Neurophysiological correlates of visual performance effects of luminous modulation

by

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Abstract

Objectives: The present study investigated the effects of luminous modulation or flicker on concurrently recorded visual event-related potentials (ERPs) to performance and accuracy in a Stroop and sentence reading tasks.

Methods: Three flicker rates were presented at 0, 100, and 500 Hz in separate blocks of trials while ERPs were recorded and participants performed a Stroop and sentence reading task.

Results: Although the sentence reading and Stroop task did not support the main hypothesis that 100 Hz would adversely affect reading and reaction times, respectively, the source analysis revealed that the 500 Hz response had approximately the same mean source activation for incongruent and congruent tasks which was not the case for 100 Hz where the incongruent task resulted in significantly higher activation for the early latencies (i.e. 60-100 ms, 170-210 ms) in the left hemisphere and in the 170-210 ms range in the right hemisphere. The overall activation localized to the pulvinar nucleus of the thalamus.

Conclusions: Source analysis results suggest that 500 Hz flicker had an effect on the secondary visual pathway as evidenced by localization of the pulvinar. Furthermore, source activation for 500 Hz was not significantly different for congruent and incongruent trials whereas 100 Hz resulted in higher average brain activation between these trials in the Stroop task suggesting that more effort was required to complete this task. The amount of time under each lighting condition was, by all standards, minimal -- only about 15 minutes. Yet, even with

this short exposure, we found data suggestive of important influences of flicker on performance and brain outcomes, particularly in the left hemisphere.

Key Words: visual performance, arousal, event-related potentials (ERPs), asthenopia, flicker, luminous modulation

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1 Chapter: Background Literature

The ability to perform visual tasks can be affected by the characteristics of the environment or the visual input. For instance, if the environment contains interfering visual conditions (e.g. low light, changes in light modulation), performance can decrease. Research regarding the visual system usually focuses on a specific environmental, or input, characteristic to attempt to investigate properly the effects on behaviour or the brain (i.e. how the brain processes this information). For instance, the visual system can detect changes, which are not consciously perceived, to inputs at specific light frequency ranges which can adversely affect performance and health. This experiment investigated whether equivalent dipole source analysis, a method used to localize brain activity, could assist in the determination of neural correlates underlying this effect and whether flickering light had an adverse effect on accuracy and performance.

1.1 Visual System

In order to better understand the process when a stimulus (e.g. light) activates the visual system, it is necessary to review briefly the visual pathways.

The human visual system transduces electromagnetic radiation between 380 and 780 nm to electrical signals via specialized cells in the retina known as photoreceptors. The information collected at the photoreceptors is processed primarily via two visual pathways, the cortical and subcortical (See Figure 1) visual systems (Eysenck & Keane, 2005). The cortical and subcortical pathways both begin at the retina. The cortical pathway proceeds to the primary visual

cortex (V1) in the occipital lobe through a 'relay' station in the lateral geniculate nucleus (LGN) of the thalamus. From V1, visual information goes to the extrastriate cortex via the ventral "what" (occipitotemporal) and the dorsal "where" (occipitoparietal) streams (Goodale & Milner, 1992).

The subcortical pathway also starts at the retina but then takes a secondary route to the superior colliculus and the pulvinar (Leh, Chakravarty, & Ptito, 2008). These two subcortical structures are interconnected with direct connections to the extrastriate visual cortex and without activating V1 (Bridge et al., 2010). The extrastriate cortex is the region of the occipital cortex located next to V1 (Wurtz & Kandel, 2000). A second V1-independent visual pathway connects the superior colliculus with the LGN and projects efferents to extrastriate cortices in the dorsal (occipitoparietal) stream.

In addition to the information processed by these visual pathways in the brain, the eye also produces simultaneous rapid muscular movements known as saccades when a change in focus occurs. Saccades and blinks occur to assist in the re-focusing of the fovea on a target. Importantly, adding to the literature on flickering light, several studies show that the frequency and amplitude of these eye movements can increase when fatigued by flicker (West & Boyce, 1968; Haddad & Winterson, 1975; Wilkins, 1986).

1.2 Cognitive Processing

The cognitive processes that can be affected by flicker include reading ability, visual performance, and visual search and several studies demonstrate this effect implementing different methods and lighting systems (See Table 1).

In 1986, Wilkins studied the size of eye movements across text as a measure of reading ability. He used cathode ray tubes (white P4 phosphors; luminance less than 2% in 10 ms) with frame rates of 50 and 100 Hz which were covered with a black matte mask and had an aperture of 0.16 wide x 0.1 m high through which a negative with typewritten text could be viewed. The light passed through the negative and gave the appearance of white text on an unlit background. Participants were instructed to focus on one target letter until a tone sounded after which the participant moved the eyes to the other target. He found that the primary saccade (i.e. the first saccade in 89% of cases) was 11% larger following the tone for the 50 Hz refresh rate display than for the 100 Hz. In addition, the number of saccades was significantly higher for the 50 Hz refresh rate display. In a second part of the study, Wilkins used ceiling-mounted fluorescent tubes (GEC warm white 40 Watt; 36% modulation). He found that the size of the main saccade at 100 Hz was somewhat larger than under the steady light condition. A saccade is measured by the horizontal distance the eye moves. A larger saccade would indicate the eye moved horizontally by a greater degree. Wilkins showed that intermittent light could affect oculomotor control at those modulations and frequencies where light appeared continuous (i.e. above the critical fusion frequency [CFF]). In addition, the modulation depth of light output has been implicated in complaints of visual discomfort (Laubli, Hunting, & Grandjean, 1980).

Research into the behavioural effects of flicker on visual performance (Veitch & McColl, 1995; Küller & Laike, 1998; Jaen, Colombo, & Kirschbaum,

2011; Sheedy, Hayes, & Engle, 2003) consistently showed decreased performance and accuracy. For example, Veitch and McColl (1995) examined the effect of low (120 Hz) versus high (20-60 kHz) frequency flicker on visual performance and comfort and found that flicker affected performance on a visual task under typical indoor light levels. Specifically, when the luminance contrast was very low, (i.e. 0.21) and, therefore, when the task was visually difficult, performance improved under the high frequency condition.

In simple visual search or discrimination tasks (Jaen, Colombo, & Kirschbaum, 2011), flicker can reduce visual performance. In this study, the researchers used four specially constructed light boxes. Two light boxes contained conventional magnetic ballasts which produced light modulated at 100 Hz and 32 percent modulation and were considered high temporal modulation (illuminance=6210, 5980 lux; luminance=812.0, 764.3 cd/m^2 respectively). The other two low temporal modulation light boxes had electronic ballasts with light of 60 kHz fundamental frequency and 3.0 percent modulation at 100 Hz (illuminance=5873, 6075 lux; luminance=710.0, 749.5 cd/m^2). These studies used young normal individuals with normal or corrected-to-normal vision and limited exposure to flicker. Participants were exposed to all four light conditions where each session took 45 minutes over a four day period at eight sessions per day. The findings indicated that flicker, beyond the point where the participant subjectively reported that flickering light was no longer perceptible (i.e. the critical fusion frequency or CFF), affected visual performance and accuracy on the

visual search task which was not due to perceptual appraisal of the side-by-side light boxes.

1.3 Background Information on Flicker

Flicker is the quick and repetitive change over time in the brightness of light (Wilkins, Veitch, & Lehman, 2010; refer to Appendix A for definitions, symbols and abbreviations). The human visual system has been found to be responsive to flicker from 1 to 70 Hz as evidenced by photosensitive epilepsy and early electro-encephalography (EEG) studies of flicker sensitivity (Thiry, 1951; Binnie, de Korte, & Wisman, 1979; Wilkins et al., 1979; Veitch & McColl, 1995; Harding & Harding, 2010; Fisher, Harding, Erba, Barkley, & Wilkins, 2005).

Most individuals report that they cannot perceive flicker above 100 Hz, however, this does not mean the flicker does not induce responses by the brain. Eysel & Burandt (1984) performed intracellular recordings in the cat visual cortex and found that the feline visual system responded to flicker frequencies well above the CFF. Berman, Greenhouse, Bailey, Clear, & Raasch (1991) also found that flicker was not reported above 100 Hz but, with the use of electroretinograms (ERGs; refer to Appendix G), they determined that the firing of the cells in the retina and subcortical visual structures was associated with flicker, thereby, producing evidence compatible with the animal research by Eysel and Burandt.

Another ERG study by Burns, Elsner, & Kreitz (1992) showed that the fundamental retinal response (i.e. the response curve of the ERG) could be recorded at frequencies greater than 100 Hz and second and higher harmonic responses were measurable up to about 200 Hz by using nonlinear systems

analyses. This would seem to indicate that the visual pathways are capable of detecting flicker at 100 Hz and higher even when reports indicate no awareness of flicker.

More recent research on flicker (Roberts & Wilkins, 2012) has shown that detection by the visual system can occur in low light conditions at frequencies up to 1000 Hz. In a low light room (<1 lux), participants made saccades back and forth between two white disks positioned 600 mm horizontal to the right and left of a green vertical line. The white disks were positioned on a black matte screen (2m) which had a 50 mm diameter opening which allowed the green line from the oscilloscope to be viewed. A 2 MHz function generator (i) controlled the oscilloscope positioned on its side, and (ii) output a vertical sine wave at frequencies of 1, 2, 3, and 5 kHz or a steady signal. All conditions had similar time-averaged voltage and luminance (0.02-310 cd/m^2). The participants made left and right saccades between the two disks and then were asked to decide which presentation had a pattern of spatially periodic lines. In one condition, the function generator modulated the lines' brightness level whereas in the other the brightness level was unchanged. Analysis, using least squares, fit two curves. The first curve fit to the cumulative normal of the group and the second to the cumulative normal of the individuals. The 75% threshold of the group fitted curve was 1.67 kHz (SD=0.52 kHz) whereas the individual threshold mean was 1.98 kHz (SD=1.13 kHz) showing that the individual mean was significantly higher than the cumulative normal curve fit. These results indicate that intrasaccadic perception of flicker could interfere with eye movements and disrupt visual

performance. The authors speculated that, perhaps, these types of flicker conditions could lead to headaches.

1.4 Brain and Behaviour effects of Flicker

The extent to which brain activity has been studied in regard to flicker has been primarily restricted to EEG. In particular, Küller & Laike (1998) examined the effects of flicker on visual performance under fluorescent lighting systems with rates of 100 versus 40,000 Hz. They recorded EEG and examined the alpha, beta, theta and gamma waves while participants performed a numerical proof-reading task consisting of 200 number pairs with 3-12 digits. They divided the participants into two groups, those with high and low CFF (i.e. where the subjective experience of flicker was no longer detectable) thresholds. They found that the group with the high CFF values had lower amplitude alpha waves as well as increased speed and decreased accuracy in the performance task. They proposed that the EEG results indicate a more general arousal effect rather than a cortico-visual mechanism affecting sensitive (high-CFF) but not less-sensitive (low-CFF) individuals. They reasoned this was due to positioning the EEG recording electrodes closer to central and parietal regions. This, in turn, may indicate that V1 was not the initial region activated by flicker similar to the Buchner et al., (1997) study using visual evoked potentials (VEPs).

In addition, Jaen, Colombo, & Kirschbaum, (2011) suggested that their task could be used as a screening tool to identify individuals sensitive to flicker prior to performing a flicker experiment.

An alternative method for determining flicker effects on the brain would be the use of ERG (Brindley, 1962; West & Boyce, 1968; Berman et al., 1991; Burns et al., 1992) or EEG. ERG performs some very accurate and direct measures of the retina, however, the invasiveness of this procedure makes it uncomfortable and, consequently, the number of participants is generally low. The high accuracy in the ERG measures provides substantial information on the effect of flicker on the brain.

With the use of ERGs, Brindley (1962) was able to detect flicker accurately (refer to Appendix A, Sub-appendix A.1 #3 for definition) through the whole illuminated portion of the visual field from 5-120 Hz which effectively demonstrated that flicker was able to exceed previously reported CFF measures. The surface luminance was calibrated at 45,000 cd/m^2 as seen through a 3 mm pupil with the other eye. When the light and the current differ by about 1 Hz and stimulate the eye, visible ‘beats’ occur for frequencies of light between 5-120 Hz. The upper frequency limit of the interruption of light was greater than the CFF over the same retinal field size and mean intensity. When the current frequency was an integral multiple of the light frequency (e.g. electrical frequency = 441 Hz and light frequency = 40 Hz), beats were recorded. They also found that the photopic (refer to Appendix A, Sub-appendix A.1 #13 for definition) CFF was not limited to the photochemical properties of the cones or by the visual neural pathways but likely due to the attenuation of high frequencies by both mechanisms.

Another study by West and Boyce (1968) used an optical lever recording system with a contact lens and a recording beam, photomultiplier masks and rotating mirrors as well as an amplified strain gauge system similar to an ERG and found that saccadic eye movements were disrupted by low frequency (1-3 Hz) flicker but not high frequency (4-5 Hz).

In addition, Berman et al., (1991) tested fluorescent light flicker oscillating at rates up to 200 Hz (i.e. F40 T12 daylight at 100% modulation and phase-locked with frequency rates from 47.5-72.5 Hz) and compared this with a slide projector stimulus with an 80-120 Hz modulation and frequency rates up to 162 Hz. They found ERG responses at all tested frequencies from 46 up to and including 200 Hz (100% light modulation). They suggested that responses to even higher frequencies were possible.

In another ERG experiment by Burns et al., (1992), the study of steady flickering fields revealed interesting results regarding flicker frequencies greater than 100 Hz and harmonics of this frequency as high as 200 Hz. They also noted an early cutoff frequency between 40-50 Hz at the retina that acted as an early low-pass temporal filter. They recommended further research into flicker activity at the retina and effects on brain activity or research into muscular activity of the saccades and muscular reactions in terms of flicker to appreciate fully the effects of flicker on the brain.

Haddad & Winterson (1975) used a specialized device (i.e. not an ERG) to examine the effects of low flicker rates on saccades using a green LED with an average luminance about 70 cd/m^2 and square wave modulation of 100%. They

found that flicker had an effect on slow control (i.e. drift correction) of saccades. The rate of saccades decreased as flicker increased. In addition, the suppression of saccades revealed that flicker had a driving effect on the slow control movement of the eyes (i.e. eyes drifted away from a target and oscillated as they drifted). Therefore, it is important to measure saccade rates to enhance findings from flicker-related research.

Under naturalistic conditions, Wilkins, Nimmo-Smith, Slater, & Bedocs, (1989) performed an intriguing experiment where the lighting in an office building was changed periodically and a weekly survey on the incidence of headaches and eyestrain was assessed. The lighting system used different fluorescent lamp types which were operated on (i) choke ballasts with switch start where 100 Hz flicker was dominant and modulation depth was about 40 percent, (ii) choke ballast with electronic circuit but with similar characteristics, or (iii) 32 kHz electronic ballasts where modulation depth was less than 7 percent. The illuminance level varied between the rooms from 400-900 lux. Timers were added to measure the length of time the lights were turned on. The survey restricted its questions to the severity of headaches or eyestrain and the possible cause of each for each day of the week. They found the high-frequency lighting was preferable and that headaches and eyestrain were reduced by half under this type of lighting and that this lighting system was kept on for longer periods of time than the others. They also found the number of headaches under conventional lighting decreased when exposure to natural light from office windows increased.

In addition, Sheedy et al., (2003) examined the effects of invisible chromatic flicker using a range of frequencies (2-60 Hz) and modulation levels (10-100%) by applying an adaptation stimulus which flickered for two minutes in either luminance or chromaticity. Participants observed a 3 degree spot where red and green lights were superimposed and counter-phase-modulated at a frequency of 30 Hz, which was above the chromatic CFF and below luminance CFF. The chromatic CFF is the point where the colour (i.e. the flashing red or green light) was no longer perceived to flicker. The luminance CFF is the point where the amount of light is no longer perceived as white since luminance is, in essence, the white light that hits the retina. The red modulation was fixed and the participant adjusted the green modulation until no flicker was perceived. The researchers suggest that the ability to distinguish differences in luminance or chromaticity was impaired under invisible flicker. They suggested that visual sensitivity was increased by prolonged exposure to image flicker (e.g., refresh rates of computer terminals). They concluded that adapting to flicker, for luminance or contrast above the respective CFFs, was more sensitive at high (in this case, 60 Hz) frequencies that are not consciously perceived and prolonged exposure results in visual sensitivity. Furthermore, this sensitivity is related to the flicker filtering system which they found to be distributed across multiple retinal and cortical regions with at least one peripheral and one central site.

A recent study by Roberts and Wilkins (2012), performed under low light conditions, had shown that flicker could also occur at frequencies far in excess of the CFF and the highest levels that other researchers had previously assessed in

photopic vision. The frequencies beyond the CFF and the highest level previously found in the research (i.e. without harmonics, about 120 Hz) have not been examined and require investigation.

From these studies, it is evident that adverse effects of flicker occur from 1 to 200 Hz in photopic vision and, perhaps, even higher under low light conditions. Furthermore, some of these lighting conditions have been shown to implicate physiological problems (e.g., headaches, eyestrain) in sensitive individuals.

1.5 Studying Brain Function Correlates of Flicker

One method to assess both the physiology and psychology behind the effects of flicker is to use event-related potentials (ERPs). Event-related potentials are averaged waveforms of electrical brain activity that occur in response to sensory stimulus presentation. Several averages are required to increase the signal to noise ratio and obtain a waveform with minimal noise and artefacts. It is essential to remove ocular artefacts from the recorded EEG in order to obtain an averaged ERP waveform that is representative of the cognitive task being performed.

A second method to examine the effects of flicker on brain function is to use equivalent current dipole sources to propose possible activation regions within the brain that could support the resultant peak and latency information.

1.5.1 Dipole source analysis

Dipole source analysis evaluates location and orientation of current flow of activation within the brain. Current flow in the cortex travels perpendicular to the cortical surface because the orientation of the pyramidal cells is perpendicular to

the skull and because the dendritic trees, although parallel to the cortical surface, tend to cancel out. For these reasons, the intracellular postsynaptic current vectors can sum linearly and be represented by equivalent compound dipole current vectors. The possible orientation for currents at the cortex include, radial, tangential, and oblique. Generally, motor and sensory areas have oblique orientations but this is dependent on the net orientation of the activated cortex. Radial orientations occur at the superolateral surface of the brain, and tangential orientations are usually found at cortical fissures. Equivalent current dipoles are specified by location and orientation. The location (x, y, z axes) is modeled at the centre of the gray matter area and the orientation is the net direction as modeled by the postsynaptic current which is usually perpendicular to the modeled gray matter. The dipole orientation indicates the pyramidal cell's local orientation. It is important to note that this is not the direction of signal transmission.

Equivalent current dipoles also have strength and amplitude as measured in nAm (nano-Ampere x metre) of a dipole moment. This can be shown as

$$\text{net postsynaptic current flow} = \text{total postsynaptic current flow (nA)x length over which current flows (m)}$$

Once modeled, the dipole moment is measured and saved as a source waveform which is then applied to the collected electrophysiological data. It is important to understand that the maximum EEG activity does not necessarily occur on top of the active brain region.

