quantify light colors. The 3 shortest wavelengths show high illuminance values of 30lx or above; the 3 longest wavelengths are 20lx or below. This suggests agreement with Gaston [3] that shorter wavelengths cause greater dispersion and skyglow. Results for 'Cyan' to 'Yellow-green' are likely erroneous and provide evidence that more vigorous data collection methods should be employed.

Though it is beyond the scope of this experiment, it is suggested that similar studies are repeated with Correlated Color Temperature (CCT) for all white and RGB shades to provide quantitative and highly repeatable light color results and reduce random error. Future studies should also use a greater range of colors (20 or more) to allow determination of a Gaussian or polynomial fit.

PART 2

Methodology

Focusing on integrating the public with sustainability research, a mixed-methods pilot intervention study was performed. 9 participants were recruited from outreach mailing lists with a poster (Fig.13), aiming for largely North-east locals of diverse ages and backgrounds.

Fig.13: Recruitment poster.

Ethical approval was obtained from the Physics Ethics Committee. Participants, after consenting to the study, completed the pre-survey detailed subsequently. In the planetarium, they were first shown the following local dark sky image (Fig.14) projected onto the dome, with no light sources. Then they were given scoring sheets to record how 5 LED sources alter image visibility when placed in front of it.

Scores indicate 1 - 'I can't see the image at all' to 10 - 'The image looks exactly as it did with no light in front of it'.

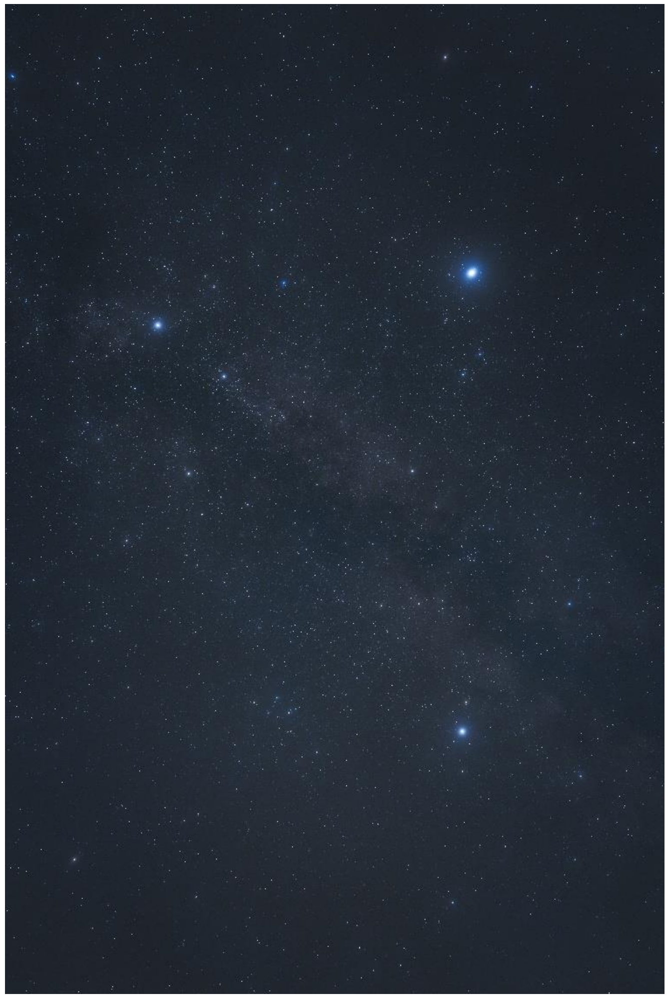

Fig.14: Summer Triangle in the dark skies over Kielder Observatory, photographed by Dan Monk.

The sources 1-5 match those used in Part 1:

1: Orange

2: Yellow-white

3: Pale blue

4: Neutral White with Hood 6.

5: Neutral White with Hood 8.

Fig.15 shows sources inside the planetarium, obscuring the projected Fig.14 by different amounts.

