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Office Lighting for Light-Sensitive Individuals: A Pilot Test

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Executive Summary

Background

Documents that specify office lighting requirements are written to provide suitable working conditions for the majority of employees while also balancing the need to be energy efficient. The implementation of those requirements in any particular instance also reflects the need to balance the architectural and interior design features of the space within the budget. The result can be adequate lighting for most public servants, but might not provide a good fit for employees with special requirements, particularly those with light sensitivities of various kinds. With the coming into force of the *Accessible Canada Act*, the need to provide accommodation for this group has been brought into greater focus.

Most workplaces have a fixed grid layout, often of recessed luminaires (light fixtures), with a single on/off control for a large area. This leaves one option for changing the workplace lighting at a given workpoint: to remove the light source from the luminaire directly over the cubicle (fluorescent lamps in the past, LED tubes now) and to rely on the lower level of light received from nearby luminaires. When the luminaire has LED boards integrated into the housing, this option is not available. Other accommodation options for individuals have been to relocate to a place with a different installation or to work from home. Some individuals have made personal modifications such as wearing sunglasses indoors, wearing a hat with a brim to block overhead light, or otherwise shielding the overhead light. None of these is an elegant solution, and few would argue that these solutions meet the mandate established by the *Accessible Canada Act* to provide a safe, accessible, and inclusive workplace.

Testing a new lighting solution

With funding from the Centralized Enabling Workplace Fund, Public Services and Procurement Canada (PSPC) and the National Research Council of Canada (NRC) conducted a pilot test of a new lighting solution in summer-fall 2021. The goal was to identify a lighting system that might serve the needs of both the community of light-sensitive public servants and the larger general population. If successful, this new solution might become a way to provide an inclusive environment for all public servants, reducing the need for individual accommodations.

The joint PSPC-NRC team explored various solutions, learned about lighting innovations elsewhere in the public service, and took guidance from members of the light-sensitive community before settling on a target lighting solution from an Ottawa-based manufacturer. The NRC team contributed its expertise in office lighting quality to narrow down the specifications for the chosen system. Health Canada's Learning Centre in the Brooke Claxton building loaned its space for the pilot test, which made it possible to install the test lighting and compare it to conventional office lighting in an accessible space with suitable security while also following the public health guidance on physical distancing during the COVID-19 pandemic. The pilot test took place in two classrooms that normally would accommodate 12 people each, but for this study during the pandemic only one person occupied each room at a time.

The reference lighting – the typical lighting in many public service offices – consisted of recessed luminaires 1 foot wide by 4 feet long, with acrylic lenses with a prismatic ('bumpy') surface designed to spread the light somewhat, while still directing most of the light directly down to the desk surface. The light sources in the luminaires were LED tubes that are in widespread use across Government of Canada offices with a correlated colour temperature (CCT) of 4000 K and colour rendering index of ~80. This system was not dimmable, and it was designed to deliver ~420 lx on the desk surface. The reference lighting is shown on the left side of Figure ES1 and the top of Figure ES2.

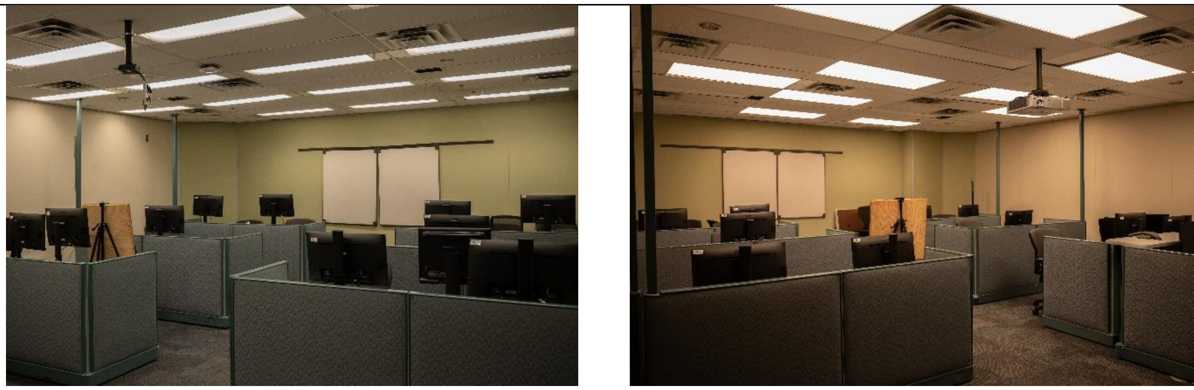

Figure ES1. The view from the front of the Brooke Claxton classrooms, reference lighting left and test lighting right.

The test lighting consisted of recessed luminaires 2 feet wide by 4 feet long. These integrated LED luminaires have a proprietary optical design that delivers the light in a more diffuse way, with more light directed to the sides, and less directly down, than the reference lighting. These LEDs had a slightly warmer CCT of 3500 K, and a higher colour rendering index (~90). This means that the lighting appeared less blue and it provided a more accurate colour appearance. The test lighting was dimmable over a range from ~50 lx to ~800 lx. This is a much larger range than would be installed in a regular office, but it was a deliberate choice for this pilot test to enable participants to have a broad choice of lighting conditions to meet their needs. The right side of Figure ES1 and the bottom of Figure ES2 show the test lighting. By comparing the two rooms one can see the difference in the light distribution. The difference in colour appearance is not accurately shown in these photos.

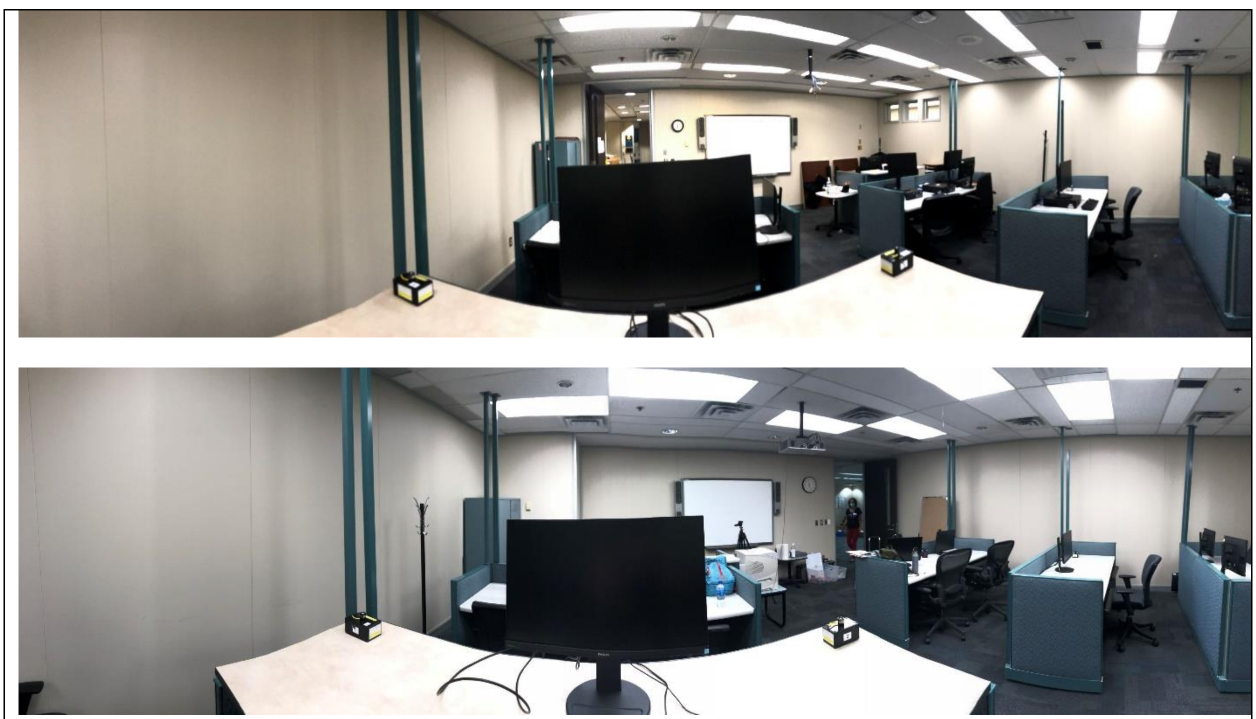

Figure ES2. Panoramic views of the two rooms, from the vantage point of the seated occupant. The top photo shows the reference room, and the bottom photo shows the test room.
Note that the colour appearance has not been corrected in these images.

How the test proceeded

The research protocol was reviewed and approved by the NRC Research Ethics Board. Research ethics review seeks to ensure that research projects meet Canadian standards of ethics. Knowing that participants might experience adverse effects from the lighting conditions, a dedicated commissionaire with first aid training was present at all times during testing sessions.

Over the summer of 2021 we recruited 14 public servants with light sensitivities who lived in the National Capital Region. The light sensitivities could be either self-identified or from a medical diagnosis. These people heard about the project through the Employment Equity Champions and Chairs Committee (EECCC). In October and November 2021 we recruited another seven participants (NRC employees) from the National Capital Region who did not have light sensitivities. We also had one case study participant who had limited light perception but was legally blind.

We asked participants to spend four workdays in the test office environment, two days in the reference room and two days in the test room. Most people followed this pattern, although schedules prevented some people from completing all four days, and some chose to limit their exposure to the reference room (this will be discussed below). Some people experienced the reference lighting first for two days; others started in the test lighting. The four days were spread over two weeks, always the same two days for any individual (Monday-Tuesday, or Thursday-Friday). Deep cleaning and ventilation on the Wednesday and over the weekend was part of the COVID protocol, as were requirements for physical distancing and the wearing of an NRC-supplied mask at all times.

One NRC researcher was present for each participant testing day, to ensure that things went smoothly. For most of the time participants did their own work on their own laptops, alone at an assigned location in one room or the other, where there was a sit-stand desk, a monitor, a keyboard and a mouse provided for their use. They also were permitted to bring their own peripheral devices, if preferred. Participants could choose between using WiFi and a network cable for Internet access. At three times each day (8:45, 11:30, and 15:30), an off-site NRC team member sent an e-mail invitation to each participant, asking them to complete a questionnaire about their feelings, their judgements about the lighting and the room, and their experience of visual and physical health symptoms. The questionnaires used validated scales from prior research. These repeated questionnaires allowed us to observe any developments over the workday. In the mornings we also asked about their sleep on the preceding night. There was an additional questionnaire invitation sent on the morning of the third day in each sequence (i.e., the Wednesday or the Saturday after each two-day visit to the test site). These morning questionnaires allowed us to see whether there were any aftereffects from working under one lighting type or another.

During the testing days, lighting conditions and the height of the sit-stand desks were monitored in both rooms. This made it possible to see whether or not the lighting controls had been used, and what light levels were chosen, and verified that the levels were stable in the reference lighting room. Before the start of testing in July, and after its conclusion in December, NRC researchers conducted extensive physical measurements of both lighting conditions.

What did we find?

The focus of this pilot test was on the effects of the lighting on the light sensitive participants, with the hypothesis being that the test lighting system, which was designed to be a good-practice solution based on scientific evidence, would result in better ratings of the lighting, better mood, and fewer physical and visual health problems. The aim for the general population participants was to verify that the test lighting did not cause any unintended ill effects for the general population. This Executive Summary focuses on the lighting comparisons, rather than on effects of the time of day or day in the study (which were few in any case). The results reported here are statistically significant effects from linear mixed models analyses (with a few exceptions, noted below).

Use of lighting controls

The light-sensitive participants were somewhat more likely to use the lighting controls, and they dimmed the lighting down from the high starting level in the test lighting room to a level that was in many cases lower than the level in the reference room (Table ES1). This resulted in the test lighting room being, on average, lit to a higher level for the general population group than the light sensitive group and it was higher for many people in both groups than would be typical of electric lighting in public service offices. People who used the controls in both groups tended to make a choice in the morning and not to change it throughout the day.

Table ES1. Average lighting levels and lighting choices for the light sensitive and general population groups.

Reference lighting	**Light-Sensitive N=12 Photopic illuminance (lx)**	**General Population N=7 Photopic illuminance (lx)**
Desk surface	404	404
Vertical, seated eye height	222	222
Test lighting		
# of controls users	8/12	3/7
Desk surface (measured)		
Mean	485	657
St. Dev.	280	186
Median	353	783
Maximum	795	785
Minimum	62	254
Vertical, seated eye height (calculated from pretest measurements)		
Mean	371	499
St. Dev.	209	138
Median	272	593
Maximum	602	595
Minimum	55	198

Office Lighting Survey judgements

One of the judgements about the lighting in the two rooms involved agree/disagree statements for which normative data exist. The normative data (from offices in the northeastern United States with similar lighting to the reference room in this study), tell us what percentage of office workers can be expected to agree with each question. Table ES2 and ES3 summarize the answers to these statements after people had experienced each room for up to two days, at the end of the day. The light-sensitive participants agreed that “the light fixtures are too bright” in both rooms, to a higher degree than the normative sample, and that the reference (old) lighting was uncomfortably bright for their tasks (Table ES2. A higher-than-normative percentage of the light-sensitive participants judged the test lighting to be better than the lighting in most workplaces (Table ES3).

