Effects of Temporal Light Modulation on Individuals Sensitive to Pattern Glare

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This is an archival copy of an article published in *LEUKOS.* Please cite as:
Veitch, J. A., & Miller, N. J. (2024). Effects of Temporal Light Modulation on Individuals Sensitive to Pattern Glare. *LEUKOS*, 20(3), 310–346. https://doi.org/10.1080/15502724.2023.2299210

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Veitch, J. A., & Miller, N. J. (2024). Effects of temporal light modulation on individuals sensitive to pattern glare. *LEUKOS*, Online early. https://doi.org/10.1080/15502724.2023.2299210.

Abstract

Solid-state lighting systems can vary widely in the degree of temporal light modulation (TLM) of their light output. TLM is known to have visual, cognitive, and behavioral effects but there are few recommendations for limits on the acceptable TLM in everyday lighting systems and there is little information concerning individual differences in sensitivity. This paper is a re-analysis of previously presented data, focusing on two subgroups in a larger sample: those scoring low or high on the Wilkins Pattern Glare Sensitivity (PGS) test, which is a validated test that identifies people at high risk of visual stress. The results show that the PGS groups differed in their sensitivity to TLM conditions, despite short exposures and a restricted field of view.

Keywords: temporal light modulation; eye movements; visual comfort; phantom array; individual differences

1. Introduction

Temporal light modulation (TLM) is a fluctuation in the luminous quantity or spectral distribution of the output of a lighting system over time (Commission Internationale de l'Eclairage (CIE) 2021). Cyclic variations in light output are most familiar to us when at low frequencies (below ~80 Hz) observers see the differences between high and low levels and report it as flicker. Visual perception is not the only behavioral response to TLM; cognitive, neurological, behavioral and health effects are known to occur (Wilkins 2016).

When magnetically-ballasted fluorescent lamps (with TLM with frequency of 120 Hz in North America and 100 Hz in most of the rest of the world because of the differences in local AC frequencies) dominated commercial lighting, TLM was associated with headaches and eyestrain (Wilkins and others 1989) and with reduced visual and reading performance (Veitch and McColl 1995; Wilkins 1986). Although the belief that fluorescent lighting could cause headaches was widespread (Stone 1992; Veitch and Gifford 1996), the effects were most noted among people with a tendency to headache (Wilkins and others 1989). Weak evidence suggested that younger people might be more susceptible (Brundrett

1974), but there was no systematic effort at that time to understand how everyday lighting conditions might affect subpopulations. With the introduction of electronic ballasts, with their higher operating frequency (~40 kHz) than magnetically-ballasted fluorescent lamps (120 Hz in North America, 100 Hz in most other parts of the world), the problem appeared to have been solved (Veitch and Newsham 1998) and interest in the topic waned.

The advent of solid-state lighting (SSL) brought renewed interest in TLM because unlike legacy technologies, every SSL product and system can exhibit a different TLM waveform depending on the system electronics. Solid-state emitters are current-driven, and unlike the behavior of incandescent, fluorescent, or discharge sources, exhibit little persistence of light output when the current drops to low values. Furthermore, the driving electronics vary widely and can incorporate simple circuits for operation (e.g., some AC LEDs) or pulse-width modulation techniques for dimming. Sudden changes in light output can result at frequencies of twice the mains frequency, and multiples of those frequencies up to 10 kHz or more. These can be surprisingly visible, given the conventional wisdom that higher frequency would eliminate visual perception effects (Brown and others 2020; Kang and others 2023; Roberts and Wilkins 2013), and can affect the strength of brain activity (e.g., Veitch and others 2023), depending on the characteristics of the waveform and the viewing conditions.

There were no recommendations to limit TLM from SSL until the IEEE published its standard S1789-2015 (IEEE Power Electronics Society 2015). That document characterized TLM with two parameters, the dominant frequency and the modulation depth, and proposed limits based on the combination of these parameters. The limits were derived from visual perception research involving the general population. The recommendations have been controversial because some benign legacy sources fall in the higher risk operating areas, because the recommendations do not take waveshape or duty cycle into account, and because implementing the recommendations could have substantial cost and product life implications (National Electrical Manufacturers Association (NEMA) Lighting Systems Division 2015).

Along with the diversity of TLM properties from SSL lighting systems has come the ability to systematically investigate TLM in all of its parameters: frequency, modulation depth, waveform, and (for rectangular waves) duty cycle. Visual perception phenomena – flicker, the stroboscopic effect, and the phantom array – have attracted the most research attention (Brown and others 2020; Bullough and Marcus 2016; Bullough and others 2011; Perz and others 2017; Perz and others 2015; Roberts and Wilkins 2013; Vogels and others 2011). The currently available indices that integrate across parameters, such as the Stroboscopic Visibility Measure (SVM; Perz and others 2015) derive from this work, but it is not known whether these quantities can also predict behavioral or health outcomes beyond the visual perceptions that underpin them (CIE, 2017); that is, could an index that predicts the visibility of the stroboscopic effect also predict task performance or headache incidence?

One study that did explore this issue used a windowed office and bench-top laboratory space occupied by the same employees during their regular jobs over several months. They found no significant differences in self-reported health and well-being between the baseline LED lighting (12.5% modulation, 100 Hz, sinusoidal waveform, SVM = 0.47) and the same lighting switched to a test driver (36.4% modulation, 100 Hz, sinusoidal waveform, SVM = 1.34) (Sekulovski and others 2020). Others have observed that the luminous environment in this office was moderated by daylight during all but the early and late hours of the workday (which would reduce the strength of the TLM stimulus, as had been noted in Wilkins and others [1989]), and that there is no information about possible individual differences in sensitivity among the participants, which might have revealed a subset of people who were affected by the lighting condition (Veitch and others 2021).

The IES Flicker Index (FI) could be considered a classic or legacy indicator, having been developed in the 1950s to describe the luminous output from fluorescent lighting systems (Eastman and Campbell 1952). It was designed to compare light sources at the same 120 Hz frequency (the only frequency available in North America at that time) to provide an estimate of TLM waveform variability by summing the luminous output above the average output value over a cycle, and dividing by the total luminous output over that cycle. At least one study found the standalone FI value unreliable as a metric for the stroboscopic effect (Vogels and others 2011), and predictive quality for other behavioral outcomes is seemingly untested.

Nilsson Tengelin (2017) tested various combinations of light sources with output in rectangular waves varying in modulation frequency, the baseline for which was a direct current (no-TLM) condition, to see whether cognitive performance and visual perception would be affected. The combinations of light sources with different frequencies created complex TLM waveforms. Reaction time and attention performance were slightly better in conditions with more modulation in the light output (TLM conditions) than in the no-TLM condition, but the conditions with TLM were more likely to cause discomfort and to result in the stroboscopic effect when moving objects were viewed. The report did not include characterization of the stimulus conditions with SVM calculations, but the conditions with TLM would certainly have had a higher SVM than the no-TLM condition. Thus, in this study, both performance improvement and visual discomfort co-occurred with lighting conditions having a higher SVM.

Zhao, Hou, Lin and Xu (2020) conducted a factorial experiment with fundamental frequencies of 100, 400, and 1500 Hz and three modulation depths of 10%, 30%, and 70%, all with sine waves, and tested the effects of the nine conditions on brain activity, visual search, clerical work, stroboscopic detection, and ratings of lighting acceptability in a small sample of 10 young people. The experimental conditions were chosen to be in the various risk regions of the frequency-modulation depth recommendations from IEEE 1789-2015, but the results are difficult to interpret in relation to these risk regions because they were main effects, and not interactions. Brain activity showed a main effect of frequency (100 Hz vs 1500 Hz) with increased arousal (less alpha-wave activity) in the occipital lobe for 100 Hz than 1500 Hz, but there was no effect of modulation depth and no reported interaction between these variables. Fatigue, assessed by change in the critical flicker fusion frequency, was predicted by modulation depth and not by frequency, and not clearly related to the risk level associated with the frequency-modulation depth combination. Although in some instances the expected worse outcome occurred for the conditions in the high-risk area, this was not always the case. The pattern of results also did not follow the rank order of the SVM or FI of the nine conditions.

Veitch (2019) also conducted an experiment with nine TLM conditions chosen based on the IEEE 1789-2015 results, with 50 participants of varying ages, but used a different analytic strategy involving eight planned comparisons of pairs of the TLM conditions against specific expected outcomes. Some of the expected effects were observed (e.g., 30% modulation depth resulted in less physiological arousal (smaller pupil size) than

100% modulation depth, both being at 500 Hz) and others were not (visual discomfort was higher for 30% modulation depth than 100%, also at 500 Hz).

Some have argued that clarity of results would improve if researchers focused their attention on those individuals thought to be most sensitive to lighting conditions (Royer 2020; Veitch and others 2021). There is very limited evidence that the effects of TLM differ between identifiable subgroups. Veitch and Martinsons (2020) reported a stroboscopic visibility experiment in which participants (some in Canada, and some in France) viewed a rotating disc illuminated by one of five commercially-available LED lamps selected for their SVM characteristics. On the tenth trial for each lamp, they also rated the annoyingness of the condition. Participants' sensitivity to visual stress was assessed with the Wilkins Pattern Glare Sensitivity test (Wilkins and Evans 2012). Stroboscopic visibility increased with increasing SVM for both high-sensitivity and low-sensitivity participants; however, only the high-sensitivity participants showed any effect of SVM on annoyingness ratings.

The results reported here are one step towards understanding sensitivity to TLM. They are a re-analysis of the data previously reported by Veitch (2019) on a subsample of the original 50 participants. Participants' sensitivity had been assessed using the Wilkins and Evans Pattern Glare Sensitivity (PGS) test (Wilkins and Evans 2012), which has been previously validated as an indicator of whether or not an individual is susceptible to visual disturbances or headache as a result of visual conditions (Evans and Stevenson 2008; Harle and others 2006). The highest and lowest-scoring individuals on this test were selected from the original dataset, matching as much as possible for age and sex, to form a low-PGS and a high-PGS group; this new variable, sensitivity, was added to the prior analytic model to test whether or not the effects of TLM differed for the two groups. The additional hypothesis was that the effects of TLM would be larger for the high-PGS group than the low-PGS group. Thus, we report here the main effects of sensitivity, the interaction effects of sensitivity by the original eight planned comparisons, and the effects within the high- and low-PGS groups.

2. Methods and Materials

2.1 Participants

The original paper reported results based on a sample of 50 adults hired for a day each from a temporary services agency (Veitch 2019). The research protocol had been approved by the National Research Council of Canada Research Ethics Board as protocol 2017-56.

The participants had completed the Wilkins and Evans Pattern Glare Sensitivity (PGS) test (Wilkins and Evans 2012), which involves looking at three patterns of horizontal stripes, each with a different spatial frequency; following their recommendations the test distance was 40 cm and the spatial frequencies were 0.3, 2.3, and 9.4 cycles per degree. For each pattern in turn, participants answer questions about whether they experience visual disturbances such as the lines bending or false colors. The test has been shown to be a valid diagnostic tool to identify people at risk of visual stress, a collection of eight symptoms including headache, eyestrain, and reading difficulties in response to the spatial frequency of scenes. Pattern 1 has a very low spatial frequency and is not scored, and Pattern 3 has been found to have unstable scores because it is a high enough spatial frequency to be influenced by small differences in the distance between the eyes and the booklet (Wilkins and others 2016). Visual sensation scores on Pattern 2 were used to differentiate between the low-sensitivity and high-sensitivity individuals because the evidence shows that this score predicts visual discomfort (Wilkins and others 2016).

To create two groups from the original sample, we examined the frequency distribution of PGS Pattern 2 scores for the 50 people, seeking the highest 30% of the sample. We settled on the highest 26%, with PGS Pattern 2 scores ranging from 3 to 7 (of a possible 8) (high-PGS). Scores above 3 on this pattern are considered abnormal and indicate high pattern glare sensitivity (Evans and Stevenson 2008). We then matched these 13 individuals with 13 people who had scored either 0 or 1 on PGS Pattern 2 with the goal being to match the high-PGS group by age and sex in forming the low-PGS group. We chose these for the matching variables because of suggestions in the literature that younger people might be more sensitive to TLM visibility and to headaches and eyestrain as a result of TLM exposure (Brundrett 1974) and because there are sex differences in headache incidence (Smitherman and others 2013). If there was more than one possible match by age, we sought to balance by years of education and years in the workforce. The demographics of the resulting two groups (total N=26) are shown in Table 1.

Table 1. Demographic characteristics of the sample, split by PGS sensitivity groups.

		Sensitivity Group	
		low-PGS	high-PGS
Sex	Male	8	8
	Female	5	5
Age	18-29	3	4
	30-39	5	1
	40-49	3	5
	50-59	1	2
	60 & older	1	1
Education	High School	0	2
	College Diploma	2	3
	Some university	1	1
	Bachelor's Degree	3	7
	Graduate or Professional Degree	7	0
Years in workforce	Mean (SD)	16.6 (2.9)	20.7 (4.0)
Years as a temporary employee	Mean (SD)	1.5 (0.5)	2.3 (1.4)

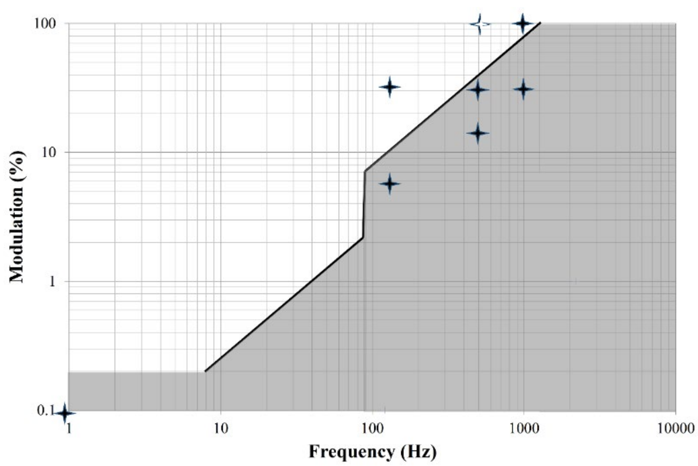
2.2 Apparatus and lighting conditions

The previously-conducted experiment had a repeated-measures design with nine TLM conditions, summarized in Table 2 using the TLM metrics available at the time of the experimental design in 2016, and illustrated in Figure 1. The experimental conditions were chosen in relation to the recommendations in IEEE 1789-2015, but with the addition of a variation in duty cycle because the effects of this parameter are less studied. The experiment was designed to test specific hypotheses, described below.

Table 2. This table describes the nine experimental conditions in terms of several TLM metrics, measured in the apparatus with the display screen on.

