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Veitch, J.A.; McColl, S.L.

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Modulation of Fluorescent Light: Flicker Rate and Light Source Effects on Visual Performance and Visual Comfort

Jennifer A. Veitch†, Ph.D. and Shelley L. McColl‡, B.Sc.(Hons.)

† National Research Council of Canada, Institute for Research in Construction
Building M-24, 1500 Montreal Road, Ottawa, Ontario, K1A 0R6 Canada.
E-mail: jennifer.veitch@nrc.ca

‡ Queen's University at Kingston

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Summary

The effects of fluorescent light spectral composition and flicker rate on visual performance and visual comfort were studied on 48 undergraduate students using two different rates of flicker: conventional low-frequency flicker (120 Hz) and high frequency flicker (between 20-60 kHz); and three different light sources; full-spectrum lamps, cool-white lamps, and filtered-cool-white lamps. The design was a 2 x 3 (Flicker Rate X Light Source) mixed within-between ANOVA. Visual performance and time on visual performance task were assessed using a Landolt ring task. Visual comfort was assessed by self-report after a period of reading difficult text. Visual performance scores of 18-24-year-old male and female university students were significantly higher in the high-frequency flicker condition than the low-frequency flicker condition. There were no other statistically significant effects. Health status was unrelated to visual performance. Neurophysiological explanations are discussed. The finding that an energy-efficient means of driving fluorescent lamps also can improve visual performance provides added impetus to adopt this new technology.

1 Introduction

Since its introduction, fluorescent lighting has elicited complaints of visual discomfort and headache.[(1)] These reports may be associated with reduced visual performance. Putative causes of these effects include both flicker rate and spectral power distribution.[(2,3)] This experiment examined both variables in relation to visual performance and visual comfort.

Luminous modulation of fluorescent lamps powered on alternating current is well-known. Conventional core-coil magnetic ballasts result in flicker at twice the frequency of the electrical supply (60 Hz in North America, resulting in flicker at 120 Hz). Energy-efficient electronic ballasts operate at substantially higher frequencies (20-60 kHz).

Less well-known is the chromatic modulation resulting from differential decay rates of light emissions from the various phosphors used in fluorescent lamps. Some of the commonly-used phosphors that emit long-wavelength light continue to do so for some time after the gas discharge, whereas phosphors with greater emission at shorter wavelengths persist for a shorter time.[(4)] The longer persisting phosphors introduce a phase lag with the result that the light alternates in colour as well as intensity. The rate of chromatic flicker depends on the type of ballast used to power the lamps and the persistence of the specific phosphors.

Although the flicker from most fluorescent sources cannot be resolved perceptually, there is evidence that the sensory system detects the oscillations. Schneider [(5)] found that evoked potentials in the rabbit's visual cortex pulse in synchrony with flashes of light presented at a frequency greater than the critical fusion frequency (CFF). In the cat, phase-locked responses to the oscillations of fluorescent light were found in the retina and the lateral geniculate nucleus. [(6-8)] Eysel and Burandt[(6)] found a two-fold increase in the mean firing rate for fluorescent light in comparison to incandescent light and natural daylight, and found phase-locked neural responses to a fluorescent light stimulus at frequencies above the perceptual CFF.

In humans, evoked potentials and electroretinogram (ERG) responses above the levels of perceptual CFF have been detected in response to luminous modulation.[(9-13)] Berman, Greenhouse, Bailey, Clear, and Raasch[(14)] found that rhythmic potentials in the human ERG can be elicited by fluorescent lighting at frequencies as high as 147 Hz, which is a higher frequency than the usual 120 Hz of a fluorescent lamp with a core-coil magnetic ballast.

The evidence for sensory and neural responses to modulations in light stimuli may provide a neurophysiological explanation for the asthenopic symptoms reported in response to fluorescent light. Rey and Rey[(15)] found that working under low-frequency (50 Hz) fluorescent light caused a larger drop in perceptual CFF and a larger increase in reaction time than working under high-frequency fluorescent light (100 kHz). They inferred from these findings that low-frequency flicker causes more visual fatigue.

In applied research, two studies have found that increasing the operating frequency of the fluorescent lighting system decreases the incidence of eyestrain, headache, and other asthenopic symptoms. [(16,17)] Wilkins et al.[(17)] found that the installation of high-frequency ballasts led to a 50% reduction in the reported incidence of eye-strain and headaches in office workers.

Flicker might also disrupt visual performance. Rey and Rey [15] found more errors on a proofreading task performed under low-frequency flicker than under high-frequency flicker. West and Boyce [18] and Wilkins [19] found that saccadic eye movements are disrupted by low-frequency flicker, but not high-frequency flicker.

To date there are no published reports on the effects of chromatic (as opposed to luminous) flicker per se on visual performance and visual comfort. The best evidence to date is indirect: Wilkins and Clark [4] established that chromatic flicker is a function of lamp type. Wilkins and Wilkinson [20] developed a tint for eyeglasses to reduce the impact of the chromatic modulation of fluorescent lamps. Wilkins and Neary [21] examined the visual, perceptual, and optometric effects of individualised tinted eyeglasses on people who had a history of reading difficulties and perceptual distortions. The tinted lenses reduced discomfort and perceptual anomalies when viewing gratings, and they caused a small improvement in the speed of visual search. It was not clear to the authors whether or not these results were caused by reductions in chromatic flicker.

In addition to the differential modulation that occurs with different lamps, it is possible that variations in spectral power distribution (SPD) might affect visual performance and visual comfort.[2,3] Particular attention has focused on full-spectrum fluorescent lamps:[*] For example, anecdotal reports[22] have contended that full-spectrum lighting allows students to see the blackboard as clearly from the back of the classroom as from the front.

In the research literature, beneficial effects reported for full-spectrum lamps include improved visual acuity [23,24] and reduced fatigue.[24] Berry [25] found that electronic assembly workers reported clearer vision under full-spectrum fluorescent illumination than cool-white lighting, although her study did not include a direct measure of visual performance or acuity. Berman's [26] scotopic sensitivity theory predicts that light sources rich in short wavelength illumination will maximally stimulate the scotopic visual system, reduce pupil size, and increase visual acuity relative to other light sources. Full-spectrum lamps are scotopically rich in comparison to cool-white or warm-white lamps.

Berman, Fein, Jewett, and Ashford [27,28] found that scotopically rich fluorescent sources do indeed reduce pupil size and improve visual acuity, but the effect was measurable only for low contrast, briefly presented stimuli, and the two lamp type conditions represented the extremes of scotopically rich (blue-green) and scotopically poor (pinkish-red) light. Several other studies encompassing both strict laboratory conditions and more realistic settings have failed to find effects of lamp spectral composition on visual performance or visual acuity. [29-33]

Overall, it is not clear whether or not spectral differences affect visual performance. There is some evidence suggesting that full-spectrum lighting may provide a slight advantage in visual acuity for tasks that are extremely difficult, but these effects do not appear to generalise to more common tasks, light levels, or settings. Methodological limitations in the research on full-spectrum fluorescent lighting weaken the causal inferences that the investigators seek to make. [35,36]

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[*] For the purposes of this study, a full-spectrum lamp is a fluorescent lamp with a correlated colour temperature (CCT) of 5000 K or greater, a colour rendering index (CRI) value of 90 or greater, relatively equal emissions in all portions of the visual spectrum and some emissions in the near ultraviolet range.

The present experiment was an examination of the effects of SPD and flicker rate on visual performance and visual comfort. There were three SPD conditions: full-spectrum fluorescent light [FS], cool-white fluorescent light [CW], and filtered-cool-white fluorescent light [FCW]. The filter used in this study is marketed in Canada as a low-cost alternative to full-spectrum lamps; the manufacturer claims that the filter, when applied to a cool-white lamp, produces a SPD similar to that of a full-spectrum lamp and to natural daylight. The filter does not, however, produce the chromatic flicker that is inherent to the full-spectrum lamp. Chromatic flicker would be greatest in the FS condition, lower in the CW condition, and least in the FCW condition (cf., Ref. 4, 20). Chromatic and luminous flicker differences between the CW and FCW conditions would be small because the lamps and ballasts in both cases were the same.

These SPD conditions were crossed with two flicker rates: low-frequency (120 Hz) [LF], created by using a dimmable core-coil magnetic ballast; and high-frequency (20-60kHz) [HF], created by using a dimmable electronic ballast. The design was a 2 x 3 (Flicker Rate X Light Source) mixed within-between analysis of variance (ANOVA). Visual performance, time on the visual performance task, and visual comfort were assessed using a battery of tests.

Three hypotheses were tested:

1. An interaction was expected between light source and flicker rate. No light source effect was expected for the HF condition. In this condition there would be no detectable modulation, neither luminous nor chromatic. However, a light source effect was hypothesised for the LF condition. The chromatic modulation theory would predict the poorest visual performance and least visual comfort under FS fluorescent light, followed by CW and FCW, which would be nearly equal in visual performance and visual comfort.

2. A main effect of flicker rate was expected between lamps operating at low frequencies and those operating at high frequencies; visual performance and visual comfort were expected to be significantly higher for HF than for LF.

3. Berman's theory of scotopic sensitivity predicts a lamp type main effect in which the lighting condition with the greatest proportion of short-wavelength light (FS) would produce the best visual performance. This prediction contrasts with the prediction based on chromatic modulation, in which the full-spectrum lamp would cause the poorest performance.

2 Participants

Participants were 48 volunteers (16 male and 32 female) from an introductory psychology course at medium-sized Canadian university. They ranged in age from 18 to 24 years; however, 32 were age 19. Participation was for course credit points, and all participants were treated in accordance with the rules of the university's ethics policy for research on human participants.

Age was restricted to this narrow range to limit the influence of age-related changes in vision, such as presbyopia. All participants had self-reported normal or corrected-to-normal vision and normal colour vision. Normal vision was verified using the Titmus vision test (Titmus Optical Vision Tester Model OV7-M, Titmus Optical Co.), which includes six Ishihara Pseudo-

Isochromatic Plates to determine the presence or absence of colour vision deficiencies. All participants wore their corrective lenses, if any, during the entire session.

3 Setting

Tests were administered in a small windowless room, 2.5 m wide, 3 m long and 2.2 m high. Three of the walls of the room were dark grey with a matte finish, and a white light proof curtain made the fourth wall. The ceiling was constructed of white fibreboard tiles. The floor covering was white speckled black tile. The room was equipped with four tables, three of which were used to support the main apparatus. A fourth small desk was used by the participants when completing written material.

