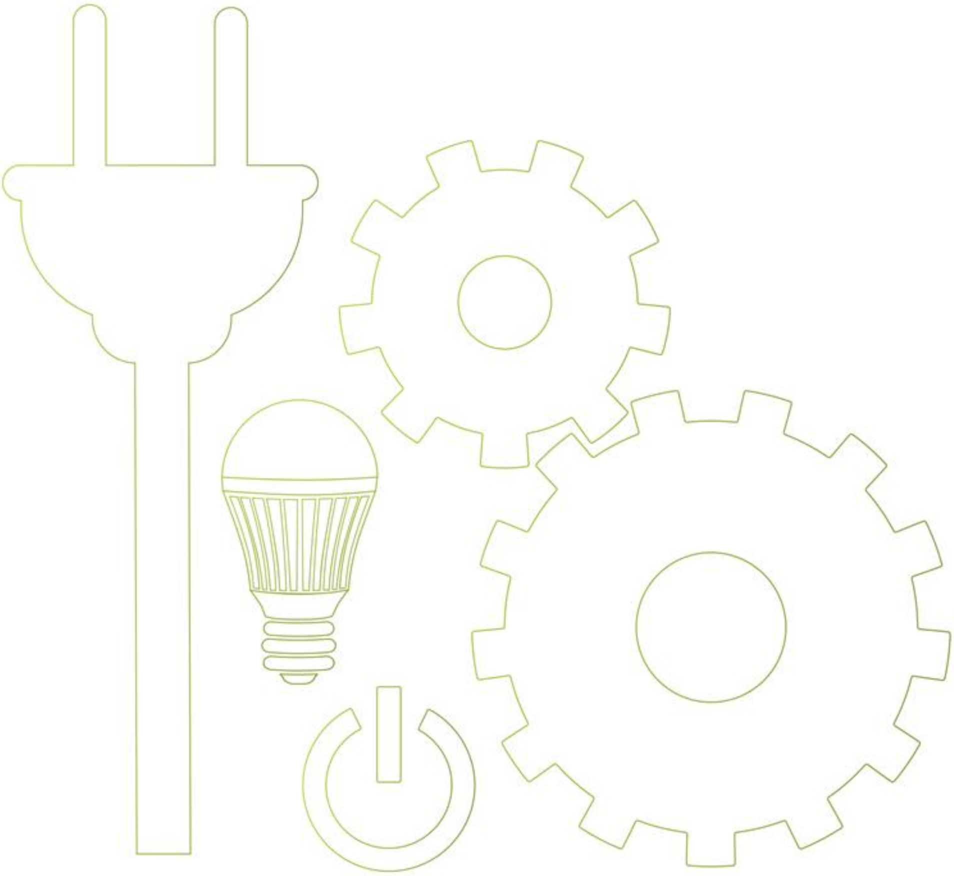
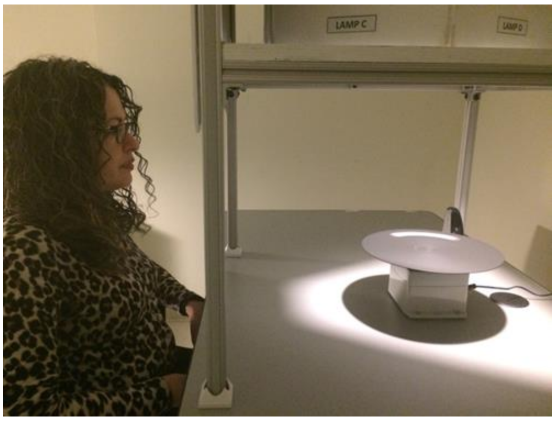


Solid State Lighting Annex: Visual Perception under Energy-Efficient Light Sources – Detection of the Stroboscopic Effect under Low Levels of SVM

FINAL REPORT

Energy Efficient End-use Equipment (4E)
International Energy Agency

DECEMBER 2019



Final Report:

Visual Perception under Energy-Efficient Light Sources – Detection of the Stroboscopic Effect under Low Levels of SVM

Jennifer A. Veitch
National Research Council of Canada

and

Christophe D. Martinsons
Centre Scientifique et Technique du Bâtiment (France)

December 2019

National Research Council Canada
Conseil national de recherches Canada

CSTB
le futur en construction

Dr. Jennifer A. Veitch
Principal Research Officer
NRC Construction, Building M-24
National Research Council of Canada
1200 Montreal Road
Ottawa, Ontario, K1A 0R6
Canada

https://nrc.canada.ca/en

Dr. Christophe Martinsons
Head of Division
Division of Lighting and Electromagnetic Fields
Centre Scientifique et Technique du Bâtiment
24, rue Joseph Fourier
38400 Saint Martin d'Hères
France

http://www.cstb.fr/en/

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This document updates the report titled "Interim Report: Visual Perception under Energy-Efficient Light Sources – Detection of the Stroboscopic Effect Under Low Levels of SVM", dated 11 December 2018. This report includes new data and new analyses. A peer-reviewed version of this final report is available:

Veitch JA, Martinsons C. Detection of the stroboscopic effect by young adults varying in sensitivity. *Lighting Research & Technology*, in press, 2020. https://doi.org/10.1177/1477153519898718.

About the IEA 4E Solid State Lighting Annex
The SSL Annex was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement to provide advice to its member countries seeking to implement quality assurance programmes for SSL lighting. This international collaboration currently consists of the governments of Australia, Canada, Denmark, France, the Republic of Korea, Sweden and the United Kingdom. Information about the IEA 4E SSL Annex is available online at http://ssl.iea-4e.org/

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Executive Summary

Temporal light modulation (TLM, known colloquially as “flicker”) of light sources has visual, neurobiological, and performance and cognition effects on viewers. This study aims to address an important gap in the scientific literature on the measurement of levels of TLM of light emitting diode (LED) light sources that may affect human health and productivity.

The outcomes of this research are intended to assist decision makers when developing lighting policy measures and regulations. This study was initially proposed in response to a request for public comment on the draft European ecodesign regulation for lighting before a vote by the European Union (EU) member countries. An interim report was provided in December 2018, and those data were also presented at the CIE 29th Quadrennial Session in June 2019. This final report is based on a larger data set and contains a more detailed analysis of the subgroups.

The International Electrotechnical Commission (IEC) and the Commission Internationale de l’Eclairage (CIE) have identified two metrics which may be measured and used to characterize lighting systems’ TLM:

- P_{st}^{LM}, short term flicker metric for visible flicker at frequencies below 80 Hz, and
- SVM, Stroboscopic Visibility Measure, for the higher frequency stroboscopic effect.

Although the scientific development of these metrics and their associated measurement protocols continues, there is a parallel discussion concerning the appropriate levels of these metrics in regulations. At present there is limited public information concerning the occurrence of the stroboscopic effect under lamps of varying SVM values. To provide further information on levels of SVM, the IEA 4E SSL Annex commissioned this study to test the visibility of the stroboscopic effect for five levels of SVM (targeting values of 0, 0.4–0.6, 1, ~1.6, and >2) using an experimental method similar to previous research from which the metric was developed. The preliminary report was based on a sample of 36 people across two sites (NRC in Canada and CSTB in France). This final report is based on data from 85 people (58 from Canada and 27 from France). The study focused on the effects on people under the age of ~30 because there is evidence that younger people may be more sensitive to TLM.

The decision to place a limit on any metric involves three choices: (1) The acceptable frequency of the outcome occurring in the population; (2) the acceptable proportion of the population who might experience this outcome; and (3) whether there are sensitive individuals in the population, whose needs might be considered to have a higher priority over those who are less sensitive. These choices are value judgements that research can inform but cannot determine. These data provide a first step towards discussions among stakeholder groups about suitable limits on lighting system TLM. The following guidance can be drawn from this work:

- An SVM>2.0 caused virtually all of the participants to perceive stroboscopic effects of the rotating disk in every trial, and caused 50% of the participants to perceive stroboscopic effects of the metronome in 5 or more trials out of 8.
- The proposed upper limit of SVM=1.6 is higher than the SVM for magnetic-ballasted T12 lamps, which are known to cause headaches and eyestrain and to disrupt eye movements.
- 25% of the people detected stroboscopic effects with the disk in 7 or more of the 8 trials (i.e., 88% detection), and 6 or more of the 8 trials (i.e., 75% detection) for the metronome at SVM=1.4 (75th percentile overall). The EU-28 population includes ~101 million people between the ages of 0–30. Based on the data presented here, SVM=1.6 would mean that on most of the occasions when they were exposed to that condition, one quarter of these 101 million young people could perceive the stroboscopic effect at greater than chance levels for both horizontal and vertical movement.

- The 75th percentile detection rate dropped to 2 out of 8 trials (i.e., 25%) when the SVM was ~0.9. This is lower than the chance level of detection.
- At SVM levels of 0.4 and below, the disc stroboscopic detection rate for the top quartile of the people dropped to 0.
- Those in the population who are more at risk of visual stress (the top 30% of a measure of this risk) are more annoyed by an SVM of ~1.4 or greater than are those who are at low risk, even when the exposure is short (noting that long exposures were not included in this investigation).

1. Introduction

The introduction of solid-state lighting to the marketplace has brought renewed concern about possible adverse consequences of exposure to temporal cyclic or transient variations in lighting system luminous flux, known as *temporal light modulation* (TLM), or more commonly referred to as 'flicker'. TLM may have visual, neurobiological, performance and cognition effects on viewers[1-3]. Visual perception effects such as the stroboscopic effect occur very quickly, with very short exposures[1-3]. TLM can also cause ill effects on a longer time scale, such as disruptions to eye movements, headaches, and eyestrain[1-3]. There is not yet expert consensus about all of the possible health and behavioural effects of TLM, and no single metric to predict their occurrence. This remains an active area for research and standardization[4].

The visual perception effects are collectively known as *temporal light artefacts* (TLA), comprising flicker, the stroboscopic effect, and the phantom array effect. Definitions of these phenomena, proposed TLM frequency ranges for their occurrence, and guidance for possible TLM metrics to predict the artefacts may be found in the Commission Internationale de l'Eclairage (CIE) Technical Note TN006:2016[5]. TLM can be characterized in several ways, all derived from measurements of the light output waveform. Among the parameters available to describe TLM are the dominant frequency, the modulation depth, the IES flicker index[6], a predictor of visible flicker from the International Electrotechnical Commission (IEC), called P_{ST}^{LM} [7], the stroboscopic visibility measure (SVM)[5, 7, 8], and the ASSIST Stroboscopic Acceptability Measure[9]. Others may be developed as research progresses, and to support the development of new metrics the CIE Technical Committee TC 2-89 is tasked with developing a technical note to describe a rigorous method for measuring and reporting TLM waveforms. Regulators in some regions are considering the importance of establishing limits on TLM from lighting products under the precautionary principle, to prevent large numbers of long-life light sources coming into use that could adversely affect the health and well-being of the public.