Label	Condition	Hz	Mod %	duty cycle	Waveform shape	Meas. FI	Meas. P_{st}^{LM}	Meas. SVM
TLM1	no-TLM	0	0		flat	0	0.06	0.01
TLM2	120Hz_60WA19	120	7%		sine	0.03	0.05	0.31
TLM3	120Hz_T12mag	120	28%		sine-ish	0.07	0.03	0.78
TLM4	500Hz_MD100_DC50	500	100%	50%	rectangular	0.51	0.42	1.89
TLM5	500Hz_MD30_DC50	500	30%	50%	rectangular	0.14	0.12	0.52
TLM6	500Hz_MD100_DC30	500	100%	30%	rectangular	0.69	0.51	2.46
TLM7	500Hz_MD15_DC50	500	15%	50%	rectangular	0.05	0.07	0.20
TLM8	1000Hz_MD100_DC50	1000	100%	50%	rectangular	0.52	0.47	1.46
TLM9	1000Hz_MD30_DC50	1000	30%	50%	rectangular	0.10	0.10	0.30

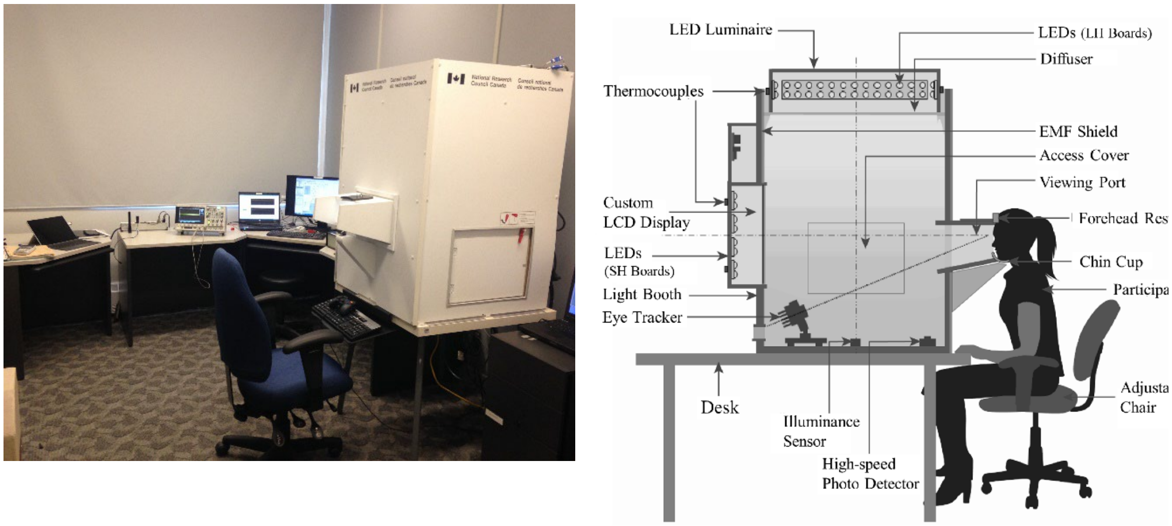
Figure 1. This is redrawn from Figure 20 of IEEE S1789-2015. The grey area marks the recommended operating conditions (IEEE 2015, p. 44). Overlaid stars mark the experimental conditions tested here. See Table 2 for parameter details. At 500 Hz and 100% modulation depth there were two conditions with different duty cycles, shown as one light (white) star over one larger dark (black) star.



The conditions were presented in a custom viewing box shown schematically in Figure 2 and described in detail elsewhere (Veitch and others 2023). All of the LEDs, both those illuminating the inside of the box and those behind the LCD monitor, were nominally 3500 K, R_a = 80 packages controlled by a programmable Agilent power supply. The illuminance inside the box was maintained at approximately 400 lx on the bottom horizontal surface while the TLM conditions varied. Each participant experienced a unique random order of TLM condition presentations.

Testing took place in a small office lit with overhead fluorescent luminaires with prismatic lenses; these were nominally 3500 K, CRI=80, T8 lamps powered by electronic ballasts. The room lights were controlled to match the illuminance in the light box (~400 lx on the keyboard and desk), and daylight was excluded by opaque blinds. During testing, a black canopy over the viewing port prevented any sight of the overhead lights.

Figure 2. The left panel shows a photograph of the experimental room. The right panel shows a cutaway view of the experimental apparatus.



2.3 Dependent measures

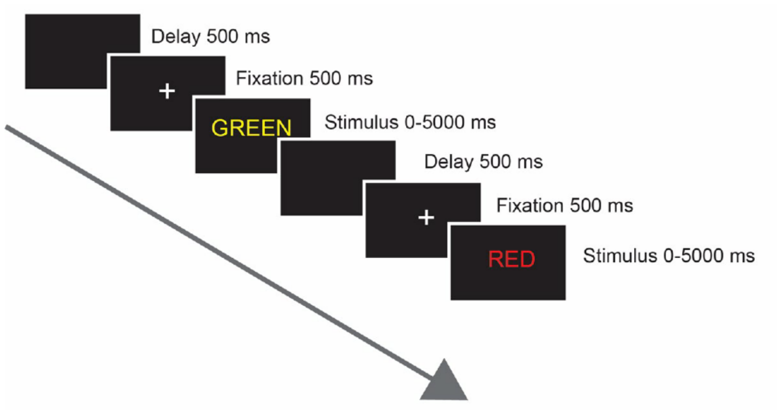
2.3.1 Reading performance

Participants completed the Wilkins Rate of Reading Test (Wilkins and others 1996). The task consists of trials in which the participant reads a series of random words presented in a chunk of 15 words per line and 15 lines on the video monitor in the light box with black text on a white background. Each trial is one minute long, and the participant is instructed to read aloud as many of the words as possible as correctly as possible in that time. The experimenter codes both the total words read and the number of errors by scoring the task on a paper copy in real time. In this case, an audio recording was made to permit later verification. In each TLM condition, the participant performed six reading trials, three in small text (e.g., 8 pt font) and three in large text (e.g., 12 pt font). The order of text sizes was counterbalanced across experimental conditions. We predicted for this analysis that the high-PGS group would show more effects of TLM on both performance accuracy and speed than the low-PGS group.

2.3.2 Cognitive load: Stroop task

The Stroop task is a well-established test of cognitive load (Stroop 1935), shown pictorially in Figure 3. For each trial, participants are shown a colour word (in this instance, RED, GREEN, or BLUE) in random order, in either red, blue, or green text on a white background. On some trials the meaning of the word and the text colour match ("congruent" trials) and on some trials they do not ("incongruent). The task of the participant is to press, as quickly as possible, a button on a gamepad to indicate either the meaning of the word ("word" trials) or the colour in which it was presented ("colour" trials). Incongruent trials are more difficult than congruent ones, showing lower performance accuracy and slower responding. The difference between incongruent and congruent trials is larger if participants are experiencing higher cognitive load. There are two dependent variables: the accuracy difference between the incongruent and congruent trials, and the difference in average response time between correct incongruent and correct congruent trials. In the present analysis we predicted that the originally-predicted effects (see Table 4) would be seen in the high-PGS group, but probably not in low-PGS group, and with larger effect sizes than previously reported (Veitch 2019).

Figure 3. The task sequence for two trials of the Stroop task. Participants pressed a button indicating either the color of the word or its meaning, depending on the instruction. The first trial shown below is incongruent, and the second is congruent.



Each participant completed 24 training trials at the start of the session, presented under TLM1 (no-TLM). This taught them the mapping of colours to keys on the gamepad; this was confirmed before continuing to the experimental trials. The training trials were not included in the data analysis. During each of the nine TLM conditions, participants completed a block of 96 trials for which the instruction was to respond to the meaning of the word (word block), and a block of 96 trials during which the task was to respond to the colour of the text (colour block). Half of the trials in each block were congruent, and half were incongruent, and this was randomly ordered. The word and colour blocks were counterbalanced across participants, but always in the same order for all TLM conditions.

2.3.3 Phantom array

We attempted a conceptual replication of the findings of Roberts and Wilkins (2013). Fixation dots were placed on either side of the monitor in the light box, and a vertical black line was displayed down the center of the monitor. The spacing of the dots provided a visual angle of approximately 20° (as was used in Roberts and Wilkins, experiment 2). The task differed from theirs in polarity: in this experiment, the white monitor luminance was ~150 cd/m^2 and the black line luminance was ~0.5 cd/m^2.

The participant was instructed to move their eyes back and forth from the left to right dot and back. If they saw a pattern of lines while doing this, they were instructed to press an assigned key on the keyboard, on the right to report "yes" and on the left to report "no". One trial was presented per lighting condition. We predicted that the high-PGS group would be more likely to detect the phantom array for conditions with more TLM (e.g., as expressed by the IES Flicker Index and the SVM).

2.3.4 Eye movements

An Eyelink 1000 eye tracking system (SR Research, Kanata, ON) recorded and scored eye movements and blinks throughout the TLM conditions. The system is capable of saccade resolution to 0.05 degrees of visual angle. For the reading task we examined blinks, saccades, fixations, and pupil size. We took the mean across all reading trials by print size for the number of blinks, number of saccades taken and the mean saccade velocity, and the mean number of fixations and the duration of fixations. We also examined these eye movements during the phantom array task. The Stroop task involved viewing one word only, so saccades and fixations were not meaningful. We analyzed only pupil size during the Stroop task. Mean pupil size was calculated by trial type and congruency (i.e., congruent color trials, congruent word trials, incongruent color trials, incongruent word trials). For the current analysis, we predicted that eye movements would differ between the low-PGS and high-PGS groups, but did not predict the direction of the differences, in the absence of clear guidance from the literature: for example, would there be more, shorter saccades, or longer saccades and fewer fixations?

2.3.5 Discomfort

At the end of each exposure condition, participants were asked to rate their discomfort on a 5-point scale from 0 (no discomfort) to 4 (extreme discomfort) on each of the following eight symptoms: overall comfort; smarting, itchy, or aching eyes; sensitivity to light; teary eyes; dry eyes; sore back, wrists or arms; excessive fatigue; headache. Veitch and Newsham (1998) and Newsham and others (2004) have found these discomfort measures to be sensitive to changes in lighting conditions. For the current analysis, we predicted that the high-PGS participants would report higher discomfort.

2.3.6 Lighting beliefs

This is a 32-item questionnaire concerning the effects that people believe lighting has on them (Veitch and Gifford 1996). Participants indicate agreement or disagreement with statements on a scale from 0 to 4. It has six subscales, formed by averaging individual questions: Lighting Importance; Brightness; Major Health Effects; Minor Health Effects; Social Setting; Daylighting. For the current analysis, we predicted that the sensitivity groups might differ in their lighting beliefs. The questions were presented on the monitor in the light box, using TLM1 (no-TLM) for the light source.

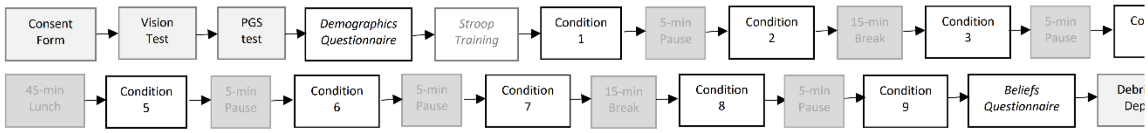
2.3.7 Expectancies

At the very end of the day, we asked participants to record their opinions about the purpose of the experiment and to make any comments about the day. These were used to check for expectancy biases, and to improve the running of the experimental sessions. The questions were presented on the monitor in the light box, using TLM1 (no-TLM) for the light source.

2.4 Procedure

Participants were tested individually. Each attended for one day and was paid for a day's clerical work. Figure 4 shows the sequence of events during the day. The day commenced with an informed consent procedure conducted in a reception room where they also could take coffee and lunch breaks. Once in the experimental room, the session began at a side table with vision screening to confirm normal or corrected-to normal vision (Keystone View 1969), followed by the Pattern Glare Sensitivity test (Wilkins and Evans 2012). These are shown in light grey boxes in Figure 4.

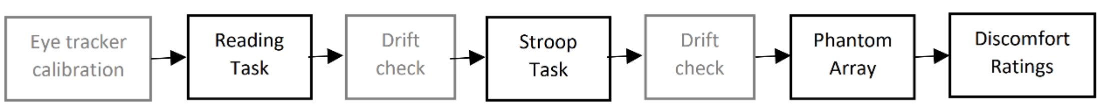
Figure 4. The daily experimental sequence shows the chunks during which the participant was seated at the apparatus in white, and elements always presented with no-TLM illumination in italic. See the text for further explanation



The participant then moved to the seat in front of the apparatus (Figure 2). Time spent seated at the apparatus is shown in white boxes in Figure 4. Period 1 included two experimental conditions. Between back-to-back experimental conditions there was always a 5-min pause during which the participant was asked to sit back from the apparatus and to rest with eyes closed, or they could stand and stretch. After a coffee break taken in another room, Period 2 had two experimental conditions. Lunch was 45 min and was taken either in another room, or at a cafeteria in a nearby building. Period 3 had three conditions and then there was a second coffee break, also taken elsewhere. Period 4 had two blocks and the final two questionnaires (see sections 2.3.6 and 2.3.7). After watching a video with debriefing information, the participant departed.

Each experimental condition lasted approximately 16 minutes, although they had been planned to require 30 minutes. Within this, the tasks were presented in a fixed order, shown in Figure 5: reading, Stroop task, phantom array, and discomfort rating. The presentation of tasks and the collection of Stroop performance data, eye movements, and questionnaire variables were automated by Experiment Builder software (SR Research, Kanata, ON).

Figure 5. The sequence of tasks within each experimental condition was always the same. Measurements occurred during the tasks shown in dark text.



2.5 Data analysis

2.5.1 Data quality

Equipment and scoring errors resulted in randomly missing data within every analysis. Examples of such random errors were lost eye tracking focus (e.g., reflections from eyeglasses) leading to gaps in eye movement data, or gaps in reading scoring resulting from difficulty hearing the participant. Necessarily, only cases with complete data for all conditions and all dependent measures in any given analysis could contribute to that analysis, meaning that if data were missing for one condition out of nine (e.g., no pupil size data for one condition), then that participant's data on the other conditions were also excluded from analysis. This resulted in one or two cases being missing from most analyses, but not always the same ones.

We examined each dependent variable for normality and considered whether to exclude outliers to improve the distributions. We ran analyses with up to five outliers excluded, but found that this made no difference to the outcomes. Here we report analyses based on all complete cases for the variables in each analysis. Given that the purpose of the experiment was to create possibly extreme conditions, and to seek to identify sensitive individuals, it was appropriate to keep as much data as possible.

2.5.2 Inferential test models

As had been done by Veitch (2019) for the full sample of 50 people, we analyzed the variables in conceptual groups (Table 3), using multivariate analysis of variance (MANOVA) and analysis of variance (ANOVA) to test planned single degree-of-freedom contrasts (Table 4) without the problem of multiple contrasts. We report the inferential test results, the associated effect size statistics (Cohen 1988), and descriptive statistics.

The focus of this work is the effect of sensitivity on the TLM responses, so we report the main effects of sensitivity, the interactions of sensitivity with the TLM planned comparisons, and the effects of the TLM conditions within the low-PGS and high-PGS groups. The main effects of sensitivity can provide insight into this individual difference, about which little is known. The interaction of sensitivity by TLM planned comparisons can address the question of whether the responses to variations in TLM differed for the high-PGS and low-PGS groups. If PGS sensitivity is a predictor of sensitivity to temporal patterns in the luminous stimuli, then people who are higher in PGS sensitivity might show effects that the low-PGS sensitivity group does not. The effects of the TLM planned comparisons within the two PGS groups probe this possibility in more detail and provide insight into the effect sizes in each group.

For information about the effects of the TLM conditions without consideration of sensitivity, including the effects of task variables such as print size and Stroop task type, see Veitch (2019). These are best approached with the full sample, and to report them here would be redundant.

Table 3. The conceptual categories of dependent variables in MANOVA and ANOVA analyses.

Task category	Effects (& Interactions)	Dependent Variable Type
Discomfort	2 Sensitivity X 9 Condition	rating
Stroop Task – Pupil size	2 Sensitivity X 9 Condition X 2 Congruence X 2 Trial Type	pupil size
Stroop – Performance	2 Sensitivity X 9 Condition x 2 Trial Type	interference accuracy interference reaction time
Reading – Eye movements	2 Sensitivity X 9 Condition x 2 Size	6 eye movement measures: blink count, saccade count, saccade amplitude, fixation count, fixation duration, pupil size
Reading - Performance	2 Sensitivity X 9 Condition x 2 Size	overall score
Reading - Performance	2 Sensitivity X 9 Condition x 2 Size	words read per min (speed); Errors (accuracy)
Phantom array – Eye movements	2 Sensitivity X 9 Condition	6 eye movement measures: blink count, saccade count, saccade amplitude, fixation count, fixation duration, pupil size
Phantom array detection	2 Sensitivity X 9 Condition	detection

Table 4. The eight planned comparisons for lighting conditions and expected outcomes for the statistical tests.

Test Label	Condition 1	Condition 2	Originally Expected Outcome; larger effect sizes expected for high-PGS group
LS1	no-TLM	60 W incandescent	No effect
LS2	no-TLM	T12 magnetic ballast	Diminished performance and disrupted eye movements under 120Hz_T12 mag
MD1	500 Hz, 100% MD, 50% Duty	500 Hz, 30% MD, 50% Duty	100% modulation depth should give poorer performance than 30%
MD2	500 Hz, 30% MD, 50% Duty	500 Hz, 15% MD, 50% Duty	30% vs 15% modulation depth, probably no effect
MD3	1000 Hz, 100% MD, 50% Duty	1000 Hz, 30% MD, 50% Duty	100% modulation depth should give poorer performance than 30%
DUTY	500 Hz, 100% MD, 50% Duty	500 Hz, 100% MD, 30% Duty	30% duty cycle should give poorer performance and greater discomfort than 50%
FR	T12 magnetic ballast	1000 Hz, 30% MD, 50% Duty	At 30% modulation depth, the simulated T12 magnetic ballast (120 Hz) should show worse performance than the 1000 Hz rectangular wave
REP	no-TLM	500 Hz, 100% MD, 50% Duty	Replicating prior work, predicted better performance under 500 Hz, 50% modulation depth, 50% duty cycle than under no-TLM.