Caveat: If two dipoles are used in the model, they can separate to two activities for their respective source waveforms provided that appropriate

equivalent locations and orientations are chosen. However, if the data are modeled with only one dipole, an incorrect localization can occur and orient itself between both sources. The source waveform combines the underlying activities of both sources into a larger pattern which had a single latency between the original source activations.

Source analysis (i.e. dipole moments) = linear inverse x data waveforms

Previous research on the visual system using dipole source analysis had used random dot kinematograms and pattern reversal (Probst, Plendl, Paulus, Wist, & Scherg, 1993) to examine the spatial distribution for motion and pattern with a latency of 160–200 ms in the brain. They found a motion-related source in the region of the contralateral occipital-temporal-parietal border and a pattern-related source more medial and deeper within the brain during the same epoch. For this reason, the flicker source localization could likely occur in the occipital-temporal-parietal region because flicker may be interpreted by the brain as a form of motion (e.g. stroboscopic effect) even though the individual subjectively perceives the light as continuous.

In support of the assumption for localizing flicker to the occipital-temporal-parietal region, a review (Lindner & Kropf, 1993) on the neural generators of the P300, which is a positive-going ERP component occurring 300 ms post-stimulus onset, showed that the inferior temporal and superior parietal cortex were the primary regions for processing visual P300 stimuli. Flicker could potentially have an effect on this component by reducing the amplitude, increasing the latency, or reducing alpha activity (Küller & Laike, 1998).

Finally, an experiment (Buchner et al., 1997) implementing source analysis techniques for the motion processing area located in the lateral occipito-temporal cortex using visual evoked potentials to checkerboard stimuli showed that the source localization provided evidence that very fast inputs occur in area V5 before V1 activation. This information is important with respect to flicker because it showed that the visual system can activate other regions prior to activating V1.

In summary, there exists very little research on localization in the brain for directly measuring the neural correlates of flicker, and how these are associated with performance. Performance and brain function have been investigated for frequencies below 100 Hz and above 500 Hz; however, the range from 100-500 Hz has not been examined in this manner. Therefore, one of the goals of this study was to study the visual phenomena associated with flicker in this unexamined frequency range. A further objective was to determine if flicker had an effect on the behavioural performance and accuracy in cognitive tasks.

1.6 Research Design and Hypothesis

To our knowledge, research has not included dipole source analysis or ERPs to assess cognitive performance under specific flicker frequencies. In order to fill this gap in knowledge, the following experiment was designed as a within-subjects comparison of reading and cognitive performance as a function of three flicker rates (0, 100, and 500 Hz). In addition to state anxiety and behavioral performance, brain functions were assessed using ERPs and source analysis based on the EEG correlates measured concurrently to the tasks. Research

goals for electrophysiology and source analysis included determining if the peak amplitudes and latencies of the electrophysiological response were affected by the flicker frequencies and supported the behavioural response, and if source analysis could localize the current generators for flicker or would the sources localize to the standard locations for this type of cognitive task (i.e. anterior cingulate, calcarine fissure – See Figure 2).

The 0 Hz DC stimulus provided a condition of no flicker and no contamination of 60 Hz AC mains frequency. The 100 Hz frequency was beyond typical CFFs, which starts at about 60 Hz, and beyond the possibility of producing epileptogenic responses reported in the range from 40 to 70 Hz (Binnie et al., 1979; Wilkins, 1987; Harding & Jeavons, 1994; Ishiguro et al., 2004; Harding, Harding, & Wilkins, 2008). This frequency will help determine cognitive effects (e.g. reading performance) and substantiate the information from ERG studies (Brindley, 1962; Berman et al., 1991; Burns et al., 1992). The 500 Hz frequency has not been previously examined or reported, however, this frequency is below frequencies found in scotopic vision research by Roberts & Wilkins, (2012), which found responses to flicker at 1000 Hz, and could provide information on flicker effects well above the CFF and photopic vision responses. The Roberts and Wilkins research showed that the visual system responded to flicker well beyond the CFF levels previously thought to be undetected.

In this experiment, state anxiety was also assessed because previous research implicated “asthenopic” effects such as visual fatigue, headaches and eyestrain (Brundrett, 1974; Küller & Laike, 1998; Maddocks, Goldsmith, & Cuthill,

2001; Sheedy et al., 2003) which, by speculation, may increase state anxiety levels. In addition, an animal study of European starlings by Maddocks, Goldsmith, & Cuthill, (2001) found increased plasma corticosterone levels (i.e. a stress-regulator hormone) when flicker rates were low (100 Hz) as compared to high (35-40 kHz). One goal of this study was to determine if flicker, under short-term lighting conditions (i.e. 45 minutes or less), had an effect on state anxiety.

2 Chapter: Materials and Methods

2.1 Participants

Healthy university students were recruited from the Carleton University SONA system. Of the original 54 participants who volunteered to participate in this study, 6 were excluded on arrival because they did not meet the recruitment requirements of the study (5 did not meet the physical requirements, 1 was excluded due to technological difficulties – i.e. a power failure). Of the 48 participants who completed the experiment, data from 14 were excluded from analysis due to (i) technological issues (N=5), (ii) EEG artefacts (N=6), (iii) an inability to follow instructions (N=1), and (iv) an inability to meet the requirements of the study (N=2). Complete data were obtained from 34 participants (7 males, 27 females) with (mean age 19.65 years; range: 18-26 years).

Participants reported English as their first or second language with fluency in English (N=5) if English was not the first language. All participants were right-handed as tested with the Edinburgh Handedness Inventory (EHI; Oldfield, 1971) and the average right-handedness quotient was 76.2 (SD=18.4) per cent. All participants reported corrected-to-normal (N=12; 8=near-sighted, 2=far-sighted,

2= astigmatism) or normal (N=22) vision (See Table 2 for full set of ophthalmologic tests) and were tested for and found no inter-optic differences or colour-blindness.

No participants reported any history of neurological impairment or were currently using psychoactive medications. The average number of hours of sleep on the previous night was 7.5 (minimum of 5 hours, maximum of 10 hours; SD=1.2). Nineteen participants were tested in the morning session from 9:00 a.m. to 12:00 p.m. and 15 were tested in the afternoon session from 1:00 p.m. to 4:00 p.m. The average depression score on the Beck Depression Inventory (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961, See Table 3) was 4.06 (SD=5.5). Thirty participants had scores relating to minimal depression, two participants' scores indicated mild depression and two with moderate depression. Refer to Table 4 for full demographic information.

2.2 Materials

2.2.1 Apparatus

Light emitting diodes (LEDs) were mounted at the top of a specially-constructed 72 cm by 72 cm booth secured to a table top 73 cm above the ground (See Figure 3). LEDs are semiconductor devices with semi-conductive materials which together create a diode. A diode conducts an electrical current in only one direction (See Figure 4). The booth was situated within a Faraday cage to shield the EEG recording from external radiation sources that would otherwise add noise to the brain wave recordings. The inside of the booth was spectrally neutral white in colour in order to minimize possible colour distortion and to

achieve efficient target illuminance. The monitor settings were selected to avoid creating ‘beat’ frequencies between the monitor and the LED lighting (See Figure 5). Furthermore, the heat sink levels of the monitor and the lighting system were assessed to ensure these operated within reasonable limits (See Figure 6) as measured on different days. An eye tracking camera was positioned inside the booth below the monitor. The controls for the lighting system were integrated with the Neuroscan EEG Acquisition system and the Brain Vision stimulus presentation equipment (see Figure 7).

The operation of the LEDs in the booth was controlled by an external power supply which maintained a constant luminance and illuminance even when the flicker rates varied between randomly presented blocks. The laptop interface controlling this system was positioned outside the Faraday cage and allowed for real-time monitoring of the illuminance levels. The constant illuminance was achieved by adjusting the number of LED chips activated for the different flicker conditions. In addition to using different numbers of LED chips for the different conditions, the voltage levels were varied slightly between conditions to maintain a constant illuminance level. Illuminance levels were verified using sensors positioned inside the booth and the values were plotted to show upper and lower acceptable limits on the laptop monitor (See top chart of Figure 8). A final calibration was performed at the end of the experiment to ensure the illuminance levels and those of the monitor had not changed over the course of the experiment.

The parameters of the LED output which could be manipulated were the light level, the frequency of operation (e.g., 0, 100, and 500 Hz), the duty cycle (i.e. 50% in this experiment), and the amplitude of the flicker (i.e. 100% modulation) with a digital square-wave circuit (i.e. the signal instantaneously changes from on to off). The only parameter altered in this experiment was the frequency. Chromaticity was not controlled; however, it was not varied in this experiment. Since only one LED type was used, chromaticity was not a variable.

During the experiment, participants viewed the task materials on a specially constructed 19” computer monitor to prevent differences between the LED lighting and the computer monitor backlighting (Refer to Figure 3). All questionnaires and tasks were presented on the same 19” monitor, positioned 100 cm in front of the participant, from the centre of the participant side of the viewport to the centre of the monitor inside the light booth.

The viewport allowed participants to view the inside of the booth while sitting on a comfortable height-adjustable chair. The viewport was 25.5 cm wide x 11.0 cm high and 27 cm above the table top. A chin cup was secured in front of the viewport 34 cm from the top of the table to the bottom of the chin cup. A headrest attached to the front of the viewport also provided additional support to minimize fatigue and this was positioned 16 cm from the top of the headrest to the bottom of the chin cup.

Responses to the questionnaires and the tasks were made using a computer keyboard on a pull-out tray attached to the underside of the table; others were made using a Sidewinder gamepad (Microsoft, 1998, See Table 6

for specifications). The gamepad was secured to a height-adjustable stand so that it could also be raised or lowered for comfort.

2.3 Independent Variable: Flicker Rate

The specially-constructed booth mimicked office space conditions while flicker was randomly adjusted between the three experimental blocks. Direct-current (DC) cool-white LEDs [4000 K, 85 CRI] controlled by a programmable power supply using pulse-width modulation delivered each of the three flicker conditions: no modulation (0 Hz DC), 100 Hz at 100% modulation and 500 Hz at 100% modulation. The order of presentation of the three conditions was counterbalanced.

The light level was held constant at about 500 lux (a typical level for office environments). Luminance, illuminance, and flicker parameters in the booth were thoroughly measured at the beginning and the end of the data collection period, and the apparatus' electrical performance was logged during operation. Colour shifts were minimal and these were also measured and recorded.

2.4 Dependent Variables

2.4.1 The State-Trait Anxiety Inventory

The State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, & Lushene, 1970) was presented after the BDI at the beginning of the experiment and between each experimental block for a total of four repetitions. The STAI is a validated 20-item self-assessment survey which includes separate measures for state anxiety. Additional questions may be added to the survey to assess trait anxiety but this was not done for this experiment. Various reliability and validity

tests have been conducted on the STAI and have provided sufficient evidence that the STAI is an appropriate and adequate measure for studying state anxiety in research and clinical settings (Sesti, 2000). Several items on the STAI were reversed coded (Items 1, 2, 5, 8, 11, 15, 16, 19, 20) to prevent automated responses from participants. Participants were also reminded that the responses required were to be “at this moment in time, right now, how you are feeling”. This experiment used the state anxiety survey measures.

2.4.2 Sentence reading time

The task to assess visual performance consisted of reading 100 eight-word sentences presented in 12-point Arial font in black lettering on a white background. The sentences were randomly presented, one sentence at a time in the centre of the monitor, without repetition from a pool of over 300 sentences, followed by a five minute rest period. Each sentence began with either the word “A”, “The”, or “There” adapted from the Harvard Sentences (Rothauser et al., 1969) because these sentences are phonetically balanced. An invisible boundary box around the first and last word of each sentence triggered when the participant’s eyes were within the bounding box.

In order to provide a more naturalistic sentence reading experience, the sentences in this experiment were presented as full sentences on the screen and read from left to right. This procedure provided a sentence reading time for each of the three flicker conditions. Other sentence reading tasks using EEG usually present the sentences one word at a time in the centre of the screen to control for saccades (Kutas et al., 1980).

Participants were instructed to read each sentence from left to right and to ensure that they read each word individually. The program was constructed such that the next sentence was not presented until the participants' eyes have reached the first invisible bounding box followed by the last invisible bounding box. Participants were informed that the eye tracker (See Table 5 for specifications and Appendix E for additional information) would register when the sentence was completed and would control the presentation of the next sentence.

The sentence reading task triggers corresponded to the first word presented in the sentence followed by the last word which were used to assess the interest period duration (IPD; See Figure 10). The eye tracker sent a trigger to the recording equipment to indicate that the participant had focused on the word or when the participant started and finished reading each sentence. The sentence reading task began with a cue which lasted for 300 ms. The sentence was presented 200 ms later. Once the eye tracker registered the pupil on the first word, the participant continued reading the sentence until the eyes focused on the last word of the sentence and then the next sentence was presented. The sentence was kept on the screen for a maximum of 5000 ms.

2.4.3 Stroop performance and accuracy

The Stroop (Stroop, 1935; West, 2003) condition was adapted to a non-verbal computer-generated task which allows the collection of brain wave responses to the stimuli (Refer to Figure 12). The Stroop task involves responding to four coloured words (i.e. RED, GREEN, BLUE, and YELLOW)

presented randomly on a black background. The coloured words were either congruent (i.e. the colour of the word matches the word displayed such as the word BLUE displayed in the colour BLUE) or incongruent (i.e. the colour of the word does not match the word displayed such as the word BLUE displayed in the colour RED). Words were presented randomly in the centre of the screen with a 500 ms fixation cross between each trial to restrict eye movements. If asked to respond to “colour”, the participant was required to push a button on a Microsoft Sidewinder gamepad (See Table 4, Microsoft, 1998) corresponding to the colour displayed regardless of the letters read. Similarly, for the word task, the participant was to respond to the word read regardless of the colour in which it was presented. The participant was instructed to respond as quickly and accurately as possible using the index finger of the right hand. The participant was unable to view the gamepad; therefore, a colour-to-key matching task was implemented to ensure the participant was able to match the colour to the correct key on the gamepad. The neutral stimulus was a series of Xs in the colour and length of the word they represented. For example, XXX in the colour red for the corresponding red key, etc. The practice was repeated if the percent correct was less than 85. Most participants were able to complete the colour-to-key matching task in one to two practice blocks.

Participants completed three blocks of 96 trials per flicker condition for each Stroop type (i.e. colour, word) resulting in 576 total experimental trials plus 24 practice trials and provided millisecond resolution of the brain wave

responses. The practice trials had an equal number of congruent and incongruent trials.

The Stroop task (see Figure 11) began with a blank black screen for 500 ms followed by a fixation screen for 500 ms. The stimuli were presented on the screen for a maximum of 5000 ms until the participant responded and then the next blank screen was presented.

Although most of the instructions for the STAI, Stroop, and sentence reading tasks were read on the computer monitor, some additional instructions were provided verbally for these tasks (see Appendix C).

The EEG was also recorded during the subsequent five minute rest period.

2.4.4 Event-related potentials

ERPs were recorded from the participant during the eye calibrations, the cognitive task, and sentence reading task. The EEG recordings were obtained from electrodes held in place by means of an elastic cap (Quik Cap, Neuroscan, El Paso, TX, USA) adhering to the ten-twenty system of measurements (American Electroencephalographic Society, 1991) with 68 recessed Ag-AgCl electrodes (10 mm each) mounted in an electrode cap (see Figure 9) amplified (0.5 to 500 Hz sampled up to 2000 Hz) and referenced to a separate reference electrode located directly behind Cz with AFz ground. This montage was based on external landmarks of the skull (i.e. the inion, the nasion, the left and right pre-auricular points) and the electrodes were distributed based on percentage distances from these reference points. The channel configuration included:

Frontal, Fronto-central, Fronto-temporal, Central, Parieto-central, Parietal, Temporal, Temporo-parietal, and Occipital. Vertical and horizontal eye movements were monitored with electrodes positioned at the outer canthi at LO1 and LO2 and on the suborbital ridge of each eye at IO1 and IO2. All impedances were kept under 10 kOhms so that they provided effective electrical signal with minimal noise. Regions of interest (ROI) were determined for specific latencies and the amplitudes were assessed for all electrode sites.

ERPs were recorded while the flicker rate was adjusted between blocks of no flicker, 100 Hz at 100% modulation, and 500 Hz at 100% modulation while the participant performed the cognitive and sentence reading tasks.

2.4.4.1 Electrophysiological measures

Electrophysiological signals were amplified (gain of 10; Range of +/-200 μV, or 400 μV peak-to-peak; Accuracy 29.80 nV/LSB) and low pass filtered at 500 Hz via SynAmps RT with a sampling rate of 2000 Hz. Acquisition filters were single-pole Butterworth, 6 dB per octave, 3 dB down at 500 Hz. All electrodes were referenced to a separate reference electrode and all data were re-referenced to a common average reference (i.e. the average was subtracted from each electrode for each time point). Offline averaging was performed such that ERPs were averaged separately for each stimulus type and condition for each electrode with an epoch of -200 ms prestimulus to 1000 ms post-stimulus. For the cognitive task, ERPs to targets included the individual trials that were followed by a correct response immediately following target presentation. Trials contaminated by excessive peak-to-peak deflection (i.e. $> 100\,\mu V\ or\ <$

$-100\ \mu V$) at non-ocular electrode sites were excluded from the average. The proportion of rejected trials was less than 95 percent after artefact correction and removal.

2.5 Methods

The protocol described below was approved by the Carleton University Psychology Research Ethics Board and the National Research Council Research Ethics Board. All participants provided informed, written consent before participating in this study and were given course credits for their participation.

The experiment consisted of five parts (See Table 7 for full experiment routine): introduction and preparation (comprising consent, screening and demographic questionnaires, and EEG cap application), followed by three debriefing (See Appendix B for advertisement, consent, and debriefings). The experimental session consisted of an initial eye movement calibration, tasks (sentence reading and Stroop, in counterbalanced order across participants), anxiety assessment, and a final eye movement calibration. The eye movement (EOG) calibration used an in-house EOG calibration program (See Figure 13).

2.5.1 General procedures

Prior to the ERP recording session and the participant's arrival, a noise spectrum analysis was performed in Neuroscan 4.5 (Neuroscan, Charlotte, NC, USA) to ensure environmental noise levels were acceptable (See Figure 14). The noise test was recorded with the same parameters as the electrophysiological recordings.

After completing informed consent, the participant then completed a vision test followed by the general, health, mental health, and handedness questionnaires. Following these screening assessments (see Appendix H for results of screening assessments), participants were fitted with the electrode cap and a bio-information calibration was also performed to ensure electrodes were placed in the correct locations. The electrodes then measured the difference in potential between two electrode locations (i.e. any particular electrode and a reference).

The eye tracking calibration was performed at the beginning of the experimental session (i.e. prior to the electrooculogram) and at the beginning of each experimental block (no-flicker, 100 Hz, and 500 Hz). Each eye tracking session (See Figure 15 and 16) took about two minutes and consisted of assessing if the eye location had moved significantly from its previous position. A chin cup was used to retain the participant's head position and prevent fatigue. Following the calibration, the participant performed a randomly presented Stroop or sentence reading task within the light booth. All experimental blocks were performed with the room lights off to prevent any introduction of electromagnetic interference (NLPIP Report, 2000) which would compromise the EEG data collection and introduce additional confounding flicker. Participants were given a rest break after each experimental block to reduce tension and the possibility of eye strain.

