Optimizing spectrum to increase spatial brightness: effect on visual performance, eye fatigue and comparison of 5-second and 20-minute exposure durations

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Abstract

An experiment was conducted to evaluate the effect of a spectral power distribution optimized to increase spatial brightness compared to one approximating a typical blue-pump, phosphor converted LED (YAG:Ce). Chromatically- and luminance-adapted participants completed a reading task, visual search task, numerical verification task, and provided ratings for brightness, vividness, warmth, and preference over the course of approximately 20 minutes for each of four lighting conditions (2 SPDs by 2 illuminance levels [nominally 250 lx and 500 lx]). As a final task, the participants chose the brighter SPD between the two SPDs that were alternated every five seconds.

In alignment with a past experiment where participants provided ratings after viewing 60 stimuli for about 20 to 30 seconds each, the brightness-optimized SPD was rated as brighter, more vibrant, and more preferred than the PC-like SPD. When evaluated as a choice in a rapid sequential presentation, the brightness-optimized SPD was chosen as brighter than the PC-like SPD 28 out of 30 times. There was not a statistically significant change in spontaneous blink rate (an indicator of visual fatigue) or blink duration, nor any difference in glare, eye fatigue, or eye discomfort. Results for visual performance were mixed.

Keywords: spatial brightness perception, color preference, alpha-opic, TM-30, scene brightness, adaptation

1. Introduction

Spatial brightness (SB), sometimes called scene brightness, is an important aspect of illuminated interiors that describes whether there appears to be more or less light (CIE 2011). While illuminance is an obvious key factor and distribution of light has also been studied, the effect of spectrum on SB has received widespread attention since at least the 1970s (Boyce 1977; Flynn and Spencer 1977; Berman et al. 1990; Boyce and Cuttle 1990; Berman and Liebel 1996 Nov; Fotios and Levermore 1997; Fotios and Levermore 1998a; Fotios and Levermore 1998b; Fotios and Levermore 1998c; Vrabel et al. 1998; Boyce et al. 2003; Fotios and Gado 2005; Tiller et al. 2005; Akashi and Boyce 2006; Hu et al. 2006; Manav 2007; Houser et al. 2009; Vienot et al. 2009; Ju et al. 2012; Royer and Houser 2012; Wei et al. 2014; Baniya et al. 2015; Fotios, Atli, Cheal, Houser, et al. 2015; Fotios, Atli, Cheal, and Hara 2015; Kim et al. 2015; Rea et al. 2016; Bullough 2018; Zele et al. 2018; Yu and Akita 2019; DeLawyer et al. 2020; Ma et al. 2022; Jin et al. 2023; Khanh et al. 2023; Van de Perre et al. 2023; Yu and Akita 2023). Spectrum is an intriguing topic because the potential to hold input power constant while increasing SB could lead to substantial energy savings. While there is widespread acknowledgement that spectrum influences SB, there is no consensus on what attributes of spectrum have the greatest potential to influence SB.

1.1 Adaptation and Duration of Exposure

Past experiments on SB have primarily used short-duration exposures—especially in recent work utilizing LEDs, because they make changing the spectrum easier. Since 2015, 2 minutes is the longest observed duration before providing a rating in a laboratory experiment (Hu et al. 2022). Many experiments utilized 5 second exposures, often in sequential alternating presentation patterns (Fotios, et al. 2015; Rea et al. 2016; Besenecker and Bullough 2017; Yamakawa et al. 2019). Some of these works have utilized metamers and addressed chromatic adaptation, but even with such controls individual differences in color matching may elicit differences in the appearance of colorimetric metamers (Royer and Houser 2012); this could be particularly problematic in rapid sequential or side-by-side presentations. While all these works found some effect of spectrum on SB, how well the findings apply in more naturalistic viewing conditions (i.e., long-term immersive exposure) is less certain.

A smaller number of experiments have considered longer-duration evaluations. Wei et al. (2014) completed a long-term field study with exposure over the regular work period, finding an effect of spectrum on brightness perception, while Boyce and Cuttle (1990) found a statistically significant affect of fluorescent lamp CCT on rated dimness, but not brightness, after approximately 20 minutes. Fotios et al. (2006) reviewed the effects of chromatic adaptation and presentation method (i.e., side-by-side comparisons, sequential comparisons, or individual evaluations); they concluded that the effect of spectrum on SB persisted over longer durations of viewing (i.e., when chromatically adapted), but was reduced in size compared to short-term evaluations.

The human visual system adapts in many ways, over many time scales. Dark adaptation occurs over multiple phases: first rapidly (seconds), then longer term photochemical changes typically lasting 30 to 40 minutes (Kolb et al. 1995). Light adaptation of the scale relevant in SB experiments may occur more rapidly; neural changes alone, which are rapid (< 1 second) are sufficient to address luminance changes of 2 to 3 log units. Chromatic adaptation also has a rapid initial stage and a slower stage with a 10 second to 20 second half life; it is about 90% complete after 60 seconds and 95% complete after 2 minutes (Fairchild and Reniff 1995; Rinner and Gegenfurtner 2000; Zhang et al. 2023). In SB experiments, overall chromatic adaptation and adaptation to individual metamers are separate considerations; for example, Royer et al. (2024) allowed for chromatic adaptation in a separate room before evaluations of a series of metamers in the experimental room after 20 seconds of viewing for each (with movement through a dark room in between). If adaptation is expected to occur only while viewing an experimental stimulus, it may be difficult for participants to not include initial impression in evaluations.

Besides dark/light and chromatic adaptation, intrinsically photosensitive retinal ganglion cells (ipRGCs) also adjust their sensitivity based on photic history, although over longer timescales than rods and cones and with variation among the subtypes (Wong et al. 2005; Do and Yau 2013; Sexton et al. 2015; Mure 2021). Importantly, they do contribute to some short-term effects, like pupil dilation. Outside of the photoreceptors, our sensory systems adapt to the visual world over days, weeks, months, or even years (Webster 2015). It is possible that the visual system could adapt to changes in chroma that increase vividness by altering color perception over time. While part of the impetus for this experiment was exploring changes to SB over longer durations of exposure, the experiment was not designed to explicitly investigate the effects or time course of visual adaptation.

1.2 Visual Fatigue and Visual Performance

Modifying the spectrum of light to improve SB may have other consequences. For example, increasing the relative amount of short-wavelength content—which is generally associated with increasing SB, through multiple mechanisms—has been linked to increased visual fatigue (Hoffmann et al. 2008; Viola et al. 2008; Chiu and Liu 2020; Zhang et al. 2020; Shi et al. 2021). Likewise, ipRGCs contribute to changes in pupil size (Chen et al. 2011; Chakraborty et al. 2022; Mathôt et al. 2023), which may in turn affect visual acuity and thus visual performance. Pupil size has also been identified as a correlate of cognitive load (Piquado et al. 2010).