The ambient room lighting consisted of three 60 W incandescent lamps, with 200 lx provided on the work surfaces. This level is consistent with the Illuminating Engineering Society of North America (IESNA) recommendations.[37]

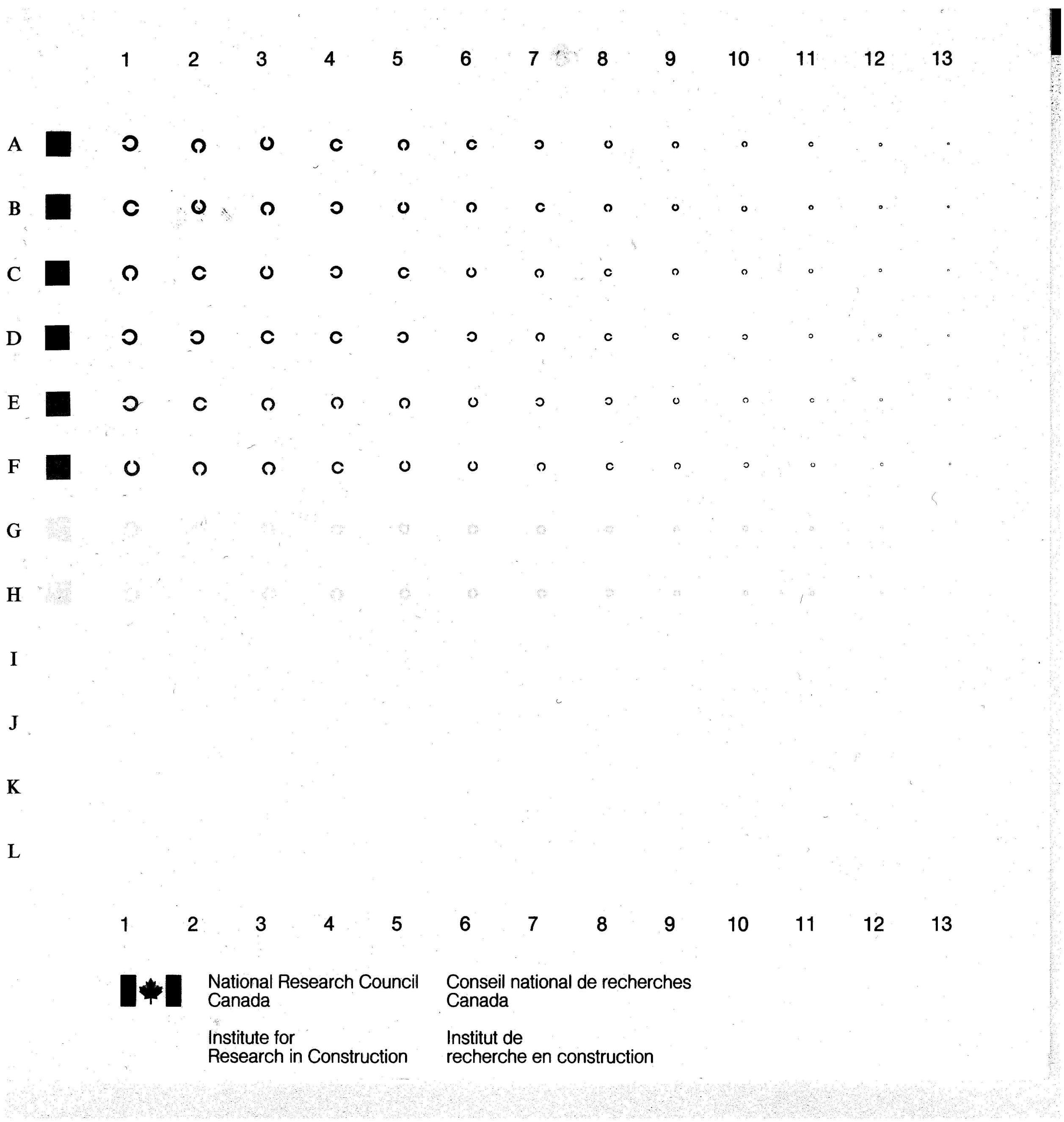
4 Dependent Variables

4.1 Visual performance task.

The measure of visual performance was the Vision and Lighting Diagnostic Kit (VALiD).[38] The Landolt ring task used in this kit consists of 12 rows (labelled A to L) and thirteen columns (numbered one to thirteen) of Landolt rings, printed onto a white card of high quality paper (18 cm x 19 cm) mounted on a metal plate. The rings vary systematically in size and luminance contrast. From the top left corner, ring size and gap size decrease across the columns (gap size ranges from 0.051 cm to 0.009 cm). Moving down columns, from top to bottom, the luminance contrast decreases systematically by rows of two (from .90 to .08). This provides two equivalent forms of the task (odd- and even- rows). The contrast is greatest for the top two adjacent rows and the least for the bottom two rows. The task page is reproduced in Figure 1.

The dependent measure was the number of rings per row for which the participant correctly identified the orientation of the gap in the ring. This gave a separate score for each of the 6 luminance contrasts. A stopwatch was used to time participants as they performed the VALiD task, to provide a measure of the time spent on the visual task.

Figure 1. The Vision and Lighting Diagnostic Kit (VALiD) Landolt ring task.



4.2 Visual comfort task.

Visual comfort was assessed by self-report after a period of reading difficult text lit by one of the 6 lighting conditions. The text was printed in 5-pt Helvetica type on matte white paper. This point size was selected to make the task difficult enough to detect effects during the short exposure of participants to the lighting condition. The content of the text was two non-fiction selections from standard reading tests appropriate to the participants' education level. The print size was too small to permit direct luminance measurements for the calculation of luminance contrasts. Therefore, the luminance of the print was measured from the thick stroke of a 16-pt letter M printed on the same matte white paper, using the same laser printer. The luminance contrasts were .92, .84, and .86 for the FS, CW, and FCW conditions respectively.

Participants read the material for 5 min, then completed a questionnaire on visual comfort, printed in high-contrast black on matte white paper. There were sixteen 7-point Likert items in the questionnaire. For each item, the participant rated the degree to which he or she currently experienced a particular sensation, from 1 = not at all to 7 = very much. The visual comfort score was the average of the ratings on seven items: blurred or narrowed vision; irritated eyes; dry eyes; spots or shapes in front of the eyes; eyestrain; headache; other vision problems. These seven items were adapted from Wilkins and Neary. [21] The remaining nine items were fillers (e.g., restless; hungry; anxious; bored; back strain).

4.3 Health status questionnaire.

A questionnaire administered at the end of the session was used to record information about personal health and well-being and family health history. Its purpose was to allow for the identification of possible individual differences affecting the principal dependent measures. The content of the questionnaire was based on factors identified in the literature with a susceptibility to light modulation effects. These are: migraine [39]; reading difficulties [40]; anxiety [41]; ocular pathologies [42]; eye-strain and headaches [17]; epilepsy [42]. The questionnaire also included questions about diseases which have effects on the visual system, sleep habits, colds, and the intake on that day of caffeine and decongestants, which are known to affect pupil size. The latter variables were included as possible explanations of any outlying cases in the performance data.

5 Independent Variables

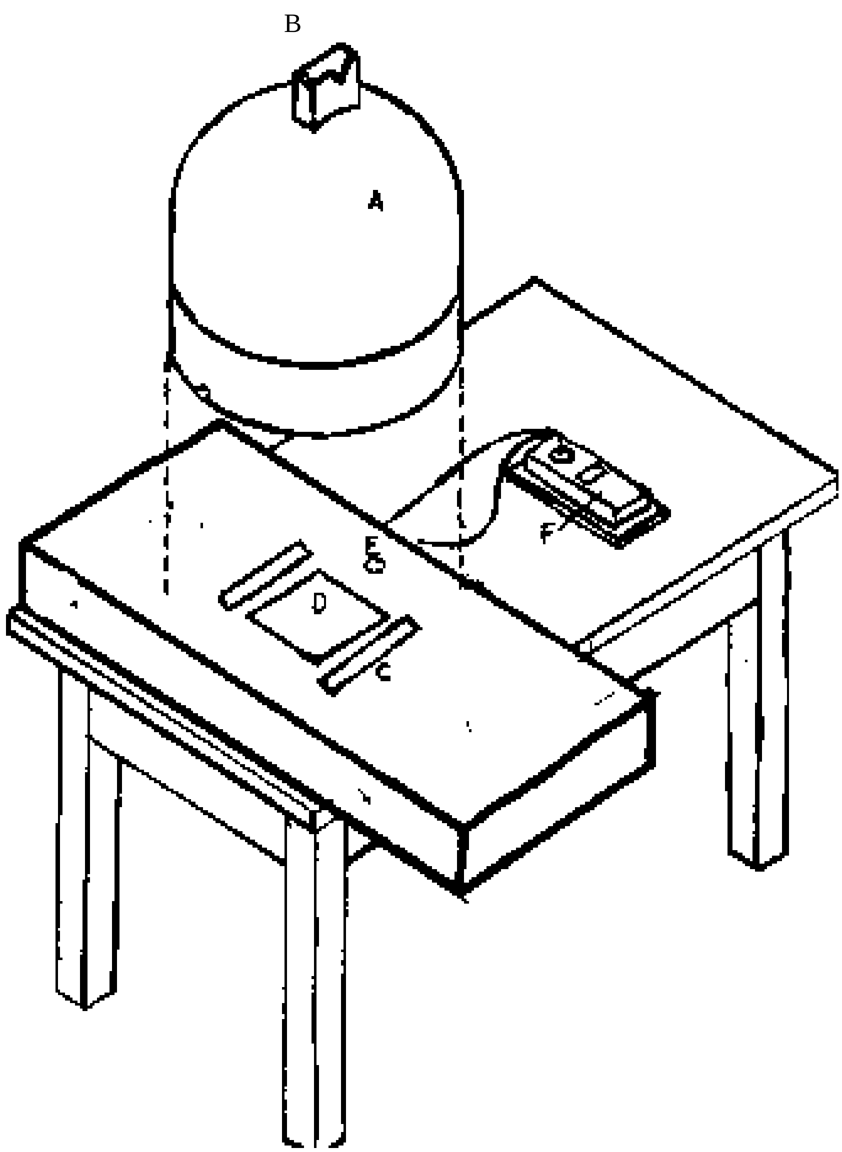
5.1 Flicker rate.

Flicker rate was controlled using two ballast conditions: low-frequency (120 Hz) flicker, created by driving the lamps using a standard 120 V, F40T12 dimmable magnetic ballast (Magnetek Universal model 502-A-TC-P); and very high-frequency (20-60 kHz [manufacturer's data]) flicker, created by driving the lamps using a controllable electronic integrated-circuit ballast (Advance Mark VII model RDC 2S40-TP). Each ballast type was wired to two luminaires (four lamps). The source of electricity was provided by the mains 60 Hz, 120 V supply maintained within ± 1% V by an uninterruptible power supply (ME Series, 2.1 kVA).