At the end of the experiment, the cap was removed, the participant's hair was washed and each participant was verbally debriefed (See Appendix B.1 and

B.2) and given a summary of the experiment. After the debriefing, the participant was asked to relax in a normal lit room with eyes closed for ten minutes.

Each experimental session lasted from 1.5 to 3 hours. Participants were not kept beyond the 3 hours as this would have increased the participant's discomfort in the cap. Each participant completed 100 task-set reading trials and 192 task-set Stroop trials (i.e. 96 trials for each task of word and colour) over three separate trial blocks. ERPs require several averages to obtain a clean signal to noise ratio. The presentation of the three lighting conditions (one for each block) was counterbalanced across participants. Counterbalancing order was obtained using a research randomizer to generate the random presentation of blocks (http://www.randomizer.org/form.htm). The STAI was repeated at the end of each block followed by a five minute rest period. During the rest period, the participant was allowed to sit back in the chair with eyes closed and relax.

If at any time during the experiment the participant felt uncomfortable, he/she had the opportunity to stop the experiment and received his/her credits for the participation time completed. The researcher then removed the EEG cap from the participant and completed the appropriate debriefing.

2.5.2 Electrooculogram (EOG)

The electrooculogram (i.e. eye movement calibration) was performed after the questionnaires and vision test were completed and assessed. A separate EOG calibration was recorded for each participant. Participants made lateral and vertical eye movements to a fixation circle that alternated between the centre and the edge of the screen, in the right, down, left, and up directions (refer to Figure

13). An additional task to record intermittent blinks was performed by asking the participant to blink when the fixation circle turned off. This process allowed for the separate analyses of each participant's ocular data. With the use of ocular source component techniques, each individual average would have the ocular (EOG) artefacts (i.e. blinks and saccades) removed from the EEG signal by the artefact rejection criteria (Berg & Scherg, 1994; Lins, Picton, Berg, & Scherg, 1993a, 1993b). Principal component analysis was used to analyze each ocular data set and provide a set of components that represented the variance in the EEG correlated to the eye movements. Components that explained more than 5% of the variance and were specifically related to EOG waveforms were used as source components to subtract EOG contamination from the averaged ERPs (Lins et al., 1993a; 1993b). The eye movement program instructions were presented on the screen and the researcher reviewed them with the participant. This was repeated at the end of the experiment so that the total possible successful saccades per direction and total blinks would be ten each.

One advantage of removing ocular source components was that trials contaminated by eye movements were not removed from the data analysis; the artifact correction only removes activity explained by the source activity of the ocular source components retaining the underlying brain activity for analysis.

3 Results

To summarize, the main objectives of this experiment were to determine if (i) flicker had an effect on state anxiety, (ii) flicker had an effect on the behavioural performance and accuracy in the Stroop tasks, (iii) the

electrophysiological response supported the behavioural data, (iv) the amplitudes and peak latencies of the electrophysiological response were affected by the flicker frequencies, and (v) source analysis could localize the current generators for flicker as opposed to the sources which were typically identified for the Stroop task (i.e. anterior cingulate, calcarine fissure). In the Statistics Section, results were organized and presented in keeping with these objectives.

3.1 Data Preparation and Data Cleaning

3.1.1 Stroop ERP

Several peaks were identified in the ERP waveforms (Picton, Lins, & Scherg, 1995; Picton et al., 2000). At parieto-occipital electrodes, the N100 was defined as the maximum negativity between 60 and 100 ms followed by the N200 as the maximum negativity between 170 and 210 ms. The next distinctive feature of the ERP waveform was a P300 parietal positive wave between 300 and 340 ms. For each component, the latency was assessed at the electrode site where the peak was most prominent and individual participant averages and amplitudes for all sites were measured at the peak latency of the right parieto-occipital electrode (PO8; See Figure 17). The amplitude values for each electrode were based on the peak latencies at PO8. Since the parietal peak at P300 was difficult to distinguish in the waveforms for the Stroop colour task, the peak amplitude at PO8 was measured over the same latency ranges as for Stroop word. Mean amplitudes over specific latency periods were also measured at pronounced peaks.

ERPs were originally averaged according to the following conditions: Flicker (0, 100, 500 Hz), Colour (Red, Blue, Green, Yellow), Congruency (Congruent, Incongruent), Accuracy (Correct, Incorrect), Reaction Time (RT), Electrodes, and Task (Word or Colour). When the participant was asked to respond to Word, the participant was to ignore the colour and respond to the word read on the monitor. When the participant was asked to respond to colour, the participant was to ignore the colour of the word and respond only to the colour in which it was written. Since the response accuracy was very high, there were too few incorrect responses to average together, therefore, only the correct responses were analyzed. To simplify analyses and focus only on the effect of flicker, electrodes were grouped into regions of interest (ROI; See and Figure 18) and colour was collapsed across conditions. The final averages included Flicker, Congruency, Reaction Time, ROI, and Task.

3.1.2 Source analysis

The collection of the brain wave information from several electrode locations (68 channels in this study), provided enough information to perform dipole source analysis.

The source analysis was performed using Brain Electric Source Analysis software (BESA v. 5.2.4.48). The analysis used the grand mean waveform recorded from -200 to 1000 ms relative to the onset of the stimulus (Scherg & Picton, 1991). Source analysis was first performed on the grand average of the collapsed colour conditions of each Stroop task (Stroop colour, Stroop word) and was applied to the grand average of all participant averages for each Stroop task

to increase the signal to noise ratio. The dipole sources were fitted using a 4-ellipsoidal head model (thickness – head=85.0, scal*p*=6.0, bone=7.0, csf=1.0; conductivity – brain 0.330, scal*p*=0.330, bone=0.0042, csf=1.0). Two dipoles were positioned one in each hemispheres, posterior to the central sulcus, prior to performing the analysis.

The source analysis was computed over the entire waveform and allowed the dipoles to re-position themselves in accordance with the BESA algorithm. Reliable fit was identified for the -200 to 1000 ms range (See Figure 18). The explained variance (See Table 13) for (i) 60 to 100 ms, (ii) 170 to 210 ms, and (iii) 300 to 340 ms was based on this original fitting and results were stored as separate source solutions. Each solution was then applied to the averages for each of the Stroop tasks and source waveforms (nA) were output for further analysis in SPSS. The SPSS table consisted of the two dipoles (2 levels: Dipole 1 for the right hemisphere, Dipole 2 for the left hemisphere), congruency (2 levels: congruent and incongruent), intervals (4 levels: 60-100 ms, 170-210 ms, 300-340 ms, and -200-1000 ms), and flicker (3 levels: 0, 100, and 500 Hz) for each point of the waveform (i.e. the sampling rate was 2000 Hz therefore the number of points output was 2400 for each dipole).

3.2 Statistics

Mean results were reported with their respective standard deviations in the tables. For all analyses, statistical significance was set at $p<0.05$. The Greenhouse-Geisser epsilon was incorporated into any analysis involving a factor with more than two levels. Post-hoc pairwise comparisons were conducted

using Bonferonni corrections. Repeated measures ANOVAs were used to analyze flicker in the STAI, sentence reading time, Stroop performance and Stroop accuracy.

Initial analyses were performed on behavioural and electrophysiological data using a one-way within-subjects repeated measures ANOVA with three levels of the independent variable FLICKER at 0, 100, and 500 Hz and the dependent measures of ERP amplitudes and latencies, Stroop Reaction Time (RT; ms), and Stroop performance (percent correct). (Note: For all figures and tables, the standard deviation will be reported in brackets.)

3.2.1 The State-Trait Anxiety Inventory

The STAI values (See Table 8 for means and standard deviations) were first analyzed in Excel and then recoded per STAI requirements before statistical analyses in SPSS. The STAI is a 20-question survey which requires a four-point Likert scale response to a state or trait psychological characteristic (depending on the instruction set) with a total minimum score of 20 and maximum score of 80.

In order to determine if any of the flicker rates increased the participant's state anxiety level during a flicker condition, difference scores were computed for the difference between the STAI score (maximum score is 80) at each flicker rate (0,100, 500 Hz) and the condition immediately preceding it. Following this computation, the corrected STAI mean scores (refer to Table 8 for the change in STAI means and standard deviations) were analyzed using a one-way repeated measures ANOVA with CHANGE (3 levels: 0,100,500) and factor ORDER (6

levels: 1, 2, 3, 4, 5, 6) to determine if the STAI changed according to the lighting condition under which the participant was exposed. The possible flicker rate orders were: 0,100,500; 100,0,500; 500,100,0; 0,500,100; 500,0,100; and 100,500,0. In order to calculate the change in anxiety, the other frequencies were subtracted from the initial order. For instance, if the first frequency was 0, then the other frequencies (i.e. 0-pre-test; 0-100 Hz, 0-500 Hz) would be calculated to determine the change in anxiety. Flicker was not significant $F_{(2,64)}<1.0$, therefore, flicker did not affect the participant's anxiety level during the period of time the person was exposed to a particular frequency.

Another method to examine the state of anxiety would be to analyze the scores in the order they were recorded to determine if the experiment itself had an effect on anxiety. BLOCK was not significant ($F_{(3,99)}<1.0$), therefore, the experiment did not increase the participant's anxiety.

In summary, flicker did not affect the participant's anxiety, when corrected for order of presentation and normality, between the anxiety score of one flicker condition and the one immediately preceding it. Furthermore, the anxiety scores were not affected by the experiment procedures.

3.2.2 Sentence reading

In order to analyze reading performance, the interest period duration (IPD) was examined. The rationale for this was that the measurement of sentence reading time began at the offset of the first word and ended with the onset of the last word. Often when a person reads a sentence, the eyes will jitter back and forth over the sentence. In order to obtain a clear start point, the first word

without jitter was captured and the participant was then allowed to read naturally. Once the last word was triggered, the next sentence would be presented. The interest period durations in the reading sentences task were corrected for normality and the statistics re-run on the inverse transforms.

The experimental condition included analysis of the IPD assessed as Last Word Hit minus First Word Hit (ms). The IPDs were averaged over three blocks of 100 trials each for each participant and the means and standard deviations and the corrected means and standard deviations are shown in Figure 20. The IPD was analyzed over the 100 trials with variables FLICKER (0, 100, 500) and ORDER (refer to Table 8 for the sentence reading means and standard deviations).

One-way within subjects repeated measures ANOVA corrected for normality on sentence reading speed as the Interest Period Duration (IPD) was calculated on the interest period of the right eye for the variable FLICKER (0, 100, 500 Hz) to determine if flicker affected sentence reading under the different lighting conditions. Due to a programming error, the analysis for this task is for the right eye only. There was no main effect of FLICKER rate for IPD for the right eye ($F_{(2,66)}$=1.134, p=0.328). The IPD was then analyzed to see if there were any order effects or gender differences in reading time over the interest period though this was unlikely. An independent samples t-test was performed to determine if any GENDER (t_{32}=0.792, t_{32}=0.642, t_{32}=0.204 for 0, 100, and 500 Hz respectively) differences or ORDER ($F_{5,28}$=1.603, p=0.192) of presentation effects existed at each flicker rate. Neither GENDER nor ORDER effects were

significant indicating no difference between male and female response scores for sentence reading speed under each flicker condition and no effect of ORDER for presentation of flicker rates. Thus, the results indicate that there were no differences in the reading speed in the interest period duration for the right eye under the different lighting conditions.

3.2.3 Stroop

An initial t-test to determine if the colour mapping practice session was the same for both tasks revealed ($t_{(13)}$=1.64,p=0.125) no significant differences in the colour mapping between the word mapping or colour mapping which indicates that participants performed equally well on the key-to-colour mapping trials. Even though participants could not see the gamepad to make responses, they pressed the correct keys for the coloured words presented on the monitor.

A within-subjects repeated measures ANOVA design with dependent variables, speed and accuracy, and independent variable FLICKER (0, 100, 500), with factors of TASK (Word, Colour) and CONGRUENCY (Congruent, Incongruent) were used to examine these data. For the mean speed difference in performance of all the incongruent trials less the mean speed in performance on the congruent trials in a given flicker condition were assessed and analyzed in SPSS. For speed in a given flicker condition, the calculation was as follows:

$$(100 * \frac{\mathrm{SUM(correct\ incongruent\ trial\ times)}}{\mathrm{N(correct\ incongruent\ trials)}} - (100 * \frac{\mathrm{SUM(correct\ congruent\ trial\ times)}}{\mathrm{N(correct\ congruent\ trials)}}$$

Similarly, for Stroop accuracy in a given flicker condition and corrected for normality, the dependent variable was (mean incongruent Accuracy) - (mean congruent Accuracy).

Higher positive values in the Stroop speed or accuracy meant that participants responded better on congruent trials as would be expected. If the number was zero, then the congruency variable did not have an impact on answering the trials differently.

The Stroop behavioural mean processing cost (See Table 9) indicated that when participants responded to colour, the incongruence was more difficult than when responding to word. The processing cost for word was lowest at 100 Hz which was not as expected.

In order to investigate the RTs in the colour and word tasks, one-way repeated-measures ANOVA was performed on the mean RTs, corrected for normality, in the Stroop task to determine if FLICKER (0, 100, 500) had an effect on Stroop mean RTs. The main effect for FLICKER ($F_{(2,66)}$<1.0) was not significant indicating no effect of flicker on the mean RTs. The participants showed similar response times for all lighting conditions (See Figure 22).

The Stroop behavioural scores for mean accuracy, as shown in Table 10, revealed that 500 Hz seemed to be consistently better than 0 and 100 Hz for all flicker conditions. Furthermore, the participants appeared to respond more accurately to the word than the colour task.

In order to examine these possibilities, a one-way repeated-measures ANOVA was performed on the mean difference in accuracy scores in the Stroop

task, corrected for normality, to determine if flicker had an effect on Stroop performance regardless of colour. The estimated marginal means of the inverse transformed data show that the means (See Table 10) were trending toward a quadratic with 500 Hz having the least negative value (i.e. the least and lowest difference in performance), then 0 and finally 100 Hz (See Figure 23). The main effect for FLICKER ($F_{(2,58)}$=2.961, p=0.06) approached significance with a quadratic trend ($F_{(1, 29)}$=3.441, p=0.07) also approaching significance. Thus, this pattern of results indicated that mean performance may be better for 500 Hz than for the other flicker conditions.

A paired samples t-test was then performed to examine the differences between the 500 Hz flicker rate and the 0 and 100 Hz flicker rates respectively. The difference in flicker rate was statistically significant ($t_{(33)}$=2.17, p<0.05) between 0 and 500 Hz as well as 100 and 500 Hz ($t_{(33)}$=2.93, p<0.05). Thus, this pattern of results confirmed that the processing cost for 500 Hz was lower to the incongruent trials as compared with 0 Hz or with 100 Hz but there was no difference between 0 and 100 Hz. A univariate ANOVA was run to test if ORDER of flicker rate affected performance. There were no main effects for ORDER ($F_{(5,24)}$ =0.753, p=0.592) indicating that the order in which the flicker was presented did not confound the findings.

3.2.4 Electrophysiological data

3.2.4.1 Peaks and latencies

The peak amplitudes for the correct trials were selected on a fixed interval 40 ms around the peak of the right parieto-occipital electrode (PO8, refer to

Figure 17) as it showed the most defined peaks for N1, N2, and P3 in the grand average waveform (See Figure 24). A grand average for each Stroop task (i.e. colour and word) was computed by collapsing the data across all colour or word conditions for each flicker rate and used for the peak and latency measures. Intervals of 60-100 ms, 170-210 ms, and 300-340 ms were used to capture the largest peak deflections corresponding to N1, N2, and P3. For each participant, the greatest peak deflection within each of these ranges is computed and stored as a peak latency measure for all the channels.

Ocular channels were not included in this analysis due to possible contamination by eye movements.

For Stroop Colour, a 3 x 3 x 9 repeated measures ANOVA was conducted on the factors: INTERVAL (3 levels: 60-100 ms, 170-210 ms, 300-340 ms), FLICKER (3 levels: 0 Hz, 100 Hz, 500 Hz) and REGION (9 levels: RF, RTm, RP, RO, LF, LTm, LP, LO, Midline) to determine if flicker affected the amplitude of the peak response at each of the intervals for the groups of electrodes within a region (See Figure 18).

There were significant quadratic trends for INTERVAL ($F_{(1, 33)}$=119.38, p<0.05), and REGION ($F_{(1, 33)}$=65.34, p<0.05) because the ERP changes polarity at different latencies and over different brain regions (refer to Table 11 for means and standard deviations). A quadratic trend ($F_{(1,33)}$=12.50, p<0.05) was significant for the INTERVAL x REGION interaction. There were no other significant interactions and no main effects of luminous modulation for Stroop Colour. There were significant main effects for INTERVAL ($F_{(2, 66)}$=56.92, p<0.05), REGION ($F_{(8,}$

$_{264)}$ = 55.18, p<0.05) and an INTERVAL x REGION interaction ($F_{(16, 528)}$=57.44, p<0.05). Since the interval corresponds well with the region and the interaction is significant, this indicates that the polarities at the different regions for the different intervals correspond accurately for the Stroop colour task.

For Stroop colour, the lowest activations appeared to be for the earliest (60-100 ms) interval. The 170-210 ms interval showed some very large mean amplitudes at the occipital and frontal sites. The 300-340 ms interval showed the largest mean amplitude at the left temporal region. Also, the selected sites (See Figure 29), showed frontal channels had more positive deflection for 500 Hz response at 330 ms and this was maintained to the end of the epoch.

For Stroop Word, the 3 x 3 x 9 repeated measures ANOVA was repeated on INTERVAL (3 levels: 60-100 ms, 170-210 ms, 300-340 ms), FLICKER (3 levels: 0 Hz, 100 Hz, 500 Hz) and REGION (9 levels: RF, RTm, RP, RO, LF, LTm, LP, LO, Midline).

There were significant quadratic trends for INTERVAL ($F_{(1, 33)}$=123.08, p<0.05), and REGION ($F_{(1, 33)}$=75.70) and a quadratic trend was significant for the INTERVAL x REGION interaction ($F_{(1,33)}$=12.50, p<0.05). There were significant main effects for Interval ($F_{(2, 66)}$=70.31, p<0.05), Region ($F_{(8, 264)}$ = 60.39, p<0.05) and an INTERVAL x REGION interaction ($F_{(16, 528)}$=63.75, p<0.05) (refer to Table 12 for means and standard deviations). There were no other significant interactions. Therefore, again the interval corresponds well to the electrodes selected for that region in the Stroop Word task.

In the figure above, the 60-100 ms and 300-340 ms have the smallest mean amplitudes at all brain regions. The 170-210 ms interval showed large responses at occipital and frontal electrodes (See Figure 30). There was no effect of flicker on Stroop colour or Stroop word.

3.2.4.2 ERP correct trials

Correct trials were chosen for this analysis because the interest was in determining if FLICKER had an effect on performance even under optimum conditions by only examining the correct trials.

Observational review of the ERPs for the Stroop Colour showed some small differences at frontal (F7, AF4), temporal (Tp10), parietal (PO8), and cerebellar (Cb1) sites (See Figures 25 and 26).