For the present investigation, which concerns the stroboscopic effect, we characterized the independent variable in terms of the SVM. The SVM is a visibility measure that is derived from measurements of the TLM of the light source or lighting system. This characterization of the TLM relates to the visibility of the stroboscopic effect and is scaled such that, by definition, a value of 1 means that the average person would detect the phenomenon 50% of the time; thus, a light source having an SVM value of 1 would mean that the average person can detect the stroboscopic effect 50% of the time when that light source is the sole source of illumination[5, 10]. As noted by the CIE[5] and by the National Electrical Manufacturers' Association (NEMA)[11], the visibility threshold (i.e., SVM=1) is not a guarantee of acceptability of the visible phenomenon. At SVM=1.6, the level presented in NEMA 77-2017 (the only published standard containing a suggested SVM level), the average person would detect stroboscopic motion considerably more than 50% of the time, and many people would have an even higher probability of detection, with some people likely to detect it on all exposures to that condition.

There is some evidence of adverse effects that develop over a longer time course of exposure to TLM than occurs in experiments looking for the stroboscopic effect. In particular, the value of SVM of 1.6 is slightly higher than the TLM characteristic of a magnetically-ballasted T12 fluorescent lamp (SVM of 1.3), which prior research established as a cause of disrupted visual performance[12, 13] and a likely cause of headache and eyestrain[14]. Prior to the development of the SVM, Bullough and colleagues[15] examined the visibility and acceptability of flicker and of the stroboscopic effect across a range of TLM frequencies, modulation depths, and duty cycles, and obtained data from ten participants viewing each of nine conditions once, for less than two minutes. The stroboscopic effect was detectable at frequencies up to 300 Hz for a hand waving under the lamp, but acceptability of what had been seen was high for all frequencies at and above 120 Hz (controlling for modulation depth), and when modulation depth was 33% (but not 50% or 100%). A subsequent experiment[16], also with ten participants but changing the task to a wand waved under the light source, found that 100 Hz TLM was detected 80% or more of the time for modulation depths equal to or greater than 25%. The conditions were rated as just acceptable, on average, when the modulation depth was 25%, but unacceptable at higher values of modulation depth. The small sample sizes in these two studies (N=10 each, with more males than females in each one) limit their generalizability to the general population, and the fact that individuals controlled the wand movement risks inconsistency in the visual task.

The most relevant paper to the question of acceptability is that of Perz and colleagues , who reported a series of experiments as one data set with a combined range of SVM conditions from 0 to 4.9. An unknown number of participants performed various office-work-type tasks for variable amounts of time under varying sets of these conditions, and then rated the acceptability of the room conditions. Based on these data, Perz et al. constructed a logistic function to predict the percentage of annoyed people in relation to SVM, concluding that 20% of the population would be annoyed at an SVM of 1.5, and ~12% at an SVM of 1. It is problematic that there is no information available about the sample size or composition, because it is impossible to assess how generalizable the results might be. Moreover, by combining the results from studies in this way, the function combines within-subject and between-groups variation, which adds to the difficulty of interpreting the outcomes.

To the best of our knowledge, the published literature does not address the population rates for stroboscopic motion detection under varying levels of SVM. The metric's development has included several experiments, each with samples ranging from 20 to 35 individuals, the data from which show considerable individual variability in responses to TLM[10, 17]. Perz and colleagues found that the relationship between the visibility threshold and TLM frequency held for individuals and for the average across individuals[10], and on this basis they developed SVM based on an averaging function across participants, then normalized to provide the definition that at SVM=1, the average individual should detect the stroboscopic effect 50% of the time (the visibility threshold). Data have not been published showing the effect of varying levels of SVM on stroboscopic visibility in the population at large: That is, what proportion of the population do, in fact, detect the stroboscopic effect when SVM=1? Put another way, at what value of SVM does the stroboscopic effect become almost undetectable? This experiment was designed to provide some answers to these questions, although for this experiment the focus was on people under 30 years of age, to increase statistical power by focusing on those thought to be most sensitive[18].

This document provides the final findings of a project designed to provide some of the necessary data to support policy-makers' determination of a suitable limit for SVM. (A preliminary report was submitted to the funders in December 2018, and a paper based on that work was presented at the CIE 29th Quadrennial Session in June 2019[19].) To increase the sample size in the time available and to ensure applicability of the results around the world, the experiment was conducted at two sites in parallel, using the same experimental design and methods. The two subject test sites were in Ottawa, Canada, led by the Jennifer Veitch at the National Research Council of Canada (NRC), and Saint Martin d'Hères, France, led by Christophe Martinsons at the Centre Scientifique et Technique du Bâtiment (CSTB). Additional support was provided by other experts affiliated with the IEA 4E SSL Annex, particularly Carsten Dam-Hansen (Technical University of Denmark, Roskilde, Denmark) and Steve Coyne (Light Naturally, Brisbane, Australia).

The objectives of the project were as follows:

- Test the visibility of the stroboscopic effect for five levels of SVM (targeting 0, 0.4–0.6, ~1, ~1.6, and >2*) using an experimental method as similar as feasible to the published work from which the metric was developed[10, 17, 20], with a target sample size of ~50 people across the two sites;
- Examine the population frequency of pattern glare sensitivity [PGS][21], which is known to predict sensitivity to headache and disrupted eye movements in response to TLM (see Appendix A, section A.3.2);
- If possible, establish preliminary information about the visibility of the stroboscopic effect by individuals high in PGS; and
- Collect preliminary information about how people judge the acceptability of their perceptions under the five SVM levels, in terms of comfort, pleasantness, and annoyingness.

2. Results

2.1 Sample and lighting details

This final report is based on data from 85 people, 27 tested in France and 58 tested in Canada. Table 1 summarises their characteristics. The samples in the two sites were comparable, although NRC had more female than male volunteers. All participants were university students, and none were older than 32. The limited age range was chosen because there is evidence that younger people may be more sensitive to TLM[18], and all had self-reported normal or corrected-to-normal vision, and normal hearing.

Sensation scores on Pattern 2 of the Wilkins and Evans Pattern Glare Sensitivity test were used as the indicator of a higher risk of visual stress[21, 22]. There was no difference between NRC and CSTB on this variable (Mann–Whitney U test, Z=-0.50, p=0.62). The sensation scores for pattern 2 in the full sample correlated moderately with discomfort ratings for viewing that pattern (r=0.31, p=0.004, N=85).† The relationship between pattern 2 sensation scores and discomfort ratings for pattern 2 was very high for CSTB (r=0.53, p=0.005, N=27), whereas it was moderate for NRC (r=0.26, p=0.05, N=58). We considered this adequate evidence for the validity of the pattern 2 sensation scores as the indicator of sensitivity and of risk of visual stress. Therefore, we created a grouping variable (PGS) for this purpose by selecting the top 30% of the full sample, which were the individuals having scores of 4 or greater on this variable ("high-PGS"), versus the lower 70% of the sample ("low-PGS"). We chose this value based on the evidence that for the highest scores on that pattern, approximately 30% of the population report adverse effects (discomfort)[22].

Table 1. The number of participants in each demographic group, shown by location.

	Sex		Age		Pattern 2 high score
	Male	Female	18 to 29	30 to 39	(High PGS) Group
CSTB	16	11	26	1	7
NRC	18	40	56	2	19

* The high level of SVM>2 was included to provide a validation of the test method by including a level known to be above the proposed limit value, and for which it should be the case that stroboscopic effect detection rates would be high.

† Another suggested indicator of pattern glare sensitivity is the difference between responses to pattern 3 and pattern 2[21]. We have not reported this value because we have learned that scores on pattern 3 may be unduly affected by visual capabilities, making it less reliable than is desirable[22].

LED lamps were selected and purchased from the market to match the five levels of SVM, and hence represent SSL products available in the market in North America and Europe. Although the specific lamps used by the laboratories were different in the two countries, the five experimental conditions were matched in terms of SVM for methodological consistency. P_{st}^{LM} is a metric that characterizes TLM in the range of 0–80 Hz, which is the range in which viewers can report seeing the temporal variation in light output (flicker). The light sources were chosen to keep P_{st}^{LM} very low to avoid experimental confounding. Details are available in Appendix A. Table 2 summarizes the key information about the lamps used at each site, showing that they are similar enough to be expected to produce comparable visual perceptions. Lamps were tested and operated with a clean sinusoidal power supply. At both sites the illuminance on the surface of the rotating disc was in the range 330–350 lx, the light source correlated colour temperatures (CCT) were in the range of 2700–3000 K, and the CIE general colour rendering index, R_a, was 80–85.

Table 2. Light source characteristics, by site, as measured by the respective research teams.

			SVM		
Condition	**1**	**2**	**3**	**4**	**5**
CSTB	0	0.43	0.96	1.47	3.09
NRC	0.04	0.42	0.91	1.38	2.80
			P_{st}^{LM}		
Condition	**1**	**2**	**3**	**4**	**5**
CSTB	0.39	0.05	0.08	0.26	0.38
NRC	0.05	0.07	0.08	0.06	0.33

2.2 Stroboscopic effect – rotating disc

Participants each completed 10 trials for each of the five lamps. For each trial, the individual looked at a rotating black disc on which was a white spot. The stroboscopic effect occurs when one sees the white spot as a distinct circle that jumps from one location to another. When there is no stroboscopic effect the white spot looks like an undifferentiated blur. For each trial the individual answered whether or not they saw the stroboscopic effect when looking at the rotating disc. Figure 1 displays this effect using the apparatus in Canada and images taken from an iPhone SE (therefore not necessarily exactly as the human eye would see).

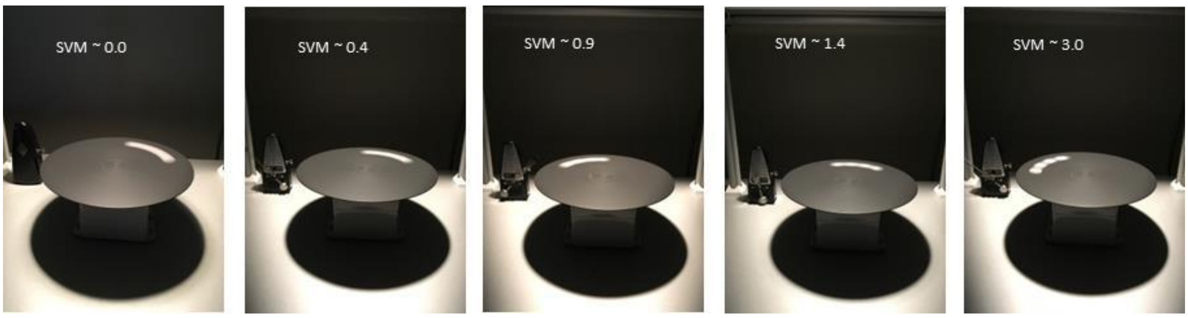

Figure 1. This series of images shows conceptually the effect of increasing SVM on the detection of the stroboscopic effect on the rotating disc.