3. Results

Appendix B reports the complete set of descriptive statistics and the detailed statistical tests for the results discussed here (Appendix C). Only statistically significant effects are reported in the text.

3.1 Main effects of sensitivity

This set of tests examined the average responses of the two groups of participants (low-PGS and high-PGS groups) over all TLM conditions. The scores on the two groups differed significantly only in the Stroop task performance, with a statistically significant multivariate test (Wilks' lambda = 0.739, $F(2,21) = 3.71$, $p = 0.04$, $\eta^2_{partial} = 0.26$) accompanied by a statistically significant univariate test for Stroop performance accuracy ($F(2,21) = 7.75$, $p = 0.01$). The average Stroop performance accuracy for the high-PGS group was -0.03 (SD = 0.10) and for the low-PGS group it was -0.01 (SD = 0.02), indicating greater cognitive load for the high-PGS group. The effect size was small ($\eta^2_{partial} = 0.26$ and Cohen's $d = 0.33$) (Cohen 1988).

3.2 Interactions of sensitivity by TLM planned comparisons

For each planned comparison, we used ANOVA or MANOVA to test the single-degree-of-freedom interactions between sensitivity and the eight planned comparisons. These are reported in detail in Appendix C. None of the interaction effects met our criterion for statistical significance ($p < 0.05$).

3.3 TLM comparisons within the high-PGS group

The statistically significant results for tests within the high-PGS group are displayed in Table 5 and all tests are reported in full in Appendix C. Three of the eight planned comparisons returned statistically significant effects, each on one of the response categories. The effects were medium-sized, and in the expected direction.

The DUTY contrast compared conditions with 500 Hz, 100% modulation depth and either a 50% (TLM4) or a 30% (TLM6) duty cycle. At $p = .054$, this inferential test is on the decision criterion to reject the null hypothesis. We have reported it because it had been predicted and because the effect size was medium (this is discussed further below).

The MD1 contrast was a comparison between TLM conditions with 500 Hz 50% duty cycle and either 100% modulation depth or 30% modulation depth. The response category for Stroop task pupil size was a univariate test (one dependent variate). During the Stroop task, pupil size was larger in the 100% modulation depth condition than the 30% condition.

The MD2 contrast involved TLM conditions with 500 Hz, 50% duty cycle and either 30% or 15% modulation depth. For this contrast, there was a statistically significant multivariate test for Stroop task performance, associated with a statistically significant effect on response time. Response times to the Stroop task were longer (i.e., slower responding) for the 30% modulation depth than the 15%. This was a small effect size, calculated using Cohen's *d* (Cohen 1988).

Table 5. Statistically significant effects of TLM conditions on behavioral responses among the high-PGS group of sensitive individuals.

Response Category	Contrast	Wilks' Λ	*df*	*F*	*p*	$\eta^2_{partial}$	M (SD)	Cohen's d
Discomfort	DUTY		1,11	4.66	0.05	0.30	TLM4 = 0.49 (0.23) TLM 6 = 0.59 (0.24)	0.43
Stroop Task – pupil size	MD1		1,12	8.97	0.011	0.43	TLM 4 = 557.15 (110.07) TLM 5 = 509.53 (92.50)	0.47
Stroop Task – Performance	MD2	0.575	2,11	4.06	0.05	.043		
Reaction time	MD2		1,12	6.96	0.02	0.40	TLM 5 = 155.14 (124.57) TLM 7 = 121.62 (109.52)	0.29

3.4 TLM comparisons within the low-PGS group

The low-PGS group also showed some statistically significant results for the TLM planned comparisons. Table 6 summarizes these, and Appendix C shows the complete set of results.

In the low-PGS group, there was a statistically significant effect for the MD1 contrast involving eye movements during reading. The significant multivariate test was associated with univariate effects for both the number of saccades and the number of fixations. There were fewer saccades and more fixations when the TLM condition had 100% modulation depth than 30% (both at 500 Hz and 50% duty cycle). These were large effects (Cohen 1988).

There also was a statistically significant effect for the MD3 contrast, which was between conditions at 1000 Hz, 50% duty cycle and either 100% or 30% modulation depth. The accuracy scores for the Stroop task showed greater cognitive interference for the 100% modulation depth than the 30%; this was a medium-sized effect (Cohen 1988).

Table 6. Statistically significant effects of TLM conditions on behavioral responses among the low-PGS group.

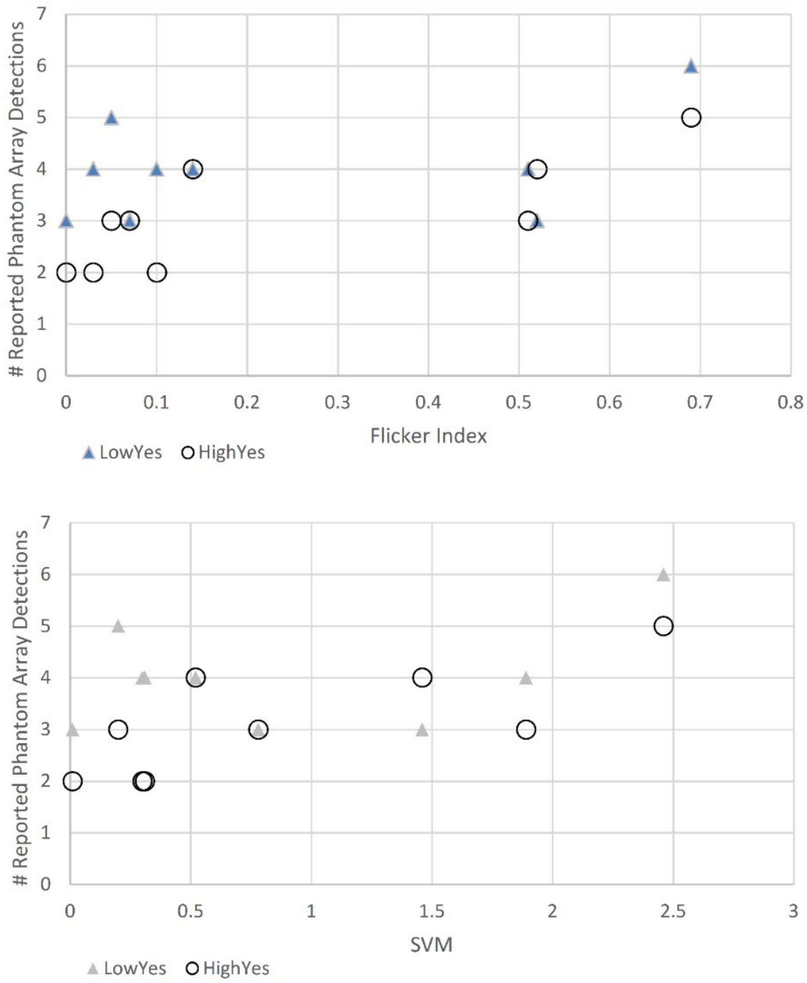
Response Category	Contrast	Wilks' Λ	*df*	*F*	*p*	$\eta^2_{partial}$	M (SD)	Cohen's *d*
Reading Eye Movements	MD1	0.22	6,7	4.13	0.04	0.78		
	MD1 – Saccades		1,12	5.21	0.04	0.30	TLM 4 = 138.10 (72.42) TLM 5 = 178.82 (29.19)	.80
	MD1 – Fixations		1,12	5.24	0.04	0.30	TLM 4 = 138.43 (72.69) TLM 5 = 179.30 (29.21)	.80
Stroop Task Performance	MD3	0.517	2,9	4.20	0.05	0.48		
	MD3 – Accuracy		1,10	7.86	0.02	0.44	TLM 8 = -0.01 (.02) TLM9 = 0.00 (0.02)	0.50

3.5 Phantom array detection

If participants had been guessing on the phantom array detection task, then for the no-TLM condition the number of positive and negative responses should have been equal. This was not the case. In the full sample of 26 participants, 5 (3 in the low-PGS group and 2 in the high-PGS group) reported seeing the phantom array in the no-TLM condition. The non-parametric test that the proportions of "yes" and "no" results is the same is the binomial test; a low probability for this test means that the observed proportions differ from the expected 0.5 in each category. This test is very sensitive to sample size, as seen by the results for the full sample and the two PGS groups. For the full sample (5/26 yes), p = 0.002, for low-PGS (3/13 yes), p = .092, for high-PGS (2/13 yes), p = 0.022. Overall it does not appear that participants responded randomly.

We calculated the Spearman *rho* – a non-parametric correlation coefficient – to test the hypothesis that the total number of phantom array detections in each TLM condition related to either the SVM or the IES Flicker Index (FI) because these were the indices available at the time to characterize TLM at frequencies above 80 Hz (no predictor for phantom array visibility existed at that time, although a provisional model of phantom array visibility has recently been proposed (CIE, 2022)). FI proved to be the better predictor in both the full sample and the high-PGS group. For the full sample, for SVM, *rho* = 0.53 (p = 0.14) and for FI, *rho* = 0.68 (p = 0.04). For the low-PGS group neither TLM metric predicted phantom array detection: for SVM, *rho* = 0.18 (p = 0.65) and for FI, *rho* = 0.28 (p = 0.46). However, for the high-PGS group, both SVM and FI predicted phantom array detection: SVM, *rho* = 0.73 (p = 0.03) and for FI, *rho* = 0.81 (p = 0.01). Figure 6 shows plots of phantom array prediction counts by FI and SVM for the low-PGS and high-PGS conditions.

Figure 6. The detection of the phantom array effect for the two sensitivity groups is plotted against the IES Flicker Index (top panel) and SVM (bottom panel) for the nine TLM conditions.



4. Discussion

This article reports exploratory analyses, using existing data to probe whether a subset of the population might be both more sensitive to visual patterns (assessed using the Wilkins and Evans Pattern Glare Sensitivity Scale) (Wilkins and Evans 2012) and more sensitive to temporal light modulation across a range of conditions possible with solid-state lighting. Past research comparing visual functions under fluorescent lighting systems having magnetic ballasts or electronic ballasts found small effect sizes when participants were from the general population (Veitch and McColl 1995; Veitch and Newsham 1998; Wilkins 1986), and sometimes no effects when lower-power between-groups contrasts were used (Veitch and others 2002).

There is precedence for seeking to understand the individual differences in sensitivity. Küller and Laike (1998) found that there was no effect of TLM (fluorescent ballast type) on the brain activity of their full sample (N=50), but the high-sensitivity group (identified as having a high critical flicker fusion frequency) exhibited greater arousal (lower alpha wave attenuation) under magnetically ballasted fluorescent lamps than electronically-ballasted lamps. The frequently-cited field study by Wilkins, Nimmo-Smith, Slater and Bedocs (1989) found that the reduced incidence of headaches and eyestrain associated with high-frequency ballasts was measurable only in those who had a predisposition to experiencing headaches.

The results of the analyses reported here tend to support this approach. Notably, although the number of statistically significant tests was small, those that were showed consistency with the prediction directions and medium sized effects.

It was previously known that sensitivity to pattern glare is associated with migraine headache, reading disruptions, and discomfort in everyday viewing of spatial patterns (Evans and Stevenson 2008; Wilkins 1995). To this we can add an increased susceptibility to cognitive interference, as indicated in the main effect of PGS sensitivity on Stroop task performance.

The visibility of the phantom array effect correlated with the IES Flicker Index for the full sample. When split by sensitivity, the low-PGS group showed no correlations between phantom array detection and either FI or SVM, whereas for the high-PGS group both indices predicted phantom array detection, at least for the range of conditions tested here. These Spearman rank correlations (*rho*) showed strong relationships worthy of further investigation.

The only other study of which we are aware that used a white background for a phantom array task found that in a sample of the general public, participants showed little ability to detect the phantom array with the white background, although they did detect it when the background was black and the fixation points white (Wang and others 2019). Perhaps a subset of sensitive individuals in that sample might have shown a stronger effect.

In the analyses reported here, the high-PGS group reported greater discomfort for the 30% duty cycle than the 50% duty cycle; the low-PGS group did not. This was a medium-sized effect, although the inferential test p was on the borderline for the test criterion. Veitch and Martinsons (2020) found that there was a relationship between light source TLM and ratings of annoyance for the high-PGS participants in their sample, but not for the low-PGS participants.

The re-analysis did not have sufficient statistical power for the between-groups comparisons to detect significant interactions between PGS sensitivity and the TLM planned comparisons, but there were interesting findings for the repeated measures tests within the PGS groups. These add to the results previously reported for the full sample (Veitch 2019) and are consistent with predictions from the IEEE 1789-2015 guidance. In the full sample, contrast MD1 between 100% and 30% modulation depth for a 500 Hz, 50% duty cycle rectangular wave found that pupil size during the phantom array task was larger (indicating more arousal) during exposure to the 100% modulation. The IEEE 1789-2015 guidance (see Figure 1) places these in the high-risk and low-risk categories. In the analyses reported here, for the MD1 contrast the high-PGS group exhibited a larger pupil size during the Stroop task under 100% modulation depth than 50%. The same group also was sensitive to the difference between 30% and 15% modulation depth, with faster response times for the Stroop task in the 15% modulation depth condition.

We also observed statistically significant effects of modulation depth in the low-PGS group, also consistent with IEEE 1789-2015. The MD1 and MD3 contrasts both involved comparisons between 100% and 30% modulation depth, with MD1 at 500 Hz and MD3 at 1000 Hz. The direction of the effects is consistent in both cases, although involving different outcome measures: Mental processing was easier for 30% modulation depth than

100%. For MD1, at 500 Hz, this was indicated by the larger number of saccades and fixations during the reading task. Veitch (2019) had found that the easier task of reading larger print was associated with more saccades and more fixations. For MD3, at 1000 Hz, Stroop task accuracy scores showed that there was less cognitive interference at 30% modulation depth than 100%.

In the set of TLM conditions tested in this experiment, the effects that tested predictions from IEEE 1789-2015 could equally well be predicted by SVM. (All the TLM conditions tested here fall into the frequency range covered by SVM.) The experiment from which these data were drawn was not designed with the intent of differentiating between these two models. SVM was derived uniquely from the visibility of stroboscopic motion of a specific stimulus, a white dot on a black surface rotating at 4 m/s. The fact that higher SVM was associated here with some adverse outcomes could be viewed as unexpected, although it would be highly desirable if a single index could predict a variety of visual, cognitive, and health outcomes (CIE, 2017). This is not a settled matter. A recent test of a broad range of dominant frequencies and modulation depths found that SVM was not a good predictor of phantom array detection, particularly above the 2000 Hz that is its upper limit (Miller and others 2023).

5. Conclusions

The basis for most lighting recommendations has been the characteristics of the average person. Given that electric lighting cannot be avoided in everyday life, and that some people are more likely than others to be adversely affected by the TLM of present-day lighting systems, further knowledge is required.

The results reported here have limitations; as a secondary analysis, the groups were small and therefore comparisons were lower in statistical power. It is therefore possible that some real effects might have failed to be observed. The effects that were observed, however, were all in the predicted directions and had medium to large effect sizes. This secondary analysis was not intended to provide the last word on the effects of TLM on sensitive people, but to demonstrate that there is more to learn about individual differences in visual stress as they could modify the effects of TLM. Some researchers may choose to pre-select participants on a validated screening test (e.g., Perenboom and others 2018; Wilkins and Evans 2012) and selecting the most sensitive individuals (e.g., the top 30%) to participants. Doing so is likely to increase the statistical power of the experiments, making it more likely that effects would be detected even with the relatively small sample sizes and short exposures that are feasible in most experiments.

The results reported here are based on relatively short exposures of under 20 minutes per TLM condition, which are not representative of the duration of exposures in most everyday settings. Of equal concern is the restricted field of view offered by the apparatus used in this experiment, with all the tasks being on-axis and foveal, and the phantom array probe spanning only 20° of viewing angle. Future research should take a more naturalistic approach, particularly for participant head and eye movement, and should expose participants to conditions for a longer time to achieve a better understanding of how various TLM conditions can influence vision, cognition, and well-being.