Research into the effect of spectrum (beyond illuminance) on visual performance dates to at least 1948 (Simonson and Brozek 1948), although much of the work has focused on outdoor nighttime environments at mesopic light levels. At photopic levels, visual performance may be affected by spectrum, but the evidence is not strongly conclusive and may only apply at suprathreshold conditions (Society 2020). Berman and colleagues have argued that melanopsin (originally rhodopsin) may affect visual performance (Berman 1992; Berman 2008a; Berman 2012), primarily acting through changes in pupil size. In contrast, Boyce et al. (2003) found the relative proportion of scotopic content to photopic content had no effect on visual performance. Performance may also be affected by cognitive or alerting affects of light, which are now more widely studied since the discovery of ipRGCs (Cajochen et al. 2005; Cajochen 2007; Mills et al. 2007; Viola et al. 2008; Lok et al. 2018). Notably, light that does not activate ipRGCs (e.g., red light) can also have alerting and performance effects (Sahin et al. 2014).

1.3 Prior Work and Hypotheses

This article reports on a recent study of the effect of spectrum on SB, visual fatigue, and performance that was a follow-up to another experiment. In the prior experiment (Royer et al. 2024), 60 SPDs were engineered to systematically vary melanopic daylight efficacy ratio (mel-DER), s-cone opic daylight efficacy ration (sc-DER), chromaticity (correlated color temperature [CCT] and distance from the Planckian locus [Duv]), color rendition, and illuminance. While prior literature had identified both sc-DER (Fotios and Levermore 1997; Fotios and Levermore 1998a; Fotios and Levermore 1998b; Fotios and Levermore 1998c; Rea et al. 2016; Khanh et al. 2023) and mel-DER (Berman 2008b; Brown et al. 2012; Rea et al. 2016; Besenecker and Bullough 2017; Spitschan et al. 2017; Zele et al. 2018; Yamakawa et al. 2019; DeLawyer et al. 2020; Hu et al. 2022; Khanh et al. 2023) as contributing to SB, our experiment identified red chroma (as measured by IES TM-30's $R_{cs,h1}$) as having the second largest effect on spatial brightness after illuminance. There was also a statistically significant interaction effect, where $R_{cs,h1}$ had a greater effect at 500 lx than 250 lx. Sc-DER was also a statistically significant effect, although it was a considerably smaller effect than $R_{cs,h1}$ at the levels tested. Mel-DER was not statistically significant at the levels examined, nor was chromaticity. Importantly, mel-DER and $R_{cs,h1}$ are correlated (Royer et al. 2024), which may explain past findings that did not carefully differentiate SPDs based on these factors.

In our prior experiment, brightness, vividness, and preference evaluations were made after at least 20 seconds in the experiment room (with additional adaptation time outside the experiment room when chromaticity or illuminance changed). The purpose of the current work was to examine if the findings held when participants spent a longer time in the experiment room (now 20 minutes), and to expand the dependent measures to include visual fatigue and performance. To this end, we designed four lighting conditions, crossing two horizontal illuminance conditions (500 lx and 250 lx) with two different relative SPDs. One of the SPDs was the same as a typical phosphor-converted (PC) LED, with a target $R_{cs,h1}$ value of -12%. The other was optimized for brightness (OB) to have a target $R_{cs,h1}$ of +12%. These were similar to the SPDs found to elicit high and low SB in the prior experiment.

We hypothesized that OB SPDs with increased $R_{cs,h1}$ would be rated (long term evaluation) and chosen (rapid sequential evaluation) as brighter than PC SPDs at equal illuminance and be more preferred. We predicted no difference in visual performance, visual fatigue, or glare perception due to the change in spectrum, given relatively small changes outside of the variation in color rendering. We specifically included the PC condition because it is ubiquitous in current architectural lighting.

2. Methods

2.1 Apparatus and test room

The primary experiment room was 4.4 m by 6.7 m with a 2.6 m ceiling height. Figure 1 shows a photo of the room captured from the eye-tracking glasses; the overlayed track and circle represent the viewers eye movement. This room was furnished to appear as an office space and did not have any windows. The ceiling was nominally 2'×2' white acoustical ceiling tiles, the walls were painted with Munsell N8 gray paint, and the floor was gray carpet tiles. It had two solid doors, one on each of the shorter sides, which were also painted gray.

The experiment room was illuminated by 12 custom-built luminaires (Telelumen, LLC), with each having 24 independently controlled LED channels. Each LED was a commercially available product. The experimental lighting conditions utilized only a subset of those channels, as needed to achieve the design targets. Near-UV and far-red content were avoided.

An adjacent room was used for adaptation purposes. The dimensions of the room were approximately 4.4 m by 8.7 m with a ceiling height of 3.0 m, but only a portion of this room was used. The adaptation room was illuminated by 28 Ketra G2 linear tunable luminaires aimed downward to provide direct illumination. Between the adaptation room and experiment room was a 2.5 m corridor that was not illuminated during the experiment but was navigable with spill light when a door was opened..

2.2 Visual stimuli

Four experimental SPDs were created, crossing two nominal horizontal illuminance conditions (250 lx and 500 lx) and two nominal color rendition conditions, while holding nominal chromaticity constant (3500 K and 0.000 Duv). The first color rendering condition was designed to optimize SB perception based on prior results. Referred to as OB (optimized for brightness), it was designed to efficiently target enhanced chroma, with $R_g \approx 110$ and $R_{cs,h1} \approx 12\%$, while maintaining values of $R_f \approx 85$, sc-DER ≈ 0.46, and minimized mel-DER ≈ 0.64. The second relative SPD type, denoted PC, was designed to mimic a blue-pump phosphor-converted LED package with YAG:Ce phosphors. The target performance was $R_g \approx 95$ and $R_{cs,h1} \approx -12\%$, which is typical for this type of product. As with the OB SPD, additional targets were R_f