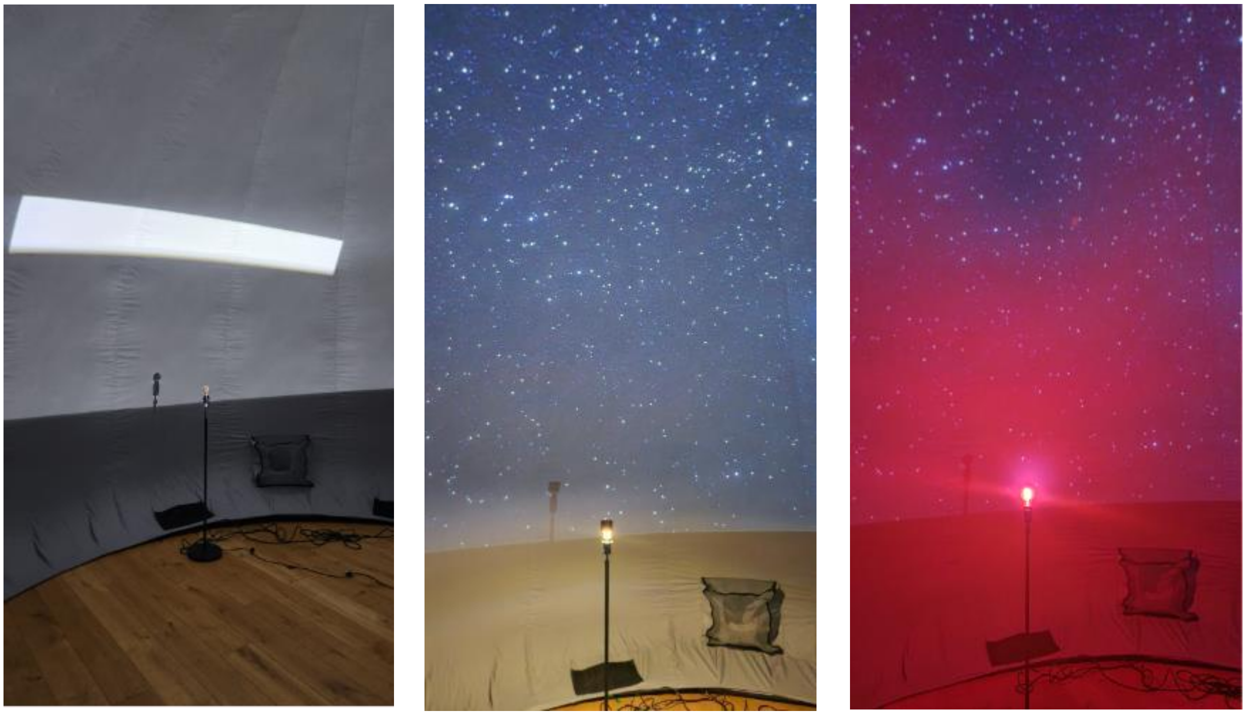

Fig.15: Planetarium set-up a) without projected image, b) source 4 against image, c) source 1 against image.

Participants then exited the planetarium and completed the post-survey, identical to the first with additional questions directly related to their experience of the demonstration. With the study finished, some participants chose to see a narrated show in the planetarium.

Surveys include a range of question styles:

-Multiple-choice demographic questions.

-Likert-scale statements regarding opinions about sustainability issues and light pollution.

-Short-answer: “In your own words, what is light pollution?”

Questions appended to the post-survey:

-Likert series of statements regarding demonstration experience.

-Short-answer: “What is the most interesting/surprising thing you learned?”

Research questions:

RQ1: Does exposure to a light pollution demonstration change people's awareness, concern, or attitudes towards light pollution?

RQ2: How closely do perceived visibility scores match the trend for the same sources in Part 1?

RQ3: How effective and realistic is the demonstration method in simulating visual light pollution?

Results and Discussion

To analyze the mixed question styles, a multi-pronged approach was employed, combining qualitative and quantitative analysis.

Demographics

Age	%	Gender identity	%	Employment sector	%	Locale	%
18-24	44	Male	33	Information Technology	11	North-east	78
25-34	11	Female	56	Education	22	South-west	22
35-44	0	Non-binary	11	Student	44		
45-54	11	Prefer not to say	0	Retired	11		
55-64	11			All other sectors	11		
Prefer not to say	22						

Table 5: Survey demographics, recording percentages of participants identifying with the above categories.

89% of participants agreed that they had taken steps to reduce environmental impact and 78% that they follow environmental news regularly. 100% agreed that they were concerned about environmental sustainability issues.

Short answer responses

Thematic analysis of responses to “In your own words, what is light pollution?” is carried out with categories identified in Table 6.

Topic mentioned	Pre-survey %	Post-survey %
Artificial light	67	56
Obscuring night sky/atmosphere	67	67
Excessive light	33	44
Night-time light	22	22
Impact on environment and/or wildlife	56	44

Table 6: Responses to short-answer definitions of light pollution for each survey, grouped by commonly mentioned topics.