With a better understanding of the effects of TLM on sensitive individuals, rather than extrapolating from the “average person”, it will become possible for organizations that establish performance criteria for lighting systems to make informed choices that weigh collective risk across the diversity of the population.

Funding

This work was supported by the U.S. Department of Energy's Lighting R&D Program, part of the Building Technologies Office within the Office of Energy Efficiency and Renewable Energy (EERE), and by the National Research Council of Canada High Performance Buildings program (project A1-018191). The data were collected in a prior project (NRC A1-008878) funded by the Jim H. McClung Foundation for Lighting Research, the Independent Electricity System Operator Conservation Fund (Province of Ontario), and the National Research Council of Canada.

Acknowledgements

The authors thank Patrick Gauthier, Sandra Mancini and Alexandra Thompson at NRC Construction and Michael Royer and Robert Davis at PNNL for their contributions and support to the work reported here.

Declaration of interest

The National Research Council of Canada receives funds from Canadian and foreign government departments and agencies and from private industry that may be affected by the research reported in this paper. Jennifer Veitch serves on committees and boards of the IES, the International Commission on Illumination (CIE), and the International Standards Organization, which write recommendations, standards, and guidance related to the topic of this work. Naomi Miller serves on related committees in the IES and the CIE.

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Appendix A: TLM conditions and measurement

A.1 Stimulus specification

The apparatus used for this experiment has been described in detail elsewhere (Veitch and others 2023). Briefly, the system incorporated a custom configuration of LED boards illuminating the inside of a viewing booth and providing the backlight for an LCD monitor mounted on the back side of the booth. The LEDs were driven by a programmable power supply (maximum operating frequency 1000 Hz) controlled using custom in-house software programmed in Agilent VEE. The system was connected to mains power through an uninterruptible power supply to reduce the risk of unintended voltage fluctuations.

The illuminance in the booth was controlled by varying the voltage supplied to the LEDs and the number of LED strings in use. Conditions were monitored inside the apparatus, including the illuminance and the temperature of the LED boards. The operator would see an alarm if the system deviated from acceptable parameters, to prevent overload, although there were no such events during testing.

In pre-testing, and again during system checks after data collection, oscilloscope captures of temporal patterns of illuminance in the apparatus revealed that the delivery of the nine conditions was imperfect. Consultation with other researchers and technical experts led us to conclude that although unwanted, these deviations from the nominal conditions were not uncommon and not unexpected (Miller and others 2023), particularly for experimental conditions at the limits of the equipment's capacity (low duty cycle and high frequency). They did not invalidate the comparisons of the effects of TLM on participants because the conditions remained demonstrably different one from another.

A.2 TLM measurement

As the time of writing, there is no measurement standard for TLM, although there is guidance in technical reports (all of which were published after the design of the experiment reported here) from the IEC (2017; 2018), the IES (2020) and NEMA (2017), and a technical note from the CIE (2021). The IEC and NEMA documents are specifications for waveform measurements that are to be used to calculate PstLM and SVM, whereas the CIE technical note is intended to provide guidance for waveform capture in preparation for the calculation of any TLM quantity. Although each specifies minimum requirements, they are not all the same (e.g., 180 sec of data collection, with at least a sampling frequency of 2500 samples per second (Sa/s), for PstLM (IEC, 2017); 60 to 180 sec and sampling frequency of at least 2,500 Sa/s for PstLM (IES, 2020); 60 sec and a sampling frequency of at least 10,000 Hz for SVM (IEC, 2018)) 1 s of data with a minimum sampling frequency of 30,000 Sa/s for SVM (ANSI/IES, 2020)), and many other measurement choices appear to be optional. For example, analog or digital filters may be used, or may not; a transimpedance amplifier is necessary, but its gain settings are not required to be reported.

In preparation for this publication, as part of an in-depth post-experimental equipment check, we conducted extensive measurements of the nine experimental conditions, consulted several TLM metrology experts, and have chosen to report the measured values from data captured and post-processed as follows:

- Measurement sampling rate: 100,000 Hz, downsampled to 20,000 Hz with a moving average of each 5 values.
- Took three measurements per condition, and averaged these.

- Reported the gain settings for each measurement, and used the same settings for pairs of measurements to be compared.
- During data capture, the system converted the few negative voltages to 0 (so that all voltages were >=0) because the calculation scripts require measurement uniformity. All values were multiplied by -1 because the scripts require negative voltages.
- Calculated dominant frequency, modulation depth, IES Flicker Index, PstLM, and SVM using Octave scripts adapted by S. Coyne from the Matlab scripts published with the IEC documents (IEC, 2017; 2018). The scripts trim the waveform to the center of period to create an integer number of cycles, and applies a Hanning window for SVM calculations (as recommended). Following the observation that the Butterworth function is unstable, we modified the Octave script to use the ZPK function instead.

Table A.1 compares the results for TLM measurements of the nine conditions in several ways. We used nominal data processed through the same calculator to show the expected values for the programmed waveforms. We measured the values for two operating conditions: with the LCD monitor ON (as it was throughout the experiment), and with the LCD monitor OFF.

Table A.1 shows, in addition to the nominal and measured values, comparisons between the results for the two screen conditions. This reveals that there were no appreciable difference in TLM as a result of a beat between the LEDs and the monitor refresh rate of 60 Hz. The bottom section shows the comparison of the nominal conditions to the viewed conditions (with the LCD monitor on). This reveals that that there were differences between the nominal and viewed conditions, and these differences were largest with lower modulation depth (conditions TLM5, TLM7, and TLM9), low duty cycle (TLM6) and high frequency (TLM8 and TLM9).

Figure A.1 shows the waveforms associated with these measurements in comparison to the ideal waveforms. These images are consistent with the visual indications from the oscilloscope used during data acquisition. Noise from the power supply affected all waveforms, but is most apparent in the no-TLM condition. Conditions that were at the limit of the equipment (1000 Hz) and that had higher modulation depth did not show the intended sharp rectangular waveform.

One lesson to be drawn from this exploration is that delivering a specific TLM waveform using commercially available equipment is not easy. This apparatus was small, not room sized, and the power supply was the best available at the time our laboratory began this line of research. Researchers intending to explore TLM effects at room scale with parametric studies will need to budget time and testing accordingly to be confident that their stimulus conditions are as intended. Alternatively, the research community could acknowledge that power supplies, dimmers, drivers, and LED systems in the real world seldom deliver clean and regular waveforms, and accept that their stimuli will be imperfect, but are realistic waveforms that viewers might experience.

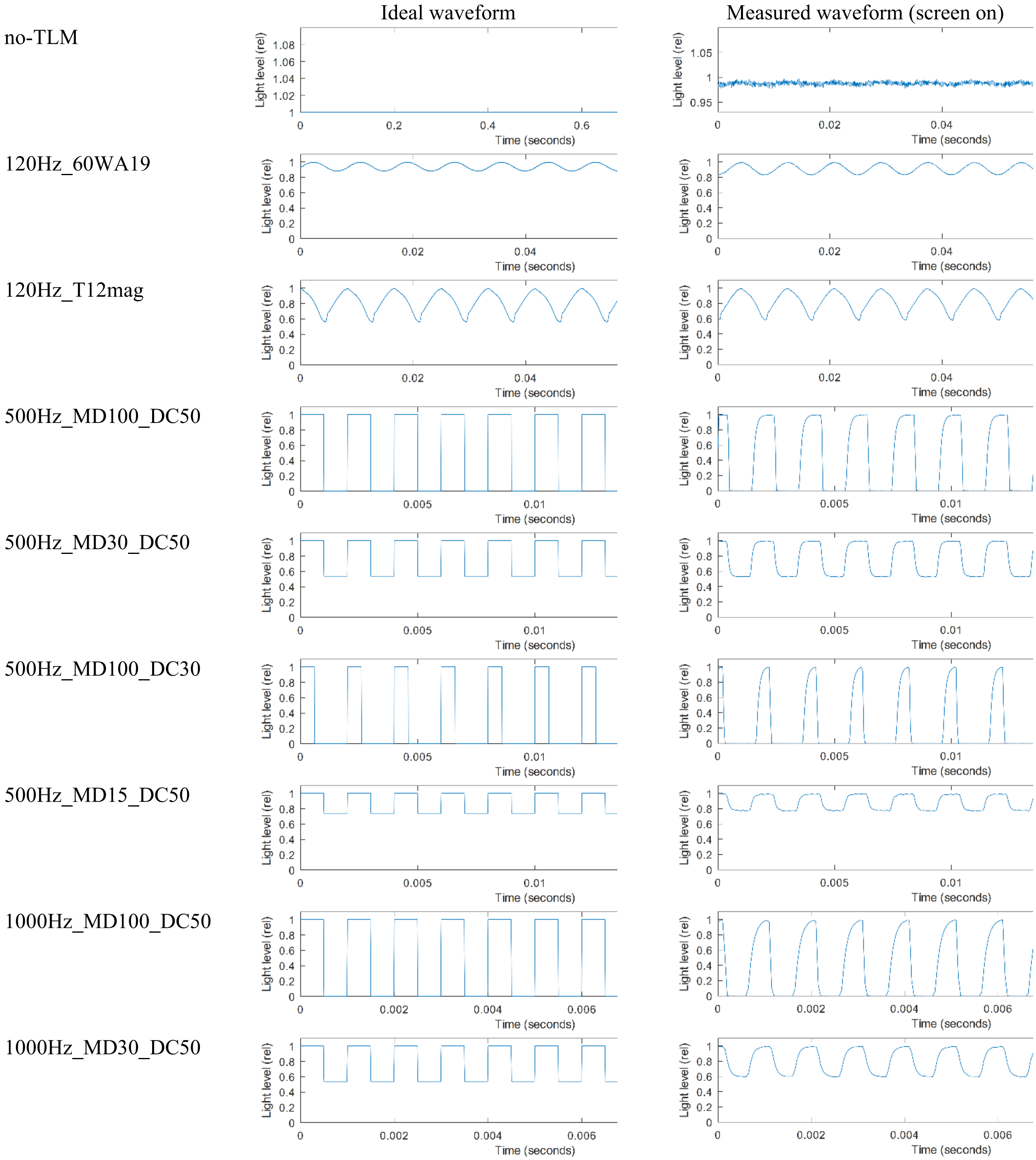
A second lesson is that this community needs to establish TLM measurement, data cleaning, calculation and reporting protocols that can be consistently applied across equipment conditions and laboratories, in addition to establishing uncertainty budgets for these measurements. Agreement on these protocols would facilitate better research and would support conformity assessment programs.

Table A.1. A summary of the principal TLM parameters for the nine conditions, and comparisons between measurements with the display screen on and off.

	Condition								
	no-TLM	120Hz_60W A19	120Hz_T12 mag	500Hz_MD100_DC50	500Hz_MD30_DC50	500Hz_MD100_DC30	500Hz_MD15_DC50	1000Hz_MD100_DC50	1000Hz_MD30_DC50
Nominal Values									
Signal Type	NO-TLM	Sine	Quasi-Sine	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular
Duty Cycle				50%	50%	30%	50%	50%	50%
DF (Hz)	0	120	120	500	500	500	500	1000	1000
MD (%)	0	6.45	28.37	100.00	30.00	100.00	15.00	100.00	30.00
FI	0.00	0.02	0.07	0.50	0.15	0.70	0.08	0.50	0.15
Pst^{LM}	0.00	0.03	0.07	0.00	0.00	0.00	0.00	0.00	0.00
SVM	0.00	0.22	0.82	1.74	0.52	2.37	0.26	1.30	0.39
Measured, Screen ON									
Amplifier Gain	3x10^-6	1x10^-5	3x10^-6	3x10^-6	3x10^-6	3x10^-6	3x10^-6	3x10^-6	3x10^-6
DF (Hz)	120	120	120	500	500	500	500	1000	1000
MD (%)	1.39	9.85	27.30	100.00	31.55	100.00	13.56	100.00	26.04
FI	0.00	0.03	0.07	0.51	0.14	0.69	0.05	0.52	0.10
Pst^{LM}	0.06	0.05	0.03	0.42	0.12	0.51	0.07	0.47	0.10
SVM	0.01	0.31	0.78	1.89	0.52	2.46	0.20	1.46	0.30
Measured, Screen OFF									
Amplifier Gain	3x10^-6	1x10^-5	3x10^-6	3x10^-6	3x10^-6	3x10^-6	3x10^-6	3x10^-6	3x10^-6
DF (Hz)	120	120	120	500	500	500	500	1000	1000
MD (%)	1.36	9.75	27.15	100.00	31.48	100.00	13.53	99.99	25.94
FI	0.00	0.03	0.07	0.51	0.14	0.69	0.05	0.52	0.10
Pst^{LM}	0.07	0.04	0.03	0.41	0.12	0.51	0.08	0.47	0.10
SVM	0.01	0.31	0.78	1.89	0.51	2.46	0.20	1.47	0.29

	Condition								
	no-TLM	120Hz_60W A19	120Hz_T12 mag	500Hz_MD100_DC50	500Hz_MD30_DC50	500Hz_MD100_DC30	500Hz_MD15_DC50	1000Hz_MD100_DC50	1000Hz_MD30_DC50
Screen discrepancy (ON-OFF)									
DF (Hz)	0	0	0	0	0	0	0	0	0
MD (%)	0.03	0.10	0.15	0.00	0.07	0.00	0.03	0.01	0.10
FI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pst^{LM}	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SVM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00
Viewed-Nominal									
DF (Hz)	120	0	0	0	0	0	0	0	0
MD (%)	1.39	3.40	-1.07	0.00	1.55	0.00	-1.44	0.00	-3.96
FI	0.00	0.01	0.00	0.01	-0.01	-0.01	-0.02	0.02	-0.05
Pst^{LM}	0.06	0.02	-0.04	0.42	0.12	0.51	0.07	0.47	0.10
SVM	0.00	0.09	-0.03	0.15	-0.01	0.09	-0.06	0.17	-0.09

Figure A.1. The processed waveform data from both ideal and measured data for each experimental condition reveals the limitations of this equipment.



Appendix B - Descriptive Statistics

B.1 Main effects of TLM for all dependent variables

Table B.1.1. This table shows descriptive statistics for the nine TLM conditions for the whole sample.