5.2 Light source.

The VALiD and visual comfort tasks were presented in a specially-constructed apparatus for indirect illumination. The task was centred on a painted white plywood platform between two 25 cm x 1 cm apertures. These apertures admitted light from a 1 x 4 - foot luminaire beneath. Light was reflected from a hemispheric dome (113 cm in diameter) coated with spectrally neutral reflective paint . Participants viewed the task through a 10.2 cm x 3.8 cm viewing port (also coated white inside) directed downward vertically from the top of the dome. The viewing distance from the top of the viewport to the task surface was 47 cm. A schematic drawing of the apparatus is shown in Figure 2.

Figure 2. Schematic representation of the apparatus. A: Hemispheric dome. B: Viewport. C: Apertures admitting light from luminaire beneath. D: VALiD task. E: Illuminance cell under dome. F: Illuminance meter.



Four luminaires in total were used for this experiment; they were laid side-by-side on the laboratory tables for convenience. Two were equipped with core-coil magnetic ballasts, and two with dimmable electronic ballasts. One luminaire of each ballast type was outfitted with cool-white fluorescent lamps (GE F40T12 CW) , and one with full-spectrum fluorescent lamps (GE F40 T12 Chroma 50). For the filtered-cool-white condition, the acrylic filter (Fluoresoft) was placed over the apertures in the platform over the appropriate luminaire.

All the lamps in all the luminaires were new at the start of the experiment. They were burned-in for 100 hours prior to the initial photometric readings, and were burned simultaneously thereafter to maintain equivalent lamp life and temperature conditions. There was a 45-minute warm-up period for the lamps prior to each day's testing. Only one luminaire provided light to the VALiD dome at a given time; the others were covered with a plywood board.

Pilot testing established that 200 lx illuminance on the task would be appropriate for participants of this age. The light level under the hemisphere was measured continuously by a Hagner Universal Photometer (Optikon, Inc., Model S2). The illuminance probe was located on the surface of the platform, adjacent to the task. The meter itself was located outside of the dome, concealed in a box, where it was accessible to the operator at all times. A conventional luminance meter was used to ascertain that the luminance was even across the task area for all lighting conditions.

5.3 Photometric details.

Table 1 gives the luminous characteristics for the six light source X ballast conditions. SPDs were measured using a Pritchard spectroradiometer (Photo Research 703A). These were expected to differ from the manufacturers' data because the task was illuminated indirectly, and the precise characteristics of the spectrally reflective paint on the dome were not known . The measurements were taken in a dark room and were made by positioning the lens of the spectroradiometer directly over a circular viewing port located on top of the dome. All readings were taken from the centre of the VALiD task because preliminary photometry indicated that luminance was even across the task surface. The SPDs, for both LF and HF flicker conditions, of the FS, CW, and FCW lighting with 200 lx on the task are shown graphically in Figures 3, 4 and 5, respectively. CCTs, chromaticity co-ordinates and luminances are displayed in Table 1.

Table 1 Light Source Specifications

Light Source	Radiance (W/ster*m²)	L_{Phot} (cd/ m²)	L_{Scot} (cd/ m²)	*S/P*	*x*	*y*	CCT	IESNA Flicker Index
Magnetic (LF) Ballast								
F40T12CW	0.1297	50.36	64.81	1.29	.4169	.4205	3485	.147
F40T12CW + filter	0.1430	49.75	52.54	1.06	.4601	.3908	2538	.137
F40T12 Chroma 50	0.1604	47.47	79.87	1.68	.3919	.4027	3888	.334
Electronic (HF) Ballast								
F40T12CW	0.1081	41.32	52.92	1.28	.4220	.4232	3410	
F40T12CW + filter	0.1262	43.48.	45.39	1.04	.4650	.3939	2498	
F40T12 Chroma 50	0.1467	41.91	69.47	1.66	.3988	.4048	3746	

Note. Magnetic ballast: Magnetek Universal model 502-A-TC-P. Electronic ballast: Advance Mark VII model RDC 2S40-TP. All measurements were taken from the task surface, indirectly lit by the hemispheric dome. Radiance values and relative spectral intensities were obtained using a Pritchard spectroradiometer with measurement from 390 to 728 nm, every 2 nm. L_{Phot} (photopic luminance) and L_{Scot} (scotopic luminance) were calculated from spectroradiometer readings. S/P ratio calculated from L_{Scot} and L_{phot}. *x* and *y* are the CIE chromaticity co-ordinates. The IESNA Flicker Index is the area above the average light output divided by the total area of the light output curve for a single cycle; possible values range from 0 to 1, zero indicating steady output.

Figure 3. Spectral power distribution in reflective dome, 200 lx indirect illumination on task: Full-spectrum lamps with magnetic and electronic ballasts.

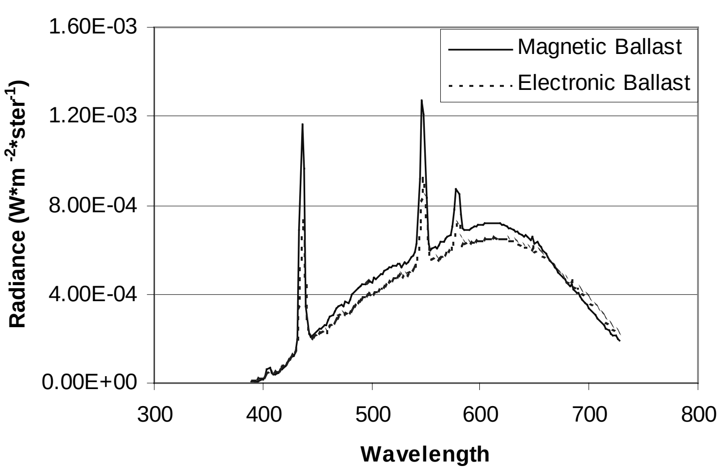


Figure 4. Spectral power distribution in reflective dome, 200 lx indirect illumination on task: Cool-white lamps with magnetic and electronic ballasts.

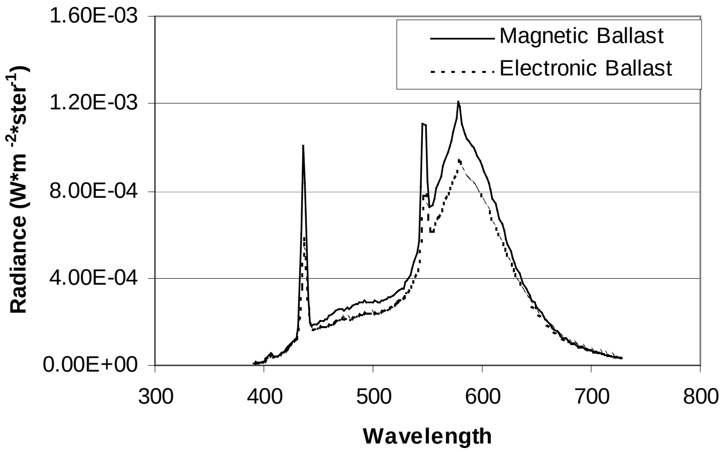
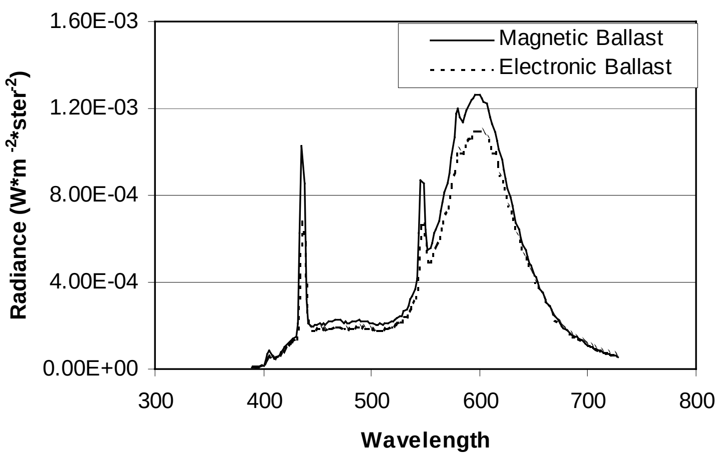


Figure 5. Spectral power distribution in reflective dome, 200 lx indirect illumination on task: Filtered-cool-white lamps with magnetic and electronic ballasts.



The CCTs were consistently somewhat lower in the HF condition. The SPDs showed the expected shapes for the FS and CW condition, given that these curves are for reflected light (manufacturers report SPDs for direct light). Contrary to the advertising literature, the SPD of the FCW condition resembled that of the CW more than it did the FS. The filter shifted the peak of the distribution up approximately 30 nm from that for the CW lamps alone. Therefore, the filtered light did not mimic either natural daylight or full spectrum light.

All lighting conditions had been previously equated (using the Hagner illuminance meter) for 200 lx horizontal illuminance on the task surface, from which the spectroradiometer readings were taken, therefore one would expect the luminances to be equal for both ballast conditions. We surmise that the lower spectroradiometric readings for the HF conditions compared to the LF conditions might be artifacts of the speed of the detector array. Differences between lamp types are attributable to the photometric error associated with differences between the (incandescent) standard lamp used to calibrate the meter, and the test lamps[43].

Both photopic and scotopic luminance were calculated from the spectroradiometric data using V_λ and V'_λ. The ratio of scotopic to photopic luminances is presented in Table 1. The FS conditions are clearly more scotopically rich than the other conditions, and by a degree sufficient that an effect of scotopic sensitivity might be expected (cf. Ref. 26).

Luminous modulation was measured directly from the lamps using a Thorlab high speed silicon detector, for the three light source conditions using the dimmable magnetic ballasts only. Equipment limitations precluded measurement of the luminance modulation for the electronic ballast conditions. We judged this to be acceptable in view of the fact that the HF condition is two orders of magnitude greater than the highest flicker rate detectable by the human sensory system, so that for practical purposes its modulation rate is zero.

Table 1 shows the values of the IESNA flicker index for the CW, FCW, and FS lamps. These values correspond to peak-to-peak modulation of 45.3% (CW), 42.7% (FCW), and 98.5% (FS), which are comparable to values reported previously for European lamps at 50 Hz AC supply. [44] The FS lamps exhibit more than twice as much luminous modulation as the other light source conditions, reflecting chromatic as well as luminous modulation (cf. Ref. 4). The filter reduced the modulation of the CW lamps only to a small degree.