The general population group also agreed that ‘the light fixtures are too bright’ to a higher degree than the normative sample (Table ES2), even though the light level from those luminaires was lower in the reference room than the test room. They also agreed more than expected with the statement “my skin is an unnatural tone under the lighting” in the reference room (Table ES1), where the colour rendering index was lower. Their judgements of whether the room lighting was worse, the same, or better than in other places did not differ from the normative sample (Table ES3).

Table ES2. Office Lighting Survey responses in the afternoon of the second testing day for agree/disagree statements.

Item	Norm	Light Sensitive – Day 2 Reference N = 9	Light Sensitive – Day 2 Test N = 11	General Population - Day 2 Reference N = 6	General Population - Day 2 Test N = 7
	Agree %	Agree %	Agree %	Agree %	Agree %
1. Overall, the lighting is comfortable.	69	67	82	83	86
2. The lighting is uncomfortably bright for the tasks that I perform.	16	44*	36	33	29
3. The lighting is uncomfortably dim for the tasks that I perform.	14	22	0	0	0
4. The lighting is poorly distributed here.	25	11	9	17	0
5. The lighting causes deep shadows.	15	11	0	33	14
6. Reflections from the light fixtures hinder my work.	19	22	0	0	0
7. The light fixtures are too bright.	14	44**	36*	67***	29
8. My skin is an unnatural tone under the lighting.	9	11	0	33*	29
9. The lights flicker throughout the day.	4	0	0	17	0

Note. * *p*<.05, ***p*<.01,*** *p*<.001 for comparisons between that group and normative North American data.

Table ES3. Office Lighting Survey responses in the afternoon of the second testing day for worse/safe/better statement.

Item			N	Worse %	Same %	Better %
		Norm (%)		19	60	22
10. How does the lighting compare to similar workplaces in other buildings?	Light Sensitive	Reference Day 2	9	11	78	11
	Light Sensitive	Test Day 2	11	9	36	55*
	General Population	Reference Day 2	6	33	50	17
	General Population	Test Day 2	7	14	57	29

Note. **p*<.05 for comparisons between that group and normative North American data.

Lighting quality and room appearance appraisals

This category includes seven measurements: lighting quality (1-5), bothersome glare (1-5), room brightness (0-100), room clarity (0-100), room attractiveness (0-100), room colourfulness (0-100), and personal appearance (0-100). Personal appearance was judged after looking at one's own image in a mirror provided for the purpose; given the need to remain alone in the room, this was a good proxy for judging how other people might look under the lighting. We have focused on the assessments made in the afternoon of each testing day.

Both groups had large, statistically-significant effects for lighting quality and personal appearance (Figure ES3). The test lighting was rated as having better lighting quality for both the light-sensitive and general population samples, and it gave a better personal appearance as well. The general population group also rated the test lighting as giving a brighter room appearance (consistent with the light level measurements) and being more attractive.

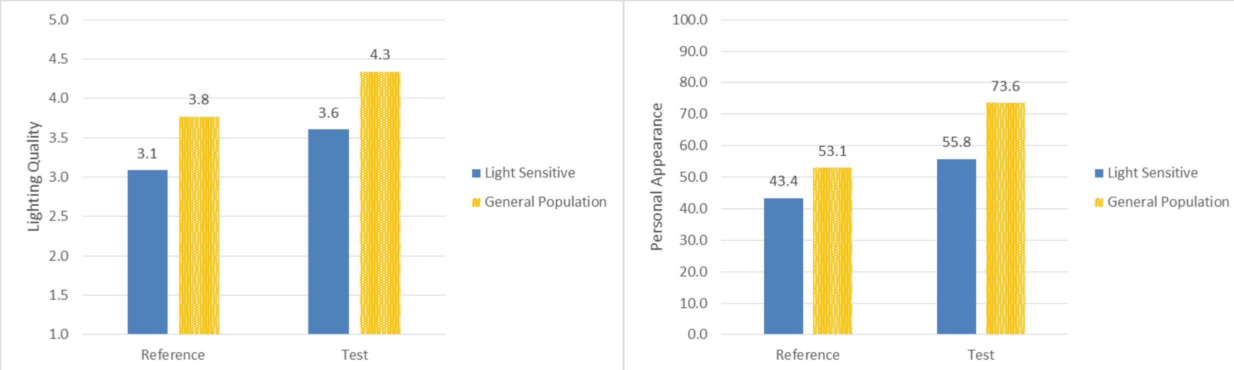

Figure ES3. Lighting quality and personal appearance judgements were higher in the test lighting for both the light-sensitive and general population groups.

At-work mood and health

At three times daily, participants answered the same questions about mood (pleasure and arousal, each scored 1-9), average visual health symptom intensity (smarting, itchy, or aching eyes; sensitivity to light; teary eyes; dry eyes, scored 0-4), and average physical health symptom intensity (sore back, wrists or arms; excessive fatigue; headache; difficulty thinking; emotionally upset; anxious; hypersensitivity to stimulation, scored 0-4). The morning responses were taken as the baseline, and we examined the change from this state at lunchtime and at the end of the day.

Figure ES4. This shows the average change (from the morning baseline) in visual symptom scores following exposure to the lighting conditions.

The light-sensitive group showed a statistically significant, medium-sized effect for visual symptoms (Figure ES4). The light-sensitive group had started the testing days with an average visual symptom score of 0.8 (on a scale from 0-4), and the general population group started the days with an average of 0.2. Averaged over the whole exposure (all times, both days), visual health symptoms tended to increase slightly in the reference lighting and to decrease slightly in the test lighting for the light-sensitive group, but the general population showed the same small increase in visual symptoms in both lighting conditions.

Carryover effects on sleep, mood, and health

In addition to the mood (pleasure and arousal) and health symptoms (visual and physical), in the mornings we also inquired about the previous night's sleep: the ease of falling asleep, sleep quality, and sleep duration. These were tested for differences between the rooms on the mornings following each day under the reference and test lighting conditions, to see whether there were after-effects of the lighting exposures. Only the visual health symptoms showed a difference, and only for the light-sensitive group (Figure ES5): on days after the test lighting, their visual health symptoms were lower than on days following the reference lighting.

Another indicator of the different effects of the lighting on the light-sensitive group was participation. Four participants of 13 chose not to return for a second day in the reference lighting, citing that they had felt unwell after the first day. One of these withdrew from the study completely. Everyone scheduled for a second day in the test lighting returned.

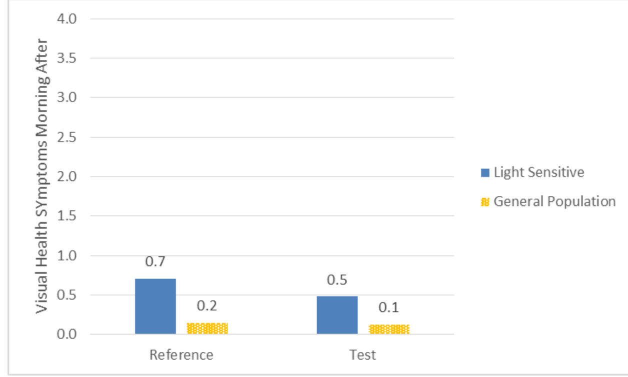

Figure ES5. After-effects of light exposures on visual health symptoms.

Case study

The case study participant was an individual who is legally blind, but perceives some light in the peripheral field of view and experiences discomfort from glare in some places. Scheduling limitations meant that this individual experienced each lighting condition for one day only, with the reference lighting first and the test lighting second. This individual did choose to lower the light level in the test lighting, making it similar to the reference lighting. The NRC experimenter assisted with questionnaire responses; those that required vision were excluded (e.g., personal appearance judgements). The case study participant agreed that the test lighting was comfortable, judged the test lighting to be better than in most workplaces, and gave it a higher score for lighting quality than the reference lighting. This participant experienced a slight increase in visual health symptoms over the day in the reference lighting, and a very small decrease in the test lighting.

Personal light recipes

At the end of each person's participation, we asked for their personal light recipes: The lighting they would have if they had free choice over their office lighting. Both the light-sensitive and general population groups emphasized the importance of daylight and the ability to personally adjust the light level. Among both groups, between 1/3 and 1/2 expressed a preference for a warmer colour to the light and half mentioned the importance of the location of overhead lights in preventing discomfort from glare.

Conclusions and next steps

The purpose of this pilot test was to determine whether this novel lighting solution might prove to be an inclusive solution to the office lighting needs of light-sensitive individuals. In this, it succeeded. The test lighting reduced the incidence of visual health symptoms for the light-sensitive participants both during the workday and for the carryover effects on the following day. Both the light-sensitive participants and those from the general population judged the test lighting to have higher lighting quality than the reference lighting.

This was a short-term test with a small number of participants, which has limitations. Some elements of the test lighting would be difficult to implement in the field, particularly the individual control over the wide range of light levels. The next step for this test is to implement a more realistic installation of the test lighting over a whole floor of an office building, where public servants doing their regular work can experience this lighting for longer periods. By monitoring lighting energy use as well as regularly surveying the occupants, it will be possible to evaluate the long-term potential of this lighting solution under more realistic conditions. Such a test is currently being planned.

1 Introduction

There is a subset of the general population that is subject to health problems triggered by light exposure. This diverse group includes people who experience migraines and those who experience asthenopia, which is a constellation of symptoms of eye fatigue including dry eyes, itchy eyes, blurry vision and headache. For the most part the causes of these problems are unknown and they appear early in life, but these problems can also arise later, for example as a result of traumatic brain injury. Whatever the cause, some of these problems are severe enough in response to common office lighting that the individual seeks a workplace accommodation to ensure a healthful workplace that supports their needs.

This investigation is an applied project to seek a lighting design solution that might be an effective intervention across the Government of Canada. In this phase, a small number of light-sensitive individuals will experience the proposed new lighting solution as well as the standard office lighting solution, to test the hypothesis that the new solution provides a more comfortable, healthful, and appropriate workplace.

2 Method

This investigation was reviewed by the NRC Research Ethics Board (REB) as protocol 2021-36. REB review seeks to ensure that research projects meet Canadian standards of ethics. In addition, because the data collection took place during COVID-19 restrictions on in-person work, the data collection protocol (Special COVID Operating Procedure) was also reviewed and approved by the Director General of the NRC Construction Research Centre to ensure that the risk of contracting the SARS-CoV-2 virus would be kept acceptably low and that the on-site practices required of NRC staff would be respected.

2.1 Participants

2.1.1 Demographics

Two groups of participants were recruited in sequence. The first group consisted of 14 people who experience a light sensitivity, either medically diagnosed or self-identified. The investigation was designed to test whether the novel lighting solution would prove beneficial to this group. The second group excluded people with a known light sensitivity. This group of seven participants was smaller because of time limitations, having been added to provide a check on the possibility that the novel lighting solution might have unintended adverse consequences for the general population. Table 1 shows the demographic characteristics of the two groups. The distributions of the characteristics were similar despite the different group sizes.

The last row of Table 1 and the frequency distribution in Figure 1 show that the two groups were markedly different in light sensitivity as assessed with the Leiden Visual Sensitivity Scale (Perenboom et al., 2018), as had been planned. There was slight overlap between the groups, but the group assignments were not changed because the recruitment information had differed between them. Participants were asked if they had received a diagnosis of a medical condition related to a light sensitivity. In the general population group, none reported such a diagnosis. In the light-sensitive group, nine reported a diagnosis, of which five were related to an injury. The non-injury causes with labels included albinism, sequelae of a childhood eye infection, migraine, and unknown origin. All of the light-sensitive individuals reported using a light-related accommodation, and most of these were aimed at reducing the light level, with eyewear (including sunglasses) being the most commonly reported. Dimming the overhead lighting or having the lights off or delamped were also common; one person in the light sensitive group reported having been unable (pre-pandemic) to work in an office at all. In the general population group, no one reported using a light-related accommodation.

One additional participant provided case study data, which were treated separately and are reported below in section 3.3. This individual has very limited light perception and is legally blind, but experiences light sensitivity. Further demographic details on the case study participant will not be reported to respect the requirements for privacy protection.

Table 1. Demographic characteristics of participants, by group.

Sex	**Male**	**Female**	**Prefer not to say**			
Light sensitive	4	8	2			
General	2	5				
Age	**18-29**	**30-39**	**40-49**	**50-59**	**60+**	**Missing**
Light sensitive	2	3	5	4		
General	1	2	2	2		
Highest Education	**High school**	**College or technical**	**Some university**	**Undergrad degree**	**Graduate or professional**	**Missing**
Light sensitive		2		6	6	
General				1	6	
Job type	**Administrative**	**Technical**	**Professional**	**Managerial**	**Missing**	
Light sensitive	1	1	11	1		
General			5	2		
Work experience	**Median years in workforce**			**Median years with current organization**		
Light sensitive	23.5			4.00		
General	18.00			3.00		
Vision correction	**None**	**Reading**	**Distance**	**Bi/tri focals**		
Light sensitive	5	4	3	2		
General	4	1	1	1		
Leiden Visual Sensitivity Scale		**Average (SD)**	**Median**	**Minimum**	**Maximum**	
Light sensitive		17.57 (7.57)	16.5	6.00	29.00	
General		6.86 (4.06)	7.00	2.00	14.00	
Health condition related to light sensitivity			**Diagnosed**	**Self-reported**	**Unknown**	**No**
Light sensitive			9	4	1	0
General			0	0	1	6

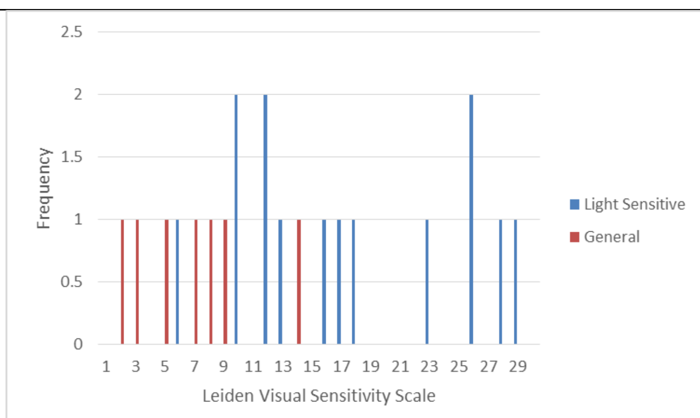

Figure 1. The frequency distribution of Leiden Visual Sensitivity Scale scores clearly differed for the two groups.