Data from the first two trials were treated as training runs, and not included in the analysis. For each participant, we averaged the responses to trials 3–10 and scaled them out of a score of 8 (detection rate, with theoretical minimum=0 and maximum=8).

The SVM metric was originally developed from this task. It is intended that the average performance for an SVM=1 light source should be a detection rate of 0.50, which would mean a score of 4 in this experiment.

We examined the data to determine whether or not there were meaningful differences using non-parametric tests because the distributions did not meet the assumptions of normality required for parametric tests (e.g., analysis of variance). This is evident, for example, in Figure 2, where the means and medians are not the same for three of the five SVM conditions. Having made this determination for the stroboscopic disc detection (because the experiment was designed to replicate the conditions under which SVM had been developed), we applied the same statistical model to all analyses. In all analyses in this report, the alpha criterion for statistical significance was set to $p<0.05$.

For every level of SVM, we compared the data from the two locations (CSTB vs NRC) and we compared the data from the groups formed based on high and low pattern glare sensitivity (PGS). These between-groups tests used the Mann–Whitney U test, which is distributed following the *Z* distribution. The tests were repeated for each individual SVM level and for an overall score formed by averaging the detection scores for the five SVM levels.

We also tested for differences between SVM levels in four successive comparisons (0 vs 0.4; 0.4 vs 0.9; 0.9 vs 1.4; 1.4 vs 3). For these repeated measures, we used the Wilcoxon Signed Ranks test. We performed these repeated measures tests both for the combined sample and separately for the two locations and for the high and low pattern sensitivity glare (PGS) groups.

For the rotating disc detection scores, there were no statistically significant differences between the two locations: the outcomes for CSTB and NRC were the same for each SVM level (Table 3) and for the overall average (Mann–Whitney U test, $Z=-0.39$, $p=0.69$). Therefore, we present the combined data for the full sample of 85 participants graphically in Figure 2. Looking to the Wilcoxon tests between the SVM levels (Table 3), we see that the distributions of rotating disc stroboscopic detection scores for SVM ~0 and SVM ~0.4 did not differ. The rotating disc detection scores did increase for each successive SVM level, with results that reached the criterion level of statistical significance. The pattern of Wilcoxon test results was similar when the sample was split into two groups by location.

Similarly, there were no statistically significant differences in the Mann–Whitney test results for comparisons between the low and high PGS groups for any SVM level, nor for the overall average (Mann-Whitney U test, $Z=-0.01$, $p=1.00$). When the sample was split into these groups, the pattern of results for the Wilcoxon comparisons between the different SVM levels was the same for both groups (Table 3). PGS, an indicator of sensitivity to ill-effects of visual stress, did not predict performance on this stroboscopic visibility task in this experiment.

Table 3. This table displays the results for the stroboscopic detection scores for the rotating disc (N=85). Splitting the sample by testing location, or by PGS, did not change the results.

	Descriptive Statistics					Wilcoxon Signed Ranks Test			
Condition	**1**	**2**	**3**	**4**	**5**	**1 vs 2**	**2 vs 3**	**3 vs 4**	**4 vs 5**
SVM	~0	~0.4	~0.9	~1.4	~3.0	*Z (p)*	*Z (p)*	*Z (p)*	*Z (p)*
Both sites (N=85)									
Means	0.25	0.34	1.26	4.12	7.92	-1.23	**-4.72**	**-7.03**	**-7.09**
(StDev)	(0.60)	(0.88)	(2.11)	(3.05)	(0.54)	(.22)	**(0.000)**	**(0.000)**	**(0.000)**
Minimum	0.00	0.00	0.00	0.00	4.00				
25th percentile	0.00	0.00	0.00	1.00	8.00				
50th percentile	0.00	0.00	0.00	4.00	8.00				
75th percentile	0.00	0.00	2.00	7.00	8.00				
Maximum	3.00	4.00	8.00	8.00	8.00				
CSTB (N=27)									
Means	0.22	0.26	1.48	4.30	8.00	-0.45	**-3.08**	**-3.83**	**-4.04**
(StDev)	(0.51)	(0.71)	(2.36)	(3.20)	(0.00)	(0.66)	**(0.002)**	**(0.000)**	**(0.000)**
Minimum	0.00	0.00	0.00	0.00	8.00				
25th percentile	0.00	0.00	0.00	0.00	8.00				
50th percentile	0.00	0.00	0.00	5.00	8.00				
75th percentile	0.00	0.00	2.00	7.00	8.00				
Maximum	2.00	3.00	8.00	8.00	8.00				
NRC (N=58)									
Means	0.26	0.38	1.16	4.03	7.88	-1.11	**-3.59**	**-5.92**	**-5.86**
(StDev)	(0.64)	(0.95)	(1.99)	(3.01)	(0.65)	(0.27)	**(0.000)**	**(0.000)**	**(0.000)**
Minimum	0.00	0.00	0.00	0.00	4.00				
25th percentile	0.00	0.00	0.00	1.00	8.00				
50th percentile	0.00	0.00	0.00	4.00	8.00				
75th percentile	0.00	0.00	2.00	7.00	8.00				
Maximum	3.00	4.00	8.00	8.00	8.00				
CSTB vs NRC Z	-0.06	-0.48	-0.52	-0.27	-0.97				
p	0.95	0.63	0.60	0.79	0.33				
Low PGS (N=59)									
Means	0.19	0.32	1.10	4.20	7.93	-1.57	**-3.91**	**-5.80**	**-5.80**
(StDev)	(.43)	(0.88)	(1.90)	(3.14)	(0.52)	(0.12)	**(0.000)**	**(0.000)**	**(0.000)**
Minimum	0.00	0.00	0.00	0.00	4.00				
25th percentile	0.00	0.00	0.00	1.00	8.00				
50th percentile	0.00	0.00	0.00	5.00	8.00				
75th percentile	0.00	0.00	2.00	8.00	8.00				
Maximum	2.00	4.00	8.00	8.00	8.00				
High PGS (N=26)									
Means	0.38	0.38	1.62	3.92	7.88	-0.72	**-2.70**	**-4.06**	**-4.12**
(StDev)	(0.85)	(0.90)	(2.52)	(2.88)	(0.59)	(0.94)	**(0.000)**	**(0.000)**	**(0.000)**
Minimum	0.00	0.00	0.00	0.00	5.00				
25th percentile	0.00	0.00	0.00	2.00	8.00				
50th percentile	0.00	0.00	0.00	3.50	8.00				
75th percentile	0.00	0.00	2.25	7.00	8.00				
Maximum	3.00	3.00	8.00	8.00	8.00				
Low vs High PGS *Z*	-0.51	-0.29	-0.68	-0.36	-0.58				
p	0.61	0.77	0.50	0.72	0.56				

Note. For all tests, the criterion for rejecting the null hypothesis of no effect (statistical significance, α) was $p<0.05$. Statistically significant test results are shown in bold text.

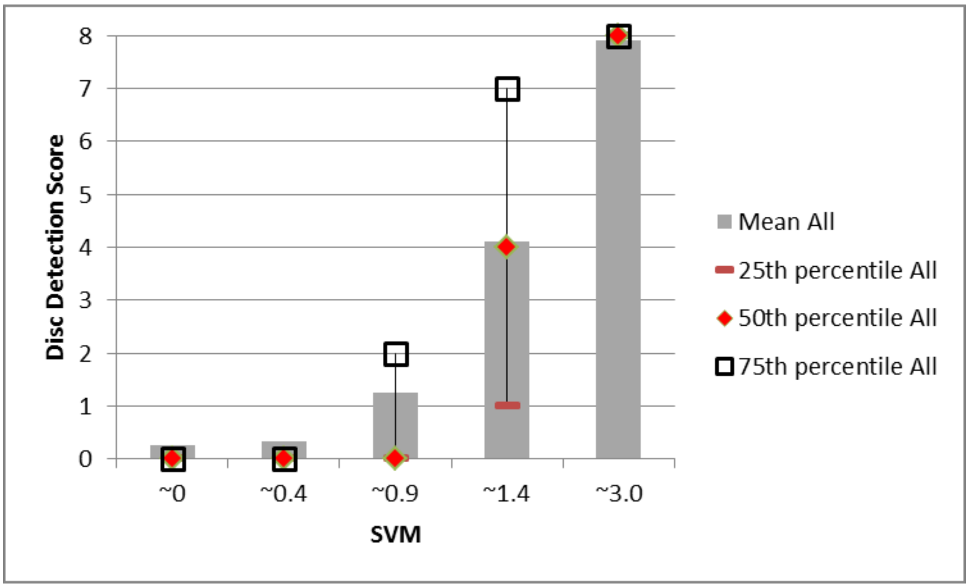

Figure 2. This chart shows the detection score for the rotating disc for the full sample at each SVM level, displaying the means in bars and the 25th, 50th, and 75th percentiles overlaid.

2.3 Stroboscopic effect – metronome

In addition to the horizontal rotating disc detection task discussed in section 2.2, the authors developed a new vertical task for this experiment. Participants were told to look at a black dot on a mechanical metronome. For the second round of data collection, both sites used 208 bpm as the speed, replicating Bullough and Marcus[23]. Only these data (N=50) are reported here. The participants were asked whether they saw a series of black dots (stroboscopic effect) or if they saw a black blur (no stroboscopic effect detected). The metronome location differed slightly for the NRC and CSTB. At NRC it was farther from the observer than the rotating disk, and slightly to the side, with the white wall of the room behind. At CSTB the line of sight placed the light grey desk surface behind the moving metronome arm. As for the horizontal disc detection task, we used only the responses from the last 8 trials averaging the responses and scaling them to a maximum of 8. One person from CSTB missed several trials of the metronome question and was not included for this variable.

Table 4 shows the results for the full sample and for the split groups by country and PGS. The two sites showed no differences for the metronome detection scores at each level of SVM, and for the overall average (Mann–Whitney U test, Z=-0.13, p=0.89). There also were no differences between the high and low PGS groups on the individual SVM scores, nor on the overall average metronome detection score (Mann–Whitney U test, Z=-1.04, p=0.30).