6 Procedure

Each of the 48 participants was randomly assigned by the experimenter to one of the three lighting source conditions, FS, CW, or FCW. There were sixteen participants per group. All participants completed the dependent measures with two flicker rates, once with HF flicker and once with LF flicker. The order of flicker rate was counterbalanced across participants.

It was not possible for the experimenter to be blind to the experimental conditions. We reduced the possibility of experimenter bias as much as possible by the strict application of a script for the session so that identical instructions were given for both flicker rate conditions, and to keep the data scoring as objective as possible. (Subject bias is discussed below.)

The time required for participation was approximately 60-70 minutes. All sessions took place in the evenings between 4 p.m. and 10 p.m. to control the initial adaptation luminance, and to limit differences between participants in alertness. During the day, brightness adaptation would have varied widely between participants who arrived from outdoors and those who had been inside for a period of time; this difference was minimised by testing at night. Furthermore, visual performance is extremely sensitive to fatigue. Evening testing sessions reduced variability associated with differences in waking time, food and caffeine intake, and activity.

The participants were told that the experiment concerned sensory processing. Approximately 15 min were required for the initial instructions; this period also served as the adaptation period. The participants were informed that they would be performing several visual tasks, an auditory task, and a few questionnaires. The experimenter then explained that participants had the right to leave at any time without penalty, and that all data provided by them would remain anonymous and confidential. These instructions were followed by the signing of a consent form. The experimenter then administered the Titmus vision test. One participant who did not pass the test was thanked for attending the session and was given course credit for attending.

The remainder of the session was carefully structured to prevent fatigue effects from biasing the outcome of the VALiD task, which is extremely sensitive to fatigue. The visual comfort task is designed to induce fatigue. Each participant completed the VALiD task, followed by the visual comfort task, for one flicker condition, then a five-minute auditory filler task, and then the VALiD task and the visual comfort task for the second flicker condition. This was followed by the health status questionnaire and, finally, a post-experimental questionnaire.

The experimenter prefaced the first VALiD task with careful instructions about the task. Participants were instructed to read every other row from left to right, starting with either row A or B. The starting row was counterbalanced across participants. The experimenter stressed that they were to read at their own pace and encouraged them to guess if they found a particular circle difficult to see.

Participants were then asked to position themselves ready to look through the viewport, and to close their eyes. When the experimenter was ready, participants were told to open their eyes. As soon as the eyes opened, the experimenter started the stopwatch. As the participant called out the orientation of each gap, the experimenter recorded it on a score sheet. When the participant reported not being able to see any further rings, the experimenter stopped the stopwatch and recorded the time.

The participant moved to the writing desk while the experimenter removed the VALiD task plate and replaced it with the visual comfort task reading material. Participants were asked to try to make their best effort to understand the material. They were allotted five minutes to read the text. If any participant finished reading the text before the five minutes were up, they were told to memorise a portion of the text. Immediately following, participants moved to the writing desk and filled out the visual comfort questionnaire.

For the filler task, participants listened to music while wearing headphones. They were instructed that the listening would be followed by subjective questions about the music. To minimise eye-strain, participants were instructed to gaze at the wall across the room while they listened. The subjective questions were ratings on three 7-point Likert scales of whether the music had been loud, pleasant, and relaxing. These data were not analysed.

While the participant listened to the music, the experimenter shifted the dome to the alternate luminaire with the second ballast type and replaced the VALiD task plate ready for the second half of the session. This repeated the testing cycle. The only difference in the second VALiD test was that participants started reading at a different row than they did during the first test. Ballast order and starting row (A or B) were counterbalanced between participants. The content of the text for the visual comfort task also was counterbalanced.

Following the second visual comfort questionnaire, participants remained at the writing desk to complete the health status questionnaire and the post-experimental questionnaire. The latter served as a cross-check to test for participant biases.

This completed their participation. A complete debriefing was posted on a public bulletin board following the completion of the data collection. This procedure was followed to ensure that all participants were equally naive as to the purposes of the study at the time of their participation.

7 Subject Bias Results

The results of the post-experimental questionnaire indicated that none of the participants were aware of the lighting manipulations. Therefore, there is no reason to believe that the results of this study were contaminated by participant biases or expectancies concerning the expected outcomes.

8 Performance Measure Results

Three conceptually distinct dependent measures were analysed: visual performance, time on visual performance task, and visual comfort. There were multiple measures of visual performance (the VALiD scores for 6 contrast levels); therefore, the analysis of those data used a multivariate analysis of variance (MANOVA); univariate ANOVA was used for the remaining dependent measures.

For all these analyses the following analytical model was used: a 2 x 3 (Flicker Rate x Light Source) mixed within-between ANOVA design in which the effects were partitioned into the following single-degree-of-freedom, planned orthogonal contrasts:

1. a main effect for flicker rate [Ballast];

2. main effects for light source:

a. a comparison of the FS condition to both CW and FCW conditions together [Lamp 1];

b. a comparison of the CW to the FCW conditions [Lamp 2];

3. an interaction between light source 2a and flicker rate [Interaction 1];

4. an interaction between light source 2b and flicker rate [Interaction 2].

8.1 Visual performance.

Visual performance scores were calculated as the number of rings reported correctly in each row. Means and standard deviations for all six experimental conditions are presented in Table 2. These data were analysed using the MANOVA described above. The MANOVA results are summarised in Table 3.

Table 2 Cell Means and Standard Deviations of Visual Performance Scores

		Light Source			
Flicker	Row (C_L)	Full-Spectrum	Cool-White	Filtered-Cool-White	Marginal Means (Flicker Rate)
Low-Frequency	A/B (.90)	12.50 (0.63)	12.75 (0.45)	12.63 (0.72)	12.63 (0.61)
	C/D (.64)	11.94 (0.85)	12.44 (0.51)	12.31 (0.60)	12.23 (0.69)
	E/F (.31)	11.68 (0.87)	12.19 (0.66)	12.19 (0.66)	12.02 (0.76)
	G/H (.21)	11.25 (0.93)	11.56 (1.03)	11.38 (1.20)	11.40 (1.05)
	I/J (.13)	10.35 (1.25)	10.69 (1.20)	10.31 (1.54)	10.35 (1.25)
	K/L (.08)	8.44 (1.59)	9.19 (1.38)	8.06 (1.61)	8.56 (1.57)
High-Frequency	A/B (.90)	12.25 (0.68)	12.94 (0.25)	12.56 (0.63)	12.58 (0.61)
	C/D (.64)	11.88 (0.62)	12.56 (0.73)	12.38 (0.62)	12.27 (0.71)
	E/F (.31)	11.75 (1.13)	12.25 (0.58)	12.13 (0.89)	12.03 (0.90)
	G/H (.21)	11.69 (1.08)	12.19 (0.83)	11.94 (1.24)	11.94 (1.06)
	I/J (.13)	10.69 (1.30)	10.94 (1.12)	10.31 (1.62)	10.65 (1.36)
	K/L (.08)	8.56 (1.48)	9.44 (0.96)	8.69 (1.66)	8.90 (1.48)
Marginal Means	A/B (.90)	12.38 (0.66)	12.84 (0.37)	12.59 (0.67)	12.60 (0.61)†
(Light Source)	C/D (.64)	11.91 (0.73)	12.50 (0.62)	12.34 (0.60)	12.25 (0.69)†
	E/F (.31)	11.72 (0.99)	12.22 (0.61)	12.16 (0.77)	12.03 (0.83)†
	G/H (.21)	11.47 (1.02)	11.88 (0.98)	11.66 (1.23)	11.67 (1.03)†
	I/J (.13)	10.38 (1.16)	10.81 (1.15)	10.31 (1.56)	10.50 (1.31)†
	K/L (.08)	8.50 (1.59)	9.31 (1.18)	8.38 (1.64)	8.73 (1.53)†

Note. Table contains *M*s and *Sd*s (in parentheses) of the number of correctly identified Landolt rings by row pairs (row pairs are equivalent forms at each luminance contrast) for all subjects in a given condition. † Grand mean and standard deviation for all subjects, all conditions. C_L = luminance contrast.

Table 3 MANOVA Summary Table for Visual Performance Data

Contrast	Wilks' λ	*F*	*df*	R^2
Interaction 1	0.861	1.073	6,40	.027
Interaction 2	0.941	0.421	6,40	.008
Lamp 1	.776	1.92	6,40	.071
Lamp 2	.847	1.20	6,40	.031
Ballast	.677	3.19*	6,40	.064
Row A/B		.184	1,45	.004
Row C/D		.136	1,45	.003
Row E/F		.033	1,45	.007
Row G/H		15.99**	1,45	.262
Row I/J		2.84	1,45	.059
Row K/L		2.54	1,45	.053

Note. Univariate test results are shown only for the significant multivariate test for the Ballast effect. Lamp 1 is a contrast of FS versus CW/FCW. Lamp 2 is the contrast of CW and FCW. Interaction 1 is the interaction of Ballast x Lamp . Interaction 2 is the interaction of Ballast x Lamp 2. R^2 is the correlation ratio (variance accounted for) associated with each effect. For multivariate effects, it is the average of the correlation ratios for the univariate effects. $^{*}p<.02$. $^{**}p<.01$.

In interpreting MANOVA results, one interprets the univariate tests only if the corresponding multivariate test reaches statistical significance. In this analysis, only the flicker rate contrast produced a statistically significant overall MANOVA test [Wilks' lambda = 0.677, F (6,40) = 3.19; $p < .02$]. This was associated with a significant univariate effect for row pair G/H [F (1,45) = 15.99, $p < .01$]. Performance on this row, for which contrast was .21, was significantly better in the HF condition (M = 11.94) than the LF condition (M = 11.40). The two rows with lower contrasts (.13 and .08, respectively) did not show significant effects; however, the scores on these more difficult rows were considerably more variable (their standard deviations are 30 - 50 % higher than for row G/H), which would have obscured any significant difference.

Table 3 includes effect size information expressed as a correlation ratio. This is the proportion of the variance accounted for by each effect. For multivariate effects, R^2 is the average of the effect sizes for the associated univariate effects. Small effects have $R^2 = .01$; medium effects have $R^2 = .09$; large effects have $R^2 = .25$.[44] The significant multivariate ballast effect is small ($R^2 = .064$), but the univariate effect for rows G/H is large. The ballast type accounts for 26% of the variance in the visual performance scores for those two rows.

No significant interactions or main effects for light source occurred. The Interaction and Lamp contrasts were less powerful than the Ballast contrast because they were between-subjects comparisons. The correlation ratio for the multivariate Lamp 1 test was nonetheless similar to that for the overall Ballast contrast (R^2 = .071). Participants in the FS group had the lowest visual performance score, followed by the FCW group and the CW group.