2.1.2 Lighting beliefs and knowledge

We assessed knowledge about lighting and beliefs in effects of light and lighting in all participants (Veitch & Gifford, 1996; Zhang, 2018). These revealed differences between the two groups in beliefs, but comparable levels of knowledge (both high, median scores ~8 of 10). Table 2 shows the results for each group. There are some notable differences (interpreted as scale scores differing by more than 0.5) between them. The light-sensitive participants placed greater importance on lighting and had stronger beliefs in minor health effects (headache, eyestrain), the median of 3.25 (maximum 4) for the light-sensitive group indicates that half of the participants had scores on this subscale larger than this. Conversely, the general population group had stronger beliefs concerning brightness and daylight than the light-sensitive group.

Table 2. Descriptive statistics for the overall Lighting Beliefs Questionnaire score and six subscales, and Lighting Knowledge test.

	Overall Lighting Beliefs	Lighting Importance	Brightness Effects	Major Health Effects	Minor Health Effects	Social Behaviour Effects	Daylight Effects	Lighting Knowledge test
Light-sensitive								
Mean	2.49	3.25	1.38	1.88	3.16	2.39	3.14	7.86
SD	0.32	0.64	0.89	0.94	0.52	0.52	0.71	1.35
Median	2.51	3.25	1.38	1.83	3.25	2.40	3.25	8.00
General								
Mean	2.36	2.79	2.25	1.48	1.96	2.23	3.71	8.00
SD	0.35	1.12	0.84	0.66	0.64	0.45	0.23	1.53
Median	2.26	2.50	2.25	1.33	2.00	2.20	3.75	8.00

Note. The Lighting Beliefs Questionnaire overall score and subscales are averages of contributing questions, minimum possible score 0 and maximum possible score 4. The Lighting Knowledge Test is scored from 0-10 with each correct question scored as 1.

2.1.3 Participation rate and order

Of the 14 participants in the light sensitive group, 12 experienced both lighting conditions for at least one day. One person experienced the reference lighting condition for one day, and then withdrew from the study. Three others did not return for a second day in the reference lighting but did return for two days in the test lighting. Two people had time only to participate in one week; one of these experienced only the reference lighting, and one experienced only the test lighting. One person missed a day in the test lighting for reasons unrelated to the investigation. Thus, the reference lighting had 13 participants on day 1 and 9 on day 2; the test lighting had 12 participants on day 1 and 11 on day 2. Six of the participants in the general population group completed all four days. One person missed one day in the reference lighting condition for reasons unrelated to the investigation.

The schedule was constructed to try to balance order effects, with half of the sample starting in the reference room and half in the test room. Despite the many schedule changes, the balance was nearly achieved: In the light-sensitive sample, eight people experienced the reference room first, and six people experienced the test room first. In the general population sample, three experienced the reference room first and four experienced the test room first.

2.2 Site and lighting

Two windowless classrooms, each normally serving 12 students at a time, at the Health Canada Learning Centre served as a field laboratory for this pilot experiment. One participant could occupy each room at one time in order to reduce the risk of exposing participants to COVID-19. Therefore, one desk in each room was chosen as the occupant desk; the choice of desk was based on photometric simulations (see below). The existing desk was replaced with a sit-stand desk for the duration of the investigation. The existing ergonomic chair was retained. Participants provided their own laptop computers, but the desk was equipped with a 19” computer monitor, a keyboard and a computer mouse to which they could connect; they also were permitted to bring their own peripherals or assistive devices. They had the choice of a cable connection or WiFi to connect to the Internet; this also supported the Internet-based data collection of survey data (see below).

One room was designated the Reference Room; its lighting was consistent with current Government of Canada office lighting practice (PSPC, 2021). The lighting in this room consisted of 1’ x 4’ recessed luminaires with 4000 K, R_a > 80 LED tubes, and was not dimmable. The existing parabolic louvres were replaced with prismatic lenses for this investigation to replicate a “worst-case” common office lighting condition. The other room was designated the Test Room. The luminaires in this room were replaced with a 2’ x 4’ recessed LED luminaire with a proprietary optical diffuser; these were 3500 K, R_a > 90 luminaires and were provided with dimming control. The differences in light distribution, correlated colour temperature, colour fidelity, and individual control were chosen to provide close to a “best case” office lighting installation as identified by prior research (Newsham et al., 2015; Veitch, Newsham, Jones, et al., 2010; Veitch & Whitehead, 2021). The test room lighting was designed to offer a very wide range of possible light levels, from ~50 lx to ~800 lx on the desk surface, to provide a wide range of choice for the participants in this investigation, knowing that regular field installations would be expected to cover a more narrow range.

Simulations in DIALux evo led to the choice of the middle of the three rows of desks as the location for the participant, with the goal of maximizing a difference between the two rooms. The simulations did not show a substantial risk of glare in either room, but the location resulted in an estimated unified glare rating (R_{UG}) of 19 for the reference room versus 18 for the test room. Nineteen is the generally accepted target value for this parameter (Comité Européen de Normalisation (CEN), 2021). Figure 2 shows panoramic views of the two rooms.

Detailed photometric measurements of the lighting conditions were made at the start (July 2021) and the end (December 2021) of the test period. Table 3 summarizes the light source characteristics for the reference room and five dimming levels in the test room. It shows the colour appearance of the light taking into account the reflections from the room surfaces, and validates the known differences between the two rooms. The reference room had a slightly cooler colour appearance with a higher correlated colour temperature at a chromaticity slightly above the Planckian locus (the D_{uv} parameter). The colour rendering was higher in the test room. The lighting in both rooms showed very low temporal light modulation, with neither parameter rising to the level at which visual disturbances would be expected in the general population, based on current knowledge. Values were stable across the dimming levels in the test room.

Table 3. Light source characteristics.

Condition	T_{cp} (K)	D_{uv}	R_a	R_f	P^{st}_{LM}	SVM
Reference	3916	0.0003	84	84	0.0743	0.0069
Test 100%	3302	-0.0008	94	89	0.0099	0.0130
Test 80%	3302	-0.0011	94	89	0.0493	0.0104
Test 60%	3290	-0.0011	94	89	0.0558	0.0149
Test 40%	3286	-0.0015	94	89	0.0702	0.0191
Test 20%	3283	-0.0018	94	89	0.0322	0.0225

Note. T_{cp} (K) is the correlated colour temperature, D_{uv} describes the light source chromaticity distance from the Planckian locus, R_a is the CIE General Colour Rendering Index; all from CIE 015 (CIE,2018). R_f is the CIE Colour Fidelity Index (CIE, 2017). These colour parameters were measured vertically for a seated occupant and with the computer monitor off. P^{st}_{LM} is an index of low-frequency temporal light modulation (International Electrotechnical Commission (IEC), 2017). SVM is the Stroboscopic Visibility Measure, an indicator of higher-frequency temporal light modulation (IEC, 2018). These were measured horizontally on the desk.

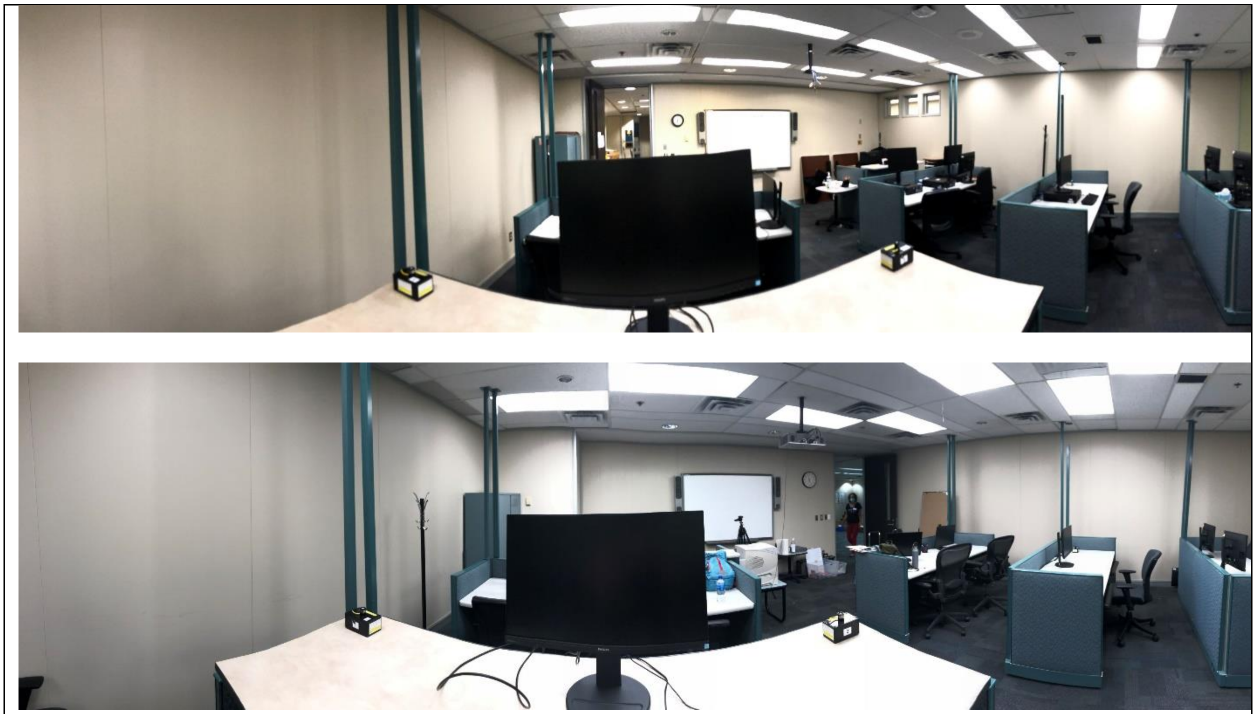

Figure 2. Panoramic views of the two rooms, from the vantage point of the standing occupant. The top photo shows the reference room, and the bottom photo shows the test room. Note that the colour appearance has not been corrected in these images.

Table 4 summarizes the light levels and light distribution in the two rooms, measured both horizontally on the desk and vertically in the direction of view. For the test room, five dimming levels were recorded. The values for the test room show that it was possible for participants to choose a wide range of light levels, with the maximum at 100% output being considerably higher than the average value in the reference room. This was a deliberate research design choice, to provide a range from which participants could choose their preferred light level, either higher or lower than the usual condition.

Table 4 also shows the difference in the light distribution resulting from the different optical design of the two luminaires. The ratio of vertical:horizontal illuminance is lower for the reference room than the test room, indicating that the lensed luminaires direct more of the light straight down onto the desk surface. The test luminaires emit less light directly down and are more diffuse, resulting a higher light level at the eye and a higher ratio of vertical:horizontal illuminance. Figure 3 shows this in the intensity distribution curves from the two luminaires, with the reference lighting[1] on the left and the test lighting on the right. This difference is also visible in the photographs in Figure 2.

[1] The intensity curve for the reference lighting is an approximation based on historical data for that luminaire type updated with the LED replacement tube currently installed. The intensity curve for the test lighting shows measured data from the manufacturer.

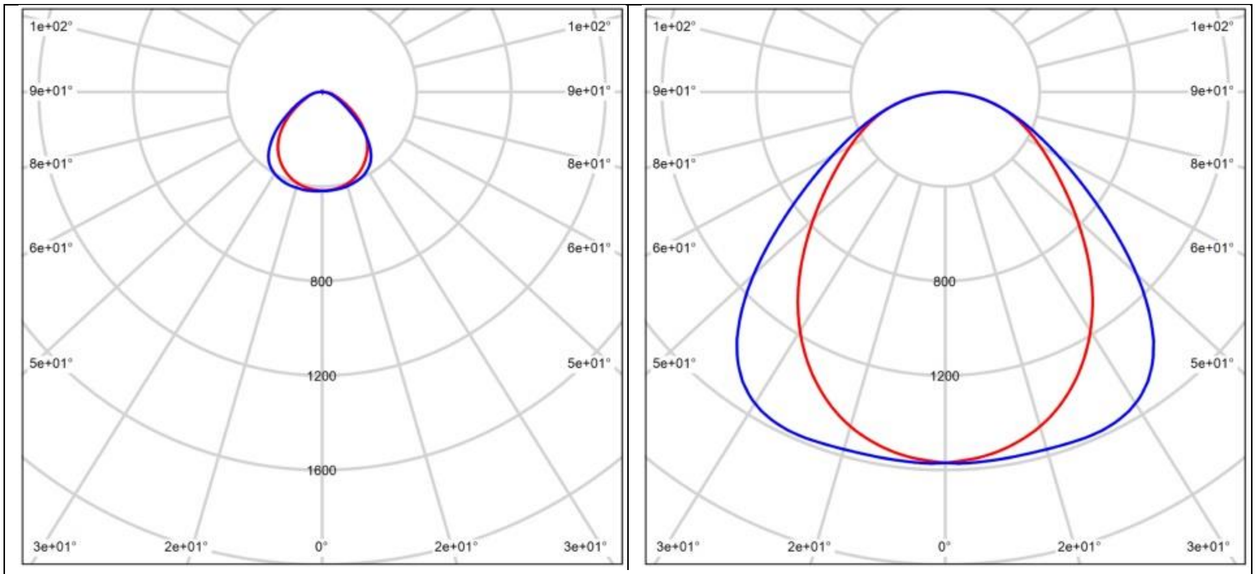

Figure 3. The intensity distributions for light from the two luminaires, with the reference lighting on the left and the test lighting on the right. The blue lines show the angular intensities measured along the short axis and the red lines show the angular intensities measured along the long axis.