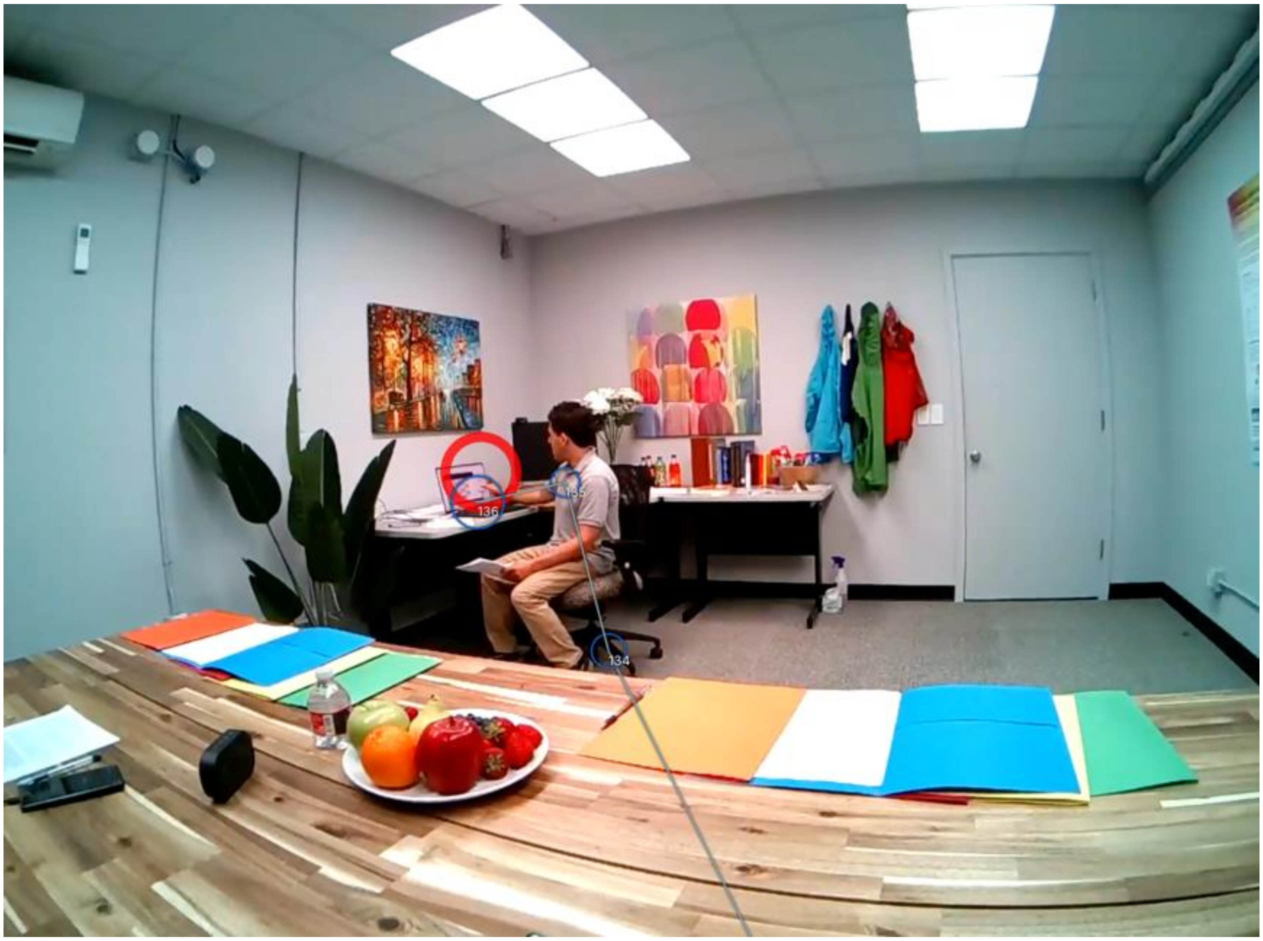

Figure 1. Screen capture from eye-tracking software, demonstrating a participant's view of the experiment room. The gray lines and red circle are the participant's eye movement and current focal point.

≈ 85 and sc-DER ≈ 0.46. At ≈ 0.56, mel-DER was slightly lower than for OB, but this is a function of the relationship between red chroma and mel-DER. An exact match in mel-DER between the two SPD types was not possible given the other parameters. As found in the prior experiment, this degree of difference in mel-DER (≈ 0.08 or 15%) was not a statistically significant predictor of SB perception, when accounting for other factors.

As previously demonstrated, the Telelumen system in the experiment room was able to maintain no discernable difference in luminance uniformity across this range of SPDs (Royer et al. 2024). Table 1 shows the measured values for each of the four experimental conditions and two adaptation conditions. Figure 2 shows TM-30 color vector graphics for each stimulus, and Figure 3 provides spectral power distributions. Measurements were made with a Minolta CL-500A spectrometer at the center of the table where participants sat. Also shown in Table 1 are eight pre-trial demonstration conditions that were used to illuminate the experiment room during the informed consent and instruction process, the latter of which included a demonstration to help anchor the responses and illustrate what changes the participants might experience. Each participants saw the demonstration conditions at one illuminance level, corresponding to the first experimental condition they would see.

The adaptation room was used between stimuli, with a 10-minute wait when the illuminance level was changed and a 2-minute wait when switching between OB and PC. The adaptation room illuminance was

Table 1. Properties of experimental conditions, adaptation conditions, and pre-trial demonstration conditions

Type	Description	E_h (lx)	CCT	Duv	R_f	R_g	$R_{cs,h1}$	mel-DER	sc-DER	Irradiance (W/m^2)
Exp.	500 lx BO	499	3482	-0.001	85	110	12%	0.65	0.46	1.65
Exp.	500 lx PC	494	3479	0.000	85	95	-12%	0.56	0.46	1.50
Exp.	250 lx BO	248	3468	0.000	85	110	11%	0.63	0.46	0.80
Exp.	250 lx PC	251	3496	-0.001	85	94	-12%	0.57	0.48	0.77
Adapt	500 lx	259	3446	0.002	85	100	-8%	0.43	0.50	0.73
Adapt	250 lx	529	3446	0.002	85	101	-7%	0.44	0.49	1.49
Demo	500 lx HF	501	3475	0.000	98	99	-1%	0.46	0.63	2.18
Demo	350 lx HF	346	3486	-0.001	98	100	0%	0.47	0.64	1.54
Demo	650 lx HF	650	3486	-0.001	98	100	0%	0.48	0.65	2.91
Demo	500 lx -Red	496	3463	0.000	85	95	-12%	0.46	0.55	1.50
Demo	500 lx +Red	502	3450	0.000	85	110	11%	0.45	0.63	1.63
Demo	250 lx HF	251	3474	-0.001	98	99	-1%	0.47	0.63	1.10
Demo	175 lx HF	176	3487	0.001	99	99	-1%	0.45	0.62	0.76
Demo	425 lx HF	326	3485	0.000	98	99	-2%	0.47	0.63	1.40
Demo	250 lx -Red	255	3521	0.000	85	95	-12%	0.47	0.55	0.77
Demo	250 lx +Red	251	3458	0.000	85	110	11%	0.45	0.63	0.81

the same as the illuminance of the next condition, which was constant for the 2-minute wait, and during the 10-minute wait changed gradually between nominally 250 lx and 500 lx. The chromaticity target was the same as for the experimental lighting and the color rendition target was high color fidelity.

While characteristics of the SPD are what were operationalized, each visual stimulus was the interaction of the SPD and the objects and surfaces within the room (see Figure 1). The objects were items commonly found in office spaces, including a desk, wood conference table, books, chairs, paper/notebooks, fresh food, packaged food, artwork, computer equipment, and jackets. An experimenter was always situated at the desk. These items were similar, but not identical, to the prior experiment. The items most noted by participants as influencing their judgments of brightness were the jackets hung on a wall (held over from the prior experiment) and the colored folders (new for this experiment).

2.3 Participants

Thirty people participated in the experiment, including 17 females and 13 males. Participants were recruited from groups on social media, with some having previously participated in experiments conducted by the researchers. One person identified that he had professional lighting experience. The age of the participants ranged from 18 years to 55 years, with a median of 34.5 years. All participants completed the experiment during the same week in August 2024.

One participant did not complete all of the tasks for 500 lx OB, due to needing a break, and completed 500 lx PC upon return without being fully adapted; data for these two conditions for that participant were excluded.