The Wilcoxon Signed Ranks tests for the full sample showed that the stroboscopic effect detection scores for the three lower SVM values did not differ from one another. However, the stroboscopic effect became more visible at SVM ~1.4 as compared to ~0.90, and still more visible for ~3.0 as compared to ~1.4. There were some differences in the subgroup analysis: At NRC, there was no difference between metronome detection scores at 1.4 and 3.0. For the high-PGS group, there were no differences in metronome detection scores between the levels. Figure 3 displays the descriptive statistics for the full sample as a bar chart.

Table 4. This table displays the results for the stroboscopic detection scores for the metronome beating at 208 bpm at both locations (N= 50).

	Descriptive Statistics					Wilcoxon Signed Ranks Test			
Condition	**1**	**2**	**3**	**4**	**5**	**1 vs 2**	**2 vs 3**	**3 vs 4**	**4 vs 5**
SVM	~0	~0.4	~0.9	~1.4	~3.0	*Z (p)*	*Z (p)*	*Z (p)*	*Z (p)*
Both sites (N=50)									
Means	3.12	2.82	2.70	3.34	4.12	-1.66	-0.64	**-2.93**	**-2.28**
(StDev)	(3.10)	(3.17)	(2.78)	(2.95)	(3.15)	(0.10)	(0.53*)*	**(0.003)**	**(.02)**
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.00	0.75				
50th percentile	2.00	1.00	2.00	3.00	5.00				
75th percentile	6.25	6.25	5.00	6.00	7.00				
Maximum	8.00	8.00	8.00	8.00	8.00				
CSTB (N= 10)									
Means	2.50	2.70	2.50	3.10	5.50	-1.00	-0.11	**-2.45**	**-2.21**
(StDev)	(3.44)	(3.47)	(3.17)	(3.00)	(2.99)	(0.32)	(0.91)	**(0.01)**	**(0.03)**
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.75	2.00				
50th percentile	0.50	1.00	1.50	2.50	7.00				
75th percentile	6.50	7.25	5.00	5.75	8.00				
Maximum	8.00	8.00	8.00	8.00	8.00				
NRC (N=40)									
Means	3.28	2.85	2.75	3.40	3.78	-1.87	-0.64	**-2.48**	-0.90
(StDev)	(3.04)	(3.13)	(2.72)	(2.98)	(3.13)	(0.06)	(0.53)	**(0.01)**	(0.37)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.00	0.00				
50th percentile	2.50	1.50	2.00	3.00	3.50				
75th percentile	6.75	6.00	5.00	6.00	7.00				
Maximum	8.00	8.00	8.00	8.00	8.00				
CSTB vs NRC Z	-0.74	-0.19	-0.46	-0.14	-1.6				
p	0.46	0.85	0.65	0.89	0.11				
Low PGS (N=38)									
Means	2.89	2.58	2.58	3.18	3.97	-1.80	-0.020	**-2.60**	**-2.12**
(StDev)	(3.18)	(3.17)	(2.88)	(3.09)	(3.34)	(0.07)	(0.98)	**(0.01)**	**(0.03)**
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.00	0.00				
50th percentile	2.00	1.00	1.50	2.00	4.50				
75th percentile	7.00	6.25	5.00	6.00	7.25				
Maximum	8.00	8.00	8.00	8.00	8.00				
High PGS (N=12)									
Means	3.83	3.58	3.08	3.83	4.58	-0.65	-1.14	-1.56	-.085
(StDev)	(2.86)	(3.18)	(2.50)	(2.52)	(2.50)	(0.52)	(*0.25)*	(0.12)	(0.40)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.50	0.25	1.00	2.25	2.25				
50th percentile	4.00	3.50	3.00	3.50	5.50				
75th percentile	6.00	6.75	5.00	5.75	6.75				
Maximum	8.00	8.00	8.00	8.00	8.00				
Low vs High PGS *Z*	-0.89	-1.08	-0.92	-0.78	-0.40				
p	0.37	0.28	0.36	0.43	0.69				

Note. For all tests, the criterion for rejecting the null hypothesis of no effect (statistical significance, α) was $p<0.05$.

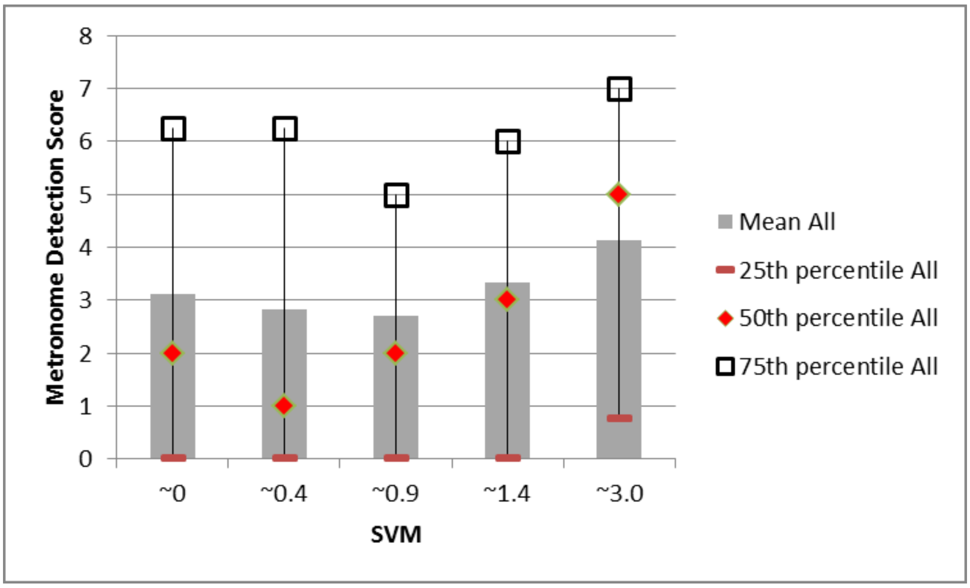

Figure 3. This chart shows the stroboscopic effect detection score for the metronome for the full sample at each SVM level, displaying the means in bars and the 25th, 50th, and 75th percentiles overlaid.

2.4 Acceptability ratings

Participants rated the acceptability of each light source in terms of comfort, pleasantness, and annoyingness on the tenth block of trials. Although for the interim report, we had combined these to form one scale, the internal reliability analysis showed that the annoyingness rating did not correlate well to the other items. Therefore, we formed one scale for "acceptability" by averaging the ratings for comfort and pleasantness (higher scores meaning better conditions, theoretical range 0 [not at all] to 4 [extremely]). The Cronbach's alpha indicator of internal consistency reliability for this two-item scale was 0.81, which is considered very good. We analysed the annoyingness rating separately as a single rating (see section 2.5).

Table 5 displays the results for the average acceptability ratings and the comparisons between SVM conditions and groups. Overall acceptability hovered around the midpoint of the scale (see Figure 4), and did not differ from one SVM condition to the other. The overall average acceptability (across all SVM conditions) was not different between CSTB and NRC (Mann-Whitney U test, Z=-1.06, p=0.11). Looking at the comparisons between locations, we see statistically significant differences between CSTB and NRC for the acceptability ratings of the conditions SVM ~0.9 and SVM ~1.4. In both cases, the CSTB conditions were rated as slightly more acceptable; however, when considered as a difference in median between 2.0 and 1.5 on a scale of 0–4, the difference is small. There also was one difference between sites in the SVM comparisons, in that at NRC but not at CSTB, with the NRC site showing a drop in acceptability between SVM ~0.40 and SVM ~0.90. This drop is consistent with predictions, but given the absence of consistent effects across the SVM conditions (higher SVM conditions were not any less acceptable), this is probably a chance occurrence.

There were no differences between the PGS groups in the acceptability of the conditions, shown in the individual SVM tests (Table 5), nor in the overall average scores by PGS groups (Mann–Whitney U test, Z=-0.62, p=0.54). Similarly, the two groups showed the same pattern of comparisons across the SVM conditions (Wilcoxon tests).

Table 5. This table displays the results for the acceptability ratings of the light sources, both the descriptive statistics and the comparisons.

	Descriptive Statistics					Wilcoxon Signed Ranks Test			
Condition	**1**	**2**	**3**	**4**	**5**	**1 vs 2**	**2 vs 3**	**3 vs 4**	**4 vs 5**
SVM	~0	~0.4	~0.9	~1.4	~3.0	*Z (p)*	*Z (p)*	*Z (p)*	*Z (p)*
Both sites (N=85)									
Means	1.90	1.87	1.79	1.85	1.97	-0.40	-0.68	-0.45	-1.15
(StDev)	(0.96)	(0.98)	(0.93)	(1.02)	(0.96)	(0.69)	(0.49)	(0.65)	(0.25)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	1.50	1.00	1.00	1.00	1.50				
50th percentile	2.00	2.00	2.00	1.50	2.00				
75th percentile	2.50	2.50	2.50	2.75	2.50				
Maximum	4.00	4.00	4.00	4.00	4.00				
CSTB (N= 27)									
Means	1.78	1.91	2.13	2.22	2.19	-1.08	-1.21	-0.51	-0.08
(StDev)	(0.74)	(0.88)	(0.83)	(0.80)	(0.88)	(0.28)	(0.23)	(0.61)	(0.94)
Minimum	0.50	0.00	0.50	0.50	0.00				
25th percentile	1.00	1.00	1.50	1.50	1.50				
50th percentile	2.00	2.00	2.00	2.00	2.50				
75th percentile	2.00	2.50	3.00	3.00	3.00				
Maximum	3.00	3.50	4.00	3.50	4.00				
NRC (N=58)									
Means	1.96	1.85	1.63	1.67	1.87	-1.34	**-2.01**	-0.24	-1.40
(StDev)	(1.05)	(1.03)	(0.94)	(1.07)	(0.99)	(0.18)	**(0.05)**	(0.81)	(0.16)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	1.50	1.38	1.00	1.00	1.00				
50th percentile	2.00	1.75	1.50	1.50	1.75				
75th percentile	2.63	2.50	2.13	2.50	2.50				
Maximum	4.00	4.00	3.50	4.00	4.00				
CSTB vs NRC Z	-0.75	-0.21	**-2.42**	**-2.67**	-1.58				
p	0.46	0.84	**0.02**	**0.01**	0.11				
Low PGS (N=59)									
Means	1.81	1.83	1.70	1.87	2.06	-0.22	-1.01	-1.16	-1.81
(StDev)	(0.99)	(1.04)	(1.01)	(1.13)	(0.91)	(0.83)	(0.31)	(0.24)	(0.07)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	1.00	1.00	1.00	1.00	1.50				
50th percentile	1.50	1.50	1.50	2.00	2.00				
75th percentile	2.50	3.00	2.50	3.00	2.50				
Maximum	4.00	4.00	4.00	4.00	4.00				
High PGS (N=26)									
Means	2.12	1.96	1.98	1.79	1.77	-1.00	-0.49	-0.93	-0.58
(StDev)	(0.88)	(0.85)	(0.70)	(0.74)	(1.07)	(0.32)	(0.49)	(0.35)	(0.56)
Minimum	0.50	0.00	0.50	0.50	0.00				
25th percentile	1.50	1.50	1.50	1.00	1.00				
50th percentile	2.00	2.00	2.00	1.50	1.50				
75th percentile	3.00	2.50	2.50	2.50	2.50				
Maximum	4.00	3.50	3.50	3.00	4.00				
Low vs High PGS *Z*	-1.54	-0.73	-1.36	-0.40	-1.42				
p	0.12	0.46	0.17	0.69	0.16				

Note. For all tests, the criterion for rejecting the null hypothesis of no effect (statistical significance, α) was $p<0.05$.