Table 4. Light levels and light distribution in the two rooms, averages of measured values on two occasions.

Condition	Average desk illuminance lx seated height	Horizontal uniformity seated height	Average desk illuminance lx standing height	Horizontal uniformity standing height	Vertical illuminance seated lx	Vertical illuminance standing lx	V:H ratio seated	V:H ratio standing
Reference	411	0.44	443	0.73	226	241	0.55	0.54
Test 100%	796	0.88	865	0.87	567	632	0.71	0.73
Test 80%	632	0.88			433	489	0.69	
Test 60%	487	0.85			334	373	0.69	
Test 40%	345	0.84			247	276	0.72	
Test 20%	194	0.77			154	166	0.79	

2.3 Outcomes measured

2.3.1 Online questionnaires

Participants provided information about their responses to the lighting using online questionnaires following a schedule described below in section 2.4. Participants reported their demographic characteristics at the start of their participation: age, sex, education, job type, years in the workforce and years working in their present organization, use of corrective lenses for vision, and use of light-related accommodations in their usual workplace.

Their light sensitivity was assessed using the Leiden Visual Sensitivity Scale (Perenboom et al., 2018), which is a validated 9-item scale in which individuals rate their experiences on a scale from 0-4 for such questions as “To what extent are you bothered by electric lighting?” ”When you look at a bright light, is your eyesight worse afterwards (e.g., blurred or distorted vision)?” and “When you look at everyday patterns, do you experience afterimages? (Seeing an image of the pattern elsewhere, for instance, on a white wall)”. The score on this scale is the sum of the responses, with a range from 0 to 36 and higher scores indicating greater sensitivity; it showed excellent internal consistency reliability (Cronbach’s alpha = 0.91 for the full sample). We also asked whether participants had received a diagnosis of a health condition related to light sensitivity, and what that was.

Two dimensions of mood, pleasure and arousal, were assessed using the Affect Grid (Russell et al., 1989) which is a 9 x 9 grid on which rows represent arousal and columns represent pleasantness. Participants choose one point on the grid to indicate their current mood. For example, high arousal and low pleasantness is a feeling of being stressed, whereas a feeling of low arousal and high pleasantness is a feeling of relaxation.

The room lighting was assessed with two scales. The 10-item forced-choice Office Lighting Survey (Eklund & Boyce, 1996) uses agree/disagree ratings with questions about the light level, distribution, colour appearance and flicker. Norms exist for a North American sample of offices with recessed lighting. The 10-item NRC Lighting Quality scale (Veitch & Newsham, 2000) asks for ratings on 5-point Likert-type rating scales concerning the degree of satisfaction with aspects of the lighting and the experience of glare. It results in two scores, one being an average lighting quality score over 5 items (scaled 1-5, higher values being better) and one being a rating of bothersome glare, averaged over 2 items (scaled 1-5, higher values being more bothersome). Cronbach's alpha for lighting quality scores for the full sample was very good (in room 3 on day 1, Cronbach's alpha = 0.92; in room 4 on day 1, Cronbach's alpha = 0.88). Bothersome glare was inconsistent in its reliability, but acceptable (in room 3 on day 1, Cronbach's alpha = 0.88; in room 4 on day 1, Cronbach's alpha = 0.63).

Participants also rated their personal appearance with ratings on five semantic differentials, scored from 0-100 using a sliding bar. The items were natural — unnatural; colourful — colourless; unhealthy — healthy; beautiful — ugly; pleasing — displeasing. These were recoded so that higher values always reflect the better judgement. Cronbach's alpha was good (in room 3 on day 1, Cronbach's alpha = 0.78; in room 4 on day 1, Cronbach's alpha = 0.93).

A set of nine semantic differential scales scored from 0-100 provided ratings of the room appearance on four dimensions: brightness (one item), distinctness (average of two items), attractiveness (average of four items) and colourfulness (average of two items). These were originally developed by Veitch and Newsham (1998), modified to add colour (Veitch et al., 2012), and scored following de Vries (de Vries et al., 2020). Internal consistency reliability was acceptable for distinctness (in room 3 on day 1, Cronbach's alpha = 0.62; in room 4 on day 1, Cronbach's alpha = 0.78) and very good for attractiveness (in room 3 on day 1, Cronbach's alpha = 0.84; in room 4 on day 1, Cronbach's alpha = 0.88). Colourfulness was very inconsistent, being very low for room 3 on day 1 (Cronbach's alpha = 0.29) and good for room 4 on day 1 (Cronbach's alpha = 0.77).

Participants rated the state of their physical and visual health on 5-point scales from 'not at all uncomfortable' to 'extremely uncomfortable'. The score for physical health was the average of scores on eight questions, range from 0-4: sore back, wrists or arms; excessive fatigue; headache; difficulty thinking; emotionally upset; anxious; hypersensitivity to stimulation. The first four questions were adapted from the literature and have been used previously by the NRC (Veitch & Newsham, 1998), and the last four were added for this study based on contributions from a subject-matter expert. Cronbach's alpha for this new symptom list was very good (in room 3 on day 1, Cronbach's alpha = 0.90; in room 4 on day 1, Cronbach's alpha = 0.89). Visual health was the average of four symptom scores: smarting, itchy, or aching eyes; sensitivity to light; teary eyes; dry eyes. These are from the literature (Wibom & Carlsson, 1987). Cronbach's alpha for the visual health symptoms was acceptable (in room 3 on day 1, Cronbach's alpha = 0.69; in room 4 on day 1, Cronbach's alpha = 0.62).

Sleep on the nights following days in the study was assessed with four questions from Smolders and de Kort (2013). Sleep duration was the difference between time at which one went to bed and the wake time. One item asked how well participants had slept on a 7-step scale from very badly (-3) to very well (+3), and one item asked how easy it had been to fall asleep, on a 7-step scale from very difficult (-3) to very easy (+3).

At the close of their last day in the study, participants completed a revised version of the 32-item Lighting Beliefs Questionnaire (Veitch & Gifford, 1996; Zhang, 2018), which was used to determine their beliefs about the importance of lighting and the effects of lighting on behaviours and health. The questions have been revised from the original to reflect technological changes, but the original subscales for lighting importance (Cronbach's alpha = 0.73); brightness (Cronbach's alpha = 0.74); daylight effects (Cronbach's alpha = 0.71); major health effects (Cronbach's alpha = 0.63); minor health effects (Cronbach's alpha = 0.71); and social behaviour (Cronbach's alpha = 0.34) were retained along with an overall score (Cronbach's alpha = 0.71). All were averages of their contributing items and scored from 0-4. Participants also completed an updated 10-item Lighting Knowledge test to assess their familiarity with how lighting technologies work. The score was the sum of correctly answered items. This survey closed with an open-ended question to describe their personal preferred “light recipe” for good workplace lighting.

2.3.2 Test room lighting and desk height choices

Data loggers with illuminance sensors were placed on the desk across the row from the participant desk, to monitor light levels throughout the study. In the reference room this verified that the lights continued to operate normally; in the test room this provided a way to determine whether or not the occupant had used the wall dimmer to change the light level.

The light level data from the loggers were cleaned to remove times when the participant had left the room (e.g., for a lunch break). The data from the four loggers on each desk were averaged to provide a single value for a morning period (from arrival to 3.5 hours later or a lunch break, whichever came first) and an afternoon period (from return from lunch to 3.5 hours later or departure [4.5 hours if the individual remained in the room over the lunch hour], whichever came first). For the test room, instances in which the light level changed by 10% or more from the last recorded value, and remained stable for 2 minutes or more, were counted as choices.

The photometric measurements at the participant desk in July and December 2021 were made at sitting and standing heights on the desk and vertically in the direction of view at the nominal eye height of an occupant. These values were correlated to the values measured on the data loggers during the phtometric measurement visits. These relationshiups between the conditions at the two desks were used to calculate the light levels to which the participants were exposed using the data logger measurements, using the average illuminances per morning and afternoon as described above. The converted values are reported below as the representative values for the levels experienced.

The sit-stand desks in both rooms were also monitored to determine whether or not desk height had changed. The data were cleaned as for the light level data. Major changes that denote a shift from sitting to standing are reported.

2.4 Procedure

Participants were recruited by e-mail. The light sensitive participants received an e-mail circulated through the Employment Equity Champions and Chairs Committee (EECCC), with the support of Deputy Minister Yazmine Laroche; the invitation was co-signed by Sam Macharia (Director, Office of Public Service Accessibility, Treasury Board of Canada Secretariat), Mario Hubert (Senior Director, Real Property Services, Public Services and Procurement Canada) and Jennifer Veitch (Principal Research Officer, NRC Construction Research Centre). EECCC members circulated the message through their networks, and interested individuals contacted the NRC for details and possible scheduling. The general population sample was recruited from the staff of the NRC by e-mail.

Participants were scheduled for four testing days, two days in each of two weeks. These were either a Monday/Tuesday, or a Thursday/Friday. In each week (with one exception, see below), participants spent both days in the same room, some starting in the test room in the first week and others starting in the reference room.

Wednesdays were always left open to permit thorough cleaning and ventilation of the rooms, as part of the COVID-19 safety protocol. The protocol also required all parties involved in the investigation to self-screen before arrival each day; to wear an NRC-supplied mask at all times while in the building; to maintain at least a 2 m distance from other people; and to use hand sanitizer regularly.

On arrival each day, participants were met at the building's front desk, signed in at security, and escorted to the Learning Centre either by a dedicated commissionaire or by a project team member. On the first day, they received instructions and signed the consent form in a space outside the testing rooms, then entered the room to which they had been assigned for that day. Participants provided their own laptop computers and any special equipment required for accessibility accommodations.

At approximately 8:45 on each testing day, participants received an e-mail sent from the NRC Construction Surveys account, inviting them to complete the first of three questionnaire occasions on that day. The second e-mail was sent at approximately 11:30 and the third at approximately 15:30. Participants were also asked to complete a questionnaire on the morning of the day after their second day in each week (i.e., at home on a Wednesday or a Saturday morning). Table 5 shows the combinations of questionnaires included in each occasion. The responses were anonymized using an identification code provided to the participant when they arrived; the code facilitated the matching of data from one occasion to another. The data were collected on a secure server with 128-bit encryption located in Ottawa.

Table 5. Questionnaire schedule and contents for each occasion.

Time	Questionnaires	# of questions
Start of day 1	Demographics, Leiden Visual Sensitivity Scale	18
Morning each day, including days 3 and 6	Mood assessment, Sleep quality assessment, visual and physical health	16
Before lunch each day	Mood assessment, Office Lighting Survey, Visual health, Physical health	22
Late afternoon each day	Mood assessment, Office Lighting Survey, Visual health, Physical health, NRC Lighting Quality scale, Personal appearance and Room appearance judgements	46
End of day 4	Lighting Beliefs Questionnaire, Lighting Knowledge Questionnaire, Personal "light recipe"	46

During their days in the study, participants occupied themselves with their own work, using a WiFi connection to access the Internet and for their own virtual meetings. They were free to leave the building for lunch and breaks. Assistance was available if required, and a first-aid-trained responder was always present. No adverse events occurred during testing.

2.5 Data analysis plan

The data for the light-sensitive and general population groups were analyzed separately, there being no intention to compare the groups. The questionnaire data were analyzed with linear mixed models (LMM) with a first-order autoregressive structure with homogeneous variance, reflecting the repeated measures time sequence of the responses. LMM accepts differences in the number of participants at different levels, which allowed us to use all of the data even if some individuals did not complete participation on all four days. Noting the fact that this was a pilot project, and therefore exploratory, we accepted all data without regard for the normality of the distributions. Each dependent variable was analyzed in a separate analysis. We report means and standard deviations, inferential test scores, and the Cohen's d effect size indicator (Cohen, 1988), using Cohen's suggested convention for interpreting the size: small effects have d ~= 0.20, medium effects have d ~= 0.50, and large effects have d ~= 0.80.