The 500 Hz response consistently showed a more negative deflection than 0 or 100 Hz at frontal (Fz), temporal (Tp9, Tp10), parietal (PO7, PO8), and occipital sites (O1, O2) for 300 ms latency. There was a sustained negative deflection for the late potential starting at about 550 ms to 1000 ms (See Figures 27 and 28).

3.3 Source Analysis

3.3.1 Localizations

A grand average (See Figures 31 and 32) for each Stroop task was computed by collapsing the data across all colour or word conditions and all flicker rates and used for the source solution to localize activity in the brain. A source solution was computed using the entire waveform from -200 to 1000 ms. This solution was stored and 40 ms intervals were selected as additional

solutions at 60-100 ms, 170-210 ms, and 300-340 ms. Each solution was applied to each participant's correct and incorrect averaged waveform in each of the Stroop tasks. The 40 ms interval was used to capture the peak activation without overlapping latencies. For Stroop Colour the intervals were: -200-1000 ms (i.e. entire epoch), 60-100 ms, and 170-210 ms corresponding to peak latencies of 80 and 190 ms, respectively. Latencies for the source waveforms for the Stroop Word task were: -200-1000 (i.e. entire epoch), 60-100 ms, 170-210 ms, and 300-340 ms corresponding to the added peak latency of 320 ms.

Over the 60-100 ms range (see Figure 33), for both tasks, Stroop colour and word, the right dipole localized to the mid-temporal gyrus and the left dipole to the supramarginal gyrus. The upper panels show the source waveforms for each task (Colour, Word) and for the right dipole (Red) and the left dipole (Blue). The lower panel shows the equivalent current dipole localization in an average MRI.

Over the 170-210 ms range (see Figure 34), for Stroop colour, the right dipole localized to the mid-temporal gyrus and the left dipole to the left temporal lobe. For Stroop word the right and left dipoles localized to their respective temporal lobe. The upper panels show the source waveforms for each task (Colour, Word) and for the right dipole (Red) and the left dipole (Blue). The lower panel showed the equivalent current dipole localization in an average MRI.

Figure 35 shows the 300-340 ms range for Stroop word, the right dipole localized to the tuber of vermis whereas the left dipole localized to the mid-frontal gyrus (MFG).

Figure 36, for the -200-1000 ms in the Stroop colour condition, showed the right dipole (Red) source localized to the right pulvinar of the thalamus and the left dipole (Blue) to the left temporal lobe, whereas for Stroop word over the same interval, the right dipole (Red) source localized to the right posterior cingulate.

Over the entire waveform for the Stroop colour task, the right dipole localized to the right lateral pulvinar nucleus of the thalamus and the left dipole to the left temporal lobe.

Therefore, to summarize, source analysis showed that the sources start in the same regions in both hemispheres (i.e. SMG and MTG) move to the temporal lobe and then to the MFG for Stroop word only. However, the localization of the entire epoch showed activation in the right pulvinar and the left temporal lobe for colour and the right posterior cingulate for word.

3.3.2 Source statistics

To test the localizations for Stroop Colour, a 2 x 2 x 2 x 3 repeated measures ANOVA was performed with DIPOLE (2 levels: dipole 1 corresponding to the right hemisphere, dipole 2 corresponding to the left hemisphere), CONGRUENCY (2 levels: incongruent, congruent), INTERVAL (2 levels: 60-100, 170-210 ms), and FLICKER (3 levels: 0, 100, 500 Hz) to see if flicker had an effect at the intervals of interest and if there were any interactions with the other variables. A DIPOLE x FLICKER interaction could be seen and showed that 500 Hz consistently had the lowest values for dipole moments (nA; See Table 12).

There was a quadratic effect for FLICKER ($F_{(1,23)}$=5.23, p<0.05, η^2=0.20). The pairwise comparison (See Table 15) showed that the difference between 100 and 500 Hz was significant.

There was also a quadratic interaction (See Figure 38) between DIPOLE and FLICKER ($F_{(2, 46)}$, p<0.05, η^2=0.30). In the left hemisphere, the 500 Hz had the lowest mean dipole (i.e. right, left) moment (DM) and 100 Hz had the highest activation. In the right hemisphere, the 500 Hz again had the lowest mean DM but the difference with the other flicker rates was not significant (See Table 14 and Figure 37 upper frame). The mean dipole moments for the right hemisphere were very close together with 0 Hz having the highest DM followed by 100 Hz and finally 500 Hz. All activations were higher for the left than the right hemisphere.

In Figure 37, the interaction between DIPOLE, CONGRUENCY and FLICKER appeared to approach significance ($F_{(1,23)}$=3.97, p=0.06, η^2=0.20).

These figures showed that in the left hemisphere the 100 Hz flicker rate had a greater mean DM difference between congruent and incongruent whereas in the right hemisphere it was 0 Hz. In both hemispheres, 500 Hz had the lowest mean DMs indicating that this frequency's DM did not change very much between congruent and incongruent conditions (i.e. the task was about the same). The congruent mean DMs were very similar in both hemispheres whereas the incongruent had more distributed mean DMs at the three flicker rates.

In order to further examine the relationships in Figure 37, a paired samples t-test for Stroop colour congruent in the right hemisphere between 500 and 100 Hz was performed for the interval 170-210 ms which proved significant ($t_{(23)}$=-2.16, p<0.05). For the left hemisphere, the t-test proved significant for incongruent for 60-100 ms ($t_{(23)}$=-2.00, p<0.05) and 170-210 ms ($t_{(23)}$=-2.44, p<0.05). The paired samples t-tests showed significance in the right hemisphere at 170-210 ms in the congruent task and in the left hemisphere for both early latency periods in the incongruent task (See Table 16).

There were also interactions between CONGRUENCY and DIPOLE ($F_{(1,23)}$=6.94, p<0.05) and main effects for CONGRUENCY ($F_{(1,23)}$=10.58, p<0.05) and FLICKER ($F_{(2,46)}$=3.98, p<0.05) but no main effect of DIPOLE ($F_{(1,23)}$=1.40, p=0.25).

There were no other interactions or main effects. Thus, this pattern of results indicates that flicker and congruency have separate effects on the mean dipole moments indicating different effects in each hemisphere. This information also matches well with the processing cost data of the Stroop task where 500 Hz showed the better processing cost for the congruent condition compared with 0 and 100 Hz.

The same analyses were applied to Stroop word. Since there were several significant main effects and interactions, the focus will be on those that involved flicker. There was no main effect of flicker, however, the interaction between DIPOLE and FLICKER was again highly significant ($F_{(2, 46)}$=31.61, p<0.000). There was no interaction between CONGRUENCY and FLICKER, however,

when DIPOLE was added, the 3-way interaction was highly significant ($F_{(2, 46)}$=41.12, p<0.000). The interaction of FLICKER and Interval was also highly significant ($F_{(2, 46)}$=22.70, p<0.000) and an interaction between DIPOLE and Interval and FLICKER was also significant ($F_{(2, 46)}$=8.85, p<0.05). The interaction between CONGRUENCY, INTERVAL, and FLICKER was highly significant ($F_{(2, 46)}$=31.81, p<0.000) and finally a four way interaction of DIPOLE, CONGRUENCY, Interval and FLICKER was highly significant ($F_{(2, 46)}$=17.69, p<0.000). These results indicate that there was a difference between the two groups of congruency (i.e. congruent and incongruent), that these differences were also related to the hemispheres and the flicker conditions with the mean dipole moments (i.e. brain activity) significantly higher in the left than the right hemisphere and much higher activation at 100 Hz than at the other frequencies. This may mean that it required more effort to adhere to the task demands under the 100 Hz lighting frequency.

4 Discussion

In this experiment, the role of flicker rate at three frequencies was examined to verify whether flicker adversely affected reading speed in a sentence reading task, reaction time or accuracy when completing the Stroop task. An additional goal was to determine if source generators could be localized, using equivalent current dipole analysis, for the different flicker frequencies and if these were possibly associated with the reduction in performance previously reported in other studies. Three lines of evidence were examined.

First, the behavioural scores were reviewed and statistically analyzed to see if the trends could be seen behaviourally even within the short time the participants were exposed to the flicker. Behavioural measures were gathered with an anxiety survey, a measure of performance and accuracy using the Stroop task and an additional performance score in a sentence reading task. Statistics were performed on the anxiety measures and showed that there were no significant responses to flicker for state anxiety. The participants' anxiety level did not change throughout the experiment differences; however, this may likely be due to insufficient exposure time to the stimulus. In addition, the sentence reading showed no effect of flicker.

Recent research by Vanagaite et al. (1997) performed CFF sensitivity threshold tests on migraineurs and controls and found a significant group difference between migraineurs and controls such that control participants had the highest CFF threshold whereas migraineurs had the lowest.

A new migraine study by Thabet's group (2013) examined the sites of abnormal sensitivity in the visual system and found that individuals who were not affected by migraines showed gradual adaptation or reduced sensitivity to an intense flickering light, while sensitivity increased with repetition for individuals prone to migraines.

They suggest the 'abnormality' may occur when the information is conveyed into the visual cortex or at an earlier point on the pathway from the retina to the visual cortex — either in the thalamus or in the retina itself. Lower

CFF thresholds may mean some individuals do not have the ability to filter flicker effectively.

Processing cost as measured by the response times in the Stroop task also showed no significant results. The last behavioural analysis performed tested accuracy in the Stroop task on the difference between incongruent and congruent trials. There were significant results with respect to the 500 Hz which indicate that participants responded better to the incongruent trials at this frequency. The 500 Hz flicker was significantly different from both 0 and 100 Hz, whereas, the 0 and 100 Hz flicker rates were not dissimilar from each other. In terms of accuracy during this simple cognitive task, it was less difficult for participants to maintain their cognitive focus at 500 Hz than at the other two frequencies.

Next, the ERPs were analyzed to determine if results from the peak analyses would support the behavioural responses found for Stroop accuracy. The early latencies of the ERP were examined because these latencies occur prior to the decision making process in the Stroop task (P300 from 300-340 ms in this task). The early peaks examined occurred at 80 ms post-stimulus (N1) and 190 ms (N2). The positive-going peak at 320 ms (P3) was also assessed to ensure that the Stroop effects occurred as expected. The P300 interval was still considered relevant as there may be evidence of interference by the flicker condition. The analysis of the peak latencies indicated that the intervals chosen corresponded well with the regions in which the electrodes were grouped,

however, there did not appear to be an effect of flicker for peaks and latency measures.

Finally, an equivalent dipole source analysis was run to determine where the activity was occurring in the brain for specific peak latencies of 80, 190, and 320 ms. The brain sources revealed some intriguing information with regard to neural correlates of flicker effects. The earliest component (60-100 ms) localized to the midtemporal gyrus and the supramarginal gyrus (SMG) in each hemisphere for each task (See Figure 33). The inferior parietal lobe is important in recognizing words presented in the visual domain and the SMG is one of the two main subdivisions of the IPL which may be involved with the phonological and semantic processing of words (Stoeckel, Gough, Watkins, & Devlin, 2009). Lesions in the SMG may cause receptive aphasia or transcortical sensory aphasia (Stoeckel Gough, Watkins, & Devlin, 2009). This may provide evidence that both tasks (i.e. colour and word) appear to affect the brain in the same manner early on in the Stroop task in both hemispheres. They suggest that the SMG has a role in reading the word even if the task does not require it and activation in this region may be due to processing automatically the sound of the word as would be the case in a computerized version of the Stroop task.

During the 170-210 ms interval, activation in the right hemisphere remained at the midtemporal gyrus for the colour task but moved to the temporal lobe for the word task for both dipoles (see Figure 34). In the colour task, only the left dipole activated the left temporal lobe. The temporal lobe contains Wernicke's

area and has been known to be involved with the understanding of words (Wernicke, 1994).

In the 300-340 ms interval, a good localization could not be achieved for the colour task, however, the word task (See Figure 35) showed clear activation at the mid-frontal gyrus and the tuber of vermis. Brain activation in the Stroop task has been found to occur typically in the anterior cingulate (Pardo, Pardo, Janer, & Raichle, 1990; Petersen et al., 1999), insula (Allen et al., 2012), inferior frontal gyrus (Taylor, Kornblum, Lauber, Minoshima, & Koeppe, 1997), parietal and mid-temporal regions (Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000; West, 2003). A Stroop-fMRI study by Adleman et al., (2002) examined young adult participants in the same age range as in this experiment and found significant activation in the mid-frontal gyrus supporting the dipole source analysis results as activation due to the Stroop task.

The activation of the tuber of vermis (See Figure 35) is interesting because this structure is believed to be responsible for proprioception (i.e. the ability to guide the body's positioning, location, and orientation for movement; (Coffman, Dum, & Strick, 2011). This is relevant in this experiment because at 300-340 ms, the decision has been made to make a response and the participant was unable to see the gamepad on which responses were made. Activation of the vermis could be interpreted as evidence that the participant was guiding the hand and fingers to make the response.

4.1 What These Results Mean in Terms of Performance

Participants performed better in the congruent than the incongruent task regardless of lighting condition but the difference between incongruent and congruent was lower for 500 Hz which may mean that participants were more alert and could perform incongruent tasks at almost the same accuracy as congruent tasks.

One of this experiment's assumptions was that the secondary visual system (See Figure 1) would be activated by imperceptible flicker because research (Brindley, 1962; Eysel & Burandt, 1984) has shown that the visual system responds to frequencies beyond the CFF. This was shown in the source analysis over the entire epoch (i.e. -200-1000 ms). The localization to the pulvinar of the thalamus (See Figure 36) for the right hemisphere was significant with respect to the secondary visual system. (Casanova, 2004) suggested that the pulvinar was not just a passive relay for the visual system but has extensive bidirectional connections in cortico-thalamo-cortical loops. The dense connectivity with many cortical areas has recently been found to regulate the transmission of information across the visual cortex (Saalmann, Pinsk, Wang, Li, & Kastner, 2012). In a diffusion tensor imaging study, Saalmann et al. examined spikes and field potentials in monkeys performing a visuospatial attention task. They found that the pulvinar synchronized thalamic activity for attentional processes and for regulating the transmission of information across the visual cortex.

The pulvinar also has inputs from the superior colliculus which are important in the control of eye movements (Berman & Wurtz, 2011; Robinson &

Petersen, 1985), and the regulation of visual attention (Petersen, Robinson, & Morris, 1987; Chalupa, 1991).

Finally, Pessoa & Adolphs (2010) suggested that affective visual stimuli can be processed non-consciously through the subcortical pathway via the superior colliculus and pulvinar to the amygdala. They further surmise that both the amygdala and pulvinar interact to interpret affective stimuli that have biological significance. Flicker, even though not consciously perceived, may nevertheless be detected and its interpretation may lead to stimulation of other subcortical pathways such as the amygdala. Projecting this theoretical interpretation onto the effects of flicker would assist in the explanation for feelings of malaise and asthenopia experienced by some individuals. Asthenopia is an ophthalmological condition which occurs when an individual is affected by light flicker and develops ocular strain, pain or fatigue in the eyes, malaise, and/or headaches (Veitch & McColl, 1995; Sheedy et al., 2003; Saks, 2011). This experiment did not specifically measure discomfort, per se; however, the source analysis clearly indicates pulvinar activation (Maleki, Becerra, Upadhyay, Burstein, & Borsook, 2012).

4.2 Assumptions

The source activation was considered to indicate that the brain was responding to the stimulus of the task.

The increased activation was considered to indicate more neural resources thus more effort to complete the task.

Decreased activation was considered to indicate the task was easier to perform as fewer neural resources were required.

4.3 Limitations and Future Directions

4.3.1 Limitations

The STAI may not be as sensitive an instrument as may have been needed for this experiment and four repetitions tended to encourage participants to attempt to memorize the previous response and match responses rather than self-assessing at this point in time. Perhaps by reducing repetitions, selecting different comparable anxiety questions for each block, and longer stimulus exposure would improve this survey. Although the measure effectively determined the anxiety state of the participant prior to the experiment, it was unable to detect any anxiety changes during the task phase of the experiment.

Source analysis, similar to questionnaires and subjective reports, requires supporting information from other imaging techniques (e.g., functional magnetic resonance imaging, transcranial magnetic stimulation, etc.) to verify the results.

4.3.2 Future directions

The extensive data collected in this experiment allows for several avenues of research that could likely support the results including:

Examine eye tracking results for both Stroop and sentence reading to show differences in the number of blinks, saccades, and fixations under the different lighting conditions with the least difference under the 500 Hz condition.

A rest phase was recorded for this experiment and the results could be used to examine frequency differences after each of the different lighting conditions.

Further calculations to examine each eye individually and both eyes together for drift, fixations, and saccade frequency for the Stroop and sentence reading tasks could provide useful insight into the physical demands under different lighting frequencies. Analysis of the blinks and saccades for amplitudes and frequencies under each lighting condition could provide additional positive affirmation of these results.

Stroop difference wave results could provide confirmatory evidence for the source localizations for later intervals, should these be explored.

Other additional directions for this body of research could include investigating the visual evoked potential under the different lighting frequencies. Combined with ERGs, these tools can provide further insight into the effects of flicker on human cognitive processing and may help explain the possible harmful health effects experienced by some people.

One final direction that may prove enlightening would be to repeat this study in older adults to see if the effects are similar or more pronounced in an elderly population. It has been suggested that flicker does not affect the elderly as strongly as young people (Lindner & Kropf, 1993; Brundrett, 1974), however, this assessment may not be accurate.

In conclusion, the results of this experiment show that there was an effect of flicker at 500 Hz such that participants performed about the same for

congruent and incongruent tasks. The 500 Hz response may suggest that participants were more vigilant or required less neural resources and thus better able to perform the incongruent tasks. For 100 Hz, participants had more difficulty performing the incongruent task under this lighting condition suggesting that flicker of this frequency interfered with visual performance in the Stroop task. Furthermore, the behavioural trends for accuracy support the source analysis results even though the exposure to each light frequency stimulus was minimal. The amount of time under each lighting condition was only about 15 minutes per lighting condition; however, even with this short exposure, the data suggest important influences of flicker on performance and brain outcomes, particularly in the left hemisphere.