8.2 Time on visual performance task.

The time taken on the visual performance task was measured by the total number of seconds from the start until the participant reported being unable to see any more rings. The raw data were positively skewed; therefore, a logarithmic transformation was applied to yield a more normal distribution. Means and standard deviations for time on visual performance task for all experimental conditions are found in Table 4. The results of the ANOVA for time on visual performance task are provided in Table 5. None of the comparisons revealed statistically significant effects. Likewise, there was very little explained variance in these data; the R^2 values were all very small.

Table 4 Cell Means and Standard Deviations of Time on Visual Performance Task and Visual Comfort Scores

	Light Source			
Flicker	Full-Spectrum	Cool-White	Filtered-Cool-White	Marginal Means (Flicker Rate)
Low-Frequency				
Log Time	2.03 (0.10)	2.05 (0.12)	2.03 (0.84)	2.04 (0.10)
Visual Comfort	2.51 (1.13)	2.64 (1.10)	3.05 (1.15)	2.73 (1.13)
High-Frequency				
Log Time	2.02 (0.08)	2.04 (0.13)	2.02 (0.08)	2.03 (0.10)
Visual Comfort	2.79 (1.27)	2.85 (1.34)	2.95 (1.05)	2.86 (1.20)
Marginal Means (Light Source)				
Log Time	2.02 (0.09)	2.04 (0.12)	2.02 (0.08)	2.03 (0.10)†
Visual Comfort	2.65 (1.19)	2.75 (1.21)	3.00 (1.09)	2.80 (1.16)†

Note. Cells in this table contain mean scores followed by standard deviations in parentheses. Time was measured in seconds spent on the VALiD task and transformed to log(10) values; lower scores reflect longer time on task. Visual comfort scores are the mean response to seven Likert-scaled items. Lower values indicate better comfort (range 1-7). † Grand mean and standard deviation for all subjects, all conditions.

Table 5 ANOVA Summary Tables for Time on Visual Performance Task and Visual Comfort

Variable	Contrast	*F* (1,45)	R^2
Log(10) Time on	Interaction 1	0.074	.000
Visual Performance	Interaction 2	0.068	.000
Task	Lamp 1	0.117	.002
	Lamp 2	0.384	.009
	Ballast	0.768	.017
Visual Comfort	Interaction 1	0.827	.002
	Interaction 2	1.134	.003
	Lamp 1	0.432	.008
	Lamp 2	0.408	.008
	Ballast	1.20	.003

Note. Lamp 1 is a contrast of FS versus CW/FCW. Lamp 2 is the contrast of CW and FCW. Interaction 1 is the interaction of Ballast x Lamp . Interaction 2 is the interaction of Ballast x Lamp 2. R^2 is the correlation ratio (variance accounted for) associated with each effect.

8.3 Order effects.

The visual performance and time on visual performance task data were examined for ballast and row order effects using separate 2 x 2 x 2 mixed between-within (Ballast Order x Row Order x Ballast Type) ANOVA. These analyses replicated the ballast main effects reported above, but revealed no significant differences based on the order of presentation of the ballast type nor of the starting row on the VALiD task.

8.4 Visual comfort.

Visual comfort was measured by calculating the mean rating on the seven visual comfort items. Possible values ranged from one to seven, with lower values indicating better visual comfort. The internal consistency of the visual comfort scale was acceptable: Cronbach's alpha of reliability was .84.

The descriptive statistics for the visual comfort scale are shown in Table 4. The overall mean comfort score was 2.80 (SD = 1.16), indicating that on average, across all conditions, the participants were somewhat visually comfortable. In no condition was there indication of discomfort; none of the means was greater than the neutral point of the scale (4). Visual comfort was somewhat poorer in the low-frequency flicker condition than the high-frequency flicker condition; however, this difference was not statistically significant (see Table 5). None of the main effects or interactions revealed a statistically significant effect, and the proportion of explained variance was very small.

9 Health Status

Responses to the health status questionnaire were used to check for markers that might identify individuals who are more sensitive to flicker than others. The frequency of these putative markers was low, both in the participants and in their families; this is not surprising in that the sample was both self-selected and small. There appeared to be approximately equal distributions of health problems across the groups, and there were no clear outlying cases that could be identified and associated with any health problem.

First, we examined the correlations between the residual error from the visual performance MANOVA and two continuous variables: the total number of health conditions reported with a self or family history, and the total frequency of health problem complaints. The sum of the squared residuals across all VALiD rows and both ballast conditions was used as the indicator of the unexplained error. There was no correlation between this value and either health indicator.

We hypothesised further that individuals with a sensitivity to flicker would show the greatest difference in the rank of their visual performance scores in the two flicker conditions. This group, we expected, should include more of the participants who reported frequent health complaints or a history of health problems previously related to a special sensitivity to flicker.

The correlation between visual performance rank scores in the low and high frequency flicker conditions was high, but not perfect (Spearman rho= .693, $p<.0001$); not every individual maintained the same rank performance in both conditions. Therefore, we formed three groups based on the difference in total performance (the total number of correctly identified rings in all rows of the VALiD task) for each ballast type. We subtracted the total performance in LF from the HF score, ranked the difference, and split the participants into low- (n=15) , medium- (n=18), and high-difference (n=15) groups on this basis. The high-difference group consisted of those participants who showed the largest improvement in HF relative to LF flicker.

To test the sensitivity hypothesis, we created three new categorical variables from continuous data, and examined cross-tabulations of these variables with the performance difference categories. The health variables were: the frequency of complaints (split into quartiles from the continuous variable); the number of conditions with a self or family history (quartile split); and, the number of neurological conditions (migraine, epilepsy, reading disorders, frequent headache) with a self or family history (possible scores 0-4; the maximum was 3). None of these tables revealed any relationship between health status and the difference in performance across flicker rates.

10 Discussion

The results of this experiment support the hypothesis that luminous modulation affects visual performance. They do not support the hypothesis that the chromatic modulation that results from the interaction of fluorescent lamps and ballasts itself influences visual performance or visual comfort; nor do they support the suggestion that the spectral composition of light affects visual performance or visual comfort. The main effect for flicker rate, in which high-frequency flicker led to improved visual performance, was small when considered over the whole range of contrasts tested; but for the luminance contrast of .21, the effect was large.

This finding is consistent with a current theory about how flicker affects the brain.[45] Cells in the brain do not fire constantly in response to stimulus features; rather, they exhibit rhythmic patterns of firing at frequencies between 40-70 Hz. The distribution of interspike intervals is the same for each population of cells responding to the different parts of the same stimulus. That is, the activity of cells responding to the same stimulus object are correlated and synchronised with one another. If a number of external stimuli occur at the same time, they are interpreted together. Integration of neural responses to the same stimulus is based on common temporal activity.

Low-frequency flicker (on the order of 120-150 Hz; cf. Ref. 14) may add extra noise to the neural activity. This noise, which has the same temporal code as the signal to be interpreted, may inhibit object or form identification by interfering with the integration of neural responses from the various neurons that respond to the specific stimulus features. The additional synchronous neural activity (noise) would therefore impede stimulus recognition, especially if the object is difficult to see, or is near threshold. In the present experiment, a large effect occurred for Landolt rings of luminance contrast .21, but not for darker rings. (The absence of a significant effect for contrasts below .21 may be an artifact of the higher variability of performance on those rows.)

Furthermore, the demands of processing this extra neural noise might translate into asthenopic symptoms, such as increased eye-strain and headache.[2] If so, this would account for the reduced incidence of headache and eye-strain when electronic ballasts were introduced into offices.[17] The absence of effects on visual comfort in this experiment probably reflects the brief exposure time (8 minutes at most before the administration of the visual comfort measure). All the participants reported being relatively comfortable in both flicker conditions.

A second possibility is that eye movements were disrupted by low-frequency flicker. Wilkins [19] found that when looking at printed text under 100 Hz or 20 kHz fluorescent light, his participants' saccadic eye movements under low-frequency light tended to overshoot the target. This might account for the results reported here.

Chromatic modulation did not appear to affect visual performance or visual comfort in this experiment. Results released after the data had been collected showed that for equiluminant stimuli, chromatic modulation does not affect saccadic suppression of displacement (the mechanism by which the world appears to remain still while the eye makes rapid movements).[46] It is possible that the mechanism governing saccadic movements is relatively insensitive to chromatic variation in comparison to luminous variation. This hypothesis requires further research.

The suggestion that certain individuals may be more sensitive to luminous modulation than others [9, 16, 20] was not supported in this sample. Our survey of health history and symptom frequency did not reveal any relationships to visual performance. It may be that the self-selection of participants to participate caused some bias, or it may be that the sample was not large enough to detect real population differences. A third possibility is that all people are somewhat sensitive to luminous modulation effects, regardless of their health status.

Regarding the spectral composition of the light source, the findings do not support Berman's (26) hypothesis. There was no statistically significant effect of light source on visual performance, time on the visual performance task, or visual comfort. Light source accounted for 7.1% of the variance in visual performance, which is on the same order as the overall multivariate effect of flicker rate. However, contrary to the predictions of Berman's scotopic sensitivity theory, the visual performance mean scores under the full-spectrum source (the most scotopically rich of the three) were the lowest of the three visual performance scores for almost all luminance contrasts and flicker conditions (see Table 2). One would expect that with a larger sample size, this trend would have achieved statistical significance*.

The results of this study have important implications for lighting practice. Under restrictive viewing conditions and tight experimental control, young people with normal vision exhibited better visual performance under high-frequency fluorescent lighting than low-frequency fluorescent lighting. Effects on visual comfort as registered in asthenopic symptoms are known to occur in field settings.(17) One might expect that under the usual conditions for visual work, with longer exposure times and for people of varying ages and visual abilities, the effect of flicker rate on visual performance would be magnified accordingly. Thus, the findings of this study add weight to the arguments in favour of high-frequency electronic ballasts for fluorescent lighting systems: Not only are they more energy-efficient than their traditional counterparts, but they have beneficial effects on human performance and well-being.

Research conducted to examine the effectiveness of different lighting systems on visual performance and comfort serves a useful purpose in helping both occupants and lighting decision makers to make the best lighting choice. These data and others show that lamp type does not appear to be the important factor in relation to visual performance or comfort(36). The evidence here and elsewhere (16, 19, 21) does show that using high-frequency circuitry could satisfy the needs of occupants, building owners, and the environment: Operating costs will be lower in the long run, less energy will be required for lighting, and the reduced luminous modulation will improve the ease of seeing. When many of the changes required to improve energy efficiency demand curtailed activity or reduced quality of life (e.g., public transportation to replace private vehicles; lower thermostat settings), it is worth noting that what is good for the environment can also be good for people.