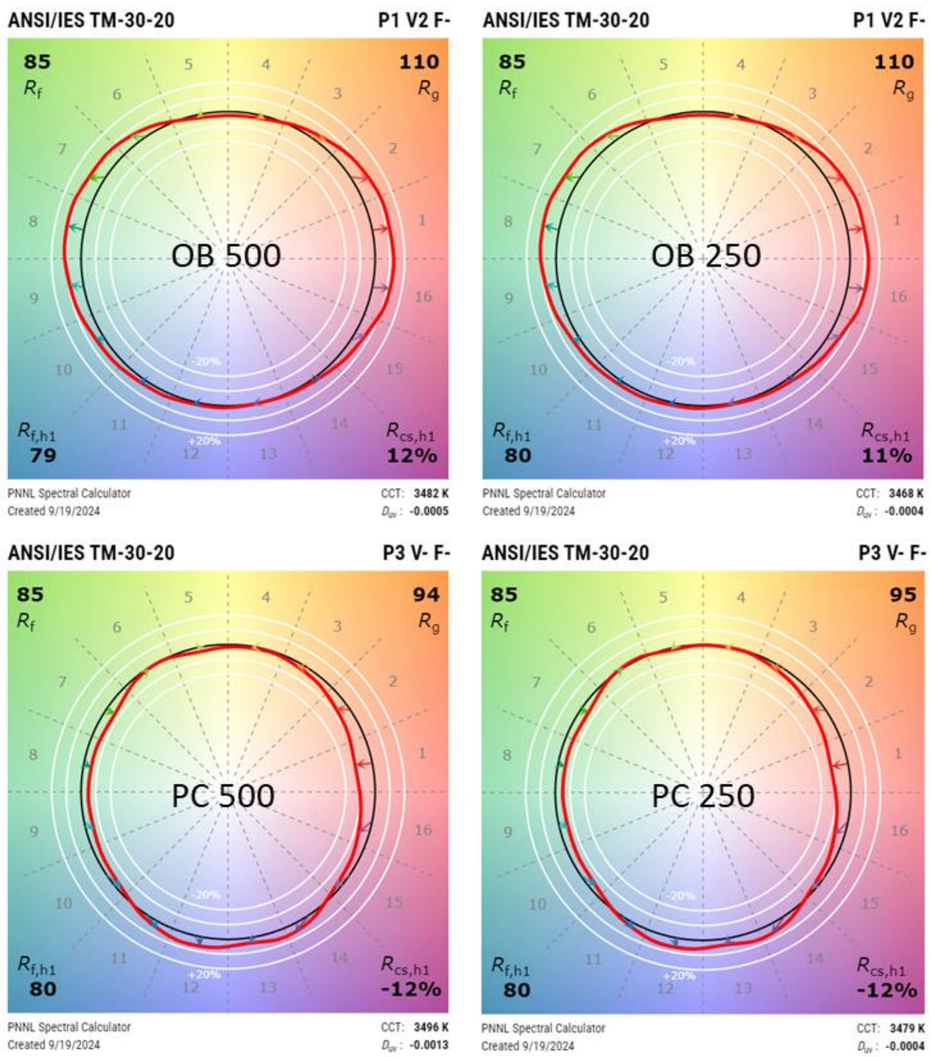

Figure 3. Color vector graphics for the four experimental stimuli.

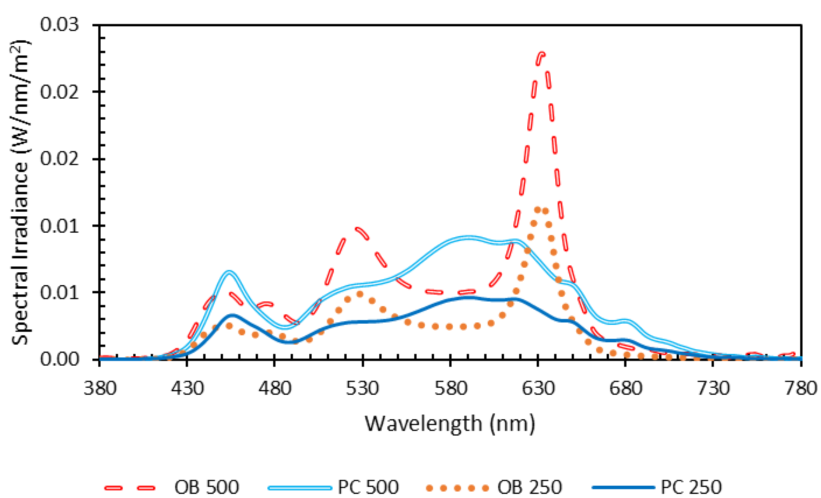

Figure 2. Spectral power distributions for the four experimental stimuli.

2.4 Procedure

This experiment was approved by the {removed for peer review}.

Participants completed the experiment individually (n = 8) or as a pair—if in a pair, they were instructed not to communicate with each other. Upon arrival, participants were escorted to the experiment room where they first provided consent to participate and were then read instructions and worked through examples of each task to be performed. The lighting during this time was set to the high-fidelity condition matching the chromaticity of the experimental conditions and having the illuminance of the first experimental condition. Part of the purpose of the instructions and practice trials was to provide for chromatic and luminance adaptation; this portion of the experiment took approximately 10 minutes.

One of the tasks during the instruction time was fitting the participants with eye- and gaze-tracking glasses (Pupil Labs Neon). Each participant wore a pair of the lens-less glasses for the duration of the experiment. The glasses were tethered to a smart phone, placed in the participant's pocket, that provided power and recorded the data.

At the conclusion of the instruction and example period, the participants saw 5 example SPDs which were designed to anchor the responses and provide an example of how color rendition can influence the appearance of objects. These five SPDs were based on the illuminance level that was presented first in that session, and included a high fidelity (HF), 30% lower illuminance HF, 30% higher illuminance HF, the OB condition, and the PC condition. They all had the same target chromaticity, with minimal variation.

After viewing the example SPDs, the participants were escorted to the adaptation room, where they waited for about a minute while the lighting in the experiment room was changed. Before re-entering the experiment room, they started recording on the eye-tracking glasses, marking the beginning of the experimental condition.

During each experimental condition, the participants completed four tasks after spending about 30 seconds looking around the room and getting comfortable:

1. A six-minute reading task. Although reading speed was not officially recorded, the experimenter asked the participant to identify the line they ended on after six minutes to give the participant the impression it was a measured task. There were four articles used, in a fixed order. Because the lighting conditions were randomized, the articles were randomly mixed with the lighting conditions.
2. A numerical verification task. The participants were presented with a paper containing eight pairs of columns of five-digit numbers and asked to circle number pairs that did not match, "as accurately and quickly" as possible. The participants were provided with a small desktop timer to start when they began and stop when they finished. This task typically took about 4 minutes. The numbers were unique on each sheet, but there were 32 mis-matched pairs on every sheet.
3. A visual search task. For this task, there were 50 T and 500 L shapes randomly distributed and having different orientations within a box. Participants were asked to circle as many T shapes as they could find in 90 seconds. Participants completed this three times per experimental condition.
4. A series of rating questions. As provided in the supplemental material, these included:
    a. A question about adjusting the brightness if this were their daily work environment.
    b. Considering the room as a whole, 1 to 8 point rating scales for bright-dim, warm-cool, vibrant-dull, and like-dislike.
    c. A question regarding glare, including a 1 to 8 point rating scale.

d. A subset of questions from the headache and eyestrain scale covering eye discomfort, eye fatigue, and difficulty focusing.