Concept	Dependent Variables	TLM	*Mean*	*SD*	Median
Reading – eye movement N=24	Blink count	no-TLM	10.42	8.37	8.50
		120Hz_60WA19	10.43	9.06	6.00
		120Hz_T12mag	10.09	8.57	5.83
		500Hz_MD100_DC50	10.67	10.95	7.17
		500Hz_MD30_DC50	9.68	8.43	6.42
		500Hz_MD100_DC30	10.04	8.46	6.92
		500Hz_MD15_DC50	9.53	7.62	5.67
		1000Hz_MD100_DC50	10.99	8.59	9.17
		1000Hz_MD30_DC50	11.15	12.45	5.75
	Saccade count	no-TLM	170.95	42.72	175.50
		120Hz_60WA19	167.12	42.05	168.83
		120Hz_T12mag	164.05	53.73	171.00
		500Hz_MD100_DC50	152.91	65.10	167.67
		500Hz_MD30_DC50	177.11	33.61	178.08
		500Hz_MD100_DC30	170.42	52.59	179.25
		500Hz_MD15_DC50	170.83	52.07	181.84
		1000Hz_MD100_DC50	164.38	52.19	168.83
		1000Hz_MD30_DC50	167.04	48.24	172.84
	Saccade amplitude (deg)	no-TLM	1.60	0.34	1.53
		120Hz_60WA19	1.58	0.32	1.58
		120Hz_T12mag	1.58	0.35	1.57
		500Hz_MD100_DC50	1.60	0.47	1.52
		500Hz_MD30_DC50	1.51	0.28	1.48
		500Hz_MD100_DC30	1.55	0.31	1.58
		500Hz_MD15_DC50	1.54	0.34	1.50
		1000Hz_MD100_DC50	1.60	0.38	1.55
		1000Hz_MD30_DC50	1.58	0.38	1.59
	Fixation count	no-TLM	171.49	42.86	176.17
		120Hz_60WA19	167.53	42.21	169.50
		120Hz_T12mag	164.58	54.00	171.67
		500Hz_MD100_DC50	153.31	65.41	168.33
		500Hz_MD30_DC50	177.57	33.67	178.42
		500Hz_MD100_DC30	170.90	52.75	179.92
		500Hz_MD15_DC50	171.19	52.34	182.33
		1000Hz_MD100_DC50	164.78	52.35	169.42
		1000Hz_MD30_DC50	167.39	48.37	173.17
	Fixation duration (msec)	no-TLM	296.49	87.30	286.96
		120Hz_60WA19	297.65	66.90	279.65
		120Hz_T12mag	350.63	321.65	286.64
		500Hz_MD100_DC50	342.38	341.87	286.12
		500Hz_MD30_DC50	303.95	71.07	297.09
		500Hz_MD100_DC30	367.79	438.11	294.09
		500Hz_MD15_DC50	297.14	80.78	295.45
		1000Hz_MD100_DC50	287.39	98.27	284.23
		1000Hz_MD30_DC50	306.35	83.06	305.70
	Pupil size (units)	no-TLM	642.37	182.04	622.82
		120Hz_60WA19	638.19	169.97	617.34
		120Hz_T12mag	634.78	164.57	610.28
		500Hz_MD100_DC50	646.40	178.86	627.75
		500Hz_MD30_DC50	626.50	160.26	590.13
		500Hz_MD100_DC30	665.53	186.51	611.73
		500Hz_MD15_DC50	632.71	157.89	600.26
		1000Hz_MD100_DC50	657.40	183.46	634.14
		1000Hz_MD30_DC50	641.84	169.48	622.95

Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**
Reading - performance	Speed (words/min)	no-TLM	143.10	34.34	133.92
		120Hz_60WA19	143.21	30.13	136.33
		120Hz_T12mag	143.53	32.97	137.67
N=24		500Hz_MD100_DC50	143.20	29.42	138.83
		500Hz_MD30_DC50	141.67	30.82	134.67
		500Hz_MD100_DC30	142.91	30.19	134.50
		500Hz_MD15_DC50	141.90	32.87	132.50
		1000Hz_MD100_DC50	141.45	31.89	137.33
		1000Hz_MD30_DC50	141.47	32.20	136.67
	Accuracy (errors/min)	no-TLM	2.47	1.93	2.00
		120Hz_60WA19	2.60	2.17	2.33
		120Hz_T12mag	2.51	2.13	2.00
		500Hz_MD100_DC50	2.74	2.37	2.17
		500Hz_MD30_DC50	2.48	2.24	2.00
		500Hz_MD100_DC30	2.43	1.98	1.83
		500Hz_MD15_DC50	2.42	1.84	2.00
		1000Hz_MD100_DC50	3.13	2.56	2.17
		1000Hz_MD30_DC50	2.47	1.99	2.00
Stroop – eye movement	Pupil size (units)	no-TLM	567.85	139.75	545.45
		120Hz_60WA19	575.13	132.16	541.94
		120Hz_T12mag	567.56	121.15	531.84
N=24		500Hz_MD100_DC50	581.42	117.39	561.84
		500Hz_MD30_DC50	550.59	116.16	521.73
		500Hz_MD100_DC30	582.14	131.74	552.79
		500Hz_MD15_DC50	572.29	122.53	548.32
		1000Hz_MD100_DC50	574.33	114.10	556.36
		1000Hz_MD30_DC50	574.22	125.30	571.94
Stroop - performance interference	Accuracy	no-TLM	-0.02	0.04	0.00
		120Hz_60WA19	-0.04	0.14	0.00
		120Hz_T12mag	-0.03	0.07	-0.01
		500Hz_MD100_DC50	-0.01	0.03	0.00
N=24		500Hz_MD30_DC50	-0.02	0.04	0.00
		500Hz_MD100_DC30	-0.01	0.03	0.00
		500Hz_MD15_DC50	-0.01	0.03	0.00
		1000Hz_MD100_DC50	-0.04	0.14	0.00
		1000Hz_MD30_DC50	-0.03	0.11	0.00
	Reaction time	no-TLM	167.51	143.14	130.61
		120Hz_60WA19	149.53	137.25	107.59
		120Hz_T12mag	155.74	111.54	134.69
		500Hz_MD100_DC50	136.79	126.16	109.04
		500Hz_MD30_DC50	158.21	143.97	120.28
		500Hz_MD100_DC30	172.94	146.45	145.96
		500Hz_MD15_DC50	142.41	118.50	135.16
		1000Hz_MD100_DC50	171.54	151.40	122.16
		1000Hz_MD30_DC50	147.31	132.69	113.02
Phantom array- eye movements	Blink count	no-TLM	3.69	3.26	2.50
		120Hz_60WA19	4.65	4.41	3.50
		120Hz_T12mag	3.88	4.24	3.00
		500Hz_MD100_DC50	4.58	4.31	4.00
N=24		500Hz_MD30_DC50	10.38	14.45	5.25
		500Hz_MD100_DC30	4.73	6.09	2.25
		500Hz_MD15_DC50	4.17	4.30	2.75
		1000Hz_MD100_DC50	5.54	6.12	4.00
		1000Hz_MD30_DC50	8.75	12.34	4.75

Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**
	Saccade count	no-TLM	65.00	41.06	60.00
		120Hz_60WA19	64.00	30.49	62.75
		120Hz_T12mag	59.33	61.20	45.25
		500Hz_MD100_DC50	62.60	40.09	46.50
		500Hz_MD30_DC50	93.75	99.36	51.50
		500Hz_MD100_DC30	55.00	19.74	52.50
		500Hz_MD15_DC50	51.98	27.84	45.50
		1000Hz_MD100_DC50	84.96	70.92	60.50
		1000Hz_MD30_DC50	82.19	60.57	69.75
	Saccade amplitude (deg)	no-TLM	10.80	4.62	10.33
		120Hz_60WA19	10.79	4.35	9.97
		120Hz_T12mag	10.60	4.08	10.35
		500Hz_MD100_DC50	10.89	4.90	10.19
		500Hz_MD30_DC50	9.83	3.84	8.60
		500Hz_MD100_DC30	9.59	4.47	9.00
		500Hz_MD15_DC50	9.76	4.16	9.37
		1000Hz_MD100_DC50	10.37	4.52	8.32
		1000Hz_MD30_DC50	9.46	4.36	9.83
	Fixation count	no-TLM	65.85	41.11	60.50
		120Hz_60WA19	64.77	30.40	63.75
		120Hz_T12mag	60.06	61.21	46.00
		500Hz_MD100_DC50	63.29	40.03	47.50
		500Hz_MD30_DC50	94.40	99.22	52.50
		500Hz_MD100_DC30	55.65	19.53	53.25
		500Hz_MD15_DC50	52.58	27.85	46.00
		1000Hz_MD100_DC50	85.77	70.81	61.25
		1000Hz_MD30_DC50	82.85	60.64	70.50
	Fixation duration (msec)	no-TLM	223.08	55.44	217.54
		120Hz_60WA19	228.05	53.36	222.59
		120Hz_T12mag	230.17	48.91	224.87
		500Hz_MD100_DC50	222.92	55.64	217.49
		500Hz_MD30_DC50	235.25	49.70	230.14
		500Hz_MD100_DC30	222.75	45.97	219.91
		500Hz_MD15_DC50	233.61	51.19	245.17
		1000Hz_MD100_DC50	222.25	52.82	222.73
		1000Hz_MD30_DC50	226.23	56.66	222.70
	Pupil size (units)	no-TLM	663.29	148.96	620.56
		120Hz_60WA19	660.48	157.24	617.80
		120Hz_T12mag	661.11	139.36	634.08
		500Hz_MD100_DC50	684.10	169.35	624.65
		500Hz_MD30_DC50	664.19	145.64	607.86
		500Hz_MD100_DC30	709.50	161.47	674.34
		500Hz_MD15_DC50	664.14	129.16	634.78
		1000Hz_MD100_DC50	683.95	142.78	634.17
		1000Hz_MD30_DC50	700.36	165.88	684.29
Discomfort N=24	Visual discomfort rating	no-TLM	0.44	0.33	0.38
		120Hz_60WA19	0.45	0.35	0.38
		120Hz_T12mag	0.47	0.34	0.38
		500Hz_MD100_DC50	0.46	0.26	0.38
		500Hz_MD30_DC50	0.53	0.42	0.38
		500Hz_MD100_DC30	0.52	0.37	0.50
		500Hz_MD15_DC50	0.47	0.33	0.38
		1000Hz_MD100_DC50	0.47	0.40	0.50
		1000Hz_MD30_DC50	0.47	0.30	0.38

Table B.1.2. This table shows the descriptive statistics for the main effects of task variables (Stroop and Reading) for the whole sample, averaged across TLM conditions.

Concept	Dependent Variables	Conditions	*Mean*	*SD*	Median
Reading – eye movement N=24	Blink count	Small text	9.37	8.24	5.84
		Large text	11.30	10.01	7.42
	Saccade count	Small text	153.77	45.97	159.67
		Large text	180.63	49.96	187.67
	Saccade amplitude (deg)	Small text	1.34	0.26	1.29
		Large text	1.81	0.26	1.79
	Fixation count	Small text	154.20	46.15	160.09
		Large text	181.07	50.18	188.42
	Fixation duration (msec)	Small text	356.76	293.48	326.57
		Large text	276.52	105.14	268.90
	Pupil size (units)	Small text	635.60	165.86	612.85
		Large text	650.12	177.29	616.13
Reading - performance N=24	Speed (words/min)	Small text	139.78	30.87	133.33
		Large text	145.21	31.76	136.83
	Accuracy (errors/min)	Small text	2.65	2.08	2.00
		Large text	2.52	2.19	2.00
Stroop – eye movement N=24	Pupil size (units)	Incongruent trials	572.69	124.44	550.19
		Congruent trials	570.76	124.64	545.96
		Colour trials	568.17	118.41	546.75
		Word trials	575.28	130.29	546.82
Stroop - performance interference N=24	Accuracy difference % (incongruent-congruent)	Colour trials	-0.02	0.07	0.00
		Word trials	-0.02	0.09	0.00
	Reaction time (msec)	Colour trials	206.85	146.45	176.90
		Word trials	104.70	97.75	79.81

Table B.1.3. This table shows the descriptive statistics for the main effects of Sensitivity on eye movements and task performance, averaged across TLM conditions and independent variables.

		Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
Reading – eye movement	N		13			11	
	Blink count	10.5	9.86	5.42	10.19	8.39	7.33
	Saccade count	167.31	52.50	176.17	167.07	46.53	173.58
	Saccade amplitude (deg)	1.58	0.36	1.53	1.57	0.34	1.55
	Fixation count	167.75	52.68	176.84	167.50	46.75	173.92
	Fixation duration (msec)	341.31	294.51	298.14	287.49	73.66	283.38
	Pupil size (units)	657.58	180.36	632.82	625.46	159.39	591.17
Reading – performance	N		13			11	
	Speed (words/min)	142.35	29.10	134.00	142.67	34.00	139.50
	Accuracy (errors/min)	1.92	1.68	1.33	3.37	2.34	2.67
Stroop – eye movement	N		11			13	
	Pupil size (units)	610.91	125.81	597.61	538.57	113.31	513.38
Stroop - performance interference	N		11			13	
	Accuracy difference % (incongruent-congruent)	-0.01	0.02	0.00	-0.03	0.11	-0.02
	Reaction time (msec)	144.42	135.83	113.06	165.38	132.82	131.29

Table B.1.4. This table shows the descriptive statistics for the main effects of task variables (Stroop and Reading) on eye movements and task performance by sensitivity group, averaged across TLM conditions.

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**Conditions**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
Reading – eye movement	N			13			11	
	Blink count	Small text	9.73	9.16	5.17	8.95	7.02	6.33
		Large text	11.18	10.51	5.83	11.43	9.44	8.67
	Saccade count	Small text	153.81	47.90	156.34	153.73	43.82	162.67
		Large text	180.82	53.62	186.84	180.40	45.52	188.33
	Saccade amplitude (deg)	Small text	1.33	0.25	1.29	1.34	0.27	1.30
		Large text	1.82	0.28	1.80	1.80	0.23	1.78
	Fixation count	Small text	154.25	48.04	157.17	154.15	44.05	162.67
		Large text	181.25	53.84	187.50	180.86	45.75	189.00
	Fixation duration (msec)	Small text	396.07	388.26	352.11	310.30	80.58	309.79
		Large text	286.55	132.00	270.31	264.67	57.99	268.64
	Pupil size (units)	Small text	656.53	177.74	629.13	610.85	147.70	583.98
		Large text	658.62	183.70	635.74	640.07	169.77	596.15
Reading – performance	N			13			11	
	Speed (words/min)	Small text	139.63	28.80	131.00	139.94	33.30	139.33
		Large text	145.06	29.25	135.00	145.39	34.63	142.33
	Accuracy (errors/min)	Small text	1.99	1.67	1.67	3.42	2.25	2.67
		Large text	1.85	1.70	1.33	3.31	2.44	2.67
Stroop – eye movement	N			11			13	
	Pupil size (units)	Incongruent trials	611.53	126.39	599.90	539.83	113.02	514.11
		Congruent trials	610.29	125.54	597.61	537.30	113.83	513.09
		Colour trials	605.18	118.03	591.64	536.84	109.59	513.07
		Word trials	616.64	133.19	604.31	540.29	117.13	513.92
Stroop - performance interference	N			11			13	
	Accuracy difference % (incongruent-congruent)	Colour trials	-0.01	0.03	0.00	-0.03	0.10	-0.02
		Word trials	0.00	0.02	0.00	-0.04	0.12	0.00
	Reaction time	Colour trials	186.50	153.87	149.27	224.07	138.19	199.20
		Word trials	102.35	99.18	72.67	106.70	96.91	81.29

B.2 Descriptive statistics for Sensitivity groups

Table B.2.1 This table displays the descriptive statistics for the nine TLM conditions for all dependent variables by low and high pattern glare sensitivity (collapsed across any other task variables, where necessary).