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* The between-subjects comparison for spectral composition was less powerful than the within-subjects design used by Berman and his colleagues (27) (and for the flicker rate comparison in this study). The between-subjects comparison was necessary because there are only two equivalent forms of the VALiD test, but we wished to compare three light source conditions. The power of this experiment to detect even a moderate difference between-groups (R^2 = .09) was .31, given a sample size of 16 per group. This is low in comparison to the desired power level of .80(45). A total sample size of 156 (52 participants per group) would have been required to achieve this level of power if the true effect size is moderate (a reasonable assumption, given that Berman et al found a large effect using extreme examples of scotopically-enriched and -deficient illuminants). Obtaining a sample of that size proved impossible. In any case, the data obtained in this experiment are inconsistent with the direction of effect predicted by Berman's theory.

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Shelley McColl is now at the Department of Psychology, Dalhousie University, Halifax, Nova Scotia, Canada.

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References

1. Stone P T Fluorescent lighting and health Lighting Research and Technology **24** 55-61 (1990)

2. Wilkins A J Visual display units versus visual computation Behaviour and Information Technology **10** 515-523 (1991)

3. Wilkins A J Health and efficiency in lighting practice Energy **18** 123-129 (1993)

4. Wilkins A J and Clark C Modulation of light from fluorescent lamps Lighting Research and Technology **22** 103-109 (1990)

5. Schneider C W Electrophysiological analysis of the mechanisms underlying critical flicker frequency Vision Research **8** 1235-1244 (1968)

6. Eysel U T and Burandt U Fluorescent light evokes flicker responses in visual neurons Vision Research **24** 943-948 (1984)

7. Kimura M Neuronal responses of cat's striate cortex to flicker light stimulation Brain Research **192** 560-563 (1980)

8. 8 Lindsey D B Electrophysiology of the visual system and its relation to perceptual phenomena In M A B Brazier (Ed) Brain and behavior (pp 359-392) Washington, D. C.: American Institute of Biological Science (1961)

9. Brundrett G W Human sensitivity to flicker Lighting Research and Technology **6** 127-143 (1974)

10. Cavonius C R and Sternheim C E A comparison of electrophysiological and psychophysiological temporal modulation transfer functions of human vision Advances in Experimental Medicine and Biology **24** 223-236 (1972)

11. Sternheim C E and Cavonius C R Sensitivity of the human ERG and VECP to sinusoidally modulated light Vision Research **12** 1685-1695 (1972)

12. Thiry S Contribution à l'étude de l'entrainement photique [Contribution to the study of photic driving] Archives Internationales de Physiologie **59** 10-25 (1951)

13. Van der Tweel L H and Verduyn Lunel H F E Human visual responses to sinusoidally modulated light Electroencephalography and Clinical Neurophysiology **18** 587-598 (1965)

14. Berman S M Greenhouse D S Bailey I L Clear R and Raasch T W Human electroretinogram responses to video displays fluorescent lighting and other high frequency sources Optometry and Vision Science **68** 645-662 (1991)

15. Rey P and Rey J-P Les effets comparés de deux éclairages fluorescents sur une täche visuelle et des tests de "fatigue" [Comparison of the effects of two fluorescent lights on a visual task and fatigue tests] Ergonomics **6** 393-401 (1963)

16. Lindner H and Kropf S Asthenopic complaints associated with fluorescent lamp illumination (FLI): The role of individual disposition Lighting Research and Technology **25** 59-69 (1993)

17. Wilkins A J Nimmo-Smith I Slater A and Bedocs L Fluorescent lighting headaches and eye-strain Lighting Research and Technology **21** 11-18 (1989)

18. West D C and Boyce P R The effect of flicker on eye movements Vision Research **8** 171-192 (1968)

19. Wilkins A J Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text Human Factors **28** 75-81 (1986)

20. Wilkins A J and Wilkinson P A tint to reduce eye-strain from fluorescent lighting? Preliminary observations Ophthalmic and Physiological Optics **11** 172-175 (1991)

21. Wilkins A J and Neary C Some visual optometric and perceptual effects of coloured glasses Ophthalmic and Physiological Optics **11** 163-171 (1991)

22. Blumenthal R G New York schools consider installing full-spectrum lights to help students The Wall Street Journal p. B2 (1992 December 31)

23. Blackwell H R Effects of light source spectral distribution upon visual functions Annals of the New York Academy of Sciences **453** 341-353 (1985)

24. Maas J B Jayson J K and Kleiber D A Effects of spectral differences in illumination on fatigue Journal of Applied Psychology **59** 524-526 (1974)

25. Berry J L Work efficiency and mood states of electronic assembly workers exposed to full-spectrum and conventional fluorescent illumination Dissertation Abstracts International **44** 635B (University Microfilms No DA8315116) (1983)

26. Berman S M Energy efficiency consequences of scotopic sensitivity Journal of the Illuminating Engineering Society **21** 3-14 (1992)

27. Berman S M Fein G Jewett D L and Ashford F Luminance-controlled pupil size affects Landolt C task performance Journal of the Illuminating Engineering Society **22** 150-165 (1993)

28. Berman S M Fein G Jewett D L and Ashford F Landolt-C recognition in elderly subjects is affected by scotopic intensity of surround illuminants Journal of the Illuminating Engineering Society **23** 123-130 (1994)

29. Boyce P R and Rea M S A field evaluation of full-spectrum polarized lighting Journal of the Illuminating Engineering Society **23** 86-107 (1994)

30. Chance R E The effects of two ranges of fluorescent lighting spectra on human physical performance Dissertation Abstracts International **43** 2862B (University Microfilms No DA8302215) (1983)

31. Halonen L Effects of lighting and task parameters on visual acuity and performance Espoo Finland: Helsinki University of Technology (NTIS No PB94-179231) (1993)

32. Kuller R and Wetterberg L Melatonin cortisol EEG ECG and subjective comfort in healthy humans: Impact of two fluorescent lamp types at two light intensities Lighting Research and Technology **25** 71-81 (1993)

33. Rowlands E Loe D L Waters I M and Hopkinson R G Visual performance in illuminance of different spectral quality Paper presented at the 17th session of the Commission Internationale de l'Éclairage, Barcelona, Spain (1971)

34. 34 O'Leary K D Rosenbaum A and Hughes P C Fluorescent lighting: a purported source of hyperactive behavior Journal of Abnormal Child Psychology **6** 285-289 (1978)

35. Gifford R Scientific evidence for claims about full-spectrum lamps: Past and future In J A Veitch (Ed) Full-spectrum lighting effects on performance mood and health (IRC Internal Report No 659 pp. 37-46) Ottawa ON: National Research Council of Canada Institute for Research in Construction (1994)

36. Veitch J A and McColl S L Full-spectrum fluorescent lighting effects on people: A critical review In JA Veitch (Ed) Full-spectrum lighting effects on performance mood and health (IRC Internal Report No 659 pp. 53-111) Ottawa ON: National Research Council of Canada Institute for Research in Construction (1994)

37. Rea M S (Ed) Lighting handbook: Reference and application (8th ed) New York: Illuminating Engineering Society of North America (1993)

38. Rea M S Population data on near field visual acuity for use with the Vision and Lighting Diagnostic (VALiD) Kit (Report no CR5544.3) Ottawa ON: National Research Council of Canada (1988)

39. Debney L M Visual stimuli migraine trigger factors In FC Rose (Ed) Progress in migraine research (Vol 2 pp. 30-54) London: Pitman-Medical (1984)

40. 40 Lovegrove W Martin F and Slaghuis W A theoretical and experimental case for a visual deficit in specific reading disability Cognitive Neuropsychology **3** 225-267 (1986)

41. Hazell J and Wilkins A J A contribution of fluorescent lighting to agoraphobia Psychological Medicine **20** 591-596 (1990)

42. Wilkins A Nimmo-Smith I Tait A McManus C della Sala S Tilley A Arnold K Barrie M and Scott S A neurological basis for visual discomfort Brain **107** 989-1017 (1984)

43. Ouellette M J Measurement of light: Errors in broad band photometry. Building Research Journal **2** 25-30 (1993)

44. Andersson N Sandström M Berglund A and Hansson K Amplitude modulation of light from various sources Lighting Research and Technology **26** 157-160 (1994)

45. Cohen J Statistical power analysis for the behavioral sciences (2nd ed) Hillsdale NJ: Erlbaum (1988)

46. Singer W Synchronization of cortical activity and its putative role in information processing and learning Annual Review of Physiology **55** 349-374 (1993)

47. Bridgeman B Space constancy on video display terminals (Report AFOSR-90-0095-Final) Santa Cruz CA: University of California (NTIS No AD-A280-015) (1994)

Discussion

Dr. A. Wilkins (UK Medical Research Council Applied Psychology Unit)

Did Schneider measure psychophysical thresholds in rabbits, using behavioural techniques in order to know that the flicker could not be perceived? The study by West and Boyce and that by Wilkins measured the effects of flicker over very different frequency ranges. It may be simplistic to refer to the conditions studies as low-frequency flicker and high-frequency flicker as it the ranges were similar.

On page 245 [of the journal article] the luminance contrasts are quoted as 0.92, 0.84, and 0.86 for the full-spectrum, cool-white and filtered cool-white conditions. I would appreciate some clarification as to why the differences should be so large given that the reflectance of the paper and the ink upon it is likely to be fairly flat over the range of visible wavelengths. What was the precision of the measurements?

I presume that the apertures either side of the stimuli did not provide glare sources. Could this be made clear? Given that the Pritchard photometer gives different results, it would be good to know the temporal characteristics of the Hagner photometer.

Dr M S Rea (Lighting Research Center, Rensselaer Polytechnic Institute)

Although the authors have conducted and analysed their study of lamp spectrum, ballast type and text contrast with professional proficiency, one would not have expected them to find any important effects of lamp spectrum or ballast type from this particular experimental design. One would only expect to find an effect of contrast on visibility, which indeed they did.

This study shows, as many have shown before, that there is no impact of conventional lamp source spectrum on performance of a foveal task at photopic levels, once the luminous contrast of the task has been equated for lamp type. I continue to hope, but in vain, that the pages of lighting journals will no longer publish studies of lamp spectrum on the visibility of foveal tasks. As the literature has shown for at least 50 years, the mechanisms leading to the very small visual effects due to lamp spectrum are well known (e.g., chromatic aberrations or pupil size) but are so small as to be safely ignore for the purposes of lighting applications.

The influence of temporal modulation on performance is perhaps less well known, or at least more confusing given the recent studies of Wilkins. Nevertheless, the present study adds nothing to our understanding of the effects that Wilkins proposes. The authors show that there is no relationship between flicker sensitivity and performance on an individual basis, so this study adds nothing to the case Wilkins has put forward.