Notable responses in the post-survey include 'bright white light shining upwards' and 'excess use of public lighting'. While ~90% of answers are accurate, crucial aspects of light pollution are neglected by all participants including effect on human circadian rhythms and health [2], indicating lack of awareness of these.

In the post-survey, responses to "What is the most interesting/surprising thing you learned?" are similarly grouped.

Topic mentioned	%
Significance of light color affecting visibility	56
Increased image visibility with orange light	22
Increased image visibility with large hood	44

Table 7: Responses to post-survey question above.

100% of participants who express opinion on which source is most effective choose Sources 1, 5, or both. As shown in Part 1, these use optimal LED parameters to reduce skyglow (warm-toned light and large hood). This preliminary analysis shows strong support for agreement between illuminance and visibility data (RQ2) and demonstration effectiveness (RQ3).

Visibility scores

Frequencies of the perceived visibility scores given by participants are recorded in Figs. 16 and 17.

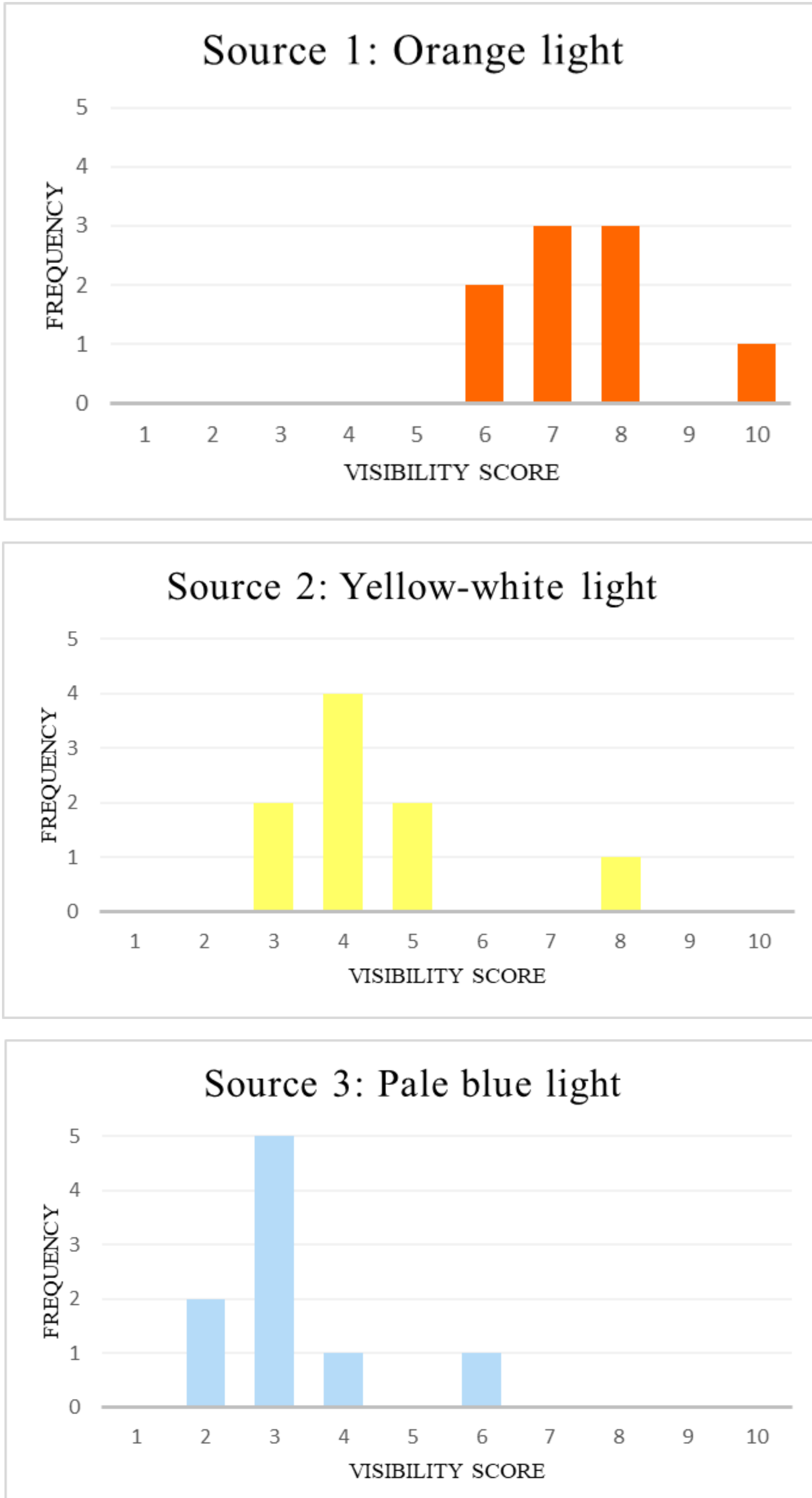

Fig.16: Frequency against visibility score plots for sources 1-3.