The varying frequency of the different questionnaires gave rise to three LMM models. Pleasure, arousal, physical health and visual health during the testing days had been measured three times. We used the morning responses as baseline values, and calculated change scores for the midday and afternoon responses. Thus, there was a 3-way analysis of these change scores: 2 lighting X 2 day x 2 time. The NRC lighting quality and bothersome glare ratings and the ratings of personal appearance and room appearance were available for the afternoon of each testing day, and were analyzed in a 2 lighting x 2 day model. To assess any possible aftereffects of exposure to the lighting conditions, the scores on sleep (duration, quality, and ease of sleeping), mood (pleasure and arousal), visual health and physical health on the mornings after testing days (i.e., days 2, 3, 5, and 6) were analysed in a 2 lighting x 2 morning model.

The Office Lighting Survey was examined for the afternoons in each lighting condition, although data were available from morning and afternoon on both days. We chose the afternoon as being based on a longer exposure (i.e., not a first impression). The chi-squared analysis used for these data is very sensitive to sample size. Responses on each question were compared to normative data from offices in the northern United States in the 1990s (Eklund & Boyce, 1996). Although the light sources in the luminaires in the reference room have been converted from fluorescent lamps to LED tubes, the luminaires themselves are similar in light distribution and layout to the normative sample, so we judged the comparison to be valid. We also attempted comparisons between the rooms on selected questions, but the sample sizes were too small for conclusive results and these are not reported.

Open-ended data, such as for the personal light recipes, was coded into categories by a single rater and reviewed by the first author.

3 Results

3.1 Light-sensitive individuals

3.1.1 Light exposures and desk use

Light level monitoring confirmed that the levels in the reference lighting room were steady throughout the investigation. Thus, all participants experienced consistent light levels for the reference lighting. The test lighting was dimmable using a wall switch, and this resulted in wide variations in light levels. Of the 12 people for whom we have data from their time in the test lighting, four made no changes to the light level. Eight dimmed down from the starting point (full power). On the first day, the number of change actions for the eight people who used the dimmer ranged from one to four; on the second day, all but one person made one change action. This suggests that the experience of the first day allowed participants to identify their preferred level. Prior research on lighting control use has also found that people tend to choose one level, set the control to that level, and not change again during the day (Boyce et al., 2006b).

Table 6 summarizes the light levels for both lighting conditions at the occupied desk location. The values in the table were calculated from values measured during the study on the unoccupied desk across the aisle using the relationship established using the measured data for both desks and the vertical eye location of the occupant during the pretest measurements. We report six quantities at each of three locations: photopic illuminance and five types of equivalent daylight illuminance (EDI). Photopic illuminance is the quantity of light falling on a surface. The five α-opic EDI values express the equivalent quantity of daylight illuminance providing the same level of stimulation to each of the five recognized photoreceptor types, taking into account the different spectral sensitivity of each photoreceptor. These provide a common scale with which to compare light sources with different spectral power distributions in terms of their ability to influence physiological and neuroendocrine effects (CIE, 2018). Of these, melanopic EDI has been recommended for use as the quantity in which to express target levels for light exposures having biological effect (CIE, 2019, October 3), for instance in the WELL building certification scheme (International WELL Building Institute (IWBI), 2020).

Table 6 shows that although the test lighting was capable of being set to provide a much higher illuminance than the reference lighting (full power for the test lighting provided ~800 lx on the desk surface, whereas the reference lighting produced ~410 lx), participants in the light sensitive group tended to reduce the level in the test lighting to levels lower than the reference lighting: The median desk illuminance was 385 lx, which means than for half of the people, the desk illuminance was considerably lower than the ~404 lx for the reference lighting.

The use of the sit-stand desk in both rooms was also recorded. There was relatively little use made of this equipment; of the total 14 people in the light sensitive group, only four ever changed the height of the desk, and only two of those did so in both rooms. One person changed desk height up to three times daily, but the others did so only once per day.

Table 6. Average light levels in the reference lighting and summary statistics for light level choices in the test lighting, expressed as photopic illuminance and five alpha-opic equivalent daylight illuminance (EDI) values.

	Photopic illuminance (lx)	S-cone-opic EDI (lx)	M-cone-opic EDI (lx)	L-cone-opic EDI (lx)	Rhodopic EDI (lx)	Melanopic EDI (lx)
Reference lighting						
Desk surface	404	239	357	404	282	257
Vertical, seated eye height	222	139	197	221	157	143
Vertical, standing eye height	235	147	208	234	166	151
Test lighting						
Desk surface						
Mean	485	212	411	489	316	284
St. Dev.	280	122	237	282	182	164
Median	353	154	299	356	230	207
Maximum	795	348	674	802	519	466
Minimum	62	27	52	62	40	36
Vertical, seated eye height						
Mean	371	232	329	370	262	239
St. Dev.	209	131	185	208	147	134
Median	272	171	241	271	192	175
Maximum	602	378	534	600	425	388
Minimum	55	34	49	55	39	35
Vertical, standing eye height						
Mean	399	250	353	398	281	257
St. Dev.	208	130	184	207	147	134
Median	300	188	266	300	212	193
Maximum	629	395	558	627	444	405
Minimum	84	53	74	84	59	54

3.1.2 Lighting and room assessments

This group of ratings are based on several hours of daily exposure to each lighting condition, having been made at the end of each day. The analyses included tests of lighting (2 levels), day (2 levels) and the interaction effect, separately for each of the seven ratings. The averages and standard deviations by room and day are shown in Table 7, and results of the main effect tests are in Table 8. There were statistically significant effects of the lighting condition on the ratings of lighting quality and personal appearance. The lighting quality effect is medium-sized; the personal appearance effect is large. In both cases, the ratings were higher in the test lighting. Room clarity (medium effect size) and room attractiveness (small effect size) had higher mean scores for the test lighting than the reference lighting, but the effects did not reach statistical significance. Ratings of bothersome glare did not differ between the rooms, nor did the ratings of colourfulness.

There was also a main effect of day on lighting quality ratings, with ratings being higher on the second day. This was a medium-sized effect. Although it could be the case that the lighting quality experience in both lighting conditions improved with experience, it could also be an artifact resulting from the fact that there were dropouts after the first day, particularly in the reference lighting, of people who reported adverse effects in the reference lighting.

There were no statistically significant interactions. The associated descriptive statistics and test results are in Appendix A.

Table 7. Means (and standard deviations) per lighting condition and per day for afternoon assessments of the lighting and the room.

	Reference Lighting	**Test Lighting**	**Day 1**	**Day 2**
Lighting quality	3.09 (1.06)	3.61 (0.96)	3.14 (1.03)	3.62 (0.99)
Bothersome glare	1.89 (1.18)	1.85 (1.07)	2.04 (1.21)	1.65 (0.97)
Room brightness	57.55 (29.24)	60.39 (21.70)	59.80 (27.38)	58.00 (23.38)
Room clarity	39.20 (16.65)	49.00 (21.46)	42.10 (20.43)	46.85 (18.86)
Room attractiveness	39.38 (15.84)	44.55 (22.46)	41.01 (18.97)	43.28 (20.49)
Room colourfulness	43.82 (18.57)	41.02 (22.73)	39.52 (21.05)	45.98 (20.00)
Personal appearance	43.39 (14.30)	55.82 (19.87)	47.16 (20.30)	52.37 (15.06)

Note. The highlighted cells correspond to statistically significant differences in the corresponding LMM analyses.

Table 8. LMM tests of fixed main effects for lighting and day.

	Lighting				**Day**			
	df	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d
Lighting quality	37.08	9.53	0.00***	0.50	30.05	7.65	0.01**	0.46
Bothersome glare	40.58	0.09	0.77	-0.03	27.27	2.07	0.16	-0.35
Room brightness	38.77	0.83	0.37	0.11	27.77	0.69	0.41	-0.07
Room clarity	40.30	2.90	0.10	0.50	23.82	0.60	0.45	0.24
Room attractiveness	40.57	0.45	0.50	0.27	23.26	0.26	0.62	0.12
Room colourfulness	37.22	0.36	0.55	-0.14	20.96	1.31	0.26	0.31
Personal appearance	38.40	5.42	0.03*	0.68	21.59	0.95	0.34	0.29

Note. * p<.05, ** p<.01, *** p<.001. The highlighted cells call attention to the statistically significant effects and their associated effect size indices. The descriptive statistics for the comparison are in the preceding table, also highlighted.

3.1.3 Office Lighting Survey

Tables 9 and 10 show the results for the reference lighting and test lighting on the first and second day, with the normative responses for comparison; Table 9 shows agree/disagree questions and Table 10 shows one question for which the answers are worse/same/better. Within each column the agreement has been compared to the normative data using the chi-squared test. This test is very sensitive to sample size. Chi-squared tests comparing the lighting conditions were impossible because the sample was too small.

The reference lighting differed from the normative sample on two questions consistently over the two days. On both days more people than expected agreed that the lighting is uncomfortably bright, and that the light fixtures are too bright. These are large difference: in this sample, ~50% agreed with these two statements, whereas the normative value is ~15%. On the last question, regarding whether the lighting in the room is worse, the same, or better than in other places, the reference room showed the expected pattern. The reference room also had a much lower-than-expected agreement with the statement "Overall the lighting is comfortable" on the first day, but not on the second. Four people did not return for a second day in the reference lighting, presumably because they had not found it comfortable.

For the test lighting, on day 2 a higher-than-expected proportion of participants agreed that the light figures were too bright, and yet also a higher than expected proportion of the people judged the lighting to be better than in other offices (Table 10, last row).

Table 9. Office Lighting Survey Responses in the afternoon of each testing day for agree/disagree statements.

		Reference		Test	
	Norm	Day 1 N = 13	Day 2 N = 9	Day 1 N = 12	Day 2 N = 11
Item	Agree %	Agree %	Agree %	Agree %	Agree %
1. Overall, the lighting is comfortable.	69	38*	67	58	82
2. The lighting is uncomfortably bright for the tasks that I perform.	16	62***	44*	33	36
3. The lighting is uncomfortably dim for the tasks that I perform.	14	15	22	8	0
4. The lighting is poorly distributed here.	25	15	11	17	9
5. The lighting causes deep shadows.	15	8	11	17	0
6. Reflections from the light fixtures hinder my work.	19	15	22	25	0
7. The light fixtures are too bright.	14	54***	44**	25	36*
8. My skin is an unnatural tone under the lighting.	9	15	11	0	0
9. The lights flicker throughout the day.	4	8	0	0	0

Note. * *p*<.05, ***p*<.01, ****p*<.001 for comparisons between that group and the normative North American data. The highlighted cells call attention to the statistically significant effects

Table 10. Office Lighting Survey Responses in the afternoon of each testing day for worse/safe/better statement.

Item		N	Worse %	Same %	Better %
	Norm (%)		19	60	22
10. How does the lighting compare to similar workplaces in other buildings?	Reference Day 1	13	15	69	15
	Reference Day 2	9	11	78	11
	Test Day 1	12	17	33	50
	Test Day 2	11	9*	36*	55*

Note. ***p*<.01 for comparisons between that group and the normative North American data. The highlighted cells call attention to the statistically significant effects

3.1.4 Workday effects

These comparisons follow the changes in mood (pleasure and arousal), visual health and physical health over the day. The responses on arrival each morning served as baseline scores. Table 11 shows the descriptive statistics and Table 12 shows the LMM test results for the lighting x day x time analyses. Only the main effects are in the table; the interaction effects are documented in Appendix A. There were no statistically significant interaction effects.

The lighting had a medium-sized effect on visual health. The visual health score increases when symptoms are worse, so a positive score is undesirable. Participants began testing days, on average, with a score of 0.78 (from a possible range of 0-4). For the reference lighting, symptoms tended to increase over the workday, whereas there was a small drop in visual health symptoms during time in the test lighting room.

There was also a medium-sized effect of day on arousal changes. During the first day in either lighting condition, arousal tended to drop (participants became more tired), whereas there was nearly no change during the second day.

Table 11. Means (and standard deviations) per lighting condition, per day, and times for the change in mood and health since arrival.

	Reference Lighting	Test Lighting	Day 1	Day 2	Time 2	Time 3
Pleasure change	0.20 (2.50)	0.24 (2.44)	0.40 (2.49)	0.00 (2.43)	0.31 (2.19)	0.13 (2.72)
Arousal change	-0.45 (2.11)	-0.35 (1.59)	-0.86 (1.87)	0.17 (1.68)	-0.18 (1.74)	-0.62 (1.96)
Visual health change	0.20 (0.50)	-0.09 (0.60)	0.05 (0.58)	0.06 (0.57)	0.02 (0.52)	0.08 (0.62)
Physical health change	0.07 (0.56)	0.08 (0.56)	0.15 (0.60)	-0.01 (0.49)	0.06 (0.44)	0.10 (0.67)

Note. The highlighted cells correspond to statistically significant differences in the corresponding LMM analyses.

Table 12. LMM tests of fixed main effects for lighting, day, and time for the change in mood and health since arrival.

	Lighting				Day				Time			
	df	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d
Pleasure change	50.20	0.01	0.91	0.01	81.38	0.71	0.40	-0.16	61.07	0.42	0.52	-0.07
Arousal change	36.93	0.00	0.97	0.06	81.81	6.24	0.01**	0.56	41.01	2.08	0.16	-0.24
Visual health change	48.73	5.85	0.02*	-0.52	81.39	1.25	0.27	0.03	60.64	0.81	0.37	0.11
Physical health change	49.72	0.02	0.90	0.02	81.33	1.70	0.20	-0.29	59.62	0.13	0.72	0.07

Note. * p<.05, ** p<.01. The highlighted cells call attention to the statistically significant effects and their associated effect size indices. The descriptive statistics for the comparison are in the preceding table, also highlighted.