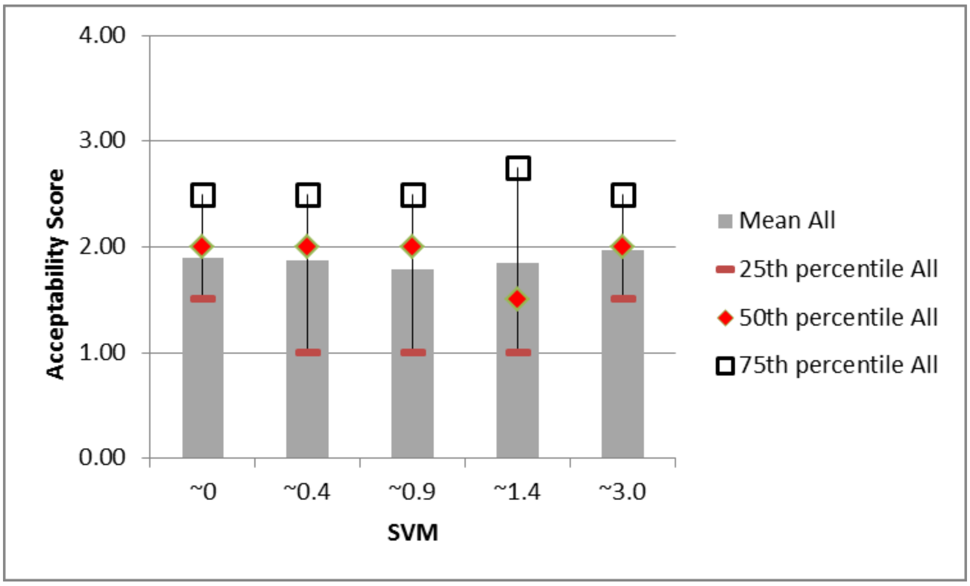

Figure 4. The acceptability of the light conditions in these short exposures did not differ by SVM condition.

2.5 Annoyingness ratings

Participants rated the annoyingness of each light source once, on the tenth block of trials. This was a single question rated on a scale from 0 (not at all) to 4 (extremely). Table 6 displays the results for this variable both for the overall sample, and for the subgroups formed by the location (CSTB or NRC) and by the PGS score.

There were differences in responding between CSTB and NRC on the ratings for each SVM level, and in their overall average annoyingness ratings (Mann–Whitney U test, Z=-4.85, p=0.000). The CSTB participants rated their light sources as consistently less annoying than the NRC participants. Note that the CSTB sessions took place in French and the NRC sessions took place in English (see Appendix A for translation). We cannot rule out the possibility that the difference in annoyingness ratings reflects a translation effect; perhaps the words used in the two languages had subtly different meanings. It is also possible that the difference reflects the fact that the dominant frequency of the TLM was 100 Hz for CSTB and 120 Hz for NRC; however, this seems unlikely to explain the difference for two reasons. First, there was no difference in perception between the two countries, as one might expect if the dominant frequency influenced perception directly[23]. Second, the direction of this effect is opposite to what would be expected; the lower frequency should be more easily detected and, by extension, more annoying. Overall, the language difference seems the most likely explanation.

Looking at the comparisons between SVM levels within the two sites, we see that none of the comparisons showed any statistically significant differences in the CSTB data. Within the NRC data, there was an increase in annoyingness between SVM ~0.40 and SVM ~0.90. The higher level of annoyingness persisted among the NRC participants for SVM ~1.4 and SVM ~ 3.0.

The split of the data set based on PGS scores also showed differences between the groups in the annoyingness ratings. These were as one would expect, with annoyingness ratings being higher for the high-PGS participants: There was an overall difference in average annoyingness between PGS groups (Mann–Whitney U test, Z=-2.12, p=0.03; low-PGS median=0.80 and high-PGS median=1.5). For SVM ~1.4 and SVM ~3.0, annoyingness was higher for the people higher in PGS. The high-PGS group showed no statistically significant differences in annoyingness ratings in the comparisons between the SVM conditions, but the low-PGS group showed a small increase in annoyingness for SVM ~0.90 in comparison to SVM ~0.40.

Table 6. This table displays the results for the annoyingness ratings of the light sources, both the descriptive statistics and the comparisons.

	Descriptive Statistics					Wilcoxon Signed Ranks Test			
Condition	**1**	**2**	**3**	**4**	**5**	**1 vs 2**	**2 vs 3**	**3 vs 4**	**4 vs 5**
SVM	~0	~0.4	~0.9	~1.4	~3.0	*Z (p)*	*Z (p)*	*Z (p)*	*Z (p)*
Both sites (N=85)									
Means	1.11	1.06	1.27	1.25	1.31	-0.55	**-2.40**	-0.29	-0.55
(StDev)	(1.01)	(0.94)	(1.07)	(1.11)	(1.22)	(0.58)	**(0.02)**	(0.77)	(0.59)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.00	0.00				
50th percentile	1.00	1.00	1.00	1.00	1.00				
75th percentile	2.00	2.00	2.00	2.00	2.00				
Maximum	3.00	3.00	4.00	4.00	4.00				
CSTB (N= 27)									
Means	0.52	0.41	0.59	0.59	0.59	-0.80	-1.39	-0.04	0.00
(StDev)	(0.80)	(0.50)	(0.80)	(0.89)	(0.89)	(0.43)	(0.17)	(0.97)	(1.00)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.00	0.00				
50th percentile	0.00	0.00	0.00	0.00	0.00				
75th percentile	1.00	1.00	1.00	1.00	1.00				
Maximum	3.00	1.00	2.00	3.00	3.00				
NRC (N=58)									
Means	1.38	1.36	1.59	1.55	1.64	-0.11	**-1.96**	-0.31	-0.68
(StDev)	(0.99)	(0.95)	(1.04)	(1.08)	(1.64)	(0.91)	**(0.05)**	(0.76)	(0.50)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	1.00	1.00	1.00	1.00	1.00				
50th percentile	1.00	1.00	2.00	1.00	2.00				
75th percentile	2.00	2.00	2.00	2.25	3.00				
Maximum	3.00	3.00	4.00	4.00	4.00				
CSTB vs NRC Z	**-3.83**	**-4.46**	**-4.02**	**-3.87**	**-3.78**				
p	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**				
Low PGS (N=59)									
Means	1.02	1.00	1.24	1.07	1.08	-0.16	**-2.45**	-1.34	-0.12
(StDev)	(1.03)	(0.91)	(1.10)	(1.14)	(1.13)	(0.87)	**(0.01)**	(0.18)	(0.90)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.00	0.00	0.00	0.00	0.00				
50th percentile	1.00	1.00	1.00	1.00	1.00				
75th percentile	2.00	2.00	2.00	2.00	2.00				
Maximum	3.00	3.00	4.00	4.00	4.00				
High PGS (N=26)									
Means	1.31	1.19	1.35	1.65	1.81	-0.69	-0.89	-1.33	-0.68
(StDev)	(0.97)	(1.02)	(1.02)	(0.94)	(1.27)	(0.49)	(0.37)	(0.18)	(0.50)
Minimum	0.00	0.00	0.00	0.00	0.00				
25th percentile	0.75	0.00	0.00	1.00	1.00				
50th percentile	1.00	1.00	1.50	2.00	2.00				
75th percentile	2.00	2.00	2.00	2.00	3.00				
Maximum	3.00	3.00	3.00	3.00	4.00				
Low vs High PGS *Z*	-1.37	-0.74	-0.56	**-2.53**	**-2.47**				
p	0.17	0.46	0.58	**0.01**	**0.01**				

Note. For all tests, the criterion for rejecting the null hypothesis of no effect (statistical significance, α) was $p<0.05$.

Figure 5 displays the overall result graphically, for the full sample. Overall, the annoyingness ratings were low, but there was a small increase from SVM ~0.40 to SVM ~0.90. Note that these ratings occurred following a very short exposure to the conditions. Longer exposures could be expected to lead to different outcomes.

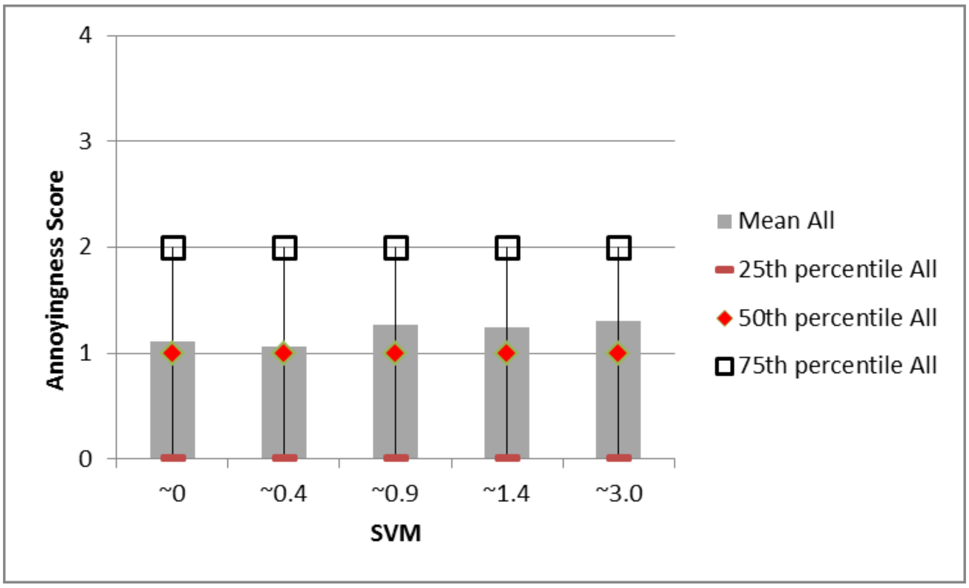

Figure 5. The annoyingness of the light conditions in these short exposures showed a small increase between SVM ~0.40 and SVM ~0.90 in the full sample.