Median visibility scores decrease from 7 (Orange) to 3 (Pale blue). This aligns with the light color and illuminance relationship observed in Part 1, confirming that blue shades of light appear brighter than orange to humans and affect skyglow more profoundly. The similarity between Part 1 and 2 results confirms reliability of this method as a realistic, effective small-scale simulation of visual light pollution (RQ3).

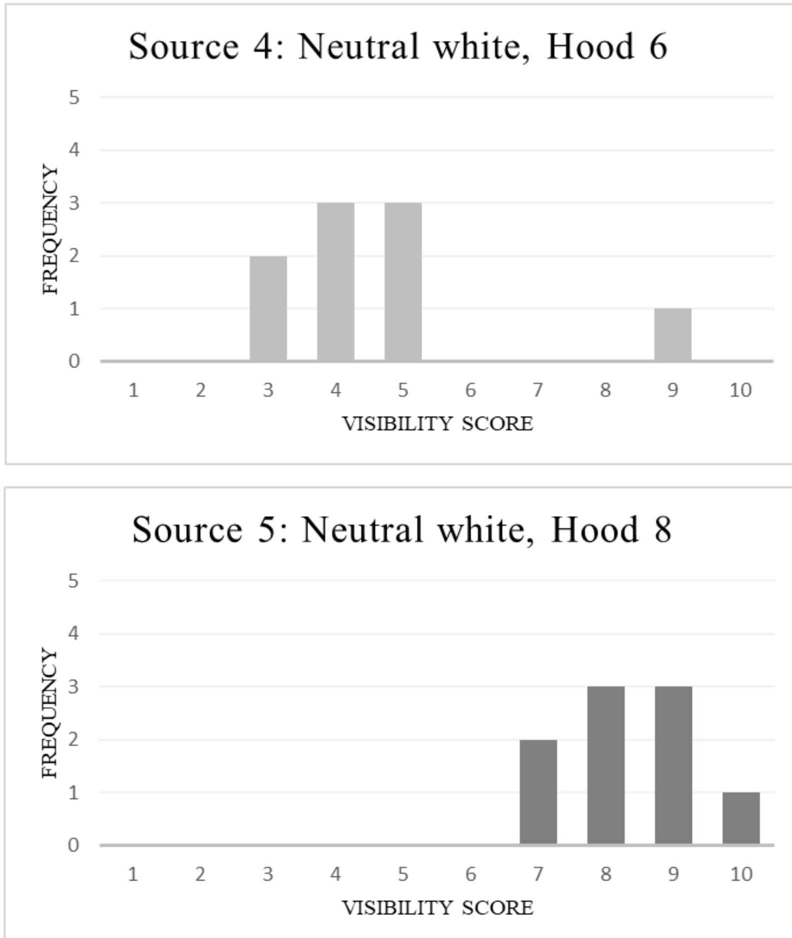

Fig.17: Frequency against visibility score for sources 4-5.

For sources 4-5, median visibility scores 4 and 8 respectively indicate agreement with Part 1 results regarding hood shape. Hood 8, causing significant reduction of illuminance and upward light dispersion, also has the highest median visibility score of all 5 sources, 8, indicating that hood shapes reduce skyglow more extremely than color. Parts 1 and 2 agree (RQ2) and as posed in RQ3, the demonstration method and equipment choices are effective simulations of light pollution aligning with real scientific data.

Likert scale responses

A two-tailed Wilcoxon signed-rank test is employed for paired Likert responses across surveys. A 5-point Likert scale is used including 'Don't know/ not enough information'.

The null hypotheses are that responses in the following categories do not change between surveys:

H1. Awareness and familiarity with light pollution.

H2. Conception of light pollution as an important sustainability issue.

H3. Knowledge of light pollution's effects.