5 References

Adleman, N. E., Menon, V., Blasey, C. M., White, C. D., Warsofsky, I. S., Glover, G. H., & Reiss, A. L. (2002). A developmental fMRI study of the Stroop color-word task. *NeuroImage*, *16*(1), 61–75. doi:10.1006/nimg.2001.1046

Allen, M., Dietz, M., Blair, K. S., van Beek, M., Rees, G., Vestergaard-Poulsen, P., Lutz, A., Roepstorff, A. (2012). Cognitive-affective neural plasticity following active-controlled mindfulness intervention. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *32*(44), 15601–10. doi:10.1523/JNEUROSCI.2957-12.2012

American Electroencephalographic Society guidelines for standard electrode position nomenclature. (1991). *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *8*(2), 200–2. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2050819

Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., & Erbaugh, J. (1961). An inventory for measuring depression. *Archives of General Psychiatry*, *4*, 561–71. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/13688369

Berg, P., & Scherg, M. (1994). A fast method for forward computation of multiple-shell spherical head models. *Electroencephalography and clinical Neurophysiology*, *90*(1), 58–64. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/7509274

Berman, R. A., & Wurtz, R. H. (2011). Signals conveyed in the pulvinar pathway from superior colliculus to cortical area MT. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *31*(2), 373–384. doi:10.1523/JNEUROSCI.4738-10.2011

Berman, S. M., Greenhouse, D. S., Bailey, I. L., Clear, R. D., & Raasch, T. W. (1991). Human electroretinogram responses to video displays, fluorescent lighting, and other high frequency sources. *Optometry and Vision Science : Official Publication of the American Academy of Optometry*, *68*(8), 645–662. Retrieved from http://journals.lww.com/optvissci/abstract/1991/08000/human_electroretinogram_responses_to_video.12.aspx

Binnie, C. D., de Korte, R. A., & Wisman, T. (1979). Fluorescent lighting and epilepsy. *Epilepsia*, *20*(6), 725–727. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/499117

Bridge, H., Hicks, S. L., Xie, J., Okell, T. W., Mannan, S., Alexander, I., Cowey, A., Kennard, C. (2010). Visual activation of extra-striate cortex in the absence of V1 activation. *Neuropsychologia*, *48*(14), 4148–4154. doi:10.1016/j.neuropsychologia.2010.10.022

Brindley, B. G. S. (1962). Beats produced by simultaneous stimulation of the human eye with intermittent light and intermittent or alternating electric current. *Journal of Physiology*, *164*, 157–167.

Brundrett, G. (1974). Human sensitivity to flicker. *Lighting Research and Technology*, *6*(3), 127–143. doi:10.1177/096032717400600302

Buchner, H., Gobbelé, R., Wagner, M., Fuchs, M., Waberski, T. D., & Beckmann, R. (1997). Fast visual evoked potential input into human area V5. *Neuroreport*, *8*(11), 2419–2422. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9261801

Burns, S. A., Elsner, A. E., & Kreitz, M. R. (1992). Analysis of nonlinearities in the flicker ERG. *Optometry and Vision Science : Official Publication of the American Academy of Optometry*, *69*(2), 95–105. Retrieved from http://journals.lww.com/optvissci/Abstract/1992/02000/Analysis_of_Nonlinearities_in_the_Flicker_ERG.2.aspx

Casanova, C. (2004). The visual functions of the pulvinar. In r J. S. Werne & L. M. Chalupa (Eds.), *The Visual Neurosciences* (Vol. 1, pp. 592–608). Cambridge, Massachusetts: MIT Press.

Chalupa, L. M. (1991). Visual function of the pulvinar. In B. Dreher & S. P. Robinson (Eds.), *Vision and Visual Dysfunction: The Neural Basis of Visual Function* (pp. 140–159). Boca Raton, FL: CRC Press.

Coffman, K. A., Dum, R. P., & Strick, P. L. (2011). Cerebellar vermis is a target of projections from the motor areas in the cerebral cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(38), 16068–16073. doi:10.1073/pnas.1107904108

De Lange Dzn, H. (1961). Eye's Response at Flicker Fusion to Square-Wave Modulation of a Test Field Surrounded by a Large Steady Field of Equal Mean Luminance. *Journal of the Optical Society of America*, *51*(4), 415. doi:10.1364/JOSA.51.000415

Electronic Ballasts. (2000). *National Lighting Product Information Program*, *8*(1), 1–32.

Evans, J. E., Cuthill, I. C., & Bennett, A. T. D. (2006). The effect of flicker from fluorescent lights on mate choice in captive birds. *Animal Behaviour*, *72*(2), 393–400. doi:10.1016/j.anbehav.2005.10.031

Eysel, U. T., & Burandt, U. (1984). Fluorescent tube light evokes flicker responses in visual neurons. *Vision Research*, *24*(9), 943–948. doi:10.1016/0042-6989(84)90069-5

Eysenck, M. W., & Keane, M. T. (2005). *Cognitive Psychology: A Student's Handbook*. (M. W. Eysenck & M. T. Keane, Eds.) (6th ed., p. 656). Hove, East Sussex: Psychology Press.

Fisher, R. S., Harding, G., Erba, G., Barkley, G. L., & Wilkins, A. (2005). Photic- and pattern-induced seizures: a review for the Epilepsy Foundation of America Working Group. *Epilepsia*, *46*(9), 1426–1441. doi:10.1111/j.1528-1167.2005.31405.x

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, *15*(1), 20–25. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1374953

Haddad, G., & Winterson, B. (1975). Effect of flicker on oculomotor performance. In G. Lennerstrand & R. Bach-Y-Rita (Eds.), *Basic Mechanisms of Ocular Motility and their Clinical Implications* (pp. 489–493). New York: Pergamon Oxford. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Effect+of+flicker+on+oculomotor+performance#0

Harding, G. F. A, & Harding, P. F. (2010). Photosensitive epilepsy and image safety. *Applied Ergonomics*, *41*(4), 504–508. doi:10.1016/j.apergo.2008.08.005

Harding, G. F. A., & Jeavons, P. M. (1994). *Photosensitive Epilepsy*. (G. F. A. H. P. M. Jeavons, Ed.) (New ed., p. 182). London, UK: Mac Keith Press.

Harding, G., Harding, P., & Wilkins, A. (2008). Wind turbines, flicker, and photosensitive epilepsy: characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them. *Epilepsia*, *49*(6), 1095–8. doi:10.1111/j.1528-1167.2008.01563.x

Ishiguro, Y., Takada, H., Watanabe, K., Okumura, A., Aso, K., & Ishikawa, T. (2004). A follow-up survey on seizures induced by animated cartoon TV

program “Pocket Monster”. *Epilepsia*, *45*(4), 377–383. doi:10.1111/j.0013-9580.2004.18903.x

Jaen, E., Colombo, E., & Kirschbaum, C. (2011). A simple visual task to assess flicker effects on visual performance. *Lighting Research and Technology*, *43*(4), 457–471. doi:10.1177/1477153511405409

Jaen, M., Sandoval, J., Colombo, E., & Troscianko, T. (2005). Office workers visual performance and temporal modulation of fluorescent lighting. *Leukos*, *1*(4), 27–46.

Jarvis, J. R., Prescott, N. B., & Wathes, C. M. (2003). A mechanistic inter-species comparison of flicker sensitivity. *Vision Research*, *43*(16), 1723–1734. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12818343

Küller, R., & Laike, T. (1998). The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal. *Ergonomics*, *41*(4), 433–447. doi:10.1080/001401398186928

Küller, R., & Wetterberg, L. (1993). 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*(2), 71–80. doi:10.1177/096032719302500203

Laubli, T., Hunting, W., & Grandjean, E. (1980). Visual impairments in VDU operators related to environmental conditions. In E. Grandjean & E. Vigliani

(Eds.), *Ergonomic Aspects of Visual Display Terminals* (pp. 85–94). London, UK: Taylor & Francis.

Leh, S. E., Chakravarty, M. M., & Ptito, A. (2008). The connectivity of the human pulvinar: a diffusion tensor imaging tractography study. *International Journal of Biomedical Imaging*, *2008*, 789539. doi:10.1155/2008/789539

Leung, H. C., Skudlarski, P., Gatenby, J. C., Peterson, B. S., & Gore, J. C. (2000). An event-related functional MRI study of the stroop color word interference task. *Cerebral Cortex (New York, N.Y. : 1991)*, *10*(6), 552–560. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10859133

Lindner, H., & Kropf, S. (1993). Asthenopic complaints associated with fluorescent lamp illumination (FLI): The role of individual disposition. *Lighting Research and Technology*, *25*(2), 59–69. doi:10.1177/096032719302500202

Lins, O. G., Picton, T. W., Berg, P., & Scherg, M. (1993). Ocular artifacts in EEG and event-related potentials. I: Scalp topography. *Brain Topography*, *6*(1), 51–63. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8260327

Maddocks, S. A, Goldsmith, A. R., & Cuthill, I. C. (2001). The influence of flicker rate on plasma corticosterone levels of European starlings, Sturnus vulgaris. *General and Comparative Endocrinology*, *124*(3), 315–320. doi:10.1006/gcen.2001.7718

Maleki, N., Becerra, L., Upadhyay, J., Burstein, R., & Borsook, D. (2012). Direct optic nerve pulvinar connections defined by diffusion MR tractography in humans: implications for photophobia. *Human Brain Mapping*, *33*(1), 75–88. doi:10.1002/hbm.21194

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/5146491

Pardo, J. V, Pardo, P. J., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proceedings of the National Academy of Sciences of the United States of America*, *87*(1), 256–259. Retrieved from http://www.pnas.org/content/87/1/256.short

Pessoa, L., & Adolphs, R. (2010). Emotion processing and the amygdala: from a “low road” to “many roads” of evaluating biological significance. *Nature reviews. Neuroscience*, *11*(11), 773–783. doi:10.1038/nrn2920

Petersen, S. E., Robinson, D. L., & Morris, J. D. (1987). Contributions of the pulvinar to visual spatial attention. *Neuropsychologia*, *25*(1A), 97–105. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3574654

Peterson, B. S., Skudlarski, P., Gatenby, J. C., Zhang, H., Anderson, A. W., & Gore, J. C. (1999). An fMRI study of Stroop word-color interference: evidence for cingulate subregions subserving multiple distributed attentional

systems. *Biological Psychiatry*, *45*(10), 1237–1258. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10349031

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology*, *37*(2), 127–152. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10731765

Picton, Terence W., Lins, O. G., & Scherg, M. (1995). The recording and analysis of event-related potentials. In F. Boller & J. Grafman (Eds.), *Handbook of Neuropsychology* (Vol. 10, pp. 3–73). Amsterdam: Elseviier Science B.V.

Probst, T., Plendl, H., Paulus, W., Wist, E. R., & Scherg, M. (1993). Identification of the visual motion area (area V5) in the human brain by dipole source analysis. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *93*(2), 345–351. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8491274

Roberts, J. E., & Wilkins, A. J. (2012). Flicker can be perceived during saccades at frequencies in excess of 1 kHz. *Lighting Research and Technology*, *45*(1), 124–132. doi:10.1177/1477153512436367

Robinson, D. L., & Petersen, S. E. (1985). Responses of pulvinar neurons to real and self-induced stimulus movement. *Brain Research*, *338*(2), 392–394. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4027606

Rothauser, E. H., Chapman, W. D., Guttman, N., Hecker, M. H. L., Nordby, K. S., Silbiger, H. R., Urbanek, G. E., & Weinstock, M. (1969). IEEE Recommnded Practice for Speech Quality Measurements. *IEEE Transactions on Audio and Electroacoustics*, *17*(3), 225–246. doi:10.1109/TAU.1969.1162058

Saalmann, Y. B., Pinsk, M. A., Wang, L., Li, X., & Kastner, S. (2012). The pulvinar regulates information transmission between cortical areas based on attention demands. *Science (New York, N.Y.)*, *337*(6095), 753–756. doi:10.1126/science.1223082

Saks, A. (2011). NSIGHT Special Edition. *Review of Optometry*, 4–5.

Scherg, M., & Picton, T. W. (1991). Separation and identification of event-related potential components by brain electric source analysis. *Electroencephalography and clinical Neurophysiology. Supplement*, *42*, 24–37. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1915020

Sesti, A. (2000). State-Trait Anxiety Inventory (STAI) in medication clinical trials. *Quality of Life Newsletter, 25,* 15–16.

Sheedy, J. E., Hayes, J. N., & Engle, J. (2003). Is all asthenopia the same? *Optometry and Vision Science : Official Publication of the American Academy of Optometry*, *80*(11), 732–739. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14627938

Spielberger, C. D., Gorsuch, R. L., & Lushene, R. E. (1970). The State-Trait Anxiety Inventory. *MANUAL*, 1–23.

Stoeckel, C., Gough, P. M., Watkins, K. E., & Devlin, J. T. (2009). Supramarginal gyrus involvement in visual word recognition. *Cortex; A Journal Devoted to the Study of the Nervous System and Behavior*, *45*(9), 1091–1096. doi:10.1016/j.cortex.2008.12.004

Stone, P. (1992). Fluorescent lighting and health. *Lighting Research and Technology*, *24*(2), 55–61.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 642–662.

Taylor, S. F., Kornblum, S., Lauber, E. J., Minoshima, S., & Koeppe, R. A. (1997). Isolation of specific interference processing in the Stroop task: PET activation studies. *NeuroImage*, *6*(2), 81–92. doi:10.1006/nimg.1997.0285

Thiry, S. (1951). Contribution a l'etude de l'entrainement photique. *Archives of Physiology and Biochemistry*, *LIX*(1), 10–25. Retrieved from http://informahealthcare.com/doi/pdf/10.3109/13813455109146620

Veitch, J. A., & McColl, S. L. (1995). Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort. *Lighting Research and Technology*, *27*(4), 243–256. doi:10.1177/14771535950270040301

Wernicke, K. (1994). The aphasia symptom-complex: A psychological study on an anatomical basis (1875). In P. Eling (Ed.), *Classics in Psycholinguistics: Reader in the History of Aphasia* (Vol. 4, pp. 69–89). Philadelphia, PA, USA: John Benjamins Publishing Co.

West, D., & Boyce, P. (1968). The effect of flicker on eye movements. *Vision Research*, *8*(2), 171–192. doi:10.1016/0042-6989(68)90005-9

West, R. (2003). Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia*, *41*(8), 1122–1135. Retrieved from http://www.sciencedirect.com/science/article/pii/S002839320200297X

Wilkins, A. (1986). Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text. *Human Factors*, *28*(1), 75–81. Retrieved from http://hfs.sagepub.com/content/28/1/75.short

Wilkins, A. J. (1987). Photosensitive epilepsy and visual display units. In E. Ross, D. Chadwick, & R. Crawford (Eds.), *Epilepsy in Young People* (pp. 147–155). Chichester, UK: John Wiley & Sons, Ltd.

Wilkins, A. J., Darby, C. E., Binnie, C. D., Stefansson, S. B., Jeavons, P. M., & Harding, G. F. (1979). Television epilepsy--the role of pattern. *Electroencephalography and clinical Neurophysiology*, *47*(2), 163–171.

Retrieved from http://www.sciencedirect.com/science/article/pii/0013469479902189

Wilkins, A. J., & Clark, C. (1990). Modulation of light from fluorescent lamps. *Lighting Research and Technology*, *22*(2), 103–109. doi:10.1177/096032719002200205

Wilkins, A. J., Nimmo-Smith, I., Slater, A. I., & Bedocs, L. (1989). Fluorescent lighting, headaches and eyestrain. *Lighting Research and Technology*, *21*(1), 11–18. doi:10.1177/096032718902100102

Wilkins, A., Veitch, J., & Lehman, B. (2010). LED lighting flicker and potential health concerns: IEEE standard PAR1789 update. In *2010 IEEE Energy Conversion Congress and Exposition* (pp. 171–178). IEEE. doi:10.1109/ECCE.2010.5618050

Wurtz, R. H., & Kandel, E. R. (2000). Central Visual Pathways. In E. R. Kandel, J. H. Schwartz, & T. M. Jessell (Eds.), *Principles of Neural Science* (4th ed., pp. 523–547). New York: McGraw-Hill.

Footnotes

1. Incidence rates (see Appendix F for rates of asthenopia) are difficult to calculate because people will often not report the symptoms because they may feel the symptoms will diminish and disappear over time, previously reporting the condition has not provided a resolution to the problem, and the condition is difficult to localize because of the varying types of symptoms.

Table 1: Background research of flicker

Reference	Dependent	Independent	Method	Result	Conclusion
Thiry, 1951. Contribution à l'etude de l'entrainement photique (Contribution to the study of photic driving). Archives Internationales de Physiologie, 59: 10-25.	EEG	Intensity and frequency of flicker	Stroboscope Light frequencies (1-70 Hz) and EEG recordings with eyes open and eyes closed – recorded from occipital, parietal and frontal lobes.	Light flicker can be detected using EEG Occipital cortex is the first activated when eyes open and from 1-70 Hz. The photic driving is two separate phenomena - (i) the arrival of impulses in the occipital cortex and limited to the occipital area, is seen especially if the subject's eyes are open for all frequencies from 1-70 Hz and the observed frequency is always that of intermittent light stimulation. (ii) There is an interaction between the influx rhythms and spontaneous cerebral rhythms (alpha, beta.) This is the drive itself, which is registered if eyes are closed, and is a mixture of complex answers to fundamentals, harmonics, and subharmonics, visible throughout the scalp.	The basic brainwave pattern (EEG) is influenced by flickering light EEG amplitudes and intensity decreased as frequency increased. For eyes closed, there was an initial reduction then an increase from 10-20 Hz followed by no detection after 30 Hz. This may be due to activation and de-activation of the rods in the retina. The subjective fusion of bright images is a distinct cortical and not peripheral phenomenon.
De Lange Dzn, H. (1961). Eye's Response at Flicker Fusion to Square-Wave Modulation of a Test Field Surrounded by a Large Steady Field of Equal Mean Luminance. Journal of the Optical Society of America, 51(4), 415. doi:10.1364/JOSA.51.000415.	CFF measures	Intensity Waveform Low and high luminance in cone vision range Modulation settings	Double-masked study of normally functioning fluorescent lighting (50 Hz ballast) with frequency range 100 Hz (small 50 Hz component). Low luminance (<5 photons) and in LF (< 2Hz)	Low luminance and low frequency = no attenuation in system Symmetrical luminance and sinusoidal or square-wave modulation (1:1) – flicker fusion equals the internal threshold value r_o Asymmetrical	Electrical analog and brightness system react the same to square waveform at low luminance Low mean retinal illumination with sinusoidal modulation as a real attenuation characteristic for the brightness system The internal

Reference	Dependent	Independent	Method	Result	Conclusion
				variation – square wave with 1:3 on-off ratio – crest value equals internal threshold ro. At high luminance – overshoot in low-frequency region for both wave-forms	threshold value is determined by amplitude of variation Low frequencies with no attenuation – second square waveform is detected and disappears at higher frequencies A pseudoresonance effect and an overshoot for square-wave modulations in the low-frequency region exist in the brightness system at high luminance values. The rising part of the eye curve using sinusoidal modulation is part of the attenuation characteristics under the specific visual conditions. The Fourier fundamental at threshold mechanism equals internal threshold therefore Fourier predicts flicker fusion
Brindley, G.S. (1962). Beats produced by simultaneous stimulation of the human eye with intermittent light and intermittent or alternating electric current. Journal of Physiology, 164, 157–167.	Beats on human retina	Light flashes and electrical stimulation	Sodium chloride solution in eye bath transmitted light and electricity to the eye. Eye anesthetised with cocaine or amethocaine drops Light/dark ratio was 1:15 but other ratios of 1:3 and 1:1 gave similar results Surface luminance was 45,000	When light and current are below 90Hz beats are waxing/waning of flicker through the whole illuminated part of visual field. Can obtain beats at harmonics of current frequency – still waxing/waning at <100Hz. Beats difficult to see below 20Hz because of flicker intensity – maybe down to 5 Hz	The beat between visual and electrical stimulation of the retina is perceived at high stimulation frequencies (i.e. 120 Hz) at the retina. May be similar to Eysel & Burandt study with phase-locked activation in LGN of cats. Fusion frequency not limited by photochemical mechanism of cones. Beats detected