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
Reading – eye movements	N			13			11	
	Blink count	no-TLM	11.05	9.89	7.08	9.68	6.27	9.17
		120Hz_60WA19	9.76	9.17	4.50	11.22	9.07	7.42
		120Hz_T12mag	10.22	9.53	5.34	9.94	7.50	6.42
		500Hz_MD100_DC50	9.65	7.62	7.00	11.89	14.01	7.17
		500Hz_MD30_DC50	9.72	9.98	4.58	9.64	6.35	7.33
		500Hz_MD100_DC30	11.34	9.06	7.17	8.51	7.61	5.83
		500Hz_MD15_DC50	9.21	8.07	4.33	9.92	7.22	7.42
		1000Hz_MD100_DC50	11.21	10.14	7.42	10.73	6.54	10.75
		1000Hz_MD30_DC50	11.95	14.80	5.00	10.20	9.19	7.58
	Saccade count	no-TLM	172.74	44.37	181.84	168.83	41.61	173.17
		120Hz_60WA19	174.44	43.17	183.25	158.46	39.93	161.75
		120Hz_T12mag	158.99	58.57	166.25	170.04	48.05	185.67
		500Hz_MD100_DC50	138.10	72.42	154.34	170.41	51.46	175.17
		500Hz_MD30_DC50	178.82	29.19	178.08	175.09	38.80	179.34
		500Hz_MD100_DC30	168.17	55.86	177.42	173.08	49.61	183.75
		500Hz_MD15_DC50	168.22	56.78	176.17	173.90	47.01	186.58
		1000Hz_MD100_DC50	176.76	53.49	189.75	149.76	47.71	165.83
		1000Hz_MD30_DC50	169.60	42.98	172.00	164.02	54.71	172.92
	Saccade amplitude (deg)	no-TLM	1.57	0.32	1.53	1.64	0.37	1.55
		120Hz_60WA19	1.58	0.28	1.59	1.59	0.37	1.55
		120Hz_T12mag	1.60	0.36	1.51	1.57	0.35	1.59
		500Hz_MD100_DC50	1.69	0.56	1.57	1.49	0.30	1.50
		500Hz_MD30_DC50	1.52	0.31	1.46	1.50	0.25	1.51
		500Hz_MD100_DC30	1.55	0.31	1.59	1.55	0.32	1.56
		500Hz_MD15_DC50	1.54	0.36	1.50	1.55	0.33	1.55
		1000Hz_MD100_DC50	1.54	0.29	1.52	1.67	0.46	1.55
		1000Hz_MD30_DC50	1.60	0.42	1.57	1.57	0.32	1.62

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
	Fixation count	no-TLM	173.31	44.51	182.50	169.33	41.76	173.67
		120Hz_60WA19	174.86	43.33	183.92	158.86	40.09	162.42
		120Hz_T12mag	159.53	58.85	167.00	170.56	48.31	186.50
		500Hz_MD100_DC50	138.43	72.69	155.00	170.89	51.84	175.67
		500Hz_MD30_DC50	179.30	29.21	178.42	175.53	38.90	179.92
		500Hz_MD100_DC30	168.68	55.97	177.92	173.52	49.85	184.42
		500Hz_MD15_DC50	168.56	57.09	177.00	174.30	47.25	186.92
		1000Hz_MD100_DC50	177.19	53.65	190.58	150.11	47.87	166.50
		1000Hz_MD30_DC50	169.90	42.96	172.34	164.42	54.98	173.25
	Fixation duration (msec)	no-TLM	295.60	89.07	291.24	297.53	87.23	284.51
		120Hz_60WA19	312.06	64.92	287.50	280.63	66.63	264.72
		120Hz_T12mag	411.72	428.47	315.36	278.43	53.91	279.94
		500Hz_MD100_DC50	392.35	457.40	290.80	283.33	75.95	282.58
		500Hz_MD30_DC50	310.92	75.82	321.38	295.72	65.79	284.84
		500Hz_MD100_DC30	429.33	589.69	300.75	295.06	73.37	290.50
		500Hz_MD15_DC50	309.22	82.80	305.30	282.87	77.77	287.58
		1000Hz_MD100_DC50	301.03	109.09	289.91	271.27	83.33	275.18
		1000Hz_MD30_DC50	309.56	86.27	308.63	302.54	80.95	303.21
	Pupil size (units)	no-TLM	650.21	194.05	630.98	633.11	170.80	593.16
		120Hz_60WA19	659.07	180.59	632.89	613.51	157.04	611.67
		120Hz_T12mag	646.86	170.86	612.97	620.51	159.58	590.34
		500Hz_MD100_DC50	649.12	190.59	647.08	643.18	168.34	609.31
		500Hz_MD30_DC50	648.23	172.63	621.78	600.81	143.97	585.92
		500Hz_MD100_DC30	695.63	205.98	655.65	629.95	157.78	585.30
		500Hz_MD15_DC50	645.78	167.94	619.35	617.26	147.50	593.96
		1000Hz_MD100_DC50	671.04	176.86	639.69	641.28	193.89	601.58
		1000Hz_MD30_DC50	652.26	182.98	634.90	629.53	155.36	573.38

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
Reading – performance	N			13			11	
	Speed (words/min)	no-TLM	142.52	29.02	133.92	143.79	40.44	132.33
		120Hz_60WA19	144.50	29.92	136.33	141.68	31.01	138.67
		120Hz_T12mag	143.09	31.54	140.00	144.05	35.33	135.00
		500Hz_MD100_DC50	142.29	27.10	136.50	144.27	32.56	147.00
		500Hz_MD30_DC50	142.65	28.30	132.83	140.50	34.21	138.33
		500Hz_MD100_DC30	143.83	29.69	134.50	141.81	31.44	134.00
		500Hz_MD15_DC50	142.72	31.00	133.33	140.92	35.66	131.50
		1000Hz_MD100_DC50	138.87	29.14	133.83	144.50	35.32	142.33
		1000Hz_MD30_DC50	140.63	30.09	129.17	142.47	35.22	146.00
	Accuracy (errors/min)	no-TLM	1.81	1.55	1.33	3.24	2.09	3.00
		120Hz_60WA19	2.00	2.04	1.33	3.32	2.14	2.67
		120Hz_T12mag	2.01	2.31	1.67	3.11	1.77	2.83
		500Hz_MD100_DC50	1.81	1.53	1.33	3.83	2.73	2.67
		500Hz_MD30_DC50	2.05	1.48	1.67	2.98	2.84	2.67
		500Hz_MD100_DC30	1.76	1.27	1.33	3.23	2.38	2.00
		500Hz_MD15_DC50	1.92	1.40	1.67	3.02	2.13	2.67
		1000Hz_MD100_DC50	2.24	2.08	1.33	4.17	2.71	3.67
		1000Hz_MD30_DC50	1.69	1.34	1.83	3.39	2.26	3.00
Stroop – eye movement	N			11			13	
	Pupil size (units)	no-TLM	615.24	135.05	577.14	527.75	132.01	492.08
		120Hz_60WA19	622.73	146.26	609.90	534.86	104.35	513.06
		120Hz_T12mag	604.15	123.44	589.60	536.59	111.16	506.80
		500Hz_MD100_DC50	610.10	120.50	595.93	557.15	110.07	543.94
		500Hz_MD30_DC50	599.12	123.34	579.74	509.53	92.50	501.38
		500Hz_MD100_DC30	618.22	130.01	610.20	551.61	126.50	521.12
		500Hz_MD15_DC50	610.48	114.61	610.30	539.98	120.70	517.07
		1000Hz_MD100_DC50	609.40	111.51	586.89	544.66	108.66	534.31
		1000Hz_MD30_DC50	608.80	133.82	597.40	544.96	110.65	527.51

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
Stroop–performance interference	N			11			13	
	Accuracy	no-TLM	-0.01	0.03	0.00	-0.03	0.04	-0.02
		120Hz_60WA19	-0.01	0.02	0.00	-0.06	0.19	-0.02
		120Hz_T12mag	0.00	0.02	0.00	-0.05	0.09	-0.02
		500Hz_MD100_DC50	0.00	0.02	0.00	-0.01	0.03	0.00
		500Hz_MD30_DC50	-0.01	0.03	0.00	-0.02	0.04	-0.02
		500Hz_MD100_DC30	0.00	0.02	0.00	-0.02	0.03	-0.02
		500Hz_MD15_DC50	0.00	0.02	0.00	-0.02	0.03	-0.02
		1000Hz_MD100_DC50	-0.01	0.02	0.00	-0.05	0.19	0.00
		1000Hz_MD30_DC50	0.00	0.02	0.00	-0.05	0.15	-0.02
	Reaction time	no-TLM	171.96	164.62	115.98	163.74	125.38	141.95
		120Hz_60WA19	147.26	164.35	96.88	151.45	112.78	137.29
		120Hz_T12mag	128.60	89.30	124.05	178.70	124.47	146.38
		500Hz_MD100_DC50	108.50	107.37	109.04	160.72	137.62	120.92
		500Hz_MD30_DC50	161.83	167.01	106.19	155.14	124.57	124.01
		500Hz_MD100_DC30	156.38	117.16	131.78	186.95	168.36	160.50
		500Hz_MD15_DC50	166.99	126.41	149.61	121.62	109.52	118.96
		1000Hz_MD100_DC50	144.78	148.65	115.18	194.19	152.86	134.97
		1000Hz_MD30_DC50	113.52	123.90	80.18	175.91	135.46	124.01
Phantom–array- eye movements	N			12			12	
	Blink count	no-TLM	3.83	3.49	2.75	3.54	3.17	2.50
		120Hz_60WA19	4.75	4.67	4.25	4.54	4.35	2.50
		120Hz_T12mag	5.42	5.38	4.25	2.33	1.87	2.00
		500Hz_MD100_DC50	4.63	4.03	4.25	4.54	4.74	3.50
		500Hz_MD30_DC50	13.63	18.08	5.25	7.13	9.31	5.25
		500Hz_MD100_DC30	6.00	8.16	2.50	3.46	2.72	2.25
		500Hz_MD15_DC50	3.54	4.37	1.00	4.79	4.32	3.00
		1000Hz_MD100_DC50	6.88	8.21	3.75	4.21	2.63	4.25
		1000Hz_MD30_DC50	11.08	16.54	4.75	6.42	5.73	5.50

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
	Saccade count	no-TLM	70.13	47.73	63.50	59.88	34.49	54.50
		120Hz_60WA19	59.75	35.47	54.00	68.25	25.42	65.50
		120Hz_T12mag	69.50	82.92	47.00	49.17	27.04	45.25
		500Hz_MD100_DC50	54.71	25.25	43.75	70.50	50.86	51.75
		500Hz_MD30_DC50	120.00	131.36	51.50	67.50	43.41	48.00
		500Hz_MD100_DC30	53.79	23.77	46.00	56.21	15.71	63.00
		500Hz_MD15_DC50	47.04	26.57	44.00	56.92	29.35	55.50
		1000Hz_MD100_DC50	85.38	91.28	40.00	84.54	46.73	72.00
		1000Hz_MD30_DC50	86.21	75.62	63.25	78.17	43.79	69.75
	Saccade amplitude (deg)	no-TLM	10.27	4.96	9.46	11.32	4.42	10.33
		120Hz_60WA19	11.34	4.65	9.97	10.25	4.17	9.76
		120Hz_T12mag	11.53	3.93	10.81	9.67	4.17	9.23
		500Hz_MD100_DC50	12.16	6.00	11.92	9.62	3.25	10.19
		500Hz_MD30_DC50	9.89	4.58	8.46	9.77	3.14	9.36
		500Hz_MD100_DC30	9.08	4.88	7.11	10.09	4.18	9.59
		500Hz_MD15_DC50	10.16	3.34	9.44	9.35	4.97	8.58
		1000Hz_MD100_DC50	10.87	5.58	8.20	9.87	3.32	9.23
		1000Hz_MD30_DC50	9.70	4.29	10.69	9.23	4.60	8.72
	Fixation count	no-TLM	70.96	47.86	64.00	60.75	34.45	55.50
		120Hz_60WA19	60.46	35.48	55.00	69.08	25.16	66.50
		120Hz_T12mag	70.17	82.96	48.00	49.96	26.98	46.00
		500Hz_MD100_DC50	55.42	25.26	44.75	71.17	50.76	52.25
		500Hz_MD30_DC50	120.58	131.14	52.50	68.21	43.50	48.50
		500Hz_MD100_DC30	54.29	23.48	46.50	57.00	15.55	64.00
		500Hz_MD15_DC50	47.46	26.52	45.00	57.71	29.35	55.75
		1000Hz_MD100_DC50	86.13	91.20	41.00	85.42	46.53	73.00
		1000Hz_MD30_DC50	86.75	75.70	63.75	78.96	43.86	70.75

			Low Sensitivity			High Sensitivity		
Concept	**Dependent Variables**	**TLM**	***Mean***	***SD***	**Median**	***Mean***	***SD***	**Median**
	Fixation duration (msec)	no-TLM	216.74	51.15	208.71	229.42	61.02	219.69
		120Hz_60WA19	225.49	49.07	222.59	230.62	59.41	223.22
		120Hz_T12mag	217.92	30.89	214.62	242.43	61.00	227.53
		500Hz_MD100_DC50	224.85	50.19	217.83	220.98	62.81	215.70
		500Hz_MD30_DC50	230.82	34.15	223.75	239.67	62.89	247.17
		500Hz_MD100_DC30	227.12	30.17	227.58	218.39	58.88	204.32
		500Hz_MD15_DC50	224.42	45.30	219.89	242.80	56.95	247.85
		1000Hz_MD100_DC50	221.22	35.96	227.39	223.28	67.36	208.47
		1000Hz_MD30_DC50	219.48	25.17	226.76	232.98	77.32	221.46
	Pupil size (units)	no-TLM	699.07	155.74	656.66	627.50	139.08	613.39
		120Hz_60WA19	688.09	175.09	641.53	632.87	139.21	594.81
		120Hz_T12mag	699.78	147.70	674.80	622.44	124.62	604.24
		500Hz_MD100_DC50	710.33	147.34	665.81	657.88	191.72	592.76
		500Hz_MD30_DC50	708.37	160.59	687.58	620.01	119.59	582.44
		500Hz_MD100_DC30	749.26	160.21	691.90	669.74	159.36	608.02
		500Hz_MD15_DC50	686.75	127.17	662.12	641.52	132.64	625.66
		1000Hz_MD100_DC50	720.57	150.89	706.43	647.32	130.12	611.74
		1000Hz_MD30_DC50	727.62	184.83	687.02	673.10	147.48	666.08
Discomfort	N			12			12	
	Visual discomfort rating	no-TLM	0.40	0.33	0.31	0.49	0.34	0.38
		120Hz_60WA19	0.42	0.40	0.31	0.49	0.30	0.44
		120Hz_T12mag	0.43	0.37	0.25	0.51	0.32	0.44
		500Hz_MD100_DC50	0.43	0.29	0.38	0.49	0.23	0.44
		500Hz_MD30_DC50	0.44	0.47	0.25	0.61	0.37	0.44
		500Hz_MD100_DC30	0.44	0.47	0.31	0.59	0.24	0.56
		500Hz_MD15_DC50	0.41	0.35	0.38	0.54	0.31	0.50
		1000Hz_MD100_DC50	0.48	0.45	0.38	0.46	0.37	0.50
		1000Hz_MD30_DC50	0.49	0.36	0.31	0.45	0.23	0.38

Appendix C - Complete Inferential Test Results

C.1 Main effects of Sensitivity

These ANOVA and MANOVA tests compared the low-sensitivity and high-sensitivity groups, without consideration of the TLM conditions or other task variables.

Concept	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
Discomfort	Discomfort score		0.498	1,22	0.488	0.022
Stroop Eye Movements	Pupil Size		2.362	1,22	0.139	0.097
Phantom array - eye movements	Multivariate	0.758	0.902	6,17	0.516	0.242
	Blink count		1.286	1,22	0.269	0.055
	Saccade count		0.271	1,22	0.608	0.012
	Saccade Amplitude		0.189	1,22	0.668	0.009
	Fixation count		0.258	1,22	0.616	0.012
	Fixation duration		0.194	1,22	0.664	0.009
	Pupil size		1.359	1,22	0.256	0.058
Reading - eye movements	Multivariate	0.871	0.418	6,17	0.857	0.129
	Blink count		0.007	1,22	0.933	0
	Saccade count		0	1,22	0.986	0
	Saccade Amplitude		0.008	1,22	0.927	0
	Fixation count		0	1,22	0.987	0
	Fixation duration		1.057	1,22	0.315	0.046
	Pupil size		0.213	1,22	0.649	0.01
Stroop - performance	Multivariate	0.739	3.706	2,21	0.042*	0.261
	Accuracy		7.746	1,22	0.011*	0.26
	Reaction time		0.346	1,22	0.562	0.015
Reading - performance	Multivariate	0.822	2.272	2,21	0.128	0.178
	Speed		0.001	1,22	0.98	0
	Accuracy		4.286	1,22	0.05*	0.163

C.2 Interactions of Sensitivity by TLM Planned Comparisons

These ANOVA and MANOVA tests were interaction effects to test whether the effect of the TLM contrast differed by sensitivity group.