The authors are to be heartily and sincerely congratulated for their documentation of measurements, procedures and results. Their documentation helps the reason to affirm his/her *a priori* expectations on the absence of an effect of ballast type on visual performance and to better understand why the results presented by the authors on ballast type are unlikely to be replicated. First, there is no reason to expect temporal modulation to affect performance at a contrast of 0.21 but not at lower contrasts. The authors argue that the reason they did not find effects at lower contrast is because insufficient data were obtained at those contrasts. This is a weak and misleading argument since nearly any effect can be shown to be statistically significant with the collection of a large number of data. If the authors believed paucity of data was a limitation of their study then they should have extended their studies before trying to publish the results of a single study whose results are unexpected. It is important to point out that the statistically significant difference between the results from the 60 Hz and from the high-frequency ballast at a contrast of 0.21 was only 11.40 versus 11.96 letters read, an extremely small effect. A more parsimonious and more likely explanation of this unexpected and curious finding is that, as in many formal studies of human behaviour, this result is a chance event. Second, one lamp has twice as great a peak-to-peak temporal modulation as the other two. Yet there is no interaction between lamp type and ballast type as would be expected if this were a real effect. Finally, and as already stated above, if their reported effect was real and the result of some higher-order neurological effect like that proposed by Wilkins and tacitly supported by the authors, then the authors should offer some evidence to support that hypothesis; they do not.

One of the tenets of scientific research is that one should accept the simpler explanation over the more complex. There is no reason to expect performance or comfort at this foveal task to be differentiated on the basis of 60 Hz versus high-frequency ballast type. Certainly, there is no evidence supplied by the authors in support of this expectation other than the single statistically significant finding at a contrast of 0.21. Indeed, the data offered by the authors themselves are contradictory to a logical argument supporting a difference in results according to ballast types. Consequently it is simpler to conclude that their statistically significant result occurred by chance.

As a teacher of statistics, I remind my students of a simple but fundamental premise of experimentation: That which is important is always statistically significant, but that which is statistically significant is not always important.

Authors' reply to discussion

To A. Wilkins:

Dr. Wilkins addresses several details that we are pleased to clarify.

Schneider[48] reported that the rabbits used in his study of electrophysiological response to flicker had previously been used in a psychophysical study to determine the flicker rate at which critical flicker fusion was achieved. Unfortunately, there is insufficient information in the journal paper to retrieve the paper in which the psychophysiological data are said to be reported.

Dr. Wilkins is correct that the ranges studied by West and Boyce (1967)[49] and Wilkins (1986)[50] differed. The highest flicker rate in any of the eight experiments in the West and Boyce study was 46 Hz. Wilkins compared CRT screens with 50 Hz and 100 Hz rates, and fluorescent lamps with 100 Hz and 20 kHz rates. Although this is a generalisation, it is nonetheless true that the degree of disruption of saccades was greater for the lower flicker rates relative to the higher rates in each experiment.

The position of the viewport over the apparatus was fixed at 90 degrees to the visual task. With this geometry it was impossible for viewers to see the apertures; only the task surface was visible. The apertures did not provide glare sources. Furthermore, luminance was equal across the visual task.

Dr. Wilkins' questions concerning the luminance contrasts and the measurements from two different photometers relate in part to the same phenomenon: the sources of inaccuracy in broad band photometry. Ouellette[51] has reported errors of 3% in measurements of one lamp with different photometers of the same make and model, and up to 11% when different lamps are compared. Differences between different photometer models and manufacturers would be expected to be greater still. This explains the differences between readings taken with the Hagner and Pritchard instruments (to answer Dr. Wilkin's specific question, at the range used, the rise time for the Hagner instrument is 70 ms). For the contrast measurements, the accuracy of measurement was 2 significant figures; in combination with the photometric errors, then, these differences in luminance contrast are not surprising. Furthermore, the luminance of the black target was probably below the photopic limit of the instrument. In any case, the contrast values are all very high and models of visual performance would not predict a measurable effect based on these differences (cf. Ref 52).

To M. S. Rea:

Dr. Rea questions the logical foundations of our work and charges that the statistical tests produced spurious outcomes that are trivial in size. He is best known for his work on visual performance, particularly his Relative Visual Performance model[52] , which provides an understanding of some of the factors that can influence the visibility of objects. This research has established a mathematical relationship between the visibility of an object and four characteristics: 1) the contrast of the object against its immediate background; 2) the size of the object, measured from the observer's point of view; 3) the age of the observer, and 4) the state of visual adaptation. Dr. Rea's comments here imply an *a priori* belief that the state of the art in visual performance research cannot be advanced further than his Relative Visual Performance model. Such a belief is premature at best; there are many variables identified in the scientific and applied literature that also affect visibility, including task colour, motion, and exposure time.

Consequently, we are puzzled by Dr. Rea's assertion that one would not expect to find an effect of flicker rate on visual performance using this experimental design. Not only was this effect predictable based on the literature, but a power analysis using Cohen's[53] guidelines for a largesized effect (as we found for the univariate row G/H effect) gives a power value of .97. This means that the experiment had a good probability of detecting a significant effect if one exists. We further protected against the possibility of spuriously detecting a statistically significant effect because of multiple, nonindependent tests, by the use of multivariate analysis of variance. Space does not permit a full discussion here of this technique; interested readers are directed to the standard texts, such as Kerlinger(54) or Tabachnick and Fidell(55). We are confident that the effect of flicker rate is real and await an independent replication.

Dr. Rea is correct in stating that the effects of lamp source spectrum on visual performance are few and not of practical importance. We reached the same conclusion elsewhere (Ref. 56), although some manufacturers do not concur. We included the light source manipulation in this experiment because the manufacturer of the filter has claimed that the product produces dramatic benefits for those who use it. Although the between-groups comparison is not as powerful as the within-groups contrast for the flicker rate, we accepted this limitation. With only two parallel forms of the task, each participant could provide data for only two conditions without risking practice or learning effects. Therefore, a fully within-subjects design was not possible. If the manufacturer's claim was correct, then we would have seen at least a trend favouring the filter condition. No such trend or effect was observed; we agree with Dr. Rea that there are many issues for lighting research that are both more interesting and more important than lamp spectral content.

Regarding the absence of an effect for the very-low-contrast targets, Dr. Rea is mistaken concerning the explanation we offered. We did not suggest that an inadequate sample size decreased the power for that comparison. We stated that the problem lies in the increased variability of performance for these targets. Participants performed more consistently for the higher-contrast rows, and more variably for the low-contrast rows. The experimenter reported that people had to be encouraged to make attempts to see the low-contrast rows, making it likely that guessing outweighed vision in the performance data for those conditions. Flicker rate may not be sufficient to overcome the inherent difficulty of the bottom two rows of the VALiD task. Increasing the sample size will not affect the outcome if the data reflect random effects such as guessing.

Dr. Rea also criticises this study for not having included direct measurements relating to the neurophysiological explanations for this phenomenon and more focused attention on the issue of individual differences in sensitivity. Such measurements, although desirable, were not feasible. Their absence does not imperil the experimental design, but leaves open questions for future research to address.

Dr. Rea correctly points out that the absolute difference between the mean scores for rows G/H for the two ballast types is small. Expressed as a percentage of variance explained, however, the effect is large. Small absolute effects can be important nonetheless, particularly when demonstrated under a minimal manipulation of an independent variable.(57) In this case, the participants were young people with excellent vision who viewed the stimulus for a very brief time - a few minutes at best. An effect, even a small one, that is detectable under those conditions is impressive indeed, particularly when it fits into other demonstrations of related effects (e.g., Ref. 58). We hope to address longer-term effects of flicker rate in future work, and we hope that others will also pursue the questions raised by this pattern of research results.

References

48 Schneider C W Electrophysiological analysis of the mechanisms underlying critical flicker frequency Vision Research **8** 1235-1244 (1968)

49 West D C and Boyce P R The effect of flicker on eye movements Vision Research **8** 171-192 (1968)

50 Wilkins A J Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text Human Factors **28** 75-81 (1986)

51 Ouellette M J Measurement of light: Errors in broad band photometry. Building Research Journal **2** 25-30 (1993)

52 Rea M S and Ouellette M J Relative visual performance: A basis for application. Lighting Research and Technology **23** 135-144 (1991)

53 Cohen J Statistical power analysis for the behavioral sciences (2nd ed) Hillsdale NJ: Erlbaum (1988)

54 Kerlinger F N Foundations of behavioral research (3rd ed) New York: Holt, Rinehart and Winston (1986)

55 Tabachnick B G and Fidell L S Using multivariate statistics. New York: Harper and Row (1983)

56 Veitch J A and McColl S L Full-spectrum fluorescent lighting effects on people: A critical review In JA Veitch (Ed) Full-spectrum lighting effects on performance mood and health (IRC Internal Report No 659 pp. 53-111) Ottawa ON: National Research Council of Canada Institute for Research in Construction (1994)

57 Prentice D A and Miller D T When small effects are impressive. Psychological Bulletin **112** 160-164 (1992)

58 Wilkins A J Nimmo-Smith I Slater A and Bedocs L Fluorescent lighting headaches and eye-strain Lighting Research and Technology **21** 11-18 (1989)

Correspondence from *Lighting Research and Technology*, vol. 29, pp. 55-56 (1997)

Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort

The study by Veitch and McColl[6] ('the authors') primarily investigated the conseuqnces of flicker in fluorescent lamps on a visual task, with a secondary evaluation of the effects of light spectrum. Examination of the protocols and data reveals that the promary study shows an effect that is probably greater than than reported in the paper, while the secondary study is weaker than described.

In this work both the horizontal illuminance at the task and the task luminance were measured. The luminances indicated in Table 1[6] are generally about 15% higher for the low-frequency (LF) operation than for the high-frequency (HF) operation, even though the task horizontal illuminance is set to the same value for both LF and HF consitions. The authors note this discrepancy and state that it might be due to 'artefacts of the speed of the detector arra' of the luminance instrument (Photo Research, Pritchard model 703A, Northridge, CA). However, the instrument maker, in telephone conversations, claims that this model records accurately in both LF and HF conditions. Likewise, the United States representative for the Hagner Illuminance meter (Cooke Corp., Hagner model S2, Buffalo, NY) claims their meter is accurate when measuring both LF and HF sources. A possible explanation for the discrepancy between results from the meter could be electro-magnetic interference (EMI) from the HF ballasts. In Figure 2[6] the illuminance probe is shown resting just above the lamp housing, and might be quite near the ballast. Various degrees of EMI can occur, depending onthe quality of grounding and the amount of shielding of the fixture, as well as the integrity of the shielding of the probe-to-meter cable (since the electrical current carried by the probe cable is very small). Cooke Corp. also indicated to us that meters have malfunctioned under high-EMI conditions associated with high-voltage switching. Since the task luminance is the psychophysically appropriate measure of stimulus, and the luminance meter was placed much further awar from the ballasts with less opportunity for an EMI problem, we consider its values to be the more representative of the test lighting conditions. In which case, according to Table 1[6], the subjects are provided with 13% to 22% less luminance under the HF conditions, and yet they perform better on the visual task. Furthermore, the data in Table 2[6] show that the effect is present for each lamp, despite the fact that each lamp's effects were studied with a separate set of 16 subjects. This result, which might be an unexpected benefit of the HF operation, deserves further careful study.