Once all participants were finished, typically after about 20 minutes (mean=19.9 minutes, SD= 2 minutes), they were escorted back to the adaptation room. The second experimental condition was always at the same illuminance level as the first, and the last two were the other illuminance level. Which illuminance level was presented first was randomized. When the illuminance level changed, participants spent 10 minutes in the adaptation room while the light gradually changed.

After the final condition was evaluated, participants were asked to complete a final questionnaire, which first asked: *If you were to select one of the four lighting conditions that you saw today to work under in an office space, which one would you prefer?* The second question was: *Was there any particular object(s) or part(s) of the room that was especially influential in your brightness ratings? (If yes, please also describe)*. Next, the participants were shown the final two (equal illuminance) conditions in sequence, alternating every 5 seconds. They were then asked to identify which appeared brighter and indicate by how much using a scale of less than 1.1 times brighter to more than 2 times brighter in 0.1 step increments. There was also an open comment box.

Once the final questionnaire was completed, participants were compensated and escorted out of the building. The total experiment took approximately 120 minutes. All sessions were held within a seven-day period. Fresh food was stored in a refrigerator when not in use and changed out when necessary.

2.4 Dependent measures and statistical models

There were several categories of dependent measures, including self-assessments, eye-tracking data, and visual performance tasks.

SB was primarily evaluated using a rating scale and adjustment question for each stimulus evaluated at the end of the approximately 20 minutes of exposure. Secondarily, each participant made a choice between two illuminance-matched but spectrally different SPDs, at one of the two illuminance conditions, following short-duration exposure; a magnitude estimation question followed.

Vibrancy, preference, and glare were evaluated with rating scales, producing interval-scale data that was analyzed using a linear mixed model. Preference was also evaluated using multiple choice question at the end of the experiment. Visual performance was measured using the numerical verification and visual search tasks. The numerical verification task included 160 pairs of numbers and the score was calculated based on the number of errors (E) which included misses and false positives, and time in seconds (T) as shown in Equation 1. The mean number of targets found in the three visual search tasks for each lighting condition were used in the analysis.

$$NV\ Score = \frac{160 - E}{T} \qquad (1)$$

Visual fatigue was assessed using data automatically generated in Pupil Cloud by the Pupil Labs eye-tracking glasses, including spontaneous blink rate and duration. Given the interest in spontaneous blinks, we analyzed blinks with a duration of 500 ms or less (Colzato et al. 2009; Maffei and Angrilli 2018). One tracker failed for one session and did not record data. Visual fatigue was also assessed using three different elements of the headache and eyestrain scale, each on a 4-point scale (absent to severe).

All data was analyzed with linear mixed models (LMMs), except frequency (count) data related to the preference to adjust the brightness (Y/N), glare (Y/N), and headache and eyestrain symptoms which were analyzed using Fisher's exact test.

In the LMMs, random intercepts and slopes were included for participants and presentation order. These random effect terms were added to account for variability across participants and how responses to subsequent conditions might have been affected by experience in previous conditions (carryover effects). This was based on boxplots that showed a likely effect of the illuminance presentation order on SB ratings; if the 250 lx conditions were seen first followed by 500 lx conditions, the SB responses to the 500 lx conditions tended to indicate a brighter perception.

While the presentation order was randomized, the number of participants in the experiment sessions varied (1 to 2 participants); this resulted in more participants experiencing the 250 lx conditions first (n = 17) versus 500 lx (n = 12), and data for one subject for the 500 lx conditions were excluded, as noted earlier). Therefore, the presentation order of lighting conditions (1 to 4) was added as a fixed effect to account for the imbalance.

All mixed models included the following checks of assumptions: linearity which was visually checked using residual plot, normality of residuals which was checked using Shapiro-Wilk test, and homoscedasticity using Breush-Pagan test using R Performance package (Lüdecke et al. 2021). To meet model assumptions, transformations were applied to some dependent variables. A Z-score transformation at the participant level was applied to numerical verification scores and mean pupil diameter, and a square-root transformation was applied to blink rate and mean blink duration. Responses from one participant who only completed two 250 lx conditions were excluded from the pupil diameter analysis to meet the residual normality assumption.

3. Results

Table 2 shows the mean and standard deviation for the rating scales, numerical verification (NV) task, visual search task, and blink measures for each experimental lighting condition. Additional data is available in the supplemental file. The following sections present the results of each dependent measure and examine differences between the OB and PC spectra at the two illuminance levels.

Table 2: Mean and (standard deviation) of the dependent measures by lighting condition. NV = Numerical Verification.

Condition	Bright-Dim	Warm-Cool	Vibrant-Dull	Like-Dislike	NV score	Visual search	Blink rate [count/min]	Blink duration [ns]
250 lx OB	5.2 (1.5)	3.9 (1.8)	4 (1.6)	4.4 (1.9)	0.65 (0.17)	36.6 (5.92)	11.7 (7.92)	281 (24.7)
250 lx PC	5.4 (1.4)	4.9 (1.7)	5.6 (1.6)	4.8 (1.8)	0.66 (0.18)	37.4 (5.67)	11.7 (7.29)	285 (25.4)
500 lx OB	3 (1.1)	4 (1.7)	3 (1.1)	3.2 (1.7)	0.69 (0.17)	38.4 (5.72)	11.7 (7.92)	282 (23.2)
500 lx PC	3.4 (1.5)	4.3 (1.9)	4.1 (1.9)	3.7 (2)	0.64 (0.14)	37.9 (5.61)	11.8 (7.92)	283 (24.7)

3.1 Spatial Brightness

A LMM showed a significant difference in brightness ratings by illuminance level, spectrum, and participant age (Table 3). Unlike in Royer et al. (2024), there was not a statistically significant interaction between illuminance and spectrum, so that term was not retained in the final parsimonious model—note that this experiment was not designed to further explore this effect. As illustrated in Figure 4, the OB spectrum was perceived as brighter than PC at both illuminance levels, with a slightly larger difference at 500 lx. Older participants tended to rate the conditions brighter.

Table 3: Type III analysis of variance table with Satterthwaite's method of the mixed linear model of brightness ratings.