2.6 Inter-relationships

As a final step to understand and to validate the pattern of responses, we explored the correlations between six variables: pattern 2 sensation scores; discomfort ratings of pattern 2; average stroboscopic effect detection of the rotating disc; average stroboscopic effect detection of the metronome (high speed only); average acceptability rating; and, average annoyingness rating. Appendix B shows the results for the full sample and when split by location (CSTB and NRC) and by low vs high PGS.

The intercorrelations show that people who tended to see the stroboscopic effect for the rotating disc also tended to see it for the metronome (r=0.40, p=0.004, N=50). Average acceptability was negatively correlated with average annoyingness (r=-0.22, p=0.04, N=85) and with the discomfort experienced in response to pattern 2 (r=-0.26, p=0.02, N=85).

3. Summary and Conclusions

In the preparations for this experiment, both laboratories acquired a variety of commercially available LED replacement lamps that are available on the North American and European markets today. In the laboratory the lamps were measured under clean sinusoidal power supply conditions and found to exhibit a wide range of TLM characteristics, from nearly none to very high SVM. In the absence of consensus concerning the best metric with which to characterise TLM, and with no requirement for package labelling or product technical specifications to report TLM characteristics (noting that it is uncertain as to whether consumers would understand this metric if declared), there is no way for a consumer to know what the TLM performance of a product will be prior to its use. Each laboratory selected five lamps for this experiment, based on their SVM characteristics, taking care to seek similar performance at each chosen level to permit the data to be combined. The primary visual perception task in this experiment was carefully chosen to replicate the rotating disc task with which the SVM was developed[10, 17, 20]. The metric is defined such that the average person ought to detect the stroboscopic effect 50% of the time if SVM=1.

The results of this experiment showed that, under these experimental conditions, the average rotating disc detection was lower than expected. For this SVM=0.9 condition, the average score was 1.26 (out of 8) and only 25% of the people scored above 2 out of 8. The definition of SVM would lead to the expectation that the average should be closer to 3, or perhaps close to 4, when SVM approaches 1.0. There were individuals who scored as high as 8 when SVM was ~0.90, but they were few. The 90th percentile was 5.4 at SVM ~0.90, indicating that 10% of the population scored higher than this. For SVM ~1.4, half of the sample scored more than the threshold detection (4 out of 8) and 25% of the sample scored 7 or 8.

The conference paper based on interim data from this project reported few results for the metronome stroboscopic detection[19], but the additional data reported here were collected after the task was changed to have the metronome move at 208 bpm. Bullough and Marcus[23] reported that a logarithmic function of the SVM values of their range of experimental conditions explained 79% of the variance in average metronome detection at 100 Hz, which compares very well to the 78% explained variance for the data reported here (excluding our SVM=0 condition, for which a log function cannot be fit). This consistency gives us greater confidence in the interpretation of the metronome detection results. Most notably, the increases in metronome detection scores between SVM ~0.9 and SVM ~1.4, and between SVM ~1.4 and SVM ~3.0, were statistically significant.

The judgements of acceptability (pleasantness and comfort average) did not show any consistent relation to SVM, but over the whole sample, annoyingness did increase from SVM ~0.4 to SVM ~0.9 and stayed at that level as SVM increased further. Annoyingness was higher for the NRC participants than the CSTB participants, a difference that could have been caused unintentionally in the translation from the English used at NRC to the French used at CSTB.

This larger sample of 85 people across the two sites was sufficiently large to permit the examination of results by comparing people expected to be at risk of visual stress (those with high sensation scores when looking at pattern 2 of the Wilkins and Evans Pattern Glare Sensitivity Test[21]), and those whose risk would be low. Visual stress is a syndrome characterized by headache and the occurrence of unwanted visual illusions. The results of this investigation did not find that stroboscopic detection of either the horizontal rotating disc or the vertical metronome differed between these groups. The acceptability ratings also did not differ; however, the more sensitive group (high-PGS) did report greater annoyance with the SVM ~1.4 and SVM ~3.0 conditions than those less sensitive.

The following are the limitations of this experiment that were identified:

- A greater number of female than male participants overall because of the participation rate at the NRC site;
- Only young participants, although this could provide guidance on the upper limit of detection, as older people might be less sensitive;
- Similarly, a limited range of eye colour and ethnicity in the sample might have excluded some sensitive individuals;
- Short viewing times;
- Only an overhead view of the horizontal task and a straight-on view of the vertical task; other geometries of moving objects should be investigated;
- Only 5 SVM levels, leaving gaps where information is lacking;
- Non-immersive surroundings, which had been the setting for prior research; perhaps SVM becomes more annoying as one moves around the space; and,
- Only one visual perception outcome investigated, the stroboscopic effect; thus, the data do not inform concerning possible effects of SVM level on detection of the phantom array, nor on complex phenomena like eyestrain, headache, reading or cognitive performance.

Decisions concerning standards and regulations are best made when based on a body of independently gathered evidence, and when limits set reflect a societal consensus that balances the evidence and the tolerance for risk[4]. Discussions concerning the best metrics to characterise TLM and suitable limits for them are expected to continue, but in the meantime our lit environment is being transformed by long life SSL products on the market today, some of which have very high SVM values. This experiment has been conducted to contribute data for discussions concerning limit values for TLM where, at present, very limited evidence exists[11, 24].

The decision to place a limit on any metric involves two choices: (1) the acceptable frequency of the outcome occurring; and (2) the acceptable proportion of the population who might experience this outcome[4]. These choices are value judgements that research can inform but cannot determine.

As a first step towards discussions among stakeholder groups about suitable limits on lighting system TLM, the following guidance can be drawn from this work:

- An SVM>2.0 caused virtually all of the participants to perceive stroboscopic effects of the rotating disk in every trial, and caused 50% of the participants to perceive stroboscopic effects of the metronome in 5 or more trials out of 8.
- The proposed upper limit of SVM=1.6 is higher than the SVM for magnetic-ballasted T12 lamps[11], which are known to cause headaches and eyestrain and to disrupt eye movements[12-14].
- 25% of the people detected stroboscopic effects with the disk in 7 or more of the 8 trials (i.e., 88% detection), and 6 or more of the 8 trials (i.e., 75% detection) for the metronome at SVM=1.4 (75th percentile overall). The EU-28 population includes ~101 million people between the ages of 0–30. Based on the data presented here, SVM=1.6 would mean that on most of the occasions when they were exposed to that condition, one quarter of these 101 million young people could perceive the stroboscopic effect at greater than chance levels for both horizontal and vertical movement.
- The 75th percentile detection rate dropped to 2 out of 8 trials (i.e., 25%) when the SVM was ~0.9. This is lower than the chance level of detection.
- At SVM levels of 0.4 and below, the disc stroboscopic detection rate for the top quartile of the people dropped to 0.
- Those in the population who are more at risk of visual stress (the top 30% of a measure of this risk) are more annoyed by an SVM of ~1.4 or greater than are those who are at low risk, even when the exposure is short (noting that long exposures were not included in this investigation).

References

1. Wilkins AJ, Veitch JA, Lehman B. LED lighting flicker and potential health concerns: IEEE Standard PAR1789 update. *Proceedings of the Energy Conversion Congress and Exposition (ECCE) 2010 IEEE, 12-16 Sept, 2010*. New York, NY: Institute of Electrical and Electronics Engineers; 2010. p. 171-8.

2. IEEE Power Electronics Society. *IEEE recommended practices for modulating current in high-brightness LEDs for mitigating health risks to viewers*. S1789-2015 New York, NY: Institute for Electrical and Electronics Engineers, Inc. (IEEE). 2015.

3. Wilkins AJ. A physiological basis for visual discomfort: Application in lighting design. *Lighting Research and Technology*. 2016;48(1):44-54.

4. Commission Internationale de l'Eclairage (CIE). *Final report CIE stakeholder workshop for temporal light modulation standards for lighting systems* CIE TN 008:2017 Vienna, Austria: CIE, 2017.

5. Commission Internationale de l'Eclairage (CIE). *Visual aspects of time-modulated lighting systems – Definitions and measurement models*. TN 006-2016 Vienna, Austria: CIE, 2016.

6. DiLaura DL, Houser KW, Mistrick RG, Steffy GR. *The lighting handbook*. 10th ed. New York: Illuminating Engineering Society of North America; 2011.

7. International Electrotechnical Commission (IEC). *Equipment for general lighting purposes - EMC immunity requirements - Part 1: An objective light flickermeter and voltage fluctuation immunity test method*. IEC TR 61547-1:2017 Geneva, Switzerland: IEC, 2017.

8. International Electrotechnical Commission (IEC). *Equipment for general lighting purposes - Objective test method for stroboscopic effects of lighting equipment*. IEC TR 63158:2018 Geneva, Switzerland: IEC, 2018.

9. Alliance for Solid-State Illumination Systems and Technologies (ASSIST). *ASSIST recommends...Evaluating light source flicker for stroboscopic effects and general acceptability*. Vol. 11(4) Troy, NY, USA: Lighting Research Center, Rensselaer Polytechnic Institute., 2017.

10. Perz M, Vogels IMLC, Sekulovski D, Wang LL, Tu Y, Heynderickx IEJ. Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems. *Lighting Research and Technology*. [Article]. 2015;47(3):281-300.

11. National Electrical Manufacturers Association (NEMA) Lighting Systems Division. *Standard for temporal light artifacts: Test methods and guidance for acceptance criteria*. NEMA 77-2017 Rosslyn, VA: NEMA, 2017.

12. Veitch JA, McColl SL. Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort. *Lighting Research and Technology*. 1995;27(4):243-56.

13. Wilkins AJ. Intermittent illumination from visual display units and fluorescent lighting affects movement of the eyes across text. *Human Factors*. 1986;28(1):75-81.

14. Wilkins AJ, Nimmo-Smith I, Slater AI, Bedocs L. Fluorescent lighting, headaches and eyestrain. *Lighting Research and Technology*. 1989;21(1):11-8.

15. Bullough JD, Sweater Hickcox K, Klein TR, Narendran N. Effects of flicker characteristics from solid-state lighting on detection, acceptability and comfort. *Lighting Research and Technology*. 2011;43(3):337-48.

16. Bullough JD, Sweater Hickcox K, Klein TR, Lok A, Narendran N. Detection and acceptability of stroboscopic effects from flicker. *Lighting Research and Technology*. 2012;44(4):477-83.

17. Vogels IM, Sekulovski D, Perz M. Visible artefacts of LEDs. *Proceedings of the 27th Session of the Commission Internationale de l'Eclairage, Sun City, South Africa*. Vienna, Austria: CIE; 2011. p. 42-51.