The primary purpose of the study (to determine the effects of ballast operation frequency on threshold size and contrast) can be inferred because it is the LF/HF comparison that is studied with the statistically strong within-subjects design. Secondarily, the authors have made some statistically weaker between-group comparisons which they interpret asa test of the 'Berman hypothesis' regarding the effecs of the scotopic spectrum on visual performance. The secondary experiment provides no such test, for several reasons.

Firstly, in all ourpapers[7-10] on the benfits of scotopic sensitivity, the experiments were conducted under full-field viewing conditions with uniform illumination. However, the testing apparatus in the authors' experiment restricted the primary visual field of view (due to the viewport dimensions) to 0.28 sr (about 5% of the solid angle covered in full field of view). The visual field at larger angles receives much less illumination due to the inter-reflected light from the sides of the viewport.

Secondly, lamps that do not differ much in *S/P* ratios do not differ much with respect to scotopic output (assuming equal photopic levels). Given the *S/P* ratios used in this experiment and our data for the spectral response of pupil size [(11)], we would predict only about a 7% change in pubject pupil area when comparing results fro the full-spectrum lamps with those from the CW lamp. This assumes a near full field of view, not the restricted field use in the authors' study. Thus, there may not have been significant pupil size differences in the authors' experiment. Without a pupil size difference, we would not predict a spectral effect on performance.

Thirdly, there is a probability that the contrast for the visual performance task were not eual for the three spectrally-different lamps. The authors found difference in contrast for the visual comfort reading material under the three test lamps, but did not state whther the contrast of the visual performance task had been measured. Any differences in task contrast due to lamp spectrum would introduce a bias of unknown magnitude and direction with respect to between-lamp comparisons.

Fourthly, the statistics used require that each of the three different groups studied be representative of the general population, i.e., have the same mean acuity. Since the smallest ring gap size was 0.66 minutes of arc, subjects who identified all rings correctly at the high contrast level had at least 6/4 (20/13) vision, which is considerably better than normal. For the CW lamp, 15 of the 16 subjecst had at least better than 20/13 vision, suggesting that this groups had better-than-average vision. In contrast, for the full-spectrum lamp, only 6 opf the 16 subjects had at least 20/13 vision. Thus the difference in mean scores can just as well be atributed to a chance difference in the mean group acuities, rather than to lamp spectrum. However, because of the experimental design, in which both lamp type and group vary together, it is not possible to disentangle these variables.

Fifth and last, even though the authors state that they have not found any statistically significant evidence of a spectral effect on visual performance, they claim that the data shows 'trends contrary to Berman's hypothesis'. There are several errors here. A trend should not be taken seriously unless the statistical probability approaches, but does not reach, significance (for example, $P<0.10$). This is not the case here. In addition, the authors have chosen to highlight only one 'trend' in their data. Examination of their data will show both the full spectrum (FS) and filtered CW (FCW) lamps to have poorer performance than the CW alone. Since the FS lamp has more scotopic content, which the FCW has less scotopic content, theese trends are in opposite directions, as might be the case for chance occurrences. Why have the authors choisen to mention only one of the two 'trends'?

The secondary study is too weak (due, at least, to between-group comparisons, small *S/P* changes, and a narrow field of view) to argue against the hypothesis that spectrally modulated changes in pupil size can affect visual acuity.

References

6 Veitch J A and McColl S L On the modulation of fluorescent light: Flicker rate and spectral distribution effects on visual performance and visual comfort *Lighting Research and Technology* **27** 243-256 (1995)

7 Berman S M Fein G Jewett D L and Ashford F Luminance-controlled pupil size affects Landolt-C task performance *Journal of the Illuminating Engineering Society* **22**(2) 150-165 (1993)

8 Berman S M Fein, G Jewett D L and Ashford F Landolt-C recognition in elderly subjects is affected by scotopic intensity of surround illuminants *Journal of the Illuminating Engineering Society* **23**(2) 123-130 (1994)

9 Berman S M Jewett D L Fein G Benson B Law T Myers A and Bullimore M A Lighting spectral effect on Landolt C performance is enhanced by blur and abolished by mydriasis *Journal of the Illuminating Engineering Society* **25**(1) 42-50 (1996).

10 Berman S M Fein G Jewett D Benson B and Myers A Luminance-controlled pupil size affects word-reading accuracy *Journal of the Illuminating Engineering Society* **25**(1) 51-59 (1996)

11 Berman S M Fein G Jewett D L Saika G and Ashford F Spectral determinants of steady-state pupil size with full field of view *Journal of the Illuminating Engineering Society,* **21**(2) 3-13 (1992)

S M Berman† and **Blaine R Benson**‡

†Energy and Environment Division
E O Lawrence Berkeley National Laboratory
Berkeley, CA 94720
USA

‡Abratech Corporation
475 Gate 5 Road, Suite 255
Sausalito, CAn 94965
USA

Authors' reply

We are pleased that our paper(6) provoked the interest of Dr. Berman and Mr. Benson. Understandably, we disagree with certain of their remarks.

At the time of the experiment, we were unaware of the potential effect of electromagnetic interference from the electronic ballasts on our illuminance meter. We concur with the conclusion that it is possible that the net effect of this discrepancy may be to underestimate the size of the flicker effect on visual performance. Therefore, we can only agree with Dr. Berman and Mr. Benson that further careful study of flicker rates on visual processing is warranted.

We disagree with their conclusions regarding the lamp type comparison, which are based on criticisms of both the methods and the results. First, we point out that the lamp type comparison was not selected solely as a test of Dr. Berman's scotopic sensitivity hypothesis, but as a means to induce chromatic as well as luminous flicker (Ref. 6, p. 244).

We are unconvinced that the differences in the field of view between our experiment and Dr. Berman's work have any implications for the outcome. In any case, we believe that the discussion of differences in methodology begs the question. If the effect of a scotopically enriched lamp on vision is robust, and if it is substantial enough to warrant changes in lighting practice, as Dr. Berman has argued(12), then it should occur reliably, across varying methodologies, and with lamps that are typical of current practice. To date, Dr. Berman's work has found the effect consistently, but using an unusual arrangement that separates task and surround lighting, and using lamps that are extreme in their S/P ratio (0.24 and 4.31(10)). The ratios of the sources employed in our study, which were typical of current practice, ranged from 1.04 to 1.68(6).

It is true that the statistical power of a between-groups comparison with 16 participants per group (total sample size of 48 in three groups) is lower than that of a within-groups comparison, and it is possible that with either a larger sample size (as we noted, Ref. 6, p 252) or a within-subjects design, a lamp type effect on visual performance might have been observed. However, as we noted in our earlier reply to Dr. M. S. Rea, (Ref 6, p. 255), the VALiD task provided only two parallel forms of the test. To have used the same task for more than one experimental condition, as a within-subjects design with six combinations of lamp and ballast type would have required, would have risked a confounding practice effect. We judged this to be more serious than the alternative, which was a less-than-optimal level of statistical power.

Differences in task contrast between the lamps were small enough that they were unlikely to have affected between-groups visual performance (cf. Ref 13). In any case, if lamp spectral qualities have this differential effect on contrast of commonly-read materials (such as the laser printer copy used for the contrast measurements), then any associated differences in visual performance would apply to real-world conditions. We note, moreover, that the order of task contrast, from highest to lowest (FS, FCW, CW), is opposite to the order of visual performance scores (CW, FCW, FS).

Dr. Berman and Mr. Benson make a logical error when they state that a priori differences in acuity between the lamp type groups confound the contrast, in that they base their statement about acuity on the dependent measure of visual performance, which could have been influenced by the lamp type. To compare the baseline acuities of participants would require a pretest (initial) measure of acuity based on identical test conditions. We are confident that the groups were comparable in this sense because all participants passed the Titmus vision test with at least 20/20 vision and were subsequently assigned randomly to one of the three groups. This is the standard procedure for a true between-groups experimental design(14,15). We quote Cook and Campbell, authors of one of the most widely-cited books on research design in the behavioural sciences: "...a properly implemented random assignment procedure will usually result in initially comparable experimental groups..." (Ref. 14, p. 342). It allows us to infer that differences in the outcome measures between the groups were caused by the treatment (lamp type) rather than by pre-existing differences between the groups.

In their fifth point, Dr. Berman and Mr. Benson ask why we highlighted only one trend. We tested two specific hypotheses using planned comparisons. Neither was statistically significant, but we highlighted the contrast between the FS group and the combined FCW/CW group because its multivariate $F(6,40)=1.92$ had $p=.10$, leading us to suggest that the trend might have been statistically significant with a larger sample size. Our interest in that contrast was related in part to the fact that the percentage of variance associate with it (7%) was as large as that explained by the statistically significant ballast effect (6%). We did not discuss the mean difference between the FCW and CW groups, which we also tested, because its $F(6,40)=1.20$ had $p=.32$. We rejected the hypothesis that these means differed.

In conclusion, we thank these researchers for their comments and we hope that their interest is reflected in independent replications of this work.

References

12 Berman S M Energy efficiency consequences of scotopic sensitivity *Journal of the Illuminating Engineering Society* **21**(1) 3-14 (1992)

13 Rea M S and Ouellette M J Relative visual performance: A basis for application *Lighting Research and Technology* **23** 135-144 (1991)

14 Cook T D and Campbell D T *Quasi-experimentation: Design and analysis for field settings* (Boston: Houghton Mifflin) (1979)

15 Kerlinger F N *Foundations of behavioral research* (3rd ed.) (New York: Holt, Rinehart, & Winston) (1986)

Jennifer A. Veitch† and **Shelley L. McColl**‡

† National Research Council of Canada
Institute for Research in Construction
Ottawa, ON K1A 0R6 Canada
E-mail: Jennifer.Veitch@nrc.ca

‡ Dept. of Psychology, McGill University
1205 Dr. Penfield Ave
Montreal, QC H3A 1B1 Canada
E-mail: mccoll@ego.psych.mcgill.ca