H4. Opinions about local areas tackling light pollution.

H5. Feeling comfortable with lower light levels at night if it reduces light pollution.

At significance level $\alpha = 0.1$, 7/9 questions result in failure to reject null hypotheses and unchanged median values, suggesting little change in opinion has taken place. 2 questions lead to rejection of their null hypotheses H1 and H5 with effect sizes $r = 0.477$ and 0.316. These are classified as 'medium', indicating that noticeable change would take place given larger sample sizes. Therefore, causing direct changes in attitude (RQ1) is beyond the scope of this study.

Post-survey Likert responses regarding participant satisfaction are given in Table 8.

Statement	**%**
After seeing the demonstration, I have a better understanding of what light pollution is.	33
The demonstration increased my awareness of the effects of light pollution.	67
The demonstration increased my concern about light pollution.	56
The demonstration was engaging and easy to understand.	89

Table 8: Percentage of participants who agree with the above statements, in the post-survey.

Given that the study is demonstrative rather than educational, the first percentage is expected and emphasizes the need for further public education regarding light pollution. The other, high, percentages mean the demonstration is effective as an illustrative method to be used in conjunction with educational initiatives.

Conclusions

In this study, illuminance reduction in LED sources was investigated based on light color and model hood shape, to reduce skyglow caused by street lighting. Large hoods covering ~80% of the source, like Hood 8, reduce illuminance and upwards light dispersion by up to 96%. Orange-yellow or warm white light reduces illuminance by 5lx to 20lx compared to blue light.

A light pollution demonstration method was tested with public participants and found to be effective as a small-scale simulation of light pollution due to 89% participant satisfaction and agreement with illuminance data. Inconclusive Wilcoxon tests suggest insufficient sample size. Median visibility scores 7 (Orange light) and 8 (Hood 8) indicate that hoods placed over the source reduce skyglow more effectively than changing the light color.

It is suggested that future illuminance studies be repeated using Correlated Color Temperature to quantify results and provide usable recommendations for street lighting. Repeating illuminance measurements with multiple sources would provide robust data for urban planning and can be used to investigate mitigating extreme brightness changes between lamps [3].

Larger participant sample sizes (>25) for Wilcoxon testing are suggested. It is recommended to increase synthesis of scientific research with public participation in sustainability issues such as light pollution, as this study shows that scientifically robust demonstrations prove effective for simulating light pollution to audiences, and should be used in conjunction with educational material to increase understanding.

Appendix and error calculation

Precautions taken to reduce error

All lights are switched off in the lab, which is designed to be pitch black. Laptop screen is dimmed and turned away from the measurement space, reducing interference. Repeat illuminance readings are taken and mean values calculated, reducing random error. Distance markers are used to ensure LED stand is consistently placed. LED is switched off between measurements, reducing risk of overheating or brightness changes and preventing eyestrain.

Error calculation

The lux meter uses multiple scales. The smallest possible scale is used for each measurement, yielding maximum precision. At 200lx and 2000lx scales, the error is simply lux meter resolution, 0.1lx and 1lx , as zero fluctuation occurred at low light levels. Fluctuations at higher light levels are observed as ~1lx and ~10lx in amplitude respectively; these determined error on measurements. At the 20,000lx scale, used for the highest light levels, fluctuations were pronounced and the error set at 200lx to reflect this.

Error α_i in mean illuminance values is propagated using Eq.3:

$$\alpha_i = \frac{\sqrt{\alpha_1^2+\alpha_2^2+\alpha_3^2}}{3} \quad (3)$$

Spectrometer resolution is <1nm [11]. Due to visual uncertainty present in placing digital markers at peak wavelength, error is set at 10nm.

Illuminance errors were included in the inverse square fit, providing parameters *L* and *i* with associated errors. Normalized residuals r_i are calculated using Eq.4 with y_i measured illuminance values and $y(x_i)$ illuminance values predicted by the fit.

$$r_i = \frac{(y_i - y(x_i))}{\alpha_i} \quad (4)$$

Reduced chi-squared values χ_ν^2 used for measurements at height 115cm are calculated using:

$$\chi_\nu^2 = \left(\frac{1}{N-p}\right) \sum_{i=1}^{N} (r_i)^2 \quad (5)$$

with *N* the number of data points, 8, and *p* the number of fitted parameters, 2.