Reference	Dependent	Independent	Method	Result	Conclusion
			cd/m^2.		from 5-120 Hz Exceeds CFF Beat harmonics – current at 441Hz & light at 40Hz gives beat at 1/sec Lasting sensation of flicker Phase relationship Interaction between light flashes and electrical pulses from 1-9 ms Cone CFF limited by high frequencies in photochemical mechanism and neural pathway
West, D.C. & Boyce, P.R. (1968) The effect of flicker on eye movements. Vision Research, 8: 171-192. Recordings of fixation eye movements were made in the presence of flickered illumination using both the optical lever and strain gauge techniques. It was found that for low frequency flicker (<=3 Hz) the saccade rate increased significantly and that there existed a definite time relationship between the onset of the light phase of the flicker and the occurrence of a saccade. Further experiments revealed that this effect only occurred when the information available concerning the position of the fixation target was intermittent. The results are discussed in terms of the control of drift rate to optimise the operation of the fixation control system.	Eye fixation mechanism	Dark target on flickering field – black circular dot 4 min arc diameter on circular field 2 or 12 degrees diameter. Mean field luminance was 3 or 3000 cd/m^2. White light used in all experiments. Steady and intermittent light	Strain gauges, Optical lever recording system, flicker projection system	Saccade rate increases when small point seen on flickering field for 1-3 Hz. Greater than 3 Hz intersaccadic interval similar to steady light condition. Time relation between change of light intensity and occurrence of saccade for flicker at 2 Hz. Presence of flicker has no effect on the distribution of intersaccadic intervals – similar to steady light – provided the eye can maintain continuous information on the position of the object (fixation point)	Drift rate larger in 2 Hz flicker than steady light. No difference in drift rate and intersaccadic interval above 5 Hz. Saccadic eye movements disrupted by LF flicker but not HF flicker Issues – For flicker at 2 Hz - 0.2 saccade/sec rate is 1/10th the saccade rate of normal fixation of a steadily illuminated field. Result may be due to instruction to subject to "fixate" voluntarily correct fixation errors produced by uncompensated drifts in the dark & only noticed when target re-appears. N very low.
Brundett GW. (1974). Human sensitivity to flicker. Lighting Research, 6:127-143	Review Eye strain, headaches	Flicker	Normal fluorescent lamps with 100 Hz modulation at 20-30% - people report	Personal peak sensitivity for 20 year olds. Variability between people and effect of flicker threshold.	Sensitivity enhanced with increasing adaptation luminance, increasing area of visual field

Reference	Dependent	Independent	Method	Result	Conclusion
			50 Hz whole tube fluctuations		and with increasing age (up to 20 years) then sensitivity declines. Human CFF varies within and between age groups. Flicker sensitivity increase to about age 20 and then decreases. Humans with high CFFs show a reduction in performance and increased fatigue under conventional, low-frequency, lighting compared to high-frequency lighting (Brundett, 1974; Kuller and Thorbjorn, 1998).
Haddad, G.M. & Winterson, B.J. (1975). Effect of flicker on oculomotor performance. In: Basic Mechanisms of Ocular Motility and Their Clinical Implications, Lennerstrand G, Back-y-Rita P (eds.) Pergamon, Oxford: New York, NY, 489-493.	Saccades	Flicker rate – 0.5, 1,2,5,10 Hz. Square wave 100% modulation.	Green LED average luminance 22mL	Subject told to suppress saccades and use slow control to maintain line of sight for 5 seconds. Subjects suppressed saccades to <0.2/sec for 75 seconds while field flickered at 2 Hz	Flicker has an effect on slow control (drift correction). Saccade rate decreased as flicker rate increased. Eye drifts from target and oscillates during drift. Flickering lights do not force saccades. Suppression of saccades reveals that flicker has a driving effect on slow control – causes eye to drift away from target position and oscillate as it drifts Propose – might be cross-talk between neural elements of lower brain afferent signals (input accommodation of lens and iris, blinking) and neural centres for slow

Reference	Dependent	Independent	Method	Result	Conclusion
					oculomotor control
Binnie C.D., de Korte, R.A., & Wisman, T. (1979). Fluorescent lighting and epilepsy. Epilepsia, 20: 725-727.	Presence or absence of paroxysmal activity - IPS Sensitivity	Fluorescent light tube modulating at 50% or 20-23% and average luminance of 80,000 cd/m^2. FR –100 Hz	Frequency range has a large 50 Hz component. Stimulation with fluorescent lighting on photosensitive patients. Brightness modulation increased until 100% attained	No patient was sensitive to normal fluorescent light function; no subject insensitive to 50-Hz IPS reacted to brightness modulation. Sensitivity to 50-Hz brightness modulation in 8 of 13 sensitive to 50 Hz IPS (50% in one subject and 70% or more in other 7)	Malfunctioning fluorescent lighting can cause epileptiform EEG in photosensitive epilepsy patients at 50% modulation
Eysel, U.T., & Burandt, U. (1984) Fluorescent light evokes flicker responses in visual neurones, Vision Research, 24(9), pp. 943-948.	Single neuron recordings in cat visual system	Fluorescent tube (modulation = 0.53 cd/m^2) and incandescent lamp (modulation = 0.14 cd/m^2) Luminance 60-195 and 128-172 (equal mean luminance) FT	Normally functioning fluorescent lighting with FR 100 Hz and 120 Hz (50 Hz AC). No perceptible flicker present	Phase-locked firing of LGN neurons in cats. CFFs in retinal ganglion cell and optic tract neurons – may be due to depth of modulation of fluorescent tube – get HF flicker responses	Flicker is not perceptible at frequencies of about 100 flashes per second, but it nevertheless affects the firing of cells in the retina and subcortical structures.
Wilkins, A. (1986) Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text. Human Factors, 28(1), 75-81. The size of eye movements across text was measured under conditions in which the text was illuminated by fluorescent light or was displayed on the screen of a cathode-ray tube. Under these conditions of intermittent illumination the high-velocity saccadic eye movements were enlarged. The extent to which they were enlarged depended on the frequency of intermittency, but was generally equivalent to the width of one letter. This disturbance of ocular motor control by intermittent illumination might help to explain why reading is generally slower on computer display terminals than with printed text.	Size of eye movements across text	Text illuminated by fluorescent light of displayed on CRT monitor (frame frequencies of 50Hz and 100 Hz). Luminance was 10 cd/m^2.	Normally functioning fluorescent lighting with 50 Hz ballast and second experiment with intermittent illumination frequency of 100 Hz and frequency rate of 20kHz. White text on unlit background.	Enlarged saccades over text. High-velocity saccades enlarged and depended on frequency of intermittency (about 1 letter width). Average size of main saccade was 11% larger for 50Hz than 100Hz display (139 versus 154 min arc). Main saccade was usually first saccade 89% of cases. #saccades was greater for 50 than 100 Hz displays	The rapid imperceptible flicker from visual display terminals and fluorescent lighting affects eye movements. Might explain why reading is slower on computer display terminals. Intermittent light affects ocular motor control at frequencies and a modulation depth when light appears continuous - style and contract of text and peripheral illumination do not matter.
Wilkins, A.J. (1987). Photosensitive epilepsy and visual display units. In E.					Certain visual display units can cause seizures

Reference	Dependent	Independent	Method	Result	Conclusion
Ross, D. Chadwick and R. Crawford (ed.), Epilepsy in Young People. Chichester: John Wiley, pp. 147-155.					for this reason. The epileptogenic properties of intermittent cathode-ray tube displays are related to: (1) The frequency with which the screen is "refreshed". Many patients are sensitive at 50 per second, very few at 60 per second. (2) The size of the screen and the distance from which it is viewed, which together determine the area of retina stimulated, and whether any line pattern from the raster will be of the critical retinal size. (3) The presence of line interlace. This doubles the number of lines, and effectively halves the refresh rate. If the screen is large enough and is viewed from a short distance the interlacing lines can form a highly epileptogenic pattern.
Wilkins, A.J., Nimmo-Smith, I.M., Slater, A., & Bedocs, L. (1989). Fluorescent lighting, headaches and eye-strain. Lighting Research and Technology, 21(1), 11-18.	Incidence of headaches and eyestrain in office workers	Fluorescent light with conventional switch=start circuit and choke ballast with 43-49% modulation; electronic circuit with choke ballast and similar characteristics ; electronic ballast at 32kHz and reducing 10 Hz modulation from 100 Hz	Conventional fluorescent lighting and high-frequency electronic ballasts (2 groups)	Double-blind cross-over study Group exposed to flickering light had reduction in complaints of headache and eyestrain by half	Fluorescent lighting causes eye-strain and headaches. Incidence of headaches and eyestrain was more than halved under high-frequency lighting. Incidence unaffected by the speed with which the tubes ignited. Headaches decrease with the height of the

Reference	Dependent	Independent	Method	Result	Conclusion
		to less than 7%			office above ground (more natural light). Office workers turned on HF lighter 30% longer.
Berman, S.M., Greenhouse, D.S., Bailey, I.L., Clear, R., & Raasch, T.W. (1991). Human electroretinogram responses to video displays, fluorescent lighting and other high frequency sources. Optometry and Vision Science 68(8), 645-662.	ERG Measures	Stimuli oscillating at rates up to 200 Hz	VDT – refresh rate 46-81Hz = about 60 Hz with 50% duty cycle. Darkened room to prevent ambient light effects. Fluorescent light stimulus F40 T12 daylight spectrum 100% modulation and phase locked. FR 47.5-72.5Hz.. Slide Projector stimulus - 80-120 Hz modulation FR up to 162Hz	Synchronous ERG to fluorescent lamps as high as 145Hz at a distance of 1 m. Human electroretinogram signals at light frequency	Flicker is not perceptible at frequencies of about 100 flashes per second, but it nevertheless affects the firing of cells in the retina and subcortical structures. Cortico visual pathways are capable of mediating flicker of 100 pps and higher for AC 50 Hz
Wilkins, A.J., & Clark, C. (1990). Modulation from fluorescent lamps. Lighting Research and Technology 22(2), 103-109.	Peak to peak modulation	Lamp type – halophosphate, triphosphor or multiband fluorescent lamps on conventional choke circuit	Temporal modulation from halophosphate, triphosphor and multiband fluorescent lamps (conventional choke circuit). Measurements taken from centre of lamp – contribution of 50 Hz modulation was less than 3% for all lamps and all wavelengths	Within category – similar peak-to-peak function. Short wavelength –all showed modulation near 100%. Halophosphate and multiband had low modulation at long wavelength and lowest modulation. Triphosphor had greater modulation than halophosphate.	Technological paper Warm white lamps flicker least. Fluorescent lamps controlled by high-frequency circuitry have very little flicker.
Burns, S.A., Elsner, A.E., & Kreitz, M.R. (1992). Analysis of nonlinearities in the flicker ERG. Optom Vis Sci. 69(2):95-105.	ERG	Steady flickering fields		Significant non-linear components	1) The fundamental retinal response can be recorded at frequencies greater than 100 Hz and the second and higher harmonic responses have measurable response frequencies as high as 200 Hz. Both the

Reference	Dependent	Independent	Method	Result	Conclusion
					fundamental response component and the second harmonic response component have multiple local maxima as a function of frequency. 2) Measurement of the response of the retina to the sum of two sine waves indicates that there is an early low-pass temporal filter in the retina. This early filter has a cut-off frequency between 40 and 50 Hz. (3) The high frequency nonlinearity is not a compressive nonlinearity.
Stone, P.T. (1992). Fluorescent lighting and health. Review Paper. Lighting Research Technology, 24(2): 55-61.	Review Paper	Review Paper	Reviewed: skin cancer and fluorescent lighting; skin photosensitivity and FL; skin erythema and eye inflammation; lighting and stress; mood states, pineal gland and lighting; glare; flicker; “sick building syndrome” and lighting; polychlorinated biphenyls	Review Paper	Glare, flicker and headaches are known to cause distraction and discomfort for some people – cause not understood. Absence of windows and lack of visual variety may increase complaints.
Kuller, R. & Wetterberg, L. (1993). 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(2): 71-81	Subjective comfort/affective state Cortisol and autonomic arousal level, cortisol and melatonin secretion Visual performance	Intensity and spectral quality of light Two types of fluorescent lamps, 'daylight' and 'warm-white', were compared, each at two different levels of illuminance. Exposure lasted one day for each of the	Warm white = Philips TLD 83, 36W, 3000K, CRI=85 Daylight fluorescent = Duro Test True-Lite, 40W, 5500K CRI=91 Power – 220V, 50Hz. Conventional ballasts	'daylight' lamps with high illuminance evoked a negative response pattern. The social evaluation went down, and visual discomfort increased. EEG contained less delta rhythm under the high illuminance conditions.	Fluorescent light of high illuminance may arouse the central nervous system and arousal will become accentuated if lamps are of the 'daylight' type. People should not be exposed to fluorescent light of high illuminance for a

Reference	Dependent	Independent	Method	Result	Conclusion
		four combinations. 450 Lux versus 1700 Lux		During the day of light exposure the alpha rhythm became attenuated under the 1700 lux 'daylight' lamps.	prolonged period of time. High illuminance values caused more glare than low. Due to power supply all lamps were at 100Hz, therefore, daylight one could have had more flicker (cf. Wilkins & Clark, 1990).
Lindner, H. & Kropf, S.(1993). Asthenopic complaints associated with fluorescent lamp illumination (FLI): The role of individual disposition. Lighting Research, 25(2):59-69	Asthenopic complaints	Questionnaires, eye tests, EEG with photic stimulation of 3,6,10,15, 30 Hz.	Questionnaires, eye tests, EEG with photic stimulation of 3,6,10,15, 30 Hz.	More females (age 20-30 years) than males complain of asthenopia. Complaints include glare, smarting, flicker, fatigue. Pathophysiology – heterophoria, low stereoscopic vision, higher peripheral flicker sensitivity, higher subjective light sensitivity, higher neurotic personality traits (psychovegetative lability), decreased concentration power, longer optical response time, higher photic driving findings in EEG	Asthenopic complaints depend on gender, age, personality, concentration. Also – longer optical response time and higher photic driving in EEG Photic driving effect, flicker and light sensitivity in complaint group was 2x control group More photic driving in females than males (cf. Shagass, 1955)
Harding, G.F.A. & Jeavons, P. (1994). Photosensitive Epilepsy. Mac Keith Press.	Seizures	Sunlight through roadside trees or reflected from waves	review and assessment of clinical histories		Body of work on photosensitive epilepsy and seizures
Harding, G.F.A. & Jeavons, P. (1994). Photosensitive Epilepsy. Mac Keith Press.	EEG	photostimulator	Xenon gas discharge photo-stimulator with FR from 3-60 Hz	Epileptiform EEG in patients with photosensitive epilepsy	Epileptiform EEG in patients with photosensitive epilepsy
Veitch, J.A., & McColl, S.L. (1995). Modulation of fluorescent light: flicker rate and light source effects on visual performance and visual comfort. Lighting Res. Tech., 27(4),243-256.	Visual performance and visual comfort	Light source, Fluorescent light spectral composition, Flicker rate – 2 rates, low = 120 Hz, high=20-60kHz Used VALiD and Landolt ring task (gap detection in # of rings per	Normally functioning fluorescent lighting with 60 Hz ballast and FR 120 Hz	Reduced visual performance and reduced speed of visual search	Flicker affects performance Chromatic modulation does not affect visual performance of visual comfort. High frequency flicker led to improved performance. Large effect of flicker on visual performance if

Reference	Dependent	Independent	Method	Result	Conclusion
		row)			luminance contrast at 0.21 – that is, when the task was visually difficult. Low frequency flicker may add noise to neural activity which leads to asthenopia
Küller, R. & Laike, T. (1998). The impact of flicker from fluorescent lighting on well-being, performance, and physiological arousal. Ergonomics, 41:433-447.	Subjective well-being, performance, physiological arousal	Conventional fluorescent light and high-frequency ballasts	EEG, EKG 37 healthy males and females were subjected to either condition in a laboratory office on two separate occasions with 1 week in between.	Subjective rating scales Conventional ballasts less pleasant than high-frequency ballasts. No effects of visual comfort, headache, stress or fatigue. Group with low CFF showed no difference in alpha but group with high CFF showed less alpha in conventional ballast (therefore, heightened arousal). No EKG response differences. Higher speed in high CFF group and with conventional ballasts, errors more than doubled. Generalized EEG arousal in high CFF group. Looking at the other characteristics of the sensitive group with high CFF values	Does not give the impression that we are dealing with a deficiency. The little data we have indicate a somewhat younger and more motivated nervous system, less addicted to alcohol and nicotine. This is consistent with previous reports of flicker sensitivity decrease in older adults (Mayer et al. 1995). Previous research has also shown an impairment of CFF under ethanol (Yap et al. 1993). Extrapolation of these suggests that children may be even more sensitive to flicker, which would in turn imply that the use of conventional ballasts in, for instance, school environments might be inappropriate. Humans with high CFFs show a reduction in performance and increased fatigue under conventional, low-frequency, lighting compared to high-frequency lighting (Brundett, 1974; Kuller and

Reference	Dependent	Independent	Method	Result	Conclusion
					Laike, 1998).
Maddocks, S.A., Goldsmith, A.R., & Cuthill, I.C. (2001). The influence of flicker rate on plasma corticosterone levels of European starlings, Sturnus vulgaris. General and Comparative Endocrinology, 124(3), 315-20.	Plasma corticosterone levels	Flicker rate	Normally functioning fluorescent lighting with 50 Hz ballast and FR 100 Hz	Inconsistent changes in plasma corticosterone levels in captive starlings	Low frequency lighting is potentially stressful – always showed higher basal corticosterone levels.
Jarvis, J.R., Prescott, N.B., & Wathes, C.M. (2003). A mechanistic inter-species comparison of flicker sensitivity. Vision Research, 43: 1723-1734.	Review of Rovamo and Barten theories	Review of Rovamo and Barten theories	Review of Rovamo and Barten theories	Review of Rovamo and Barten theories	Interesting paper on flicker sensitivity – does not address high frequency flicker.
Sheedy, J.E., Hayes, J.N., Engle, J. (2003). Is all asthenopia the same? Optom. Vis Sci. 80(11):732-739.	Rating of magnitude of descriptor symptoms (=burning, ache, strain, irritation, tearing, blurred vision, double vision, dryness, headache) and location	Eight reading conditions – mixed astigmatism, close viewing distance, upward gaze, dry eyes, lens flipper, small font, glare, flickering light	Subjects asked to read until attaining a level of self-defined discomfort.	Principal factor analysis with orthogonal varimax rotation used to test symptom by condition relationships – Two latent factors found – designated LVs as external and internal symptom factors that relate to inducing condition	ISF pattern includes ache, strain, headache behind eyes and is caused by close viewing, lens flipper, and mixed astigmatism – likely related to accommodative and vergence stress. Two different symptom constellations and therefore at least two different afferent pathways for symptoms of asthenopia.
Ishiguro, Y., Takada, H., Watanabe, K., Okumura, A., Aso, K., Ishikawa, T. (2004). Follow-up survey on seizures induced by animated cartoon TV program "Pocket Monster", Epilepsia, 45(4) 377-383.			Flashing televised cartoon with FR ~10 Hz	Seizures in children with no previous diagnosis of epilepsy (major incident)	
Jaen, M., Sandoval, J., Colombo, E.,& Troscianko, T. (2005). Office workers visual performance and temporal modulation of fluorescent lighting, Leukos, 1(4), 27-46.	Visual performance.	Flicker	Normally functioning fluorescent lighting (50 Hz ballast). Subjects (39; 20-22 years of age, no visual impairments) completed visual search tasks in 2 simulated office environments fitted with fluorescent lamps. Office 1, lamps had	Reduced visual performance and reduced speed of visual search Low temporal modulation electronic ballast (64000 Hz; modulation 3.01%; luminance 251.6 cd/m^2; Illuminance =959.4 lux) versus High temporal modulation magnetic ballast (100 Hz;	The effect of the presence of natural light in combination with fluorescent lamps in actual office environments was not addressed. Appendices containing data findings, examples of the experimental task, and the questionnaire were included. Further research was