Concept	Contrast (X Sensitivity)	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
Discomfort	LS1	Discomfort score		0.023	1,22	0.882	0.001
	LS2	Discomfort score		0.011	1,22	0.916	0.001
	MD1	Discomfort score		1.037	1,22	0.319	0.045
	MD2	Discomfort score		0.137	1,22	0.715	0.006
	MD3	Discomfort score		0.021	1,22	0.886	0.001
	DUTY	Discomfort score		0.82	1,22	0.375	0.036
	FR	Discomfort score		1.5	1,22	0.234	0.064
	REP	Discomfort score		0.084	1,22	0.775	0.004
Stroop Eye	LS1	Pupil Size		0	1,22	0.987	0.000
	LS2	Pupil Size		0.97	1,22	0.335	0.042
	MD1	Pupil Size		3.583	1,22	0.072	0.140
	MD2	Pupil Size		0.636	1,22	0.434	0.028
	MD3	Pupil Size		0.002	1,22	0.969	0.000
	DUTY	Pupil Size		0.899	1,22	0.353	0.039
	FR	Pupil Size		0.021	1,22	0.886	0.001
	REP	Pupil Size		2.755	1,22	0.111	0.111
Phantom eye	LS1	Multivariate	0.83	0.579	6,17	0.742	0.17
		Blink count		0.003	1,22	0.957	0.000
		Saccade count		1.192	1,22	0.287	0.051
		Saccade Amplitude		1.596	1,22	0.22	0.068
		Fixation count		1.195	1,22	0.286	0.052
		Fixation duration		0.193	1,22	0.665	0.009
		Pupil size		0.217	1,22	0.646	0.01
	LS2	Multivariate	0.566	2.175	6,17	0.097	0.434
		Blink count		3.653	1,22	0.069	0.142
		Saccade count		0.232	1,22	0.635	0.01
		Saccade Amplitude		6.046	1,22	0.022*	0.216
		Fixation count		0.227	1,22	0.638	0.01
		Fixation duration		0.541	1,22	0.47	0.024
		Pupil size		0.053	1,22	0.82	0.002
	MD1	Multivariate	0.808	0.672	6,17	0.674	0.192
		Blink count		1.668	1,22	0.21	0.07
		Saccade count		3.252	1,22	0.085	0.129
		Saccade Amplitude		3.495	1,22	0.075	0.137
		Fixation count		3.258	1,22	0.085	0.129
		Fixation duration		0.464	1,22	0.503	0.021
		Pupil size		1.019	1,22	0.324	0.044

Concept	Contrast (X Sensitivity)	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	MD2	Multivariate	0.649	1.529	6,17	0.228	0.351
		Blink count		2.027	1,22	0.169	0.084
		Saccade count		2.955	1,22	0.1	0.118
		Saccade Amplitude		0.169	1,22	0.685	0.008
		Fixation count		2.991	1,22	0.098	0.12
		Fixation duration		0.43	1,22	0.519	0.019
		Pupil size		2.141	1,22	0.158	0.089
	MD3	Multivariate	0.9)	0.316	6,17	0.92	0.1
		Blink count		0.129	1,22	0.723	0.006
		Saccade count		0.032	1,22	0.859	0.001
		Saccade Amplitude		0.129	1,22	0.723	0.006
		Fixation count		0.031	1,22	0.861	0.001
		Fixation duration		0.611	1,22	0.443	0.027
		Pupil size		0.203	1,22	0.657	0.009
	DUTY	Multivariate	0.768	0.854	6,17	0.547	0.232
		Blink count		0.872	1,22	0.36	0.038
		Saccade count		0.63	1,22	0.436	0.028
		Saccade Amplitude		4.227	1,22	0.052	0.161
		Fixation count		0.607	1,22	0.444	0.027
		Fixation duration		0.08	1,22	0.78	0.004
		Pupil size		0.834	1,22	0.371	0.037
	FR	Multivariate	0.755	0.920	6,17	0.505	0.245
		Blink count		0.128	1,22	0.724	0.006
		Saccade count		0.154	1,22	0.698	0.007
		Saccade Amplitude		1.642	1,22	0.213	0.069
		Fixation count		0.156	1,22	0.697	0.007
		Fixation duration		0.723	1,22	0.404	0.032
		Pupil size		0.35	1,22	0.56	0.016
	REP	Multivariate	0.79	0.753	6,17	0.616	0.21
		Blink count		0.017	1,22	0.897	0.001
		Saccade count		1.549	1,22	0.226	0.066
		Saccade Amplitude		3.899	1,22	0.061	0.151
		Fixation count		1.541	1,22	0.228	0.065
		Fixation duration		0.602	1,22	0.446	0.027
		Pupil size		0.258	1,22	0.616	0.012

Concept	Contrast (X Sensitivity)	Dependent Variables	Wilks' Λ	F	df	p	Effect Size ($\eta^2_{partial}$)
Reading - eye movements	LS1	Multivariate	0.629	1.673	6,17	0.188	0.371
		Blink count		0.905	1,22	0.352	0.039
		Saccade count		0.449	1,22	0.51	0.02
		Saccade Amplitude		0.335	1,22	0.569	0.015
		Fixation count		0.437	1,22	0.515	0.019
		Fixation duration		1.566	1,22	0.224	0.066
		Pupil size		1.258	1,22	0.274	0.054
	LS2	Multivariate	0.747	0.959	6,17	0.481	0.253
		Blink count		0.295	1,22	0.592	0.013
		Saccade count		0.818	1,22	0.376	0.036
		Saccade Amplitude		2.119	1,22	0.16	0.088
		Fixation count		0.812	1,22	0.377	0.036
		Fixation duration		1.307	1,22	0.265	0.056
		Pupil size		0.148	1,22	0.704	0.007
	MD1	Multivariate	0.745	0.971	6,17	0.474	0.255
		Blink count		0.446	1,22	0.511	0.02
		Saccade count		2.797	1,22	0.109	0.113
		Saccade Amplitude		2.148	1,22	0.157	0.089
		Fixation count		2.817	1,22	0.107	0.114
		Fixation duration		0.649	1,22	0.429	0.029
		Pupil size		2.52	1,22	0.127	0.103
	MD2	Multivariate	0.895	0.331	6,17	0.911	0.105
		Blink count		0.173	1,22	0.682	0.008
		Saccade count		0.391	1,22	0.538	0.017
		Saccade Amplitude		0.298	1,22	0.591	0.013
		Fixation count		0.395	1,22	0.536	0.018
		Fixation duration		0.55	1,22	0.466	0.024
		Pupil size		0.826	1,22	0.373	0.036
	MD3	Multivariate	0.793	0.740	6,17	0.625	0.207
		Blink count		0.153	1,22	0.7	0.007
		Saccade count		1.432	1,22	0.244	0.061
		Saccade Amplitude		3.237	1,22	0.086	0.128
		Fixation count		1.433	1,22	0.244	0.061
		Fixation duration		1.067	1,22	0.313	0.046
		Pupil size		0.079	1,22	0.781	0.004
	DUTY	Multivariate	0.661	1.451	6,17	0.253	0.339
		Blink count		3.107	1,22	0.092	0.124
		Saccade count		2.051	1,22	0.166	0.085
		Saccade Amplitude		2.268	1,22	0.146	0.093
		Fixation count		2.075	1,22	0.164	0.086
		Fixation duration		0.621	1,22	0.439	0.027
		Pupil size		7.471	1,22	0.012	0.253

Concept	Contrast (X Sensitivity)	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	FR	Multivariate	0.857	0.471	6,17	0.82	0.143
		Blink count		0.118	1,22	0.734	0.005
		Saccade count		0.932	1,22	0.345	0.041
		Saccade Amplitude		0.007	1,22	0.935	0.000
		Fixation count		0.911	1,22	0.35	0.04
		Fixation duration		1.097	1,22	0.306	0.047
		Pupil size		0.013	1,22	0.912	0.001
	REP	Multivariate	0.619	1.743	6,17	0.172	0.381
		Blink count		1.964	1,22	0.175	0.082
		Saccade count		3.178	1,22	0.088	0.126
		Saccade Amplitude		4.959	1,22	0.037	0.184
		Fixation count		3.18	1,22	0.088	0.126
		Fixation duration		0.939	1,22	0.343	0.041
		Pupil size		0.193	1,22	0.665	0.009
Stroop - performance	LS1	Multivariate	0.972	0.301	2,21	0.743	0.028
		Accuracy		0.6	1,22	0.447	0.027
		Reaction time		0.058	1,22	0.811	0.003
	LS2	Multivariate	0.789	2.801	2,21	0.084	0.211
		Accuracy		2.096	1,22	0.162	0.087
		Reaction time		3.398	1,22	0.079	0.134
	MD1	Multivariate	0.932	0.766	2,21	0.477	0.068
		Accuracy		0.004	1,22	0.951	0.000
		Reaction time		1.549	1,22	0.226	0.066
	MD2	Multivariate	0.895	1.228	2,21	0.313	0.105
		Accuracy		0.072	1,22	0.791	0.003
		Reaction time		1.691	1,22	0.207	0.071
	MD3	Multivariate	0.995	0.057	2,21	0.945	0.005
		Accuracy		0.006	1,22	0.937	0.000
		Reaction time		0.118	1,22	0.735	0.005
	DUTY	Multivariate	0.94	0.666	2,21	0.524	0.06
		Accuracy		0.584	1,22	0.453	0.026
		Reaction time		0.243	1,22	0.627	0.011
	FR	Multivariate	0.994	0.062	2,21	0.94	0.006
		Accuracy		0.004	1,22	0.952	0.000
		Reaction time		0.126	1,22	0.726	0.006
	REP	Multivariate	0.919	0.930	2,21	0.41	0.081
		Accuracy		0.047	1,22	0.831	0.002
		Reaction time		1.696	1,22	0.206	0.072

Concept	Contrast (X Sensitivity)	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
Reading - performance	LS1	Multivariate	0.966	0.372	2,21	0.694	0.034
		Speed		0.718	1,22	0.406	0.032
		Accuracy		0.076	1,22	0.785	0.003
	LS2	Multivariate	0.963	0.403	2,21	0.674	0.037
		Speed		0.007	1,22	0.935	0.000
		Accuracy		0.839	1,22	0.37	0.037
	MD1	Multivariate	0.798	2.654	2,21	0.094	0.202
		Speed		0.771	1,22	0.389	0.034
		Accuracy		5.506	1,22	0.028	0.2
	MD2	Multivariate	0.991	0.091	2,21	0.913	0.009
		Speed		0.009	1,22	0.926	0.000
		Accuracy		0.188	1,22	0.669	0.008
	MD3	Multivariate	0.965	0.376	2,21	0.691	0.035
		Speed		0.773	1,22	0.389	0.034
		Accuracy		0.139	1,22	0.713	0.006
	DUTY	Multivariate	0.791	2.767	2,21	0.086	0.209
		Speed		1.189	1,22	0.287	0.051
		Accuracy		3.671	1,22	0.068	0.143
	FR	Multivariate	0.934	0.740	2,21	0.489	0.066
		Speed		0.048	1,22	0.829	0.002
		Accuracy		1.363	1,22	0.255	0.058
	REP	Multivariate	0.947	0.587	2,21	0.565	0.053
		Speed		0.027	1,22	0.871	0.001
		Accuracy		1.213	1,22	0.283	0.052

C.3 TLM Effects within Sensitivity Groups

We tested the same set of planned comparisons, each testing a single-degree-of-freedom contrast between TLM conditions, within the two sensitivity groups separately.

C.3.1 Low Sensitivity

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
Discomfort	LS1	Discomfort score		0.028	1,11	0.87	0.003
	LS2	Discomfort score		0.205	1,11	0.66	0.018
	MD1	Discomfort score		0.014	1,11	0.909	0.001
	MD2	Discomfort score		0.241	1,11	0.633	0.021
	MD3	Discomfort score		0.011	1,11	0.917	0.001
	DUTY	Discomfort score		0.013	1,11	0.912	0.001
	FR	Discomfort score		0.846	1,11	0.377	0.071
	REP	Discomfort score		0.292	1,11	0.6	0.026
Stroop Eye Movements	LS1	Pupil Size		0.856	1,10	0.377	0.079
	LS2	Pupil Size		0.731	1,10	0.412	0.068
	MD1	Pupil Size		1.37	1,10	0.269	0.12
	MD2	Pupil Size		0.405	1,10	0.539	0.039
	MD3	Pupil Size		0.002	1,10	0.969	0.000
	DUTY	Pupil Size		0.485	1,10	0.502	0.046
	FR	Pupil Size		0.089	1,10	0.771	0.009
	REP	Pupil Size		0.176	1,10	0.684	0.017
Phantom array - eye movements	LS1	Multivariate	0.656	0.525	6,6	0.774	0.344
		Blink count		1.116	1,11	0.313	0.092
		Saccade count		0.483	1,11	0.502	0.042
		Saccade amplitude		0.477	1,11	0.504	0.042
		Fixation count		0.489	1,11	0.499	0.043
		Fixation duration		0.558	1,11	0.471	0.048
		Pupil size		0.189	1,11	0.672	0.017
	LS2	Multivariate	0.701	0.426	6,6	0.839	0.299
		Blink count		1.886	1,11	0.197	0.146
		Saccade count		0.001	1,11	0.974	0.000
		Saccade amplitude		1.404	1,11	0.261	0.113
		Fixation count		0.002	1,11	0.967	0.000
		Fixation duration		0.011	1,11	0.917	0.001
		Pupil size		0.001	1,11	0.971	0.000

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	MD1	Multivariate	0.265	2.779	6,6	0.119	0.735
		Blink count		3.938	1,11	0.073	0.264
		Saccade count		3.351	1,11	0.094	0.233
		Saccade amplitude		3.676	1,11	0.082	0.25
		Fixation count		3.359	1,11	0.094	0.234
		Fixation duration		0.17	1,11	0.688	0.015
		Pupil size		0.009	1,11	0.927	0.001
	MD2	Multivariate	0.398	1.512	6,6	0.314	0.602
		Blink count		4.624	1,11	0.055	0.296
		Saccade count		4.48	1,11	0.058	0.289
		Saccade amplitude		0.114	1,11	0.742	0.01
		Fixation count		4.523	1,11	0.057	0.291
		Fixation duration		0.422	1,11	0.529	0.037
		Pupil size		0.932	1,11	0.355	0.078
	MD3	Multivariate	0.507	0.973	6,6	0.513	0.493
		Blink count		0.623	1,11	0.447	0.054
		Saccade count		0.001	1,11	0.982	0.000
		Saccade amplitude		0.786	1,11	0.394	0.067
		Fixation count		0	1,11	0.986	0.000
		Fixation duration		0.034	1,11	0.856	0.003
		Pupil size		0.039	1,11	0.847	0.004
	DUTY	Multivariate	0.283	2.529	6,6	0.142	0.717
		Blink count		0.428	1,11	0.527	0.037
		Saccade count		0.008	1,11	0.928	0.001
		Saccade amplitude		3.69	1,11	0.081	0.251
		Fixation count		0.013	1,11	0.912	0.001
		Fixation duration		0.029	1,11	0.867	0.003
		Pupil size		5.289	1,11	0.042	0.325
	FR	Multivariate	0.521	0.918	6,6	0.540	0.479
		Blink count		1.774	1,11	0.210	0.139
		Saccade count		0.315	1,11	0.586	0.028
		Saccade amplitude		4.734	1,11	0.052	0.301
		Fixation count		0.307	1,11	0.591	0.027
		Fixation duration		0.044	1,11	0.837	0.004
		Pupil size		0.668	1,11	0.431	0.057

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	REP	Multivariate	0.38	1.634	6,6	0.283	0.62
		Blink count		0.638	1,11	0.441	0.055
		Saccade count		1.252	1,11	0.287	0.102
		Saccade amplitude		1.306	1,11	0.277	0.106
		Fixation count		1.257	1,11	0.286	0.103
		Fixation duration		0.25	1,11	0.627	0.022
		Pupil size		0.176	1,11	0.683	0.016
Reading - eye movements	LS1	Multivariate	0.304	2.669	6,7	0.112	0.696
		Blink count		0.95	1,12	0.349	0.073
		Saccade count		0.019	1,12	0.892	0.002
		Saccade amplitude		0.005	1,12	0.947	0.000
		Fixation count		0.015	1,12	0.903	0.001
		Fixation duration		1.308	1,12	0.275	0.098
		Pupil size		0.415	1,12	0.532	0.033
	LS2	Multivariate	0.453	1.408	6,7	0.33	0.547
		Blink count		0.368	1,12	0.555	0.03
		Saccade count		1.404	1,12	0.259	0.105
		Saccade amplitude		0.397	1,12	0.541	0.032
		Fixation count		1.39	1,12	0.261	0.104
		Fixation duration		1.177	1,12	0.299	0.089
		Pupil size		0.088	1,12	0.772	0.007
	MD1	Multivariate	0.22	4.127	6,7	0.043*	0.78
		Blink count		0.002	1,12	0.961	0.000
		Saccade count		5.214	1,12	0.041*	0.303
		Saccade amplitude		2.299	1,12	0.155	0.161
		Fixation count		5.241	1,12	0.041*	0.304
		Fixation duration		0.59	1,12	0.457	0.047
		Pupil size		0.005	1,12	0.942	0
	MD2	Multivariate	0.867	0.179	6,7	0.974	0.133
		Blink count		0.132	1,12	0.723	0.011
		Saccade count		0.908	1,12	0.359	0.07
		Saccade amplitude		0.594	1,12	0.456	0.047
		Fixation count		0.92	1,12	0.356	0.071
		Fixation duration		0.073	1,12	0.791	0.006
		Pupil size		0.024	1,12	0.881	0.002