3.1.5 Morning-after effects

This set of analyses examined the after-effects of a day in either the reference or test lighting by examining the mood (pleasure and arousal), visual health and physical health of participants in the morning after, and by asking them to report on the previous night's sleep. Table 13 shows the descriptive statistics for these data, and Table 14 summarizes the LMM test results for the main effects in the lighting x morning analyses. The interaction effects are documented in Appendix A. There were no statistically significant interaction effects.

Lighting showed a statistically significant effect on visual health in the mornings. Visual health symptoms were lower on the morning following a day in the test lighting, and this was a medium-sized effect.

There also were statistically significant differences involving the comparison of the mornings. These were large effects. On the morning after a second day in the study (regardless of which lighting condition had been experienced), pleasure was higher, physical health symptoms were lower, and the sleep on the previous night had come more easily and been of higher quality. Note that for many participants, this morning after was a Saturday, and for others it was a mid-week day of working at home.

Table 13. Means (and standard deviations) per lighting condition and per morning for the mornings following a day in the study.

	Reference Lighting	Test Lighting	Morning 2	Morning 3
Pleasure	5.43 (1.63)	5.91 (1.76)	5.12 (1.59)	6.42 (1.57)
Arousal	4.90 (1.61)	4.96 (1.58)	4.88 (1.79)	5.00 (1.29)
Visual health	0.71 (0.70)	0.48 (0.40)	0.74 (0.61)	0.39 (0.45)
Physical health	0.74 (0.72)	0.51 (0.62)	0.82 (0.78)	0.34 (0.34)
Sleep duration	7.48 (1.74)	7.76 (1.44)	7.42 (1.50)	7.89 (1.68)
Sleep quality	0.33 (1.46)	0.43 (1.65)	-0.16 (1.57)	1.11 (1.20)
Sleep ease	0.81 (1.66)	0.52 (2.00)	0.00 (1.91)	1.53 (1.31)

Note. The highlighted cells correspond to statistically significant differences in the corresponding LMM analyses.

Table 14. LMM tests of fixed main effects for lighting and morning.

	Lighting				Morning			
	df	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d
Pleasure	36.49	0.72	0.40	0.29	18.93	7.16	0.01**	0.77
Arousal	23.22	0.02	0.88	0.03	11.30	0.05	0.83	0.08
Visual health	38.10	4.72	0.04*	-0.40	22.25	3.02	0.10	-0.61
Physical health	38.10	3.23	0.08	-0.34	24.63	7.15	0.01**	-0.72
Sleep duration	36.04	0.26	0.61	0.18	14.21	1.04	0.32	0.30
Sleep quality	27.26	0.01	0.94	0.07	11.91	7.50	0.02*	0.82
Sleep ease	38.53	0.06	0.80	-0.16	26.13	12.63	0.00***	0.83

Note. * p<.05, ** p<.01, *** p<.001. The highlighted cells call attention to the statistically significant effects and their associated effect size indices. The descriptive statistics for the comparison are in the preceding table, also highlighted.

3.1.6 Personal light recipes

Of the 14 participants in the light sensitive group, all provided comments to this question. The general trends of the comments are shown in Table 15. The dominant elements to the personal light recipes were the use of daylight as much as possible (although most respondents recognized the need for electric light at least some of the time), and the ability for personal adjustment to the light level. However, this is a diverse group: One person specifically mentioned needing a windowless space without daylight.

Approximately 1/3 of the group expressed a desire for a warmer-coloured (“more yellow”) light source; however, one person reported a preference for a light source “like daylight”, which would likely mean a cooler correlated colour temperature than is commonly used, although common light sources in offices also differ from daylight in having poorer colour fidelity.

The light-sensitive individuals also reported wanting better attention to the distribution of light in the space than they commonly experience, for instance by better locating the luminaires to the furnishings, to put light where it is needed but also to reduce the potential for glare. One person also noted the influence of surface finishes and reflectances on light distribution, expressing a preference for lighter surfaces over darker ones.

Table 15. Classifications of the personal light recipes of the 14 respondents in the light-sensitive groups.

Daylight	No daylight	Electric like daylight	Warmer colored light	Surfaces & distribution	Adjustable lighting	Dimmer /softer light	Bright light
9	1	1	5	6	10	4	0

One person commented on the process for obtaining an accommodation for a light sensitivity problem: “I also think that if someone is sensitive to light, they should not be forced to jump through multiple hoops and tapes to get the request. If an employee or someone is light sensitive, they should not have to feel ashamed…”.

3.2 General population

3.2.1 Light exposures and desk use

Three of the seven participants from the general population made use of the lighting controls in the test lighting condition, but one of them did so only on the first day in the room. As a result, the average light exposures in the test lighting were considerably higher than in the reference lighting (Table 16). Based on prior studies (Boyce et al., 2006b; Galasiu et al., 2007; Newsham & Veitch, 2001), this is an unexpected result.

As had been seen in the light-sensitive group, there was relatively little use made of the sit-stand feature of the desks in either room. In both rooms, three of the seven participants raised the desk to standing height once each, but for very long periods each time.

Table 16. Average light levels in the reference lighting and summary statistics for light level choices in the test lighting, expressed as photopic illuminance and five alpha-opic equivalent daylight illuminance (EDI) values.

Condition	Photopic illuminance (lx)	S-cone-opic EDI (lx)	M-cone-opic EDI (lx)	L-cone-opic EDI (lx)	Rhodopic EDI (lx)	Melanopic EDI (lx)
Reference lighting						
Desk surface	404	239	357	404	282	257
Vertical, seated eye height	222	139	197	221	157	143
Vertical, standing eye height	235	147	208	234	166	151
Test lighting						
Desk surface						
Mean	657	287	557	663	428	385
St. Dev.	186	81	157	187	121	109
Median	783	342	663	790	510	459
Maximum	785	343	665	792	512	460
Minimum	254	111	215	256	166	149
Vertical, seated eye height						
Mean	499	313	442	498	352	321
St. Dev.	138	87	123	138	98	89
Median	593	372	526	591	419	382
Maximum	595	373	527	593	420	383
Minimum	198	124	176	198	140	128
Vertical, standing eye height						
Mean	527	330	467	525	372	339
St. Dev.	138	87	122	138	97	89
Median	620	389	549	618	438	399
Maximum	622	390	551	620	439	400
Minimum	227	142	201	226	160	146

3.2.2 Lighting and room assessments

The means and standard deviations for the afternoon lighting and room assessments are in Table 17. There were four statistically significant effects among the LMM tests (Table 18). These are large effects, based on the Cohen's d effect size statistic. The test lighting was rated as being of higher quality, the test lighting room was judged to be brighter and more attractive, and the individuals judged their personal appearance to be better under the test lighting. Note that the room brightness judgement is consistent with the light level data above; on average, the light level was considerably higher in the test lighting room than the reference room. There were no interaction effects; see Appendix A.

Table 17. Means (and standard deviations) per lighting condition and per day for afternoon assessments of the lighting and the room.

	Reference Lighting	Test Lighting	Day 1	Day 2
Lighting Quality	3.77 (0.92)	4.34 (0.51)	3.96 (0.75)	4.18 (0.83)
Bothersome Glare	1.42 (0.57)	1.11 (0.29)	1.29 (0.47)	1.23 (0.48)
Room Brightness	51.46 (20.29)	68.00 (14.04)	60.29 (19.05)	59.77 (19.64)
Room Clarity	39.69 (24.52)	53.50 (18.52)	49.14 (22.38)	44.38 (22.89)
Room Attractiveness	38.04 (17.64)	48.60 (15.02)	43.07 (17.73)	43.99 (16.65)
Room Colourfulness	48.77 (22.24)	56.00 (16.11)	58.89 (16.87)	45.65 (19.96)
Personal Appearance	53.07 (15.49)	73.64 (16.34)	63.66 (19.39)	63.82 (18.97)

Note. The highlighted cells correspond to statistically significant differences in the corresponding LMM analyses.

Table 18. LMM tests of fixed main effects for lighting and day.

	Lighting				Day			
	df	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d
Lighting Quality	22.33	5.14	0.03*	0.73	17.71	2.09	0.17	0.29
Bothersome Glare	22.74	3.31	0.08	-0.68	14.53	0.08	0.78	-0.12
Room Brightness	21.92	5.08	0.04*	0.87	11.54	0.01	0.91	-0.03
Room Clarity	22.06	2.46	0.13	0.62	17.42	0.36	0.55	-0.21
Room Attractiveness	20.11	5.68	0.03*	0.62	18.16	0.51	0.48	0.05
Room Colourfulness	18.15	1.39	0.25	0.38	7.58	3.46	0.10	-0.69
Personal Appearance	22.53	9.33	0.01**	1.09	11.93	0.00	0.97	0.01

Note. * p<.05, **p<.01.The highlighted cells call attention to the statistically significant effects and their associated effect size indices. The descriptive statistics for the comparison are in the preceding table, also highlighted.

3.2.3 Office Lighting Survey

Tables 19 and 20 show the results for the reference lighting and test lighting on the first and second day, with the normative responses for comparison; Table 19 shows agree/disagree questions and Table 20 shows one question for which the answers are worse/same/better. Within each column the agreement has been compared to the normative data using the chi-squared test. This test is very sensitive to sample size. Chi-squared tests comparing the lighting conditions were impossible because the sample was too small. The only statistically significant differences were for the reference room. On both days a higher than expected percentage of the participants agreed that the light fixtures were too bright. As noted above, the light levels were not higher in the reference room, but it seems that participants were responding to the different optics in the test luminaires and the different light distribution. On the second day in the reference room, more participants than expected agreed with the statement that their skin was an unnatural tone under the lighting.

Table 19. Office Lighting Survey Responses in the afternoon of each testing day for agree/disagree statements.

		Reference		Test	
Item	Norm Agree %	Day 1 N = 7 Agree %	Day 2 N = 6 Agree %	Day 1 N = 7 Agree %	Day 2 N = 7 Agree %
1. Overall, the lighting is comfortable.	69	71	83	71	86
2. The lighting is uncomfortably bright for the tasks that I perform.	16	14	33	14	29
3. The lighting is uncomfortably dim for the tasks that I perform.	14	29	0	0	0
4. The lighting is poorly distributed here.	25	29	17	0	0
5. The lighting causes deep shadows.	15	29	33	0	14
6. Reflections from the light fixtures hinder my work.	19	0	0	0	0
7. The light fixtures are too bright.	14	43*	67***	0	29
8. My skin is an unnatural tone under the lighting.	9	14	33*	29	29
9. The lights flicker throughout the day.	4	0	17	0	0

Note. * p<.05, ***p<.001 for comparisons between that group and the normative North American data.

Table 20. Office Lighting Survey Responses in the afternoon of each testing day for worse/same/better statement.

Item		N	Worse %	Same %	Better %
	Norm (%)		19	60	22
10. How does the lighting compare to similar workplaces in other buildings?	Reference Day 1	7	43	57	0
	Reference Day 2	6	33	50	17
	Test Day 1	7	29	57	14
	Test Day 2	7	14	57	29

3.2.4 Workday effects

The general population group did not show any effects of lighting on workday changes in mood or health. There were statistically significant effects of time on arousal and visual health (Table 21, Table 22) in which fatigue increased over the day and there was a small increase in visual health symptoms (from 0.19 at the start of the day, on average, to 0.31 at the end, on a scale from 0-4).

There was also a statistically significant interaction of day X time on pleasure ($F(1,34.65) = 5.14$, $p = 0.03$). On day 1, there was an increasing decline in pleasure from midday to afternoon (estimated marginal mean morning change score -0.36 [standard error = 0.42], afternoon change score -1.29 [SE = 0.42]); on day 2, pleasure declined at midday but showed a small increase at the end of the day (estimated marginal mean at midday -0.47 [SE = 0.44], afternoon 0.13 [SE = 0.44]). For most of these participants, the second day was a Tuesday, so this is not in anticipation of the weekend. The detailed results for all interactions are in Appendix A.

Table 21. Means (and standard deviations) per lighting condition, per day, and times for the change in mood and health since arrival.

	Reference Lighting	Test Lighting	Day 1	Day 2	Time 2	Time 3
Pleasure Change	-0.50 (1.30)	-0.61 (1.77)	-0.82 (1.52)	-0.27 (1.56)	-0.44 (1.65)	-0.67 (1.47)
Arousal Change	-0.38 (2.28)	0.04 (1.67)	0.04 (1.82)	-0.38 (2.16)	0.19 (1.90)	-0.52 (2.03)
Visual health change	0.08 (0.25)	0.07 (0.19)	0.11 (0.25)	0.04 (0.18)	0.02 (0.21)	0.13 (0.22)
Physical health change	0.03 (0.17)	0.05 (0.13)	0.06 (0.17)	0.02 (0.13)	0.03 (0.12)	0.05 (0.18)

Note. The highlighted cells correspond to statistically significant differences in the corresponding LMM analyses.

Table 22. LMM tests of fixed main effects for lighting, day, and time for the change in mood and health since arrival.