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Illuminance	72.1	72.1	1	57.6	80.5	<0.001**
Spectrum	4.5	4.5	1	63.4	5.0	0.029*
Presentation order	3.5	3.5	1	29.3	3.9	0.058
Age	6.4	6.4	1	27.2	7.2	0.012*

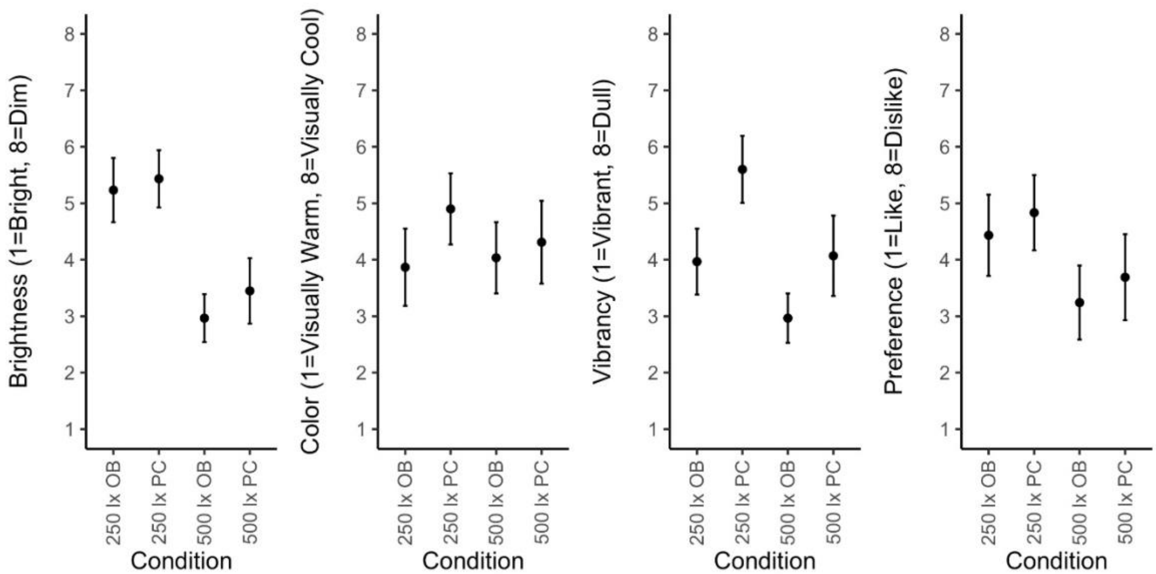

Figure 4. Mean ratings and 95% confidence intervals for ratings of brightness, warmth, vibrancy, and preference by lighting condition.

When participants were asked whether and how they would adjust brightness at the end of the 20-minute exposure, a larger number of participants indicted that they would adjust the brightness under the 250 lx conditions than under the 500 lx conditions (Table 4). Of the 22 each who chose to adjust the 250 lx brightness conditions, 86% chose to increase brightness for the OB condition and 86% also chose to increase brightness for the PC condition. Of the 14 each who chose to adjust the 500 lx brightness conditions, 50% chose to increase brightness for the OB condition and 64% chose to increase brightness for the PC condition. At both illuminance levels, PC lighting conditions had higher mean adjustment level than OB, although the difference was only 3% to 5%.

When the conditions were experienced for 5 seconds each at the end of the experiment (i.e., rapid sequential presentation), 93% of participants chose that the OB condition was brighter than PC (Table 5)—to reiterate, each participant compared the two different SPDs at either the 250 lx or 500 lx level, based on the illuminance of the last SPD they evaluated. For comparison, we converted the 8-point scale from the rating scale to a binary response, excluding ties. Under the 20-minute procedure, the

Table 4: Count of responses indicating whether participants preferred to adjust the brightness.

					Count of selected adjustment level (-=dimmer, +=brighter, 0=no change)*								
Condition	**Yes adjust**	**Dimmer**	**Brighter**	**Mean**	**-1x**	**-0.75x**	**-0.5x**	**-0.25x**	**0**	**0.25x**	**0.5x**	**0.75x**	**1x**
250 lx OB	22	3	19	0.23	0	1	1	1	8	11	2	3	2
250 lx PC	22	3	19	0.26	0	0	1	2	8	9	6	2	2
500 lx OB	14†	7	7	0.02	0	1	2	4	15	4	2	0	1
500 lx PC	14†	5	9	0.07	0	1	1	3	14	5	3	0	1

*One participant selected two values, which were averaged to 1.375; not shown in the table.
† One participant's data was removed for all 500 lx evaluations; another missed the adjustment question for 500 lx PC.

Table 5: The number of participants who indicated that a spectrum was brighter than the other at the same illuminance level viewed using two procedures. For the 5 second viewings, participants also indicated how much brighter the spectrum is.

Spectrum	**20 minutes†**	**5 seconds (sequential viewing)**												
		Total	**<1.1x**	**1.1x**	**1.2x**	**1.3x**	**1.4x**	**1.5x**	**1.6x**	**1.7x**	**1.8x**	**1.9x**	**2x**	**>2x**
250 lx OB	13	11	1	0	0	0	2	5	0	1	1	0	0	1
250 lx PC	9	1	0	0	0	1	0	0	0	0	0	0	0	0
500 lx OB	15	17	0	0	2	3	1	2	2	4	2	0	0	1
500 lx PC	6	1	0	0	0	0	1	0	0	0	0	0	0	0

† Ties were excluded from the count

frequency was reduced to 59% and 71% indicating that OB conditions were brighter than PC at 250 lx and 500 lx, respectively.

3.2 Warmth, vibrancy, and preference

The same independent variables in the SB model were also included in the rest of the rating scale measures. Table 6 shows the results of these models. For warmth, the model indicated a statistically significant effect of spectrum, but not any of the other main effects. The effect was consistent at both illuminance levels, with OB rated as warmer, but the difference was greater at 250 lx (see Figure 4).

Regarding vibrancy, there was a statistically significant impact of illuminance level, spectrum, and presentation order on the response. As shown in Figure 4, OB conditions appeared significantly more vibrant than PC at both illuminance levels, and the 250 lx OB condition was more vibrant than the 500 lx PC condition. While reducing illuminance typically leads to a reduced perception of colorfulness (Hunt

1952), the OB spectrum was able to substantially counteract that effect over the 50% reduction in illuminance.

Table 6: Type III analysis of variance table with Satterthwaite's method of the mixed linear model of warmth, vibrancy, and preference ratings.

	Term	Sum.Sq	Mean.Sq	NumDF	DenDF	F.value	Pr(>F)
Chromaticity	Illuminance	0.1	0.1	1	68.7	0.1	0.817
	Spectrum	14.1	14.1	1	61.0	9.0	0.004**
	Present order	0.9	0.9	1	29.5	0.6	0.461
	Age	0.4	0.4	1	27.3	0.3	0.611
Vibrancy	Illuminance	28.7	28.7	1	50.8	17.5	0.000**
	Spectrum	61.4	61.4	1	65.5	37.5	0.000**
	Present order	7.5	7.5	1	28.4	4.6	0.041*
	Age	0.6	0.6	1	26.8	0.4	0.542
Preference	Illuminance	17.6	17.6	1	51.5	8.4	0.005**
	Spectrum	10.0	10.0	1	64.8	4.8	0.032*
	Present order	6.3	6.3	1	28.0	3.0	0.093
	Age	4.2	4.2	1	26.2	2.0	0.169

Lastly, the preference model showed a significant effect of illuminance level and spectrum on the response. At both illuminance levels, there was greater preference for the OB condition compared to the PC condition. The 500 lx conditions were both more preferred than the 250 lx conditions. Rated brightness was more strongly correlated with rated preference than vibrancy, but all three showed similar trends in favor of the OB spectrum.