18. Brundrett GW. Human sensitivity to flicker. *Lighting Research and Technology*. 1974;6(3):127-43.

19. Veitch JA, Martinsons C. Detection of the stroboscopic effect under low levels of the stroboscopic visibility measure. *Proceedings of the 29th CIE Quadrennial Session, June 16-22, Washington, DC, USA*. Vienna, Austria: Commission Internationale de l'Eclairage; 2019. p. 682-91.

20. Perz M, Sekulovski D, Vogels IM, Heynderickx IEJ. Stroboscopic effect: Contrast threshold function and dependence on illumination level. *Journal of the Optical Society of America A: Optics and Image Science, and Vision*. [Article]. 2018;35(2):309-19.

21. Wilkins AJ, Evans BJW. *I.O.O. Pattern Glare Test*. London, UK: i.O.O Sales Ltd.; 2012.

22. Wilkins AJ, Allen PM, Monger LJ, Gilchrist JM. Visual stress and dyslexia for the practicing optometrist. *Optometry in Practice*. 2016;17(2):103-12.

23. Bullough JD, Marcus D. Influence of flicker characteristics on stroboscopic effects. *Lighting Research & Technology*. 2016;48(7):857-70.

24. Perz M, Sekulovski D, Beeckman P. Acceptability criteria for the stroboscopic effect visiblity measure. *Proceedings of the Conference "Smarter Lighting for Better Life" at the CIE Midterm Meeting 2017, October 23-25, 2017, Jeju, South Korea*. Vienna, Austria: Commission Internationale de l'Eclairage; 2017. p. 453-9.

25. European Commission. *Draft commission regulation laying down ecodesign requirements for light sources and separate control gears pursuant to Directive 2009/125/EC of the European Parliament and of the Council and repealing Commission Regulations (EC) No 244/2009, (EC) No 245/2009 and (EU) No 1194/2012* Brussels, Belgium: European Commission, 2018, October 6.

26. Whissell CM. Sex, eye-color, and aesthetic ratings of colors. *Perceptual and Motor Skills*. 1980;51(3, Pt 1):1012-4.

Appendix A - Method

In Canada, this research protocol was reviewed and approved by the National Research Council of Canada Research Ethics Board (Protocol 2018-129) and by the Carleton University Research Ethics Board-B (CUREB-B Clearance # 109982).

This research complies with the EU and French General Data Protection Regulation (GDPR).

A.1 Research design and hypothesis

This is a repeated-measures experiment with 5 levels of the independent variable, light source. The five light sources were commercially available products chosen because they are known to exhibit the chosen levels of the metric SVM[7, 8, 10]. They were chosen based on the following criteria: about 800 lm output; ~2600–3000 K correlated colour temperature; P_{st}^{LM}<<1, and having the target SVM values (0, 0.4–0.6, ~1, ~1.6, and >2). These values were chosen to provide a range of data for conditions at and below the proposed regulatory limit being considered in Europe (SVM upper limit of 1.6)[25], and one condition considerably higher as a manipulation check. To the extent possible, chromaticity coordinates were matched, although this was dependent on the existence of alternatives at any given SVM value.

Participants performed 50 trials in total, 10 blocks of five light source conditions. Within each block the order of presentation was random.

Data were collected in parallel using this same procedure by teams in Canada (NRC) and in France (CSTB). The results presented in this report are based on a combination of the data in a mixed design for analysis (site being a between-groups variable, and light source a repeated measures variable).

The hypotheses to be tested were:

> H1: The visibility of the stroboscopic effect is 50% for SVM=1. (This is the definition of the metric.)
>
> H2: The visibility of the stroboscopic effect increases with increasing SVM.
>
> H3: Comfort and pleasantness drop with increasing SVM, and annoyingness increase with increasing SVM.

A.2 Setting and lighting conditions in Canada and France

Testing occurred in a dedicated small windowless room. The room was minimally furnished with a desk and chairs. During the session trials all the illumination came from the custom desktop luminaire described below. During the instructions and demographic questionnaires, a desk lamp with the low-SVM condition was used on a separate desk from the one holding the apparatus (see photos).

The custom luminaire consisted of an aluminum frame supporting a light box. The central light box had six chambers, in each of which was a standard E27 socket. Five locations were used, each with one of the five lamps (described below). All lamps were powered continuously during the session to maintain constant temperature and light output.

At NRC, the light box drum could be rotated such that one chamber was located over an aperture that allowed light to fall onto the desk surface, while the other lamps were blocked by the plywood base of the light box (see Figure A1). The chambers in the light box were painted black (NRC) or covered with black adhesive velvet sheets, but some were modified with white reflective plastic to increase the illuminance on the desk below when that chamber was in use. There was no diffuser over the lamps, but the participant was shielded from any view of the aperture by a cover on the frame. At CSTB, each chamber of the light box had an individual shutter (see Figure A2). The selection of the chamber was also done by rotating the device.

The height of the luminaire was adjusted once so that all the lamps delivered ~330 lx on the surface of the principal task, a rotating disk (see below). There were no sides to the frame, so that viewers had the full field of view available to them and light from the luminaire could provide ambient illumination for the rest of the room beyond the desk on which it sits. An uninterruptible power supply was used by NRC to ensure clean power for the luminaire during testing. A laboratory specification AC power supply was used by CSTB for the same purpose.

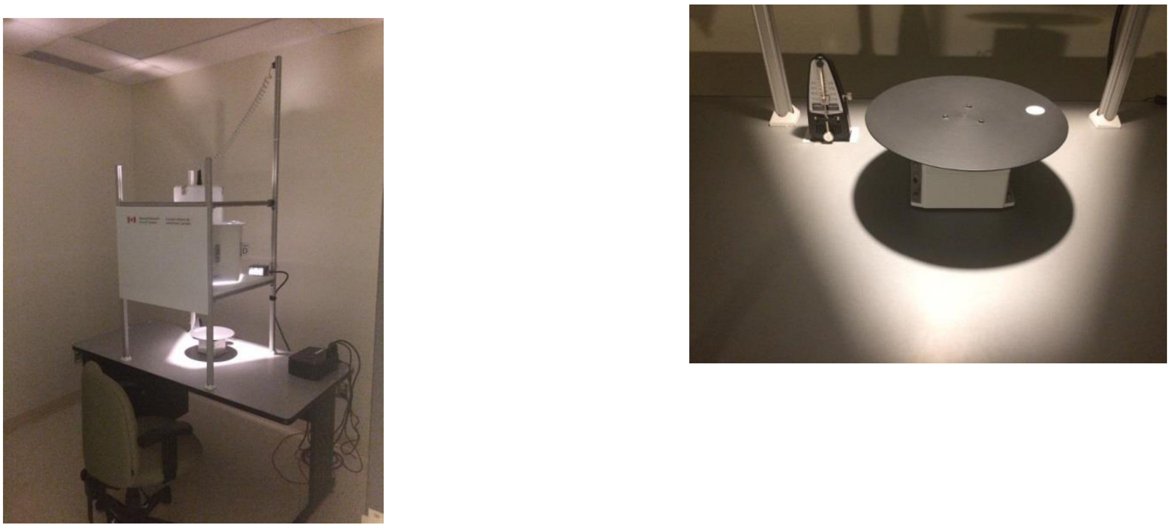

Figure A1. Images of the NRC apparatus installed in the test room. For the image on the left, the hallway outside provided ambient light for the photograph, but the door was closed during testing. The image on the right shows the desk surface as seen by the participant.

Figure A2. Images of the CSTB apparatus installed in the test room.

Each laboratory characterized its light sources based on measurements made under the light box at the location of the rotating disc (see Table A1).

Table A1. NRC and CSTB test lamp characteristics claimed CCT and luminous flux, and light characteristics measured horizontally at the location of the rotating disk under the light box for each of the five lighting conditions.

Condition	CCT (label) [K]	Lum. flux (claim) [lm]	Illum (meas) [lx]	CCT (meas) [K]	R_a (meas)	Duv (meas)	Dominant Frequency [Hz]	Modu-lation [%]	Flicker Index [%]	P_{st}^{LM}	SVM
NRC-1	2700	800	341	2872	83	-0.0008	120	4.7	0.43	0.05	0.04
NRC-2	2700	800	319	3018	84	-0.0016	120	14.0	3.79	0.07	0.42
NRC-3	2700	800	354	2717	83	-0.0001	120	32.0	8.47	0.08	0.91
NRC-4	3000	800	334	3094	83	-0.0023	120	55.6	13.25	0.06	1.38
NRC-5	3000	800	335	3027	83	-0.0003	120	91.5	29.99	0.33	2.80
CSTB-1	2700	806	344	2756	83	0.00001	100	2.1	0.6	0.39	0.00
CSTB-2	2700	810	330	2810	82	0.0009	100	11.8	3.7	0.05	0.43
CSTB-3	2600	720	318	2559	90	0.0022	100	27.8	7.9	0.08	0.96
CSTB-4	2700	810	312	2641	81	0.0016	100	40.2	12.3	0.26	1.47
CSTB-5	2700	600	324	2799	80	0.0022	100	79.4	26.9	0.38	3.09

A.3 Dependent variables

The same questions and tasks were used in both countries. They were originally written in English and translated to French at CSTB.

A.3.1 Demographics

At the start of the session (after signing the Agreement to Participate), participants answered demographic questions with paper and pen on the desk surface, under the lowest SVM condition. These questions are shown in Table A2.

Table A2. Demographic questions.

What is your sex?	0 Male	1 Female	2 Prefer not to say			
How old are you?	0 18 to 29	1 30 to 39	2 0 to 49	3 50 to 59	4 60 and older	
What type of correction lenses do you have today?	0 None	1 Reading Glasses	2 Distance Glasses	3 Bi- or Trifocal Lenses	4 Gradual or Multi-focal Lenses	5 Contact Lenses
Have you ever been diagnosed with a hearing impairment?	0 No	1 Yes				
Do you use any form of hearing aid?	0 No	1 Yes				
What best describes your eye colour? We ask because there is evidence that eye colour predicts some visual perceptions although the mechanism for this is unknown.	0 Blue	1 Grey	2 Green	3 Light brown	4 Brown or black	
What is the highest level of education you have completed?	Secondary/ high school graduation certificate or less = 1	Diploma or certificate from a community college, institute of technology etc. = 2	Some university courses or a university certificate below the Bachelor level = 3	Undergraduate (Bachelor's) degree = 4	Graduate or professional degree = 5	

A.3.2 Pattern glare sensitivity

Participants were asked to complete the Wilkins and Evans Pattern Glare Test[21] The test consists of three plates of square wave patterns, shown below in reduced size (Figure A3). Scores on this test have been shown to be correlated to the propensity for headache associated with visual stimuli. After viewing each pattern, participants were asked three questions. The number of sensations indicated is summed (maximum 7). Following advice from Arnold Wilkins, we chose to focus on the number of sensations reported to Pattern 2 as the indicator of sensitivity. (Pattern 1 is a probe for response bias, and there is a question concerning the validity of Pattern 3[22].) This was used as an individual difference variable to examine variation in response to TLM.