	Lighting				Day				Time			
	df	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d
Pleasure Change	23.72	0.17	0.68	-0.07	45.68	2.82	0.10	0.36	30.16	0.36	0.55	-0.14
Arousal Change	23.65	0.55	0.47	0.21	45.68	1.05	0.31	-0.21	30.31	4.27	0.05*	-0.36
Visual health change	21.29	0.00	0.97	-0.02	45.84	1.67	0.20	-0.31	24.31	6.35	0.02*	0.50
Physical health change	22.46	0.39	0.54	0.16	45.67	2.03	0.16	-0.30	30.27	0.28	0.60	0.11

Note. * *p*<.05. The highlighted cells call attention to the statistically significant effects and their associated effect size indices. The descriptive statistics for the comparison are in the preceding table, also highlighted.

3.2.5 Morning-after effects

As seen in Tables 23 and 24, there were no statistically significant main effects in the LMM analyses for the mood, health, or sleep responses on the mornings after days in either lighting condition. There were also no statistically significant interactions; see Appendix A.

Table 23. Means (and standard deviations) per lighting condition and per morning for the mornings following a day in the study.

	Reference Lighting	Test Lighting	Morning 2	Morning 3
Pleasure	6.67 (1.37)	6.50 (1.40)	6.62 (1.50)	6.54 (1.27)
Arousal	6.42 (1.38)	5.50 (1.95)	6.15 (1.68)	5.69 (1.84)
Visual health	0.15 (0.20)	0.13 (0.19)	0.17 (0.21)	0.10 (0.16)
Physical health	0.06 (0.10)	0.14 (0.14)	0.10 (0.11)	0.11 (0.14)
Sleep duration	7.38 (1.38)	7.50 (1.11)	7.23 (1.13)	7.65 (1.31)
Sleep quality	1.67 (1.56)	0.86 (1.83)	1.23 (1.54)	1.23 (1.96)
Sleep ease	2.08 (1.24)	1.71 (1.38)	2.15 (0.80)	1.62 (1.66)

Table 24. LMM tests of fixed main effects for lighting and morning.

	Lighting				Morning			
	df	*F*	*p*	Cohen's d	*df*	*F*	*p*	Cohen's d
Pleasure	21.74	0.01	0.94	-0.12	14.50	0.18	0.68	-0.06
Arousal	21.99	2.24	0.15	-0.53	14.95	0.76	0.40	-0.26
Visual health	21.86	0.27	0.61	-0.11	14.95	1.67	0.22	-0.40
Physical health	21.28	2.76	0.11	0.67	13.17	0.06	0.81	0.09
Sleep duration	21.91	0.27	0.61	0.10	16.25	1.94	0.18	0.35
Sleep quality	19.96	2.19	0.15	-0.47	17.44	0.00	0.97	0.00
Sleep ease	21.55	0.47	0.50	-0.28	13.43	1.94	0.19	-0.41

3.2.6 Personal light recipe

The participants from the general population expressed a very strong preference for daylight in their workplace lighting (Table 25). One person also suggested that electric lighting should be similar to daylight; however, nearly half of the participants would prefer a warmer colour. Personal adjustability of both overhead and task lighting was also suggested by nearly half the sample. That might be the best way to satisfy the range of preferences: the same number expressed a desire for a lower light level as for a high light level. This is consistent with the use of the controls by this group.

Table 25. Classifications of the personal light recipes of the 7 respondents in the general population.

Daylight	No daylight	Electric like daylight	Warmer colored light	Surfaces & distribution	Adjustable lighting	Dimmer /softer light	Bright light
6	0	1	3	3	3	2	2

3.3 Case study

Given the availability of the individual in the case study, participation was limited to two days in sequence, with one day in each lighting condition. This reduced the amount of data available as compared to the experimental groups.

The light levels were steady in the reference lighting condition, unchanged from the experimental period. As Table 26 shows, the case study participant dimmed the lights in the test lighting condition on entry to a level close to the desk illuminance of the reference lighting (although legally blind, this participant has some light perception). This participant also changed from sitting to standing once each day, but stood for longer in the test lighting condition.

Table 26. Average light levels in the reference lighting and summary statistics for light level choices in the test lighting for the one day of the case study in each condition, expressed as photopic illuminance and five alpha-opic equivalent daylight illuminance (EDI) values.

	Photopic illuminance (lx)	S-cone-opic EDI (lx)	M-cone-opic EDI (lx)	L-cone-opic EDI (lx)	Rhodopic EDI (lx)	Melanopic EDI (lx)
Reference lighting						
Desk surface	404	239	357	404	282	257
Vertical, seated eye height	222	139	197	221	157	143
Vertical, standing eye height	235	147	208	234	166	151
Test lighting						
Desk surface	453	198	384	457	296	266
Vertical, seated eye height	347	218	308	346	245	223
Vertical, standing eye height	375	235	332	374	265	242

The NRC experimenter assisted this participant to complete the surveys because there were accessibility issues with the survey website. The room and personal appearance judgements were skipped, given the participant's visual impairment; the mood data were unreliable. We further decided not to examine the data for the mornings after time in the room, because the day after the reference lighting was a workday whereas the day after the test lighting was a weekend day.

The focus here is on the responses on the afternoon of each day, which are summarized in Table 27. The pattern of results showed that the test lighting provided a better experience for this participant. The reference lighting was judged too bright, even though the horizontal illuminance in the reference room was slightly lower than for the test lighting and the vertical illuminance was considerably lower because of the different light distribution of the test luminaires. The case study participant agreed that the test lighting was comfortable, judged the test lighting to be better than in most workplaces, and gave it a higher score for lighting quality. This participant experienced a slight increase in visual health symptoms over the day in the reference lighting, and a very small decrease in the test lighting. When asked for a personal light recipe, this participant responded: “sections in the office with different lighting to accommodate different preferences”.

Table 27. Afternoon survey responses by the case study individual in each lighting condition.

Item	Reference	Test
1. Overall, the lighting is comfortable.		Agree
2. The lighting is uncomfortably bright for the tasks that I perform.	Agree	
3. The lighting is uncomfortably dim for the tasks that I perform.		
4. The lighting is poorly distributed here.		
5. The lighting causes deep shadows.		
6. Reflections from the light fixtures hinder my work.		
7. The light fixtures are too bright.	Agree	
8. My skin is an unnatural tone under the lighting.	(no response)	(no response)
9. The lights flicker throughout the day.		
10. How does the lighting compare to similar workplaces in other buildings?		Better
Lighting Quality score	3	5
Visual comfort change from arrival	0.50	-0.25
Physical comfort change from arrival	0.00	0.00

4 Discussion and Conclusions

4.1 Evaluation of the test lighting

The purpose of this pilot test was to evaluate a possible lighting solution designed to improve the office lighting for a special population comprising people with light sensitivities of various kinds. The lighting solution differed from conventional Government of Canada lighting installations in several ways, with these dimensions chosen based on the scientific literature and prior experience (Newsham et al., 2015; Papamichael et al., 2016; Veitch, Newsham, Jones, et al., 2010). Thus, the test lighting differed from the reference lighting in light distribution, correlated colour temperature, colour rendering, and in providing the ability for individuals to choose their own light levels. There were minimal, if any, differences between the lighting systems in temporal light modulation and in the likelihood of causing discomfort from glare (given the lighting layout in these rooms); values of the parameters related to these two potential problems were lower than commonly accepted criteria for each (CEN, 2021; Perz et al., 2018).

Overall, the pilot test was a success. The group of light-sensitive participants showed clear evidence that the test lighting provided a better office lighting solution than the reference lighting. The test lighting was rated higher for lighting quality (Tables 7 and 8) and, in the final time of asking, as being better than lighting in other offices (Table 10). Compared to normative data, the reference lighting was judged to be too bright and the fixtures also to be too bright (Table 9); the test lighting brightness judgements did not differ from the normative sample despite the fact that for some participants the light level was higher in the test lighting than the reference lighting. Among the features that likely contributed to these outcomes are the individual control and the less-direct light distribution (Boyce et al., 2006a; Veitch, Newsham, Jones, et al., 2010).

Under the test lighting, the room was judged by the light-sensitive participants to result in better personal appearance (judged by looking at one’s reflection in a mirror) (Tables 7 and 8). Although the research design does not make it easy to separate the specific features that underlie the effect, it is most likely that the higher colour rendering of the test lighting explains these outcomes (Aston & Bellchambers, 1969; Bellchambers & Godby, 1972; Boyce & Simons, 1977).

Furthermore, the reference lighting caused a small increase in reported visual health symptoms over a workday among the light-sensitive participants, whereas the test lighting did not (Tables 11 and 12). The visual health symptoms appeared to linger: These participants also started the day after the reference lighting with slightly more intense symptoms than they did on a day following the test lighting (Tables 13 and 14). These findings are consistent with prior research that has shown that lighting conditions that are judged to be of higher quality are associated with better health (Veitch et al., 2008; Veitch, Newsham, Mancini, et al., 2010). Four of the 13 participants in this group chose not to return for a second day in the reference lighting, citing feeling unwell. No one failed to return for a second day in the test lighting.

The test lighting also showed itself to be preferable to the reference lighting for the case study participant, who was legally blind but had some peripheral vision. This participant reported an increase in visual health symptoms over the day of working under the reference lighting, but not the test lighting.

A smaller group of participants from the general population was added to the pilot study in order to verify that the test lighting did not have adverse effects. That is, this group was a check against the possibility that in solving a problem for a smaller group of employees, we might inadvertently create a new problem for the majority. The sample size for the general population group was smaller than that of the light-sensitive group, making it more difficult to detect statistically significant effects. It was more difficult to recruit these volunteers, and the deadline to complete testing set a boundary on the possible number of sessions.

Nonetheless, the general population sample also responded positively to the test lighting. There were large effects in which the test lighting was rated as higher in lighting quality, giving a more attractive room appearance, and producing better personal appearance than the reference lighting (Tables 17 and 18). The judgement that the room was brighter demonstrates the validity of the method; for most participants, the test lighting was indeed at a higher level than the reference lighting, because the general population participants tended not to use the dimmer. Interestingly, however, it was the reference lighting that was judged by the general population group to have light fixtures that were too bright (Table 19), even though they were in general emitting less light (Table 16).

4.2 Limitations

This investigation was designed to provide a preliminary solution for office lighting problems of people with light sensitivities, which is a diverse group with a variety of needs. The lighting solution combined several improvements to lighting quality to try to maximize the likelihood that one solution could prove satisfactory to the whole group. This means that isolating which of the improvements caused the benefits is not possible, although (as noted above) the scientific literature can provide guidance.

Participants were public servants with years of experience with Government of Canada (and other) office lighting. As a result, it was evident to them on entry which lighting condition was the reference and which was the test lighting. The possibility that the observations occurred because participants expected that the test lighting would be better than the reference lighting cannot be ruled out. Conversely, however, one could expect that the light sensitive group would have made it clear if there were any adverse effects of the test lighting, because (as shown by the lighting beliefs scale scores (Table 2), lighting is very important to them and they are alert to the potential for minor health effects.

As a pilot project, the sample size was limited. This was both because of the testing schedule, which required all testing to be completed within 5 months, but also because the COVID-19 safety protocols limited the occupancy of each room to one participant at a time, even though the rooms were large enough to accommodate many more under normal circumstances. The small sample size reduces the statistical power of the comparisons so that only medium and large effects were able to be detected. This limitation affected the general population group especially. With a larger sample, effects involving this group might have been observed; however, the purpose of including that group was to exclude the possibility of adverse effects. No potential problems with the test lighting were observed in the general population group, and in fact there was evidence that the test lighting was beneficial for them as well as for the light sensitive group.

Although the lighting installations were controlled by the researchers as for an experiment, in other respects this was a field study in which participants followed their own work schedules. The invitations to do each survey were sent at fixed times by NRC staff, but there was considerable variation in the times at which they were completed. This certainly influenced the responses, particularly to questions about mood, which would also have been influenced by participants' workday experiences independent of the lighting and room. These considerations would add noise to the data and further reduced the ability to observe small or subtle effects, if there were any; but conversely this adds to the realism of the test.

4.3 Conclusion and next steps

This pilot test succeeded in its objective: The test lighting system provided an improved office work experience to the light sensitive participants on several indicators, and was judged by the general population to have higher lighting quality. Based on the results of this pilot, the system seems to have potential to be a general lighting solution that could provide an accommodation to those who need one, while also being a benefit to public servants more generally.

This was a short-term test in an unusual installation with very low occupancy and no windows. The next step is to investigate this system in a true field investigation, on a larger scale, for a longer time, with occupants performing their regular work, both those with light sensitivities and those without. Such a test is now in the planning stages.

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Appendix A - Interaction Effects

A.1 Light-sensitive people

A.1.1 Lighting and room assessments

Table A1. Light-sensitive sample: Means (and standard deviations) for days within lighting conditions and the associated LMM Lighting x Day interaction effect test results.