Reference	Dependent	Independent	Method	Result	Conclusion
			electronic ballasts and low flicker (3% modulation). Office 2, lamps had magnetic ballasts and more flicker (32% modulation). Subjects timed while working at a desk connecting numbered dots with a pencil on paper. Character size and contrast were randomly varied.	modulation 32%; luminance 266.1 cd/m^2; illuminance 961.7 lux)	recommended to identify subjects who are highly sensitive to flicker, and the use of lighting alternatives (e.g., natural light, localized incandescent) to attenuate the negative effects of flicker. Neuronal signals at the same frequency as excitation signal can be transmitted to CNS as an additional excitation charge because receptors respond to high frequencies.
Evans, J.E., Cuthill, I.C., & Bennett, A.T.D. (2006). The effect of flicker from fluorescent lights on mate choice in captive birds. Animal Behaviour, 72(2),393-400.	Comparison of female choice	LF and HF lighting (100W Truelite fluorescent tubes) Half had LF ballasts 100Hz and other half had HF ballasts (>30kHz). No difference in spectral emissions; HF irradiance = 4176.11 and for LF irradiance = 4236.92	Normally functioning fluorescent lighting (50 Hz ballast) with FR 100 Hz Each pair of female birds viewed 4 males per session – had not been housed with the males	Mate choice in captive starlings Female choice not influenced by physical characteristics of male except in the length of the males' throat feathers (longer feathers were more favoured)	Females preferred different males under the different lighting conditions Starling visual system under natural light is closer to HF lighting – therefore results of HF might represent choice of wild birds.
Harding, G.F.A, Harding, P.F., & Wilkins, A.J. (2008). Photosensitive epilepsy and image safety. Appl Ergon, Oct 16.			50 Hz and 60 Hz (discounting 25Hz component)	Epileptiform EEG in patients with photosensitive epilepsy	
Roberts, J., & Wilkins, A.J. (2013). Flicker can be perceived during saccades at frequencies in excel of 1 kHz. Lighting Research and Technology, 45, 124-132.	Subjective report of pattern Report of intrasaccadic pattern (2kHz and 3kHz)	1. Illuminated line for 3 s – two successive trials 2. Shutter at 1kHz	1. Sine wave generated at 1, 2, 3, and 5 kHz and steady signal – similar time averaged voltage and luminance from 0.02 cd/m2 and 310 cd/m2. Matte black screen with 2 white discs (fixation points)	1. 75% threshold was 1.67kHz 2. corroboration of results	Although this experiment uses low light levels and activates scotopic system (more photoreceptors activated), it invariably showed that the visual system still detects flicker even if imperceptible

Reference	Dependent	Independent	Method	Result	Conclusion
			2. 23V tungsten halogen lamp with DC supply used optic fibre to light chopper. Shutter rotated.		

Table 2: Keystone opthalmic telebinocular tests and diagnosis

All pictures are black and white or coloured images presented on a 15 cm x 7.7 cm black, white or yellow background and bonded on a black 17.8 cm x 11.4 cm cardboard cards. Each rectangle was positioned 2.8 cm from the top, 1.3 cm from each side, and 0.9 cm from the bottom of the black card.
In all cases, the participant reports what he/she sees.

Far Point Tests Include:

TEST	Assessment	Purpose	Method	Diagnosis
1	Simultaneous Perception	Gross suppression	Pictures of a dog and a pig.	Only dog or pig is present except by occluding dominate eye = gross suppression
2	Hyperphoria	Vertical imbalance	Head should be level. If line does not stabilize, report the limits of the swing. Fading of the line where it crosses the images has no diagnostic significance = retinal rivalry	Yellow line passes through ball and zero = expected Line passes through cross = 2 diopters of right hyperphoria Line passes through star = 3 diopters of left hyperphoria
3	Lateral Phoria	Lateral posture and postural stability	To what number the arrow points, whether the arrow remain still or moves quickly to other numbers and remains there, whether the arrow swings and then becomes stationary, when the arrow continues to swing.	Ascertain how far each way the movement continues Left of expected = exophoria Right of expected = esophoria Deviations from parallelism or postural instability indicate unbalanced accommodative-convergence relationship
4	Binocular Coordination	Fusion facility	Participant immediately reports the number of balls	Three in postural alignment = fusion readiness Three in oblique alignment = high phoria – fusion maintained with effort Four becoming three instantly = same as fusion readiness Four becoming three slowly = eyes not automatically positioned for fusion Four = marked interference in accommodative-convergence relationship – macular, perimacular, and peripheral cancellation-suppression Two = gross suppression – amblyopia and squint
4.5	Usable Binocular Vision	Stereoscopic vision – using both eyes together at the same time, habitual performance of each eye under fusion	Report dot position on sign board.	Distortions in depth perception and visual measurement of distance. Similar to Snellen (see ranges below)
5	Usable Vision Right Eye	Monocular discrimination under fusion	Referential backgrounds identical; black dot for test target appears only for eye under test.	Tests monocular vision while binocular vision is maintained. Scores the habitual performance of each eye under fusion. Tests for functional loss of vision. If association response is lower than monocular response (under occlusion) = central suppression, visual problem may exist.
6	Usable Vision Left Eye	Monocular discrimination under fusion		
7	Stereopsis	Gross test for loss of depth awareness	Failure on any part of this test requires attention.	Suppression of binocular foveal fixation. Deterioration of depth discrimination = evidence of central depression
8	Colour	Detects severe	Patient to report numbers	2 balls, both digits correct = pass

	Perception for severe defects	colour deficits	in coloured circles without delay	2 balls, both digits incorrect = fail, mild red-green colour blindness
9	Colour Perception for minor defects	Detects minor colour deficits (i.e. green)	Patient to report numbers in coloured circles without delay	2 balls, both digits correct = pass 2 ball, both digits incorrect = fail; mild red-green colour blindness

Near Point Tests Include:

TEST	Assessment	Purpose	Method	Diagnosis
10	Lateral Phoria	Lateral posture and lateral stability	Same as Lateral Phoria test for binocular vision	Diagnoses the effect of 2.50 diopters of accommodation on the position of the visual axes
11	Binocular Coordination	Fusion facility	Same as Binocular Coordination test for binocular vision	Same diagnosis as for Binocular Coordination test for binocular vision
12	Binocular Acuity	Binocular clarity of vision	Balls have patterns of lines, dots, or gray patterns	Same as in test 5; usable vision determined while fusion maintained
13	Usable Vision Right Eye	Monocular discrimination under occlusion	Same as test 12	Same as test 12
14	Usable Vision Left Eye	Monocular discrimination under occlusion	Same as test 13	Same as test 13

Snellen scores for usable binocular and monocular right and left vision for tests 12, 13, and 14 when one eye is occluded.

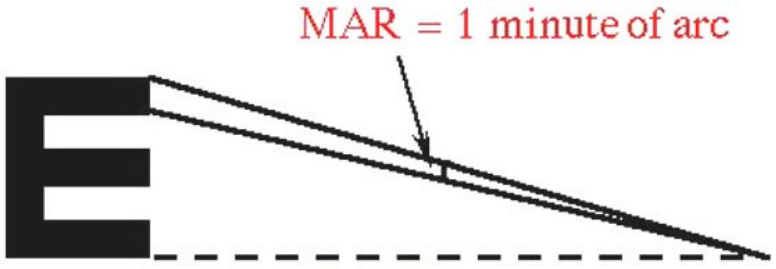
10%	20%	30%	40%	50%	60%	70%
20/200	20/100	20/67	20/50	20/40	20/33	20/28

80%	90%	100%	102%	103%	105%
20/25	20/22	20/20	20/18	20/17	20/15

Interpretation of the Snellen Scores:

The Snellen chart is placed at a standard distance of 20 ft from the individual. At this distance, the symbol subtends an angle of 5 minutes of arc and each line and space of the letter subtends one minute of arc. Visual acuity equals the test distance divided by the letter size. For example,

20 feet testing distance



20 feet testing distance

(Figure adapted from http://webvision.med.utah.edu/book/part-viii-gabac-receptors/visual-acuity/)

One degree equals 60 minutes of arc, therefore, 5 minutes of arc equals 0.083 degrees. Normal acuity of 20/20 (US) means the individual can view the smallest line of letters at a distance of 20 ft. The reciprocal of the Snellen Notation is equal to the angle (in minutes of arc) which each stroke or space of the letter subtends at the person's eye.

Results:

The following test results were obtained at far point. Test 1 determines if both the participant's eyes see at the same time. The scores were all within normal limits with 22 centred, 10 very slightly to the left, and 2 slightly to the right. Test 2 tests for hyperphoria (i.e. if one eye tends to turn upward) found none of the 34 participants indicating any evidence of hyperphoria. Test 3 determines lateral phoria (the relative drift of the eye during binocular fixation when an adequate fusion stimulus is absent) showed 33 participants within the normal range and one participant with a very slight (7.5) over-convergence. Test 4 examines an individual's binocular coordination (i.e. when the eyes work together) and the results show all individuals are within normal limits with one participant indicating a very slight accommodative-convergence interference to the left and another participant with the same interference to the right. Test 4.5, 5, and 6 tests binocular, left, and right usable vision identified two participants with scores of 92-96% usable vision. Considering the task requirements, these participants indicated that they could easily complete the task requirements. The remaining 30 participants had scores at 100% or above indicating high usable vision. Test 7 examines stereopsis (i.e. suppression of binocular foveal fixation). One participant scored below the expected values indicating slight under-convergence. The remaining 33 participants scored within normal limits. All participants correctly identified the values for the colour vision tests indicating no red-green colour blindness.

The remaining five visual examinations were done at near-point. Lateral phoria tested at 2.50 found 20 participants within the normal range, 7 participants indicating under-convergence - 4 with slight under-convergence (all wearing corrective lenses), 3 with over-convergence (1 with corrective lenses). Since the tasks did not require the use of near vision, these participants were not excused. Test 12 examines the participant's binocular acuity at 2.50 and showed all participants within the expected range with 18 normal usable vision and 16 with slight over-convergence. Tests 13, 14, and 15 examines binocular, left, and right eye acuity at 2.50 and found 33 participants at 100% (1 participant at 90%) or better for binocular and right eye visual acuity and 31 participants at 100% or better visual acuity for the left eye (the 3 remaining participants had visual acuity of 90%). The acuity of 100% is equivalent to 20/20 and 90% is equivalent to 20/22 on the Snellen Eye Chart.

Table 3: Beck depression inventory score interpretation

Score Range	Score Interpretation	N
0–9	indicates minimal depression	30
10–18	indicates mild depression	2
19–29	indicates moderate depression	2
30–63	indicates severe depression	2

Table 4: Demographics

N	Age (years)	Gender (Male=M, Female=F)	Time of Day (9am – 12pm=AM 1pm – 4pm= PM)
Recruited=54 Final=34	18-26 mean=19.7, (2.2)	F=27 M=7	AM: N=19 PM: N=15

Education (Average years after high school)	Sleep (Average hours of sleep on the previous night)	EHI Quotient (Right)	English as First Language
2.03 (2.1)	7.47 (1.2)	76.2 (18.4)	Yes=29 No=5 Fluent=34

Cap Size Used	Corrected to Normal Vision	Vision Problem	BDI (average)
50-53 cm = 5 55-59 cm = 28 60-65cm = 1	Yes = 12 No = 22	Near-sighted=8 Far-sighted=2 Astigmatism=2	4.1 (5.5)

Table 5: EyeLink 1000 specifications

EyeLink 1000 was used with a chin and forehead rest (Head Supported) attached to the light booth.

Type	Desktop
Binocular Sampling Rate	1000 Hz
Eye Tracking Principle	Pupil with Corneal Reflection (CR)
Average Accuracy	0.25° to 0.5° typical
Saccade Event Resolution	0.05° microsaccades
Spatial Resolution (RMS)	0.01° @ 1000 Hz; 0.02° @ 2000 Hz
End to End Sample Delay	M < 1.8 msec, SD < 0.6 msec @ 1000 Hz; M < 1.4 msec, SD < 0.4 msec @ 2000 Hz
Blink Recovery Time	1.0 msec @ 1000 Hz; 0.5 msec @ 2000 Hz
Pupil Detection Models	32° horizontally; 25 ° vertically
Allowable Head Movement	25 x 25 x10 mm (horizontal x vertical x depth)
Optimal Camera-Eye Distance	40 - 70 cm
Glasses Compatibility	Excellent
Infrared Wavelength	890 nm or 940 nm

Table 6: Microsoft Sidewinder gamepad specifications

Device Type	Gamepad
Color	Black, Metallic Silver
Device (s) Input	
Connectivity Technology	Wired
Number of buttons	4
Characteristic	Trigger
Expansion / Connectivity Interfaces	1 x USB - 4 pin USB Type A
Certified for Windows Vista	Software and devices"" Certified for Windows Vista have undergone compatibility tests to optimize performance and enhanced security.
Compliance with standards	Plug and Play
Software / System Requirements	
Software Included	Drivers & Utilities
OS Required	Microsoft Windows 95/98
Min Processor Type	Intel Pentium - 166 MHz
RAM minimum	8 MB

Table 7: Full experiment routine

Description of Procedure	Length (minutes)
Participant arrives, lab tour, and completes informed consent	4
Eye test using Telebinocular full set	5
Computerized questionnaires – General, Handedness, BDI, and STAI	5
Capping procedure	15
Eye calibration (follow the dot scenario)	5
Block 1	
Eye tracker calibration	1
Stroop task with practice	10
Reading Sentences task	10
Computerized STAI questionnaire	1
Break for participant (eyes closed)	5
Block 2	
Eye tracker calibration	1
Stroop task	10
Reading Sentences task	10
Computerized STAI questionnaire	1
Break for participant (eyes closed)	5
Block 3	
Eye tracker calibration	1
Stroop task	10
Reading sentences task	10
Computerized STAI questionnaire	1
Eye calibration (follow the dot scenario)	5
Debriefing and Rest Period	15
Total time commitment	130

Table 8: Means and standard deviations

STAI pre-test and after each experimental block

Average STAI Pre-test	Average STAI* After Block 1	Average STAI* After Block 2	Average STAI* After Block 3
45.18 (1.66)	31.56 (3.29)	31.03 (3.41)	29.56 (3.46)

*Regardless of flicker condition; Standard deviations are in brackets

Change in STAI after each experimental block

STAI 0 Hz	STAI 100 Hz	STAI 500 Hz
31.03 (12.10)	29.94 (10.24)	30.88 (11.76)

*Accounting for flicker condition; Standard deviations are in brackets

Sentence Reading as Average Interest Period Duration (IPD in ms/sentence) for each flicker frequency

IPD 0 Hz	IPD 100 Hz	IPD 500 Hz
2474.37 (787.73)	2440.87 (522.18)	2694.12 (534.26)

Sentence Reading as Inverse Average Interest Period Duration (IPD in ms/sentence) for each flicker frequency

IPD 0 Hz INV	IPD 100 Hz INV	IPD 500 Hz INV
0.000481 (0.000102)	0.000474 (8.67E-05)	0.000444 (7.92E-05)

Table 9: Mean Stroop processing cost (ms) for the difference of incongruent and congruent trials

Cue Type	0 Hz	100 Hz	500 Hz
Overall	133.97 (9.43)	133.55 (9.76)	135.54 (9.87)
Colour	170.08 (10.76)	174.91 (10.63)	173.63 (11.41)
Word	103.40 (11.23)	93.90 (11.04)	98.48 (11.54)

Table 10: Stroop accuracy correct trials of the inverse transform of the percent difference between incongruent and congruent responses

The table below is reported with mean (standard error) and the estimated marginal means are recorded in the lower table.