You will be asked to look at a striped pattern for 5 seconds. Please focus on the square in the centre of the pattern. If you find the pattern extremely uncomfortable to view, please avert your eyes until the pattern has been removed.

Did you experience the following when looking at the stripes?

- Colours (if yes, which? Red / Blue / Green / Yellow)
- Bending of any lines
- Blur
- Shadowy shapes amongst the lines
- Flickering / Shimmering of the lines
- Fading of the lines
- Other

Were any of the above

- Predominantly on the left of the image
- Predominately on the right of the image
- Roughly equal both sides

How uncomfortable was the pattern to look at?

- No problem
- Slightly uncomfortable
- Uncomfortable
- Very uncomfortable

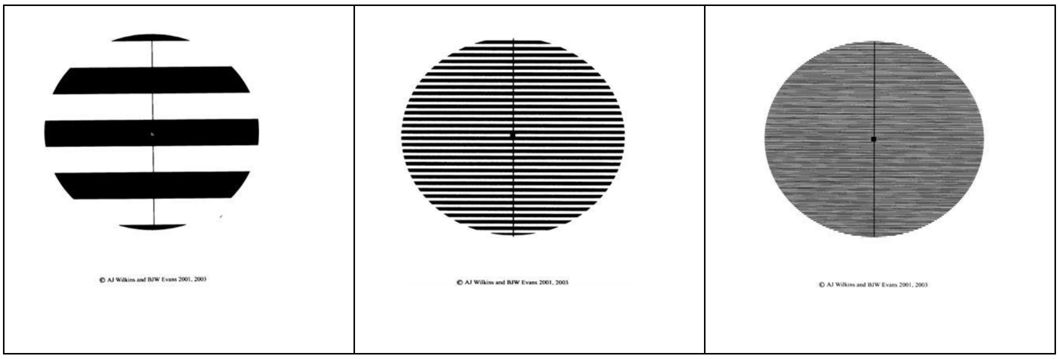

Figure A3: Pattern Glare Test

A.3.3 Stroboscopic effect

Within each trial there were two probes for the stroboscopic effect. The first of these used a white dot on a rotating horizontal black disk, as was used by prior researchers[5, 10, 17, 20]; see Figure A4. The dot on the disk rotated at a speed of 4 m/s, which the prior researchers considered to be the upper limit of the speed of hands moving in an office context. The participant was asked to look at the disk and to report whether or not they saw individual dots (stroboscopic effect) (see Figure A3). The rotating disks used in this experiment were designed, assembled, and programmed at NRC using a programmable DC motor, two being shipped to CSTB with a suitable power cable for operation in France. The reflectance of the black surface was *ρ*=6.96%. and the white dot was *ρ*=90.85%, making the luminance ratio 13.05:1, as similar as possible to the original paper[17]. For each trial, the participant was asked to answer "yes" or "no" to the question "Do you see white dots?" at NRC and "oui" or "non" to "Voyez-vous des points blancs ?" at CSTB.

We also added a vertical task. Participants were asked to look at black a dot on the end of the arm of a mechanical metronome (operating at 180 bpm in Canada and 150 bpm in France in the first round of data collection, but increased to 208 bpm for both locations in the second round) and to report whether or not they saw individual dots or a blur. See Figure A1 for the metronome used in Canada and Figure A2 for France. The metronomes were identical in the two countries, but each team made and attached its own black dot. For each trial, the participant was asked to answer "yes" or "no" to the question "Do you see black dots?" at NRC and "oui" or "non" to "Voyez-vous des points noirs ?" at CSTB.

Figure A4. These images from Reference 17 demonstrate the stroboscopic effect. When one sees this effect, the moving disk looks like the image on the left. With no stroboscopic effect, it looks like the disk on the right.

A.3.4 Judgements of light sources

On the last trial for each lamp (i.e., after having repeated the visibility task 10 times), the participants were asked to rate the comfort, pleasantness, and annoyingness of that condition, each on a 5-point Likert scale[17]. See Table A3 for the exact wording used at NRC and CSTB. At NRC, the experimenter was prepared with definitions, if needed: "*Pleasantness* refers to whether or not the condition gives a sense of satisfaction when one looks at it. *Comfort* refers to how one feels when one looks at the scene, a state that is one of physical ease and free from pain."

Table A3. The light source judgements were asked in English at NRC and in French at CSTB. The top part of the table shows the three questions in the two languages, and the bottom part of the table shows the response anchors in the two languages.

NRC	Please rate the comfort of this condition		Please rate the pleasantness of this condition		Please rate the annoyingness of this condition
CSTB	Evaluez le confort de cet éclairage		Evaluez l'aspect agréable de cet éclairage		Evaluez la gêne que procure cet éclairage
NRC	0	1	2	3	4
	not at all	a little	moderately	very much	extremely
CSTB	Pas du tout Confortable Agréable Gênant	Un peu Confortable Agréable Gênant	Modérément Confortable Agréable Gênant	Très Confortable Agréable Gênant	Extremement Confortable Agréable Gênant

A.4 Procedure

When participants arrived, a desk lamp at the lowest SVM level provided the room light and all of the lamps in the apparatus were on but covered. Participants received information about the study and signed the consent form in this condition. They also completed a short paper-based questionnaire to record demographic information (age, sex, education, eye colour[26], and visual corrections).

For the visual perception trials, the participant was asked to rotate away from the desk that held the task (facing the opposite wall) and to close his or her eyes while the researcher set up each trial. Setting up involved rotating the light box to reveal one or another light source. Light sources were presented in blocks of five with the conditions in random orders in each block. The random orders of presentation were listed on a pre-printed data sheet for that session. The experimenter asked the participant to turn around, and to look at first the rotating disk to answer the question “Do you see white dots?” with an answer “yes” or “no”. Next, the same question was asked for the metronome. After this second question, the participant turned away and closed his or her eyes while the next trial was set up.

In the final block of five trials, the participant was asked to rate the appearance of the condition on the three scales described above after the metronome question.

At the conclusion of the session, the participant was provided the debriefing information sheet and asked not to share the information with other potential participants.

Participation took approximately 50 minutes. In Canada, participants either received an honorarium of $20 for their participation or were awarded 1% bonus credit for a Psychology undergraduate course. In France, participants received a €15 gift card for their participation.

A total of 96 people were tested in the two countries. Five cases from France were excluded because one of the lamps presented was the wrong lamp and they had not seen the condition with the SVM=0.40. Six cases (two from Canada and four from France) were excluded from analysis because they scored 4 or higher positive responses to the condition SVM=0, which suggested that they might be guessing rather than giving a true response. Thus, the total sample on which results are based numbered 85, except for the metronome task, as described above in Section 2.3.

Appendix B - Supplemental Analyses

Table B1. This table shows the intercorrelations between variables for the full data set. Note that the correlations involving metronome detection have a smaller sample size.

		Discomfort _PG2	PG_2 Score	Disc Detect Average	Metronome Detect Average	Acceptability Average
PG_2 Score	*r*	**0.31**				
	p	**0.00**				
	N	**85**				
Disc Detect Average	*r*	0.06	-0.04			
	p	0.57	0.70			
	N	85	85			
Metronome Detect Average	*r*	0.16	0.08	**0.40**		
	p	0.27	0.56	**0.00**		
	N	50	50	50		
Acceptability Average	*r*	**-0.26**	0.04	-0.05	-0.19	
	p	**0.02**	0.72	0.67	0.20	
	N	85	85	85	50	
Annoyingness Average	*r*	0.09	0.20	0.13	0.23	**-0.22**
	p	0.42	0.06	0.23	0.11	**0.04**
	N	85	85	85	50	85

Table B2. This table shows the intercorrelations between variables, separately for the two measurement locations.

			Above diagonal: CSTB				
Below diagonal: NRC		**Discomfort _PG2**	**PG_2 Score**	**Disc Detect Average**	**Metronome Detect Average**	**Acceptability Average**	**Annoyingness Average**
Discomfort _PG2	*r*		**0.53**	0.18	0.04	**-0.45**	0.32
	p		**0.01**	0.38	0.91	**0.02**	0.10
	N		27	27	10	27	27
PG_2 Score	*r*	**0.26**		0.12	0.36	-0.27	**0.41**
	p	**0.05**		0.57	0.31	0.17	**0.03**
	N	58		27	10	27	27
Disc Detect Average	*r*	-0.04	-0.10		0.59	-0.24	**0.39**
	p	0.80	0.44		0.08	0.23	**0.04**
	N	58	58		10	27	27
Metronome Detect Average	*r*	0.22	0.04	**0.36**		0.31	-0.13
	p	0.17	0.83	**0.02**		0.38	0.72
	N	40	40	40		10	10
Acceptability Average	*r*	**-0.31**	0.14	0.00	-0.27		**-0.61**
	p	**0.02**	0.31	0.99	0.09		**0.00**
	N	58	58	58	40		27
Annoyingness Average	*r*	**0.33**	0.15	0.12	**0.33**	-0.07	
	p	**0.01**	0.26	0.37	**0.04**	0.59	
	N	58	58	58	40	58	

Table B3. This table shows the intercorrelations between variables, separately for the two PGS groups.

			Above diagonal: High PGS				
Below diagonal: Low PGS		**Discomfort _PG2**	**PG_2 Score**	**Disc Detect Average**	**Metronome Detect Average**	**Acceptability Average**	**Annoyingness Average**
Discomfort _PG2	*r*		-0.10	0.20	**0.62**	-0.34	-0.08
	p		0.63	0.33	**0.03**	0.09	0.69
	N		26	26	12	26	26
PG_2 Score	*r*	0.23		-0.12	-0.23	-0.20	-0.21
	p	0.08		0.58	0.47	0.33	0.30
	N	59		26	12	26	26
Disc Detect Average	*r*	-0.02	-0.14		0.31	-0.08	-0.26
	p	0.90	0.31		0.32	0.69	0.19
	N	59	59		12	26	26
Metronome Detect Average	*r*	0.06	0.04	**0.43**		-0.34	0.01
	p	0.75	0.83	**0.01**		0.28	0.97
	N	38	38	38		12	12
Acceptability Average	*r*	**-0.27**	0.05	-0.04	-0.17		**-0.41**
	p	**0.04**	0.71	0.77	0.32		**0.04**
	N	59	59	59	38		26
Annoyingness Average	*r*	0.07	0.13	**0.28**	0.24	-0.20	
	p	0.58	0.31	**0.03**	0.14	0.14	
	N	59	59	59	38	59	