3.3 Visual Performance

The linear mixed model for the numerical verification task showed statistically significant effects for illuminance, spectrum, presentation order, and the interaction of spectrum and illuminance. The numerical verification score for the 500 lx OB condition was significantly higher than all other conditions

Table 7 shows linear mixed models for the numerical verification (NV) and visual search tasks. The interaction term between illuminance and spectrum was statistically significant in the NV model, hence this term was retained. Table 7: Type III analysis of variance table with Satterthwaite's method of the linear mixed models of NV score and visual search count.

	Term	Sum.Sq	Mean.Sq	NumDF	DenDF	F.value	P
NV	Illuminance	2.1	2.1	1	54.0	5.9	0.019*
	Spectrum	2.9	2.9	1	93.7	8.0	0.006**
	Presentation order	16.1	16.1	1	28.1	45.2	0.000**
	Age	0.0	0.0	1	84.3	0.0	0.972
	Illuminance:Spectrum	5.5	5.5	1	92.9	15.4	0.000**
Visual search	Illuminance	13.5	13.5	1	85.2	3.8	0.055
	Spectrum	0.3	0.3	1	84.9	0.1	0.790
	Presentation order	30.1	30.1	1	67.2	8.4	0.005**
	Age	58.9	58.9	1	28.1	16.4	0.000**

($p < 0.001$); that is, spectrum had an effect at 500 lx but not 250 lx. There was no statistically significant difference in NV scores between the two 250 lx conditions, and there was no difference overall between the 500 lx PC and the 250 lx conditions.

In contrast with the numerical verification task, the linear mixed model for the visual search task indicated statistically significant effects only for presentation order and age. Neither illuminance or spectrum were statistically significant factors, likely because the lighting conditions were sufficiently above threshold. Nonetheless, the means follow a similar trend to the numerical verification data, with the 500 lx OB having the highest mean, indicating the best performance (see Figure 5).

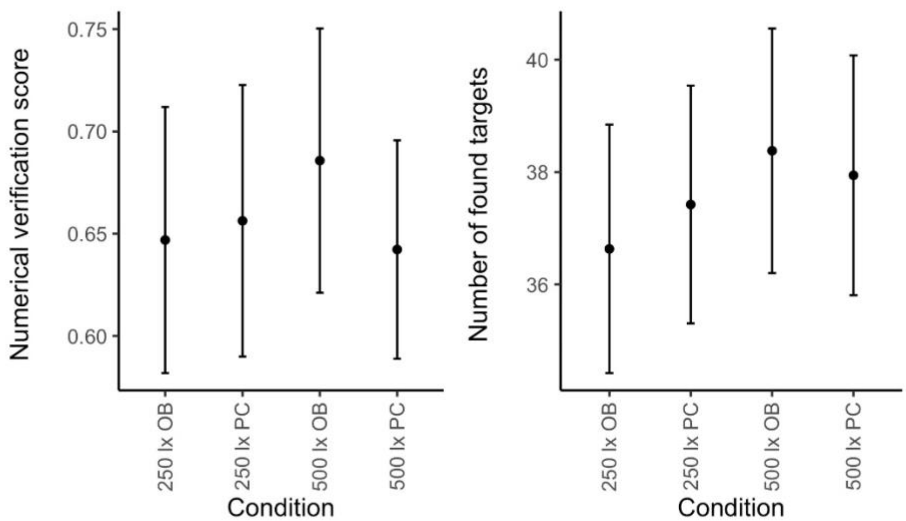

Figure 5. Mean and 95% confidence interval results for the participant's performance on the numerical verification task (left) and visual search task (right).

3.4 Glare and Visual Fatigue

When the two spectra were compared at each illuminance level using the Fischer's exact test, we did not find a significant difference in responses for glare (Y/N), eye discomfort, eye fatigue, or difficulty focusing (see Figure 6 and Table 8). Using LMMs (not shown), there was no difference in blink rate or duration by lighting condition; there were no significant terms in either of these two models.

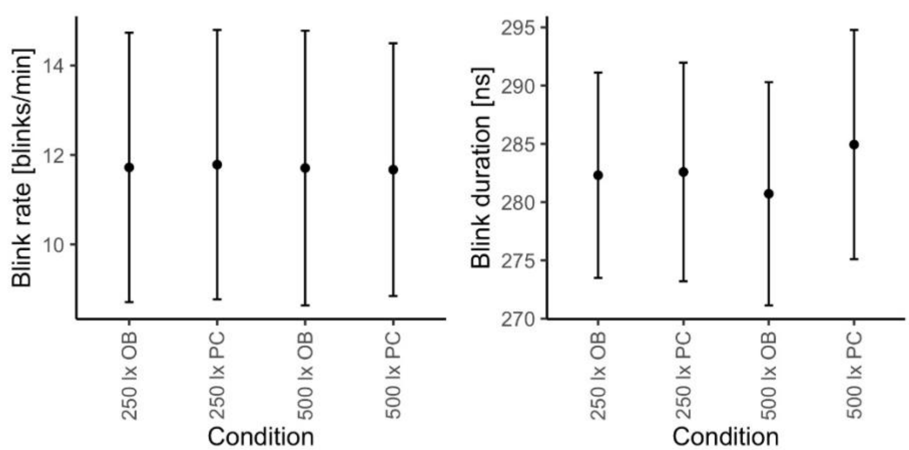

Figure 6. Mean and 95% confidence interval values for blink rate and duration for each lighting condition.

Table 8: The distribution of responses to glare (Y/N), eye discomfort, eye fatigue, and difficulty focusing.

		250 lx OB	250 lx PC	500 lx OB	500 lx PC
Discomfort from glare	No	25	26	21	24
	Yes	5	4	8	5
Eye discomfort	Absent	19	17	20	17
	Slight	9	12	9	11
	Moderate	1	1	0	1
	Severe	1	0	0	0
Eye fatigue	Absent	12	9	13	11
	Slight	13	15	13	14
	Moderate	3	6	3	3
	Severe	2	0	0	1
Difficulty focusing	Absent	15	11	17	14
	Slight	9	14	9	11
	Moderate	4	5	3	3
	Severe	2	0	0	1

4. Discussion

After 20 minutes spent under each lighting condition, the OB spectrum—with enhanced $R_{cs,h1}$—made the room appear brighter than the PC spectrum at each illuminance level. Of the 60 brightness ratings (30 participants at 2 illuminance levels each), 28 were brighter for the OB spectrum, 16 were a tie, 15 were brighter for the PC spectrum, and 1 comparison could not be made due to missing data. The proportion was slightly higher at 500 lx compared to 250 lx (see Table 5). Note that these were not direct choices, but a comparison of two rating values obtained independently without direct visual comparison.