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	MD3	Multivariate	0.6	0.777	6,7	0.613	0.4
		Blink count		0.14	1,12	0.715	0.012
		Saccade count		0.356	1,12	0.562	0.029
		Saccade Amplitude		1.074	1,12	0.32	0.082
		Fixation count		0.362	1,12	0.559	0.029
		Fixation duration		0.249	1,12	0.627	0.02
		Pupil size		2.312	1,12	0.154	0.162
	DUTY	Multivariate	0.459	1.375	6,7	0.341	0.541
		Blink count		3.263	1,12	0.096	0.214
		Saccade count		3.105	1,12	0.103	0.206
		Saccade Amplitude		1.507	1,12	0.243	0.112
		Fixation count		3.126	1,12	0.102	0.207
		Fixation duration		1.656	1,12	0.222	0.121
		Pupil size		9.852	1,12	0.009	0.451
	FR	Multivariate	0.517	1.091	6,7	0.449	0.483
		Blink count		0.232	1,12	0.639	0.019
		Saccade count		0.692	1,12	0.422	0.055
		Saccade Amplitude		0.003	1,12	0.954	0.000
		Fixation count		0.657	1,12	0.433	0.052
		Fixation duration		0.868	1,12	0.37	0.067
		Pupil size		0.089	1,12	0.77	0.007
	REP	Multivariate	0.478	1.273	6,7	0.376	0.522
		Blink count		1.423	1,12	0.256	0.106
		Saccade count		4.09	1,12	0.066	0.254
		Saccade Amplitude		1.442	1,12	0.253	0.107
		Fixation count		4.103	1,12	0.066	0.255
		Fixation duration		0.859	1,12	0.372	0.067
		Pupil size		0.007	1,12	0.937	0.001
Stroop - performance	LS1	Multivariate	0.968	0.151	2,9	0.862	0.032
		Accuracy		0.225	1,10	0.645	0.022
		Reaction time		0.255	1,10	0.624	0.025
	LS2	Multivariate	0.665	2.266	2,9	0.16	0.335
		Accuracy		3.521	1,10	0.09	0.26
		Reaction time		2.829	1,10	0.124	0.22
	MD1	Multivariate	0.824	0.960	2,9	0.419	0.176
		Accuracy		0.675	1,10	0.43	0.063
		Reaction time		1.932	1,10	0.195	0.162
	MD2	Multivariate	0.787	1.221	2,9	0.34	0.213
		Accuracy		1.448	1,10	0.257	0.126
		Reaction time		0.032	1,10	0.861	0.003

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	MD3	Multivariate	0.517	4.202	2,9	0.051*	0.483
		Accuracy		7.857	1,10	0.019*	0.44
		Reaction time		2.883	1,10	0.12	0.224
	DUTY	Multivariate	0.82	0.986	2,9	0.41	0.18
		Accuracy		0.132	1,10	0.724	0.013
		Reaction time		1.868	1,10	0.202	0.157
	FR	Multivariate	0.935	0.313	2,9	0.739	0.065
		Accuracy		0	1,10	1	0.000
		Reaction time		0.695	1,10	0.424	0.065
	REP	Multivariate	0.704	1.894	2,9	0.206	0.296
		Accuracy		2.791	1,10	0.126	0.218
		Reaction time		2.179	1,10	0.171	0.179
Reading - performance	LS1	Multivariate	0.9	0.610	2,11	0.561	0.1
		Speed		0.448	1,12	0.516	0.036
		Accuracy		0.954	1,12	0.348	0.074
	LS2	Multivariate	0.908	0.558	2,11	0.588	0.092
		Speed		0.063	1,12	0.807	0.005
		Accuracy		1.157	1,12	0.303	0.088
	MD1	Multivariate	0.716	2.181	2,11	0.159	0.284
		Speed		0.012	1,12	0.915	0.001
		Accuracy		4.429	1,12	0.057	0.27
	MD2	Multivariate	0.891	0.675	2,11	0.529	0.109
		Speed		0.001	1,12	0.982	0.000
		Accuracy		1.313	1,12	0.274	0.099
	MD3	Multivariate	0.799	1.382	2,11	0.291	0.201
		Speed		0.458	1,12	0.511	0.037
		Accuracy		1.878	1,12	0.196	0.135
	DUTY	Multivariate	0.928	0.427	2,11	0.663	0.072
		Speed		0.777	1,12	0.395	0.061
		Accuracy		0.058	1,12	0.814	0.005
	FR	Multivariate	0.891)	0.675	2,11	0.529	0.109
		Speed		1.207	1,12	0.294	0.091
		Accuracy		0.724	1,12	0.412	0.057
	REP	Multivariate	0.999	0.007	2,11	0.993	0.001
		Speed		0.014	1,12	0.906	0.001
		Accuracy		0	1,12	1	0.000

C.3.2 High Sensitivity

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
Discomfort	LS1	Discomfort score		0	1,11	1	0.000
	LS2	Discomfort score		0.092	1,11	0.767	0.008
	MD1	Discomfort score		3.3	1,11	0.097	0.231
	MD2	Discomfort score		0.616	1,11	0.449	0.053
	MD3	Discomfort score		0.01	1,11	0.923	0.001
	DUTY	Discomfort score		4.661	1,11	0.054	0.298
	FR	Discomfort score		0.673	1,11	0.429	0.058
	REP	Discomfort score		0	1,11	1	0.000
Stroop Eye Movements	LS1	Pupil Size		0.134	1,12	0.721	0.011
	LS2	Pupil Size		0.346	1,12	0.567	0.028
	MD1	Pupil Size		8.974	1,12	0.011*	0.428
	MD2	Pupil Size		3.614	1,12	0.082	0.231
	MD3	Pupil Size		0	1,12	0.986	0.000
	DUTY	Pupil Size		0.391	1,12	0.544	0.032
	FR	Pupil Size		0.18	1,12	0.679	0.015
	REP	Pupil Size		3.35	1,12	0.092	0.218
Phantom array - eye movements	LS1	Multivariate	0.609	0.641	6,6	0.698	0.391
		Blink count		0.614	1,11	0.45	0.053
		Saccade count		0.975	1,11	0.345	0.081
		Saccade amplitude		2.378	1,11	0.151	0.178
		Fixation count		0.971	1,11	0.346	0.081
		Fixation duration		0.009	1,11	0.926	0.001
		Pupil size		0.049	1,11	0.83	0.004
	LS2	Multivariate	0.314	2.190	6,6	0.181	0.686
		Blink count		1.814	1,11	0.205	0.142
		Saccade count		1.364	1,11	0.268	0.11
		Saccade amplitude		9.872	1,11	0.009	0.473
		Fixation count		1.381	1,11	0.265	0.112
		Fixation duration		1.222	1,11	0.293	0.1
		Pupil size		0.097	1,11	0.761	0.009
	MD1	Multivariate	0.453	1.208	6,6	0.412	0.547
		Blink count		1.624	1,11	0.229	0.129
		Saccade count		0.056	1,11	0.818	0.005
		Saccade amplitude		0.078	1,11	0.785	0.007
		Fixation count		0.055	1,11	0.82	0.005
		Fixation duration		2.497	1,11	0.142	0.185
		Pupil size		1.735	1,11	0.215	0.136

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	MD2	Multivariate	0.228	3.382	6,6	0.082	0.772
		Blink count		0.712	1,11	0.417	0.061
		Saccade count		0.871	1,11	0.371	0.073
		Saccade amplitude		0.08	1,11	0.782	0.007
		Fixation count		0.854	1,11	0.375	0.072
		Fixation duration		0.086	1,11	0.775	0.008
		Pupil size		1.26	1,11	0.286	0.103
	MD3	Multivariate	0.466	1.144	6,6	0.437	0.534
		Blink count		1.817	1,11	0.205	0.142
		Saccade count		0.114	1,11	0.742	0.01
		Saccade amplitude		0.854	1,11	0.375	0.072
		Fixation count		0.118	1,11	0.738	0.011
		Fixation duration		0.747	1,11	0.406	0.064
		Pupil size		1.451	1,11	0.254	0.117
	DUTY	Multivariate	0.741	0.349	6,6	0.887	0.259
		Blink count		0.468	1,11	0.508	0.041
		Saccade count		1.108	1,11	0.315	0.092
		Saccade amplitude		0.538	1,11	0.479	0.047
		Fixation count		1.106	1,11	0.316	0.091
		Fixation duration		0.056	1,11	0.817	0.005
		Pupil size		0.237	1,11	0.636	0.021
	FR	Multivariate	0.229	3.363	6,6	0.083	0.771
		Blink count		11.205	1,11	0.007*	0.505
		Saccade count		8.962	1,11	0.012*	0.449
		Saccade amplitude		0.421	1,11	0.530	0.037
		Fixation count		8.980	1,11	0.012*	0.449
		Fixation duration		0.796	1,11	0.391	0.067
		Pupil size		7.746	1,11	0.018*	0.413
	REP	Multivariate	0.292	2.427	6,6	0.152	0.708
		Blink count		0.644	1,11	0.439	0.055
		Saccade count		0.455	1,11	0.514	0.04
		Saccade amplitude		5.045	1,11	0.046	0.314
		Fixation count		0.443	1,11	0.52	0.039
		Fixation duration		0.372	1,11	0.554	0.033
		Pupil size		1.329	1,11	0.273	0.108

Concept	Contrast	Dependent Variables	Wilks' Λ	F	df	p	Effect Size ($\eta^2_{partial}$)
Reading - eye movements movements	LS1	Multivariate	0.498	0.840	6,5	0.587	0.502
		Blink count		0.294	1,10	0.6	0.029
		Saccade count		0.625	1,10	0.448	0.059
		Saccade amplitude		0.335	1,10	0.575	0.032
		Fixation count		0.628	1,10	0.446	0.059
		Fixation duration		0.517	1,10	0.489	0.049
		Pupil size		0.77	1,10	0.401	0.072
	LS2	Multivariate	0.169	4.086	6,5	0.072	0.831
		Blink count		0.031	1,10	0.863	0.003
		Saccade count		0.011	1,10	0.919	0.001
		Saccade amplitude		1.642	1,10	0.229	0.141
		Fixation count		0.011	1,10	0.918	0.001
		Fixation duration		0.847	1,10	0.379	0.078
		Pupil size		0.311	1,10	0.589	0.03
	MD1	Multivariate	0.462	0.971	6,5	0.524	0.538
		Blink count		0.46	1,10	0.513	0.044
		Saccade count		0.214	1,10	0.653	0.021
		Saccade amplitude		0.181	1,10	0.679	0.018
		Fixation count		0.208	1,10	0.658	0.02
		Fixation duration		0.73	1,10	0.413	0.068
		Pupil size		2.936	1,10	0.117	0.227
	MD2	Multivariate	0.517	0.778	6,5	0.621	0.483
		Blink count		0.052	1,10	0.824	0.005
		Saccade count		0.015	1,10	0.905	0.001
		Saccade amplitude		2.192	1,10	0.17	0.18
		Fixation count		0.016	1,10	0.902	0.002
		Fixation duration		0.777	1,10	0.399	0.072
		Pupil size		1.764	1,10	0.214	0.15
	MD3	Multivariate	0.155	4.534	6,5	0.059	0.845
		Blink count		0.04	1,10	0.846	0.004
		Saccade count		1.147	1,10	0.309	0.103
		Saccade Amplitude		2.057	1,10	0.182	0.171
		Fixation count		1.138	1,10	0.311	0.102
		Fixation duration		6.03	1,10	0.034	0.376
		Pupil size		0.262	1,10	0.62	0.026

Concept	Contrast	Dependent Variables	Wilks' Λ	F	df	p	Effect Size ($\eta^2_{partial}$)
	DUTY	Multivariate	0.524	0.756	6,5	0.633	0.476
		Blink count		1.324	1,10	0.277	0.117
		Saccade count		0.305	1,10	0.593	0.03
		Saccade Amplitude		1.133	1,10	0.312	0.102
		Fixation count		0.297	1,10	0.598	0.029
		Fixation duration		2.598	1,10	0.138	0.206
		Pupil size		0.679	1,10	0.429	0.064
	FR	Multivariate	0.368	1.430	6,5	0.356	0.632
		Blink count		0.021	1,10	0.888	0.002
		Saccade count		0.295	1,10	0.599	0.029
		Saccade Amplitude		0.005	1,10	0.946	0.000
		Fixation count		0.303	1,10	0.594	0.029
		Fixation duration		2.039	1,10	0.184	0.169
		Pupil size		0.104	1,10	0.754	0.01
	REP	Multivariate	0.312	1.838	6,5	0.26	0.688
		Blink count		0.819	1,10	0.387	0.076
		Saccade count		0.033	1,10	0.86	0.003
		Saccade Amplitude		5.165	1,10	0.046	0.341
		Fixation count		0.032	1,10	0.862	0.003
		Fixation duration		1.178	1,10	0.303	0.105
		Pupil size		0.197	1,10	0.667	0.019
Stroop - performance	LS1	Multivariate	0.93	0.417	2,11	0.669	0.07
		Accuracy		0.582	1,12	0.46	0.046
		Reaction time		0.284	1,12	0.604	0.023
	LS2	Multivariate	0.856	0.925	2,11	0.425	0.144
		Accuracy		1.059	1,12	0.324	0.081
		Reaction time		0.601	1,12	0.453	0.048
	MD1	Multivariate	0.939	0.359	2,11	0.706	0.061
		Accuracy		0.739	1,12	0.407	0.058
		Reaction time		0.037	1,12	0.851	0.003
	MD2	Multivariate	0.575	4.064	2,11	0.048*	0.425
		Accuracy		0.083	1,12	0.778	0.007
		Reaction time		6.957	1,12	0.022*	0.367
	MD3	Multivariate	0.97	0.169	2,11	0.847	0.03
		Accuracy		0.01	1,12	0.92	0.001
		Reaction time		0.347	1,12	0.566	0.028
	DUTY	Multivariate	0.927	0.430	2,11	0.661	0.073
		Accuracy		0.513	1,12	0.487	0.041
		Reaction time		0.911	1,12	0.359	0.071

Concept	Contrast	Dependent Variables	Wilks' Λ	*F*	*df*	*p*	Effect Size ($\eta^2_{partial}$)
	FR	Multivariate	0.998	0.010	2,11	0.99	0.002
		Accuracy		0.004	1,12	0.948	0.000
		Reaction time		0.01	1,12	0.922	0.001
	REP	Multivariate	0.847	0.996	2,11	0.4	0.153
		Accuracy		2.083	1,12	0.175	0.148
		Reaction time		0.018	1,12	0.896	0.001
Reading - performance	LS1	Multivariate	0.968	0.149	2,9	0.864	0.032
		Speed		0.29	1,10	0.602	0.028
		Accuracy		0.037	1,10	0.852	0.004
	LS2	Multivariate	0.983	0.077	2,9	0.926	0.017
		Speed		0.007	1,10	0.936	0.001
		Accuracy		0.163	1,10	0.695	0.016
	MD1	Multivariate	0.755	1.457	2,9	0.283	0.245
		Speed		1.29	1,10	0.283	0.114
		Accuracy		3.011	1,10	0.113	0.231
	MD2	Multivariate	0.997	0.013	2,9	0.987	0.003
		Speed		0.028	1,10	0.87	0.003
		Accuracy		0.006	1,10	0.937	0.001
	MD3	Multivariate	0.643	2.500	2,9	0.137	0.357
		Speed		0.328	1,10	0.579	0.032
		Accuracy		3.142	1,10	0.107	0.239
	DUTY	Multivariate	0.58	3.263	2,9	0.086	0.42
		Speed		0.517	1,10	0.489	0.049
		Accuracy		6.975	1,10	0.025	0.411
	FR	Multivariate	0.780	1.271	2,9	0.326	0.220
		Speed		0.200	1,10	0.664	0.020
		Accuracy		0.678	1,10	0.430	0.063
	REP	Multivariate	0.868	0.682	2,9	0.53	0.132
		Speed		0.014	1,10	0.91	0.001
		Accuracy		1.445	1,10	0.257	0.126