Illuminance data

Distance (cm)	Illuminance (lx)								
	Hood 0	Hood 1	Hood 2	Hood 3	Hood 4	Hood 5	Hood 6	Hood 7	Hood 8
0	211±5.77	212±5.77	165±5.77	134±5.77	106±5.77	82.7±5.77	27.8±2.89	1.67±0.0577	0.733±0.0577
15	240±5.77	152±2.89	163±2.89	110±5.77	109±5.77	54.2±2.89	33.8±2.89	2.07±0.577	0.933±0.0577
30	152±2.89	126±2.89	131±2.89	116±2.89	130±2.89	88.3±2.89	48.5±2.89	1.8±0.577	1.13±0.0577
45	87.2±2.89	90.0±2.89	87.3±2.89	85.2±2.89	85.8±2.89	76.5±2.89	50.7±2.89	2.4±0.577	0.867±0.0577
60	57.4±0.577	54.2±2.89	58.7±2.89	58.8±2.89	57.0±2.89	55.5±2.89	37.3±2.89	3.53±0.577	0.700±0.0577
75	40.3±0.577	44.0±0.577	43.8±0.577	41.6±0.577	41.1±0.577	41.1±0.577	31.6±0.577	7.70±0.0577	0.633±0.0577
150	15.4±0.0577	15.5±0.0577	15.5±0.0577	15.1±0.0577	14.9±0.0577	14.9±0.0577	11.4±0.0577	3.37±0.0577	0.500±0.0577
225	8.73±0.0577	8.70±0.0577	8.60±0.0577	8.37±0.0577	8.27±0.0577	7.70±0.0577	6.00±0.0577	2.13±0.0577	0.400±0.0577
300	5.93±0.0577	5.97±0.0577	5.73±0.0577	5.57±0.0577	5.57±0.0577	5.13±0.0577	3.97±0.0577	1.50±0.0577	0.300±0.0577

Table 9: Distance-dependent illuminance data for height 115cm.

Distance (cm)	Illuminance (lx)								
	Hood 0	Hood 1	Hood 2	Hood 3	Hood 4	Hood 5	Hood 6	Hood 7	Hood 8
0	211±5.77	212±5.77	165±5.77	134±5.77	106±5.77	82.7±5.77	27.8±2.89	1.67±0.0577	0.733±0.0577
15	240±5.77	152±2.89	163±2.89	110±5.77	109±5.77	54.2±2.89	33.8±2.89	2.07±0.577	0.933±0.0577
30	152±2.89	126±2.89	131±2.89	116±2.89	130±2.89	88.3±2.89	48.5±2.89	1.8±0.577	1.13±0.0577
45	87.2±2.89	90.0±2.89	87.3±2.89	85.2±2.89	85.8±2.89	76.5±2.89	50.7±2.89	2.4±0.577	0.867±0.0577
60	57.4±0.577	54.2±2.89	58.7±2.89	58.8±2.89	57.0±2.89	55.5±2.89	37.3±2.89	3.53±0.577	0.700±0.0577
75	40.3±0.577	44.0±0.577	43.8±0.577	41.6±0.577	41.1±0.577	41.1±0.577	31.6±0.577	7.70±0.0577	0.633±0.0577
150	15.4±0.0577	15.5±0.0577	15.5±0.0577	15.1±0.0577	14.9±0.0577	14.9±0.0577	11.4±0.0577	3.37±0.0577	0.500±0.0577
225	8.73±0.0577	8.70±0.0577	8.60±0.0577	8.37±0.0577	8.27±0.0577	7.70±0.0577	6.00±0.0577	2.13±0.0577	0.400±0.0577
300	5.93±0.0577	5.97±0.0577	5.73±0.0577	5.57±0.0577	5.57±0.0577	5.13±0.0577	3.97±0.0577	1.50±0.0577	0.300±0.0577

Table 10: Distance-dependent illuminance data for height 130cm.

White color label	Illuminance (lx)	RGB color label	Illuminance (lx)
1	48.3±0.577	1	16.6±0.289
2	52.7±0.577	2	19.2±0.289
3	59.8±0.577	3	22.5±0.289
4	62.1±0.577	4	26.9±0.289
5	56.2±0.577	5	24.4±0.289
6	61.7±0.577	6	21.9±0.289
7	62.3±0.577	7	37.2±0.289
8	63.0±0.577	8	42.9±0.289
		9	34.0±0.289
		10	32.3±0.289

Table 11: Light color dependent illuminance data. See tables 3-4 for wavelength data.

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