To contextualize the SB result, we re-evaluated the data from Royer et al. (2024) in the same way—converting rating scales to binary ranks—using the two most similar SPDs (SPDs identified as 4/46 for PC and 8/50 for OB [500lx/250 lx]). Across the same two illuminance levels, the numbers are very comparable: 29 of 64 pairs of evaluations were rated as brighter for the OB-like spectrum, 15 were the same, and 19 were higher for the PC-like spectrum, with 1 not possible due to a missing data point. Notably, the effect was stronger at 500 lx (19/8/4/1) and actually the opposite at 250 lx (10/15/7/0)—although condition 50 at 250 lx appeared to be anomalous given broader trends in that experiment. As a reminder, in that experiment, evaluations were made after 20-seconds of exposure to an individual stimulus and the participants did not perform any tasks.

In contrast, in the current experiment the OB spectrum almost always (93% of observations) led to the room being chosen as brighter following 5-second sequential viewing conducted at the end of the experiment. While all three of these results point to the OB spectrum increasing perceived SB, the latter suggests that comparative, rapid evaluations may lead to reduced noise (i.e., a procedural effect where the choice is more straightforward and repeatable than the rating) or a stronger effect (i.e., a greater visual difference resulting from the reduction in time to adapt and lack of washout between stimuli, whereby the effect of object color changes on SB are perhaps amplified relative to other effects). Differentiating between these two mechanisms is not possible with the current data. Nonetheless, it is an important finding that the prior 20-second individual exposures produced results more like 20-minute individual exposures than rapid sequential exposures.

While the statistical model indicated that there was an overall significant difference in SB by spectrum but not a significant interaction effect with illuminance, it can be observed in Figure 4 that the difference was slightly smaller at the 250 lx level. Again, this is in line with earlier results where the impact of $R_{cs,h1}$ on SB was stronger at the 500 lx level compared to 250 lx level. While the present experiment did not provide any new insight on this interaction effect for SB (although the interaction was present for numerical verification), it would be possible to examine in future work by including additional illuminance levels. The effect may be linear or non-linear, and ideally both should be accounted for in the experimental design.

Regarding visual performance, there was an improvement in numerical verification scores under 500 lx OB compared to 500 lx PC, but there was no difference at 250 lx and there was no difference based on spectrum for the visual search task. Visual performance may have been improved by increasing alertness, which is linked to spectrum. There were unavoidable but relatively small differences in melanopic content: the mel-DER was approximately 14% and 9% lower for PC spectra compared to OB at the 500 lx and 250 lx levels, respectively. Higher melanopic content would be expected to increase alertness, although the performance differences observed from a relatively small difference would be unexpected. Red light has also been linked to alertness, so the changes in color rendition may have also contributed—again, it is difficult to isolate the relative contributions as mel-DER and $R_{cs,h1}$ are correlated. It is possible that one or both mechanisms interact with illuminance to produce the net effect shown. Further investigation is necessary.

A third explanation of the improved NV scores under 500 lx OB is the smaller pupil diameter under this condition compared to 500 lx PC and the two 250 lx conditions (Figure 7), which might have contributed to visual acuity. A linear mixed model in the same form as others previously reported showed that both illuminance and spectrum had a statistically significant effect on pupil size ($p < 0.001$). This explanation seems implausible because the mean NV score for 500 lx PC was lower than both 250 lx conditions despite the former having a significantly smaller pupil diameter. Both illuminance levels would generally be considered above threshold, where differences in pupil size would not be expected to have significant effect on visual performance.

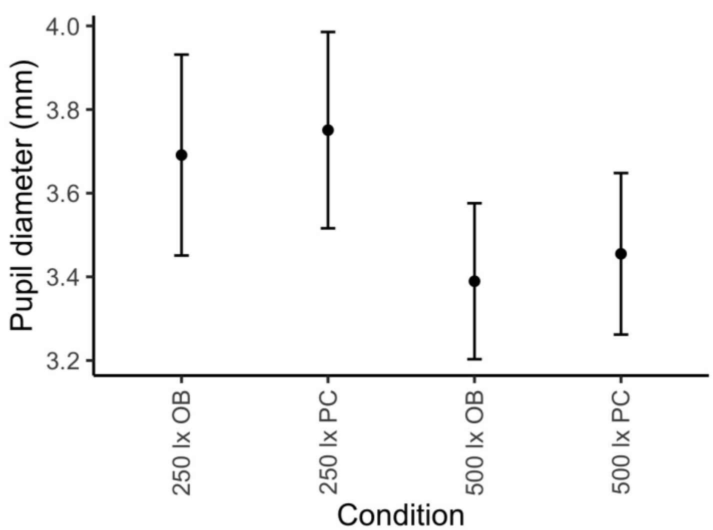

Figure 7. Means and 95% confidence intervals of pupil diameter by lighting condition.

4.4 Limitations and Future Work

This study featured four SPDs, and studies of spectral effects relying on a limited number of SPDs are prone to confounding or hidden factors. However, this was a follow-up to a prior experiment that was more exploratory in nature, utilizing 60 SPDs. One of the primary goals of this work was to explore if longer term exposure while performing office-like tasks would lead to different findings than short-term evaluations. There were some carryover order effects, and further validation with even longer exposures or more separation between evaluations (i.e., on different days) would be warranted. Even longer duration exposures may allow for additional adaptation or signaling from ipRGCs. A field study comparing optimized and baseline conditions is justified.

Ideally, mel-DER would be held constant between the BO and PC conditions, but this was not possible within the other spectral constraints and the constraints of the lighting system. Although it was minimized (and previously found not to be statistically significant for subjective SB assessments in a similar context), the small difference in mel-DER may have contributed to a difference in pupil size, which could have contributed to the observed difference in numerical verification performance. While there was some correlation between pupil size and performance, this experiment was not designed to find a causal effect in this domain. Given the present results interaction of different mechanisms is possible.

5. Conclusion

Overall, the findings from this experiment are consistent with prior work: over longer durations of exposure, the spectral effects on SB were reduced in size but remained significant. We found that a spectrum optimized to increase SB by increasing red chroma shift (and slightly increasing the ratio of melanopic content) led to the office-like room being rated as brighter. The effect was slightly greater at 500 lx than 250 lx, although there was not a statistically significant interaction effect in this experiment. After 20 minutes of exposure to each SPD while performing paper-based visual tasks, 65% of the (non-tie) ratings for the red-chroma-enhancing optimized SPD were lower (i.e., brighter) than for the non-optimized SPD (similar to a typical blue-pump LED) at the same illuminance. In contrast, when viewed in a sequence alternating every 5 seconds, 93% of participants chose the optimized SPD as brighter. As expected, the SPD optimized for spatial brightness was rated as providing more vibrant colors and was more preferred; thus, there is an opportunity to simultaneously improve quality and reduce energy use.

The SPD optimized for spatial brightness did not lead to statistically significant changes in perceived glare, eye fatigue, eye discomfort, or difficulty focusing. The effects on visual performance were mixed: the optimized SPD improved performance on the numerical verification task at 500 lx, but not at 250 lx. The trends were similar for the visual search task, but no differences were statistically significant. Given the presence of statistically significant interaction terms (as was found in the initial experiment for spatial brightness), investigation of spectral effects at more illuminance levels is warranted.

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Declaration of competing interest

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

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