	Reference		Test		*Lighting x Day Interaction*		
	Day 1	**Day 2**	**Day 1**	**Day 2**	***df***	***F***	***p***
Lighting quality	2.88 (1.03)	3.40 (1.07)	3.43 (1.00)	3.80 (0.93)	25.66	0.03	0.87
Bothersome glare	2.08 (1.27)	1.61 (1.05)	2.00 (1.19)	1.68 (0.96)	25.98	0.05	0.83
Room brightness	57.46 (31.91)	57.67 (26.79)	62.33 (22.60)	58.27 (21.55)	23.98	0.26	0.62
Room clarity	38.65 (17.75)	40.00 (15.94)	45.83 (23.20)	52.45 (19.90)	30.30	0.23	0.63
Room attractiveness	37.40 (16.40)	42.22 (15.49)	44.92 (21.45)	44.15 (24.57)	28.58	0.34	0.57
Room colourfulness	39.81 (16.73)	49.61 (20.54)	39.21 (25.71)	43.00 (20.02)	34.69	0.26	0.62
Personal appearance	42.33 (15.77)	44.91 (12.64)	52.86 24.16)	59.08 (14.36)	29.90	0.27	0.61

A.1.2 Workday effects

Table A2. Light-sensitive sample: Estimated marginal means (and standard errors) for days within lighting conditions and the associated LMM Lighting x Day interaction effect test results.

	Reference		Test		*Lighting x Day Interaction*		
	Day 1	**Day 2**	**Day 1**	**Day 2**	***df***	***F***	***p***
Pleasure change	0.62 (0.62)	-0.18 (0.69)	0.28 (0.64)	0.32 (0.67)	81.58	0.63	0.43
Arousal change	-1.19 (0.41)	0.37 (0.48)	-0.54 (0.43)	-0.24 (0.45)	69.13	2.34	0.13
Visual health change	0.18 (0.15)	0.38 (0.16)	-0.12 (0.15)	-0.08 (0.16)	81.92	0.39	0.53
Physical health change	0.09 (0.14)	0.06 (0.15)	0.18 (0.14)	-0.06 (0.15)	80.77	0.83	0.37

Table A3. Light-sensitive sample: Estimated marginal means (and standard errors) for times within lighting conditions and the associated LMM Lighting x Time interaction effect test results.

	Reference		Test		*Lighting x Time Interaction*		
	Midday	**Afternoon**	**Midday**	**Afternoon**	***df***	***F***	***p***
Pleasure change	0.21 (0.60)	0.23 (0.60)	0.50 (0.60)	0.09 (0.60)	67.34	0.42	0.52
Arousal change	-0.07 (0.41)	-0.75 (0.41)	-0.33 (0.40)	-0.46 (0.40)	54.27	0.83	0.37
Visual health change	0.29 (0.14)	0.27 (0.14)	-0.18 (0.14)	-0.03 (0.14)	65.82	1.42	0.24
Physical health change	0.09 0.13)	0.07 (0.13)	0.02 (0.13)	0.09 (0.13)	67.43	0.35	0.56

Table A4. Light-sensitive sample: Estimated marginal means (and standard errors) for times within days and the associated LMM Day x Time interaction effect test results.

	Day 1		Day 2		*Day x Time Interaction*		
	Midday	**Afternoon**	**Midday**	**Afternoon**	***df***	***F***	***p***
Pleasure change	0.43 (0.53)	0.46 (0.53)	0.28 (0.57)	-0.14 (0.57)	58.17	0.39	0.53
Arousal change	-0.70 (0.36)	-1.03 (0.36)	0.31 (0.40	-0.18 (0.40)	58.61	0.06	0.80
Visual health change	0.05 (0.12)	0.01 (0.12)	0.06 (0.13)	0.23 (0.13)	55.25	1.67	0.20
Physical health change	0.12 (0.12)	0.15 (0.12)	-0.01 (0.13)	0.01 (0.13)	59.69	0.00	0.95

Table A5. Light-sensitive sample: Means (and standard deviations) for times within days within lighting conditions and the associated LMM Lighting x Day x Time interaction effect test results.

	Reference				Test				*Lighting x Day x Time Interaction*		
	Day 1		Day 2		Day 1		Day 2				
	Midday	**Afternoon**	**Midday**	**Afternoon**	**Midday**	**Afternoon**	**Midday**	**Afternoon**	***df***	***F***	***p***
Pleasure change	0.31 (2.14)	0.92 (1.98)	0.00 (3.04)	-0.78 (3.11)	0.42 (2.35)	-0.08 (3.50)	0.45 (1.44)	0.18 (2.23	62.95	1.08	0.30
Arousal change	-0.85 (1.77)	-1.54 2.22)	1.00 (1.66)	0.22 (1.99)	-0.50 (1.88)	-0.50 (1.57)	0.00 (1.18)	-0.36 (1.80)	59.30	0.08	0.77
Visual health change	0.23 (0.54)	0.13 (0.61)	0.19 (0.39)	0.28 (0.44)	-0.10 (0.48)	-0.10 (0.67)	-0.23 (0.54)	0.07 (0.73)	60.29	0.24	0.63
Physical health change	0.10 (0.39)	0.09 (0.74)	0.02 (0.50	0.06 (0.61)	0.18 (0.48)	0.24 (0.78)	-0.09 (0.38)	-0.03 (0.53)	64.25	0.00	0.98

A.1.3 Morning-after effects

Table A6. Light-sensitive sample: Means (and standard deviations) for mornings within lighting conditions and the associated LMM Lighting x Morning interaction effect test results.

	Reference		Test		*Lighting x Morning Interaction*		
	Morn 2	**Morn 3**	**Morn 2**	**Morn 3**	***df***	***F***	***p***
Pleasure	5.08 (1.75)	6.00 (1.31)	5.17 (1.47)	6.73 (1.74)	31.61	0.47	0.50
Arousal	4.92 (1.75)	4.88 (1.46)	4.83 (1.90)	5.09 (1.22)	38.70	0.06	0.81
Visual health	0.81 (0.78)	0.56 (0.55)	0.67 (0.37)	0.25 (0.31)	21.51	2.26	0.15
Physical health	0.96 (0.79)	0.39 (0.43)	0.68 (0.77)	0.30 (0.27)	23.57	0.05	0.82
Sleep duration	7.50 (1.85)	7.44 (1.66)	7.33 (1.07)	8.23 (1.69)	25.70	0.82	0.37
Sleep quality	0.00 (1.47)	0.88 (1.36)	-0.33 (1.72)	1.27 (1.10)	34.19	0.45	0.51
Sleep ease	0.23 (1.83)	1.75 (0.71)	-0.25 (2.05)	1.36 (1.63)	23.88	1.38	0.25

A.2 General population sample

A.2.1 Lighting and room assessments

Table A7. General population sample: Means (and standard deviations) for days within lighting conditions and the associated LMM Lighting x Day interaction effect test results.

	Reference		Test		*Lighting x Day Interaction*		
	Day 1	**Day 2**	**Day 1**	**Day 2**	***df***	***F***	***p***
Lighting quality	3.69 (0.89)	3.87 (1.04)	4.23 (0.51)	4.46 (0.53)	15.23	0.00	0.98
Bothersome glare	1.36 (0.56)	1.50 (0.63)	1.21 (0.39)	1.00 (0.00)	17.40	1.42	0.25
Room brightness	52.29 (20.65)	50.50 (21.79)	68.29 (14.51)	67.71 (14.72)	17.26	0.00	0.99
Room clarity	44.36 (26.65)	34.25 (22.90)	53.93 (17.94)	53.07 (20.51)	14.64	0.14	0.71
Room attractiveness	39.21 (19.05)	36.67 (17.52)	46.93 (16.83)	50.26 (14.11)	15.46	0.43	0.52
Room colourfulness	58.21 (21.33)	37.75 (19.26)	59.57 (12.69)	52.43 (19.27)	20.10	0.90	0.35
Personal appearance	55.84 (18.37)	49.83 (12.15)	71.49 (18.29)	75.80 (15.27)	15.45	0.56	0.46

A.2.2 Workday effects

Table A8. General population sample: Estimated marginal means (and standard errors) for days within lighting conditions and the associated LMM Lighting x Day interaction effect test results.

	Reference		**Test**		***Lighting x Day Interaction***		
	Day 1	**Day 2**	**Day 1**	**Day 2**	***df***	***F***	***p***
Pleasure change	-0.57 (0.50)	-0.20 (0.53)	-1.07 (0.50)	-0.14 (0.50)	1,42.00	0.38	0.54
Arousal change	-0.36 (0.65)	-0.59 (0.69)	0.43 (0.65)	-0.36 (0.65)	1,42.18	0.22	0.64
Visual health change	0.14 (0.07)	-0.01 (0.07)	0.07 (0.07)	0.07 (0.07)	1,37.69	1.35	0.25
Physical health change	0.07 (0.05)	-0.04 (0.05)	0.05 (0.05)	0.05 (0.05)	1,42.86	1.46	0.23

Table A9. General population sample: Estimated marginal means (and standard errors) for times within lighting conditions and the associated LMM Lighting x Time interaction effect test results.

	Reference		**Test**		***Lighting x Time Interaction***		
	Midday	**Afternoon**	**Midday**	**Afternoon**	***df***	***F***	***p***
Pleasure change	-0.40 (0.47)	-0.37 (0.47)	-0.43 (0.46)	-0.79 (0.46)	1,37.43	0.38	0.54
Arousal change	0.01 (0.61)	-0.96 (0.61)	0.29 (0.59)	-0.21 (0.59)	1,37.50	0.36	0.55
Visual health change	0.01 (0.06)	0.13 (0.06)	0.02 (0.06)	0.12 (0.06)	1,32.89	0.01	0.91
Physical health change	0.01 (0.05)	0.02 (0.05)	0.04 (0.05)	0.06 (0.05)	1,37.18	0.04	0.84

Table A10. General population sample: Estimated marginal means (and standard errors) for times within days and the associated LMM Day x Time interaction effect test results.

	Day 1		**Day 2**		***Day x Time Interaction***		
	Midday	**Afternoon**	**Midday**	**Afternoon**	***df***	***F***	***p***
Pleasure change	-0.36 (0.42)	-1.29 (0.42)	-0.47 (0.44)	0.13 (0.44)	1,34.65	5.14	0.03*
Arousal change	0.43 (0.55)	-0.36 (0.55)	-0.13 (0.57)	-0.82 (0.57)	1,34.41	0.01	0.91
Visual health change	0.02 (0.06)	0.20 (0.06)	0.01 (0.06)	0.06 (0.06)	1,36.06	1.59	0.22
Physical health change	0.04 (0.04)	0.08 (0.04)	0.01 (0.04)	0.00 (0.04)	1,32.48	0.66	0.42
Note. * $p<.05$. The highlighted cells call attention to the statistically significant effects and their associated effect size indices.							

Table A11. General population sample: Means (and standard deviations) for times within days within lighting conditions and the associated LMM Lighting x Day x Time interaction effect test results.

	Reference				**Test**				***Lighting x Day x Time Interaction***		
	Day 1		**Day 2**		**Day 1**		**Day 2**				
	Midday	**Afternoon**	**Midday**	**Afternoon**	**Midday**	**Afternoon**	**Midday**	**Afternoon**	***df***	***F***	***p***
Pleasure change	-0.29 (0.95)	-0.86 (1.57)	-0.67 (1.63)	-0.17 (1.17	-0.43 (1.90)	-1.71 (1.38)	-0.43 (2.23)	0.14 (1.21)	1,37.14	0.26	0.61
Arousal change	-0.14 (1.68)	-0.57 (2.44)	0.33 (2.94)	-1.17 (2.32	1.00 (1.29)	-0.14 (1.68)	) -0.43 (1.62)	-0.29 (1.98)	1,37.03	2.03	0.16
Visual health change	0.07 (0.28)	0.21 (0.27)	-0.04 (0.25)	0.04 (0.19)	-0.04 (0.17)	0.18 (0.24)	0.07 (0.12)	0.07 (0.19)	1,36.02	0.66	0.42
Physical health change	0.06 (0.16)	0.08 (0.28)	-0.02 (0.06)	-0.02 (0.06)	0.02 (0.10)	0.08 (0.08)	0.06 (0.14)	0.04 (0.20)	1,35.72	0.21	0.65

A.2.3 Morning-after effects

Table A12. General population sample: Means (and standard deviations) for mornings within lighting conditions and the associated LMM Lighting x Morning interaction effect test results.

	Reference		Test		*Lighting x Morning Interaction*		
	Morn 2	**Morn 3**	**Morn 2**	**Morn 3**	***df***	***F***	***p***
Pleasure	7.00 (1.26)	6.33 (1.51)	6.29 (1.70)	6.71 (1.11)	1,15.57	1.86	0.19
Arousal	6.17 (1.72)	6.67 (1.03)	6.14 (1.77)	4.86 (2.04)	1,14.20	3.54	0.08
Visual health	0.17 (0.20)	0.13 (0.21)	0.18 (0.24)	0.07 (0.12)	1,15.41	0.45	0.51
Physical health	0.07 (0.08)	0.05 (0.12)	0.12 (0.13)	0.16 (0.15)	1,15.93	0.61	0.45
Sleep duration	7.08 (1.32)	7.67 (1.51)	7.36 (1.03)	7.64 (1.25)	1,14.46	0.14	0.71
Sleep quality	1.67 (1.37)	1.67 (1.86)	0.86 (1.68)	0.86 (2.12)	1,14.74	0.00	0.97
Sleep ease	2.33 (0.82)	1.83 (1.60)	2.00 (0.82)	1.43 (1.81)	1,15.18	0.01	0.93