Cue Type	0 Hz	100 Hz	500 Hz
Overall	-2.95 (2.05)	-2.78 (1.66)	-1.67 (1.57)
Colour	-3.65 (2.63)	-3.69 (2.01)	-2.21 (1.88)
Word	-2.26 (2.07)	-1.95 (1.79)	-1.35 (1.74)

FLICKER Overall Estimated Marginal Means and Standard Error
Measure: MEASURE_1

FLICKER	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
0 Hz	-2.326	0.411	-3.167	-1.486
100 Hz	-2.639	0.369	-3.395	-1.883
500 Hz	-1.458	0.355	-2.185	-0.732

Table 11: Peak latency (μV) means and standard deviations of each region, flicker rate, and interval for Stroop colour

Descriptive Statistics

	Mean	Std. Deviation
RF_0Hz_60_100ms	.545671	.7791102
RT_0Hz_60_100ms	-.321143	.5356196
RP_0Hz_60_100ms	-1.090348	.8806459
RO_0Hz_60_100ms	-.817791	1.5621378
LF_0Hz_60_100ms	.917886	.7966623
LP_0Hz_60_100ms	-.474924	.7927976
LT_0Hz_60_100ms	.442353	.5682492
LO_0Hz_60_100ms	-.612690	1.5359206
RF_100Hz_60_100ms	.667382	.7761482
RT_100Hz_60_100ms	-.291217	.5299629
RP_100Hz_60_100ms	-1.182646	.8955933
RO_100Hz_60_100ms	-.963000	1.3655834
LF_100Hz_60_100ms	.968744	.6394429
LP_100Hz_60_100ms	-.586297	.6037969
LT_100Hz_60_100ms	.422142	.4943219
LO_100Hz_60_100ms	-.789300	1.2868175
RF_500Hz_60_100ms	.698543	1.1031501
RT_500Hz_60_100ms	-.334753	.5607633
RP_500Hz_60_100ms	-1.196913	1.2482853
RO_500Hz_60_100ms	-1.037318	1.6945040
LF_500Hz_60_100ms	.940170	1.2297355
LP_500Hz_60_100ms	-.459211	.9021367
LT_500Hz_60_100ms	.415700	.5902235
LO_500Hz_60_100ms	-.745131	1.4884179
RF_0Hz_170_210ms	1.993079	1.4634833
RT_0Hz_170_210ms	-.870487	.8554286
RP_0Hz_170_210ms	-1.810523	1.7265303
RO_0Hz_170_210ms	-3.863225	2.4327295
LF_0Hz_170_210ms	2.164405	1.4177386
LP_0Hz_170_210ms	-1.441520	1.4510131
LT_0Hz_170_210ms	.246475	1.2141928
LO_0Hz_170_210ms	-4.234990	1.9715005
RF_100Hz_170_210ms	1.893285	1.6975678
RT_100Hz_170_210ms	-.957596	.7100445
RP_100Hz_170_210ms	-1.739691	1.8398946
RO_100Hz_170_210ms	-3.784181	2.4293882

	Mean	Std. Deviation
LF_100Hz_170_210ms	2.150344	1.5798646
LP_100Hz_170_210ms	-1.337633	1.7407365
LT_100Hz_170_210ms	.166955	.9868267
LO_100Hz_170_210ms	-4.161515	2.1725960
RF_500Hz_170_210ms	1.864770	1.5154587
RT_500Hz_170_210ms	-.817821	.8239484
RP_500Hz_170_210ms	-1.509539	1.6669047
RO_500Hz_170_210ms	-3.873624	2.7837841
LF_500Hz_170_210ms	1.953096	1.7016573
LP_500Hz_170_210ms	-1.259501	1.6065181
LT_500Hz_170_210ms	.021655	1.1048311
LO_500Hz_170_210ms	-4.333518	2.6132308
RF_0Hz_300_340ms	-.939125	1.1053868
RT_0Hz_300_340ms	-.645004	.8051293
RP_0Hz_300_340ms	1.569952	1.4240828
RO_0Hz_300_340ms	-1.025438	2.3783381
LF_0Hz_300_340ms	-1.494782	1.4562616
LP_0Hz_300_340ms	1.919914	1.1438057
LT_0Hz_300_340ms	-.698553	1.3253177
LO_0Hz_300_340ms	-.288079	2.2080480
RF_100Hz_300_340ms	-.981041	1.0980588
RT_100Hz_300_340ms	-.459544	.5860842
RP_100Hz_300_340ms	1.478786	1.0997772
RO_100Hz_300_340ms	-.935444	1.9783368
LF_100Hz_300_340ms	-1.365110	.8922519
LP_100Hz_300_340ms	1.903792	.9525773
LT_100Hz_300_340ms	-.628600	.9305223
LO_100Hz_300_340ms	-.226681	2.1105981
RF_500Hz_300_340ms	-.893318	1.0914040
RT_500Hz_300_340ms	-.565036	.6676400
RP_500Hz_300_340ms	1.501883	1.1281638
RO_500Hz_300_340ms	-.920456	2.1538476
LF_500Hz_300_340ms	-1.396784	1.2067364
LP_500Hz_300_340ms	1.959852	1.3643781
LT_500Hz_300_340ms	-.644555	1.0170741
LO_500Hz_300_340ms	-.487591	2.1842825

Table 12: Peak latency (μV) mean and standard deviations of each region, flicker rate, and interval for Stroop word

Descriptive Statistics

	Mean	Std. Deviation
RF_0Hz_60_100ms	.707032	.8499077
RT_0Hz_60_100ms	-.179067	.4764701
RP_0Hz_60_100ms	-1.213900	.9710941
RO_0Hz_60_100ms	-1.051157	1.3989377
LF_0Hz_60_100ms	.966880	.9779235
LP_0Hz_60_100ms	-.574950	.9325082
LT_0Hz_60_100ms	.466051	.5387599
LO_0Hz_60_100ms	-.929756	1.3597140
RF_100Hz_60_100ms	.635191	.7266656
RT_100Hz_60_100ms	-.367319	.4662574
RP_100Hz_60_100ms	-.999803	.6537465
RO_100Hz_60_100ms	-.790182	1.1349081
LF_100Hz_60_100ms	.967675	.6484061
LP_100Hz_60_100ms	-.589683	.7038610
LT_100Hz_60_100ms	.344242	.4625628
LO_100Hz_60_100ms	-.728041	1.2598212
RF_500Hz_60_100ms	.718076	.9017245
RT_500Hz_60_100ms	-.090752	.5332463
RP_500Hz_60_100ms	-1.166674	1.0172004
RO_500Hz_60_100ms	-1.111631	1.4583696
LF_500Hz_60_100ms	.866908	.9720940
LP_500Hz_60_100ms	-.562324	.7887282
LT_500Hz_60_100ms	.484245	.5105558
LO_500Hz_60_100ms	-.856809	1.3772842
RF_0Hz_170_210ms	2.069380	1.6933445
RT_0Hz_170_210ms	-.854613	1.0644956
RP_0Hz_170_210ms	-1.910513	1.6772687
RO_0Hz_170_210ms	-3.940622	2.4537848
LF_0Hz_170_210ms	2.263865	1.6213386
LP_0Hz_170_210ms	-1.448214	1.6673186
LT_0Hz_170_210ms	.209151	1.0813770
LO_0Hz_170_210ms	-4.431613	2.4983210
RF_100Hz_170_210ms	2.081027	1.6226101
RT_100Hz_170_210ms	-.943918	.6967728
RP_100Hz_170_210ms	-1.816781	1.8763907

	Mean	Std. Deviation
RO_100Hz_170_210ms	-3.718287	2.1318720
LF_100Hz_170_210ms	2.259030	1.5971241
LP_100Hz_170_210ms	-1.483644	1.7666242
LT_100Hz_170_210ms	.060919	1.2998622
LO_100Hz_170_210ms	-4.356704	1.9627106
RF_500Hz_170_210ms	1.942213	1.6365232
RT_500Hz_170_210ms	-.913903	.7677645
RP_500Hz_170_210ms	-1.852916	1.7604534
RO_500Hz_170_210ms	-3.922231	3.0139461
LF_500Hz_170_210ms	2.087712	1.7153009
LP_500Hz_170_210ms	-1.309451	1.6951780
LT_500Hz_170_210ms	.306922	1.0965301
LO_500Hz_170_210ms	-4.111226	2.6252755
RF_0Hz_300_340ms	-.925561	1.2819927
RT_0Hz_300_340ms	-.359368	.7575313
RP_0Hz_300_340ms	1.485045	1.3794385
RO_0Hz_300_340ms	-.838931	2.1705301
LF_0Hz_300_340ms	-1.474136	1.5045259
LP_0Hz_300_340ms	1.776180	1.4464518
LT_0Hz_300_340ms	-.674398	1.0917665
LO_0Hz_300_340ms	-.109268	2.4412529
RF_100Hz_300_340ms	-.827240	1.2356506
RT_100Hz_300_340ms	-.478770	.7036362
RP_100Hz_300_340ms	1.445419	1.2597256
RO_100Hz_300_340ms	-1.080241	1.7737164
LF_100Hz_300_340ms	-1.345189	.9395905
LP_100Hz_300_340ms	1.861178	1.2202687
LT_100Hz_300_340ms	-.556558	1.0933142
LO_100Hz_300_340ms	-.657375	1.6631621
RF_500Hz_300_340ms	-1.080037	1.1118101
RT_500Hz_300_340ms	-.186416	.5337838
RP_500Hz_300_340ms	1.408274	1.0062691
RO_500Hz_300_340ms	-.876615	1.6484593
LF_500Hz_300_340ms	-1.542489	1.0359775
LP_500Hz_300_340ms	1.906643	1.3560428
LT_500Hz_300_340ms	-.491759	.9451180
LO_500Hz_300_340ms	-.069990	1.9402199

Table 13: Source analyses explained variances for each interval of interest

	Stroop Colour	Stroop Word
Interval (ms)	Explained Variance (%)	Explained Variance (%)
60-100	91.9	92.2
170-210	92.7	95.4
300-340	------	72.3
-200-1000	69.7	81.0

Table 14: Dipole and flicker interaction shows 500 Hz consistently has the lower mean response (nA) for source dipole moments

Dipole * Flicker Measure: MEASURE_1					
Dipole	Flicker	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Right	0 Hz	2.762	0.694	1.326	4.198
	100 Hz	2.493	0.616	1.219	3.767
	500 Hz	**2.170**	**0.564**	1.003	3.337
Left	0 Hz	4.317	2.280	-0.399	9.034
	100 Hz	6.318	2.279	1.603	11.032
	500 Hz	**3.409**	**2.063**	-0.859	7.676

Table 15: Pairwise comparison between 100 and 500 Hz of dipole (nA) and flicker (Hz) interaction

Pairwise Comparisons Measure: MEASURE_1						
(I) Flicker	(J) Flicker	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
0 Hz	100 Hz	-0.866	0.591	0.470	-2.392	0.661
	500 Hz	0.750	0.514	0.475	-0.578	2.079
100 Hz	0 Hz	0.866	0.591	0.470	-0.661	2.392
	500 Hz	1.616*	0.610	**0.043**	0.042	3.190
500 Hz	0 Hz	-0.750	0.514	0.475	-2.079	0.578
	100 Hz	-1.616*	0.610	**0.043**	-3.190	-0.042

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

* Highlighted Result indicates a significant difference between 100 and 500 Hz.

Table 16: Pairwise comparison of 100 and 500 Hz dipole (nAm) and flicker (Hz) interactions

Comparisons are for the right hemisphere, Dipole 1 (SD1), in Stroop Colour Congruent (SCC) for 170 to 210 ms between 100 and 500 Hz, the left hemisphere, Dipole 2 (SD2), in Stroop Colour Incongruent (SCI) for 60-100 and 170-210 ms

Paired Samples Test									
SD1 = Right hemisphere SD2 = Left hemisphere		Paired Differences					t	f	Sig. (2-tailed)
		Mean	SD	E	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	SD1_SCC_500Hz_170_210ms - SD1_SCC_100Hz_170_210ms	0.65	0.48	0.30	-1.28	-0.03	2.16	3	**0.04**
Pair 2	SD2_SCI_500Hz_60_100ms - SD2_SCI_100Hz_60_100ms	4.24	0.38	0.12	-8.62	0.14	2.00	3	**0.06**
Pair 3	SD2_SCI_500Hz_170_210ms - SD2_SCI_100Hz_170_210ms	5.46	0.97	0.24	-10.09	-0.83	2.44	3	**0.02**

Highlighted values indicate a significant difference between 100 and 500 Hz for Stroop colour congruent from 170 to 210 ms and for incongruent for the same condition, for both early intervals.

Figure 1: Cortical and subcortical visual pathways

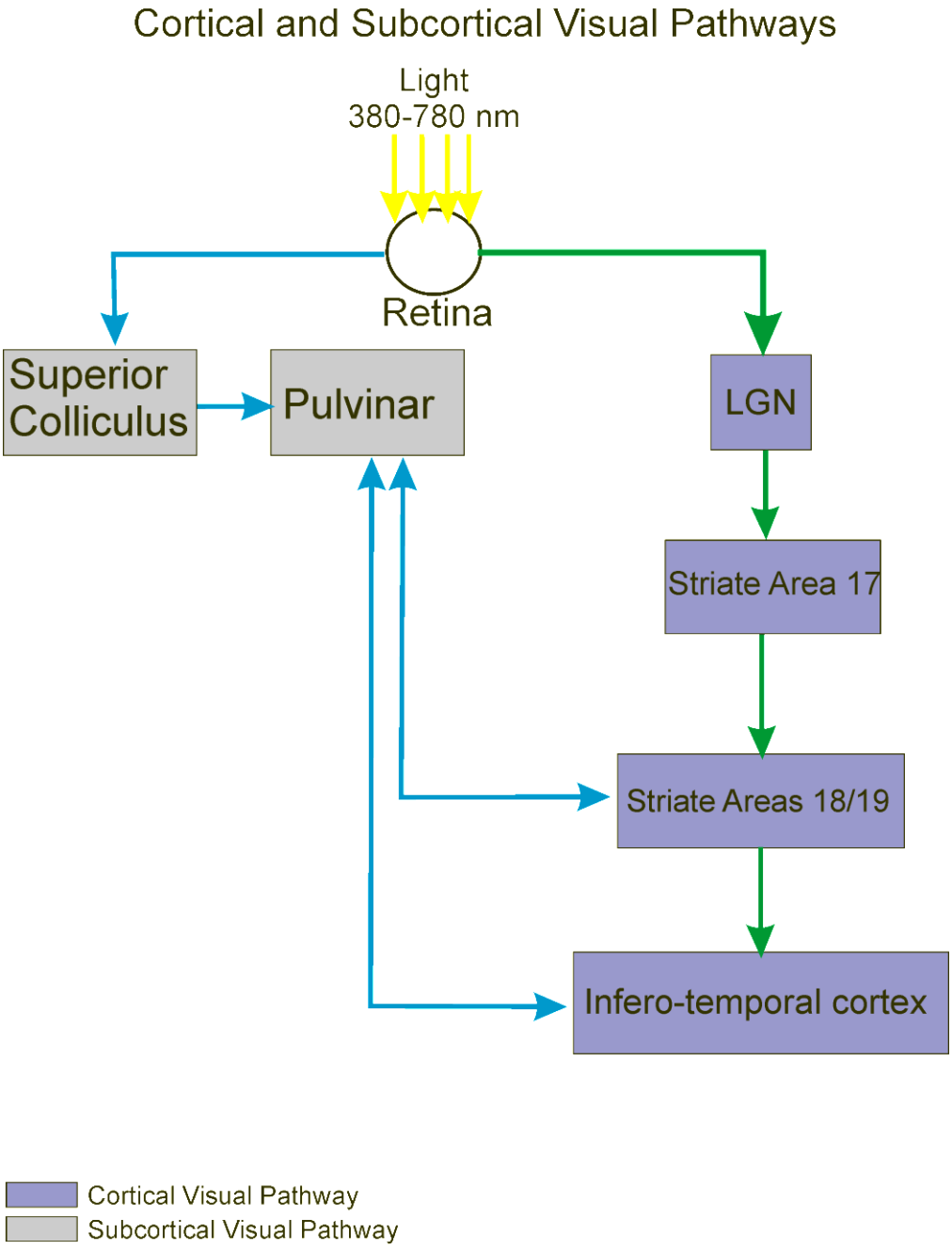
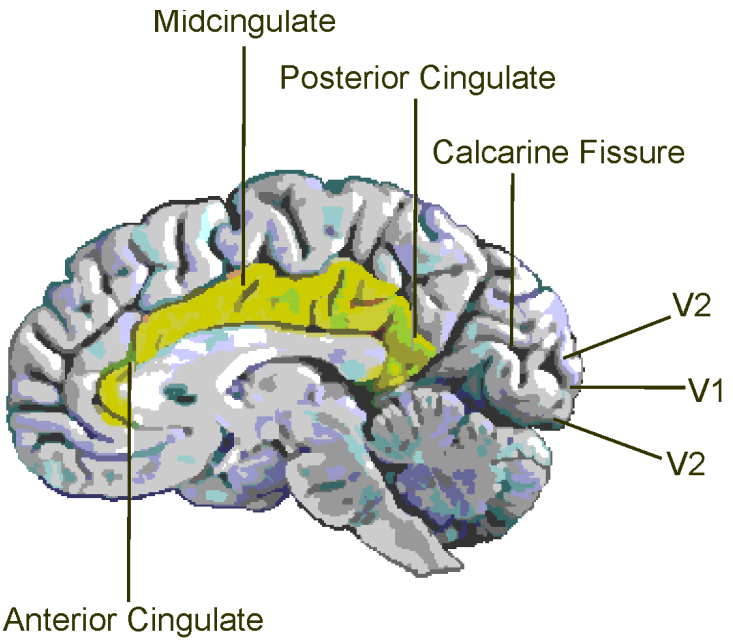


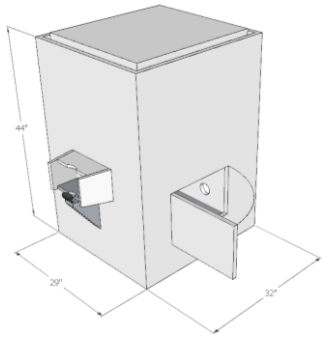
Figure 2: Sagittal section showing anterior cingulate cortex and calcarine fissure



*The anterior cingulate cortex and calcarine fissure have been localized as areas of activation during the Stroop task.

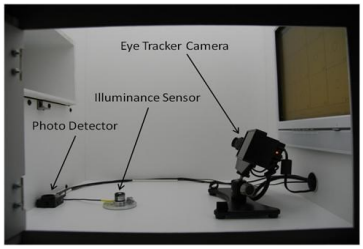
Figure 3: Photographs and schematic of light booth system

Booth front



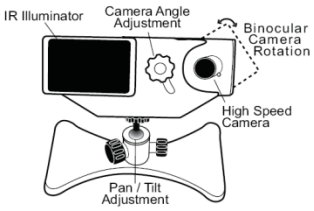
Booth dimensions

Viewport



Booth interior

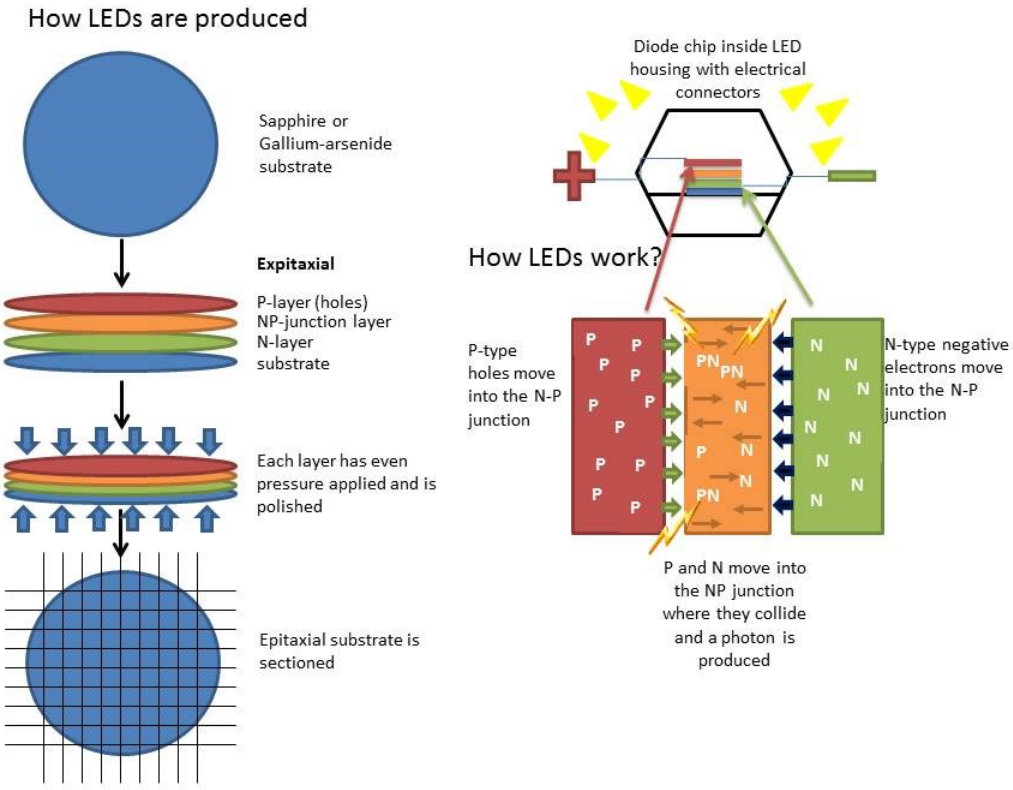
Monitor



Eye tracker camera schematics

Detailed photograph of eyetracker camera

Figure 4: Manufacture and operation of light emitting diodes



Note: an additional wire (i.e. the driver) would be added to the chip to control the LED.

Figure 5: Luminance measures of light system walls and monitor at three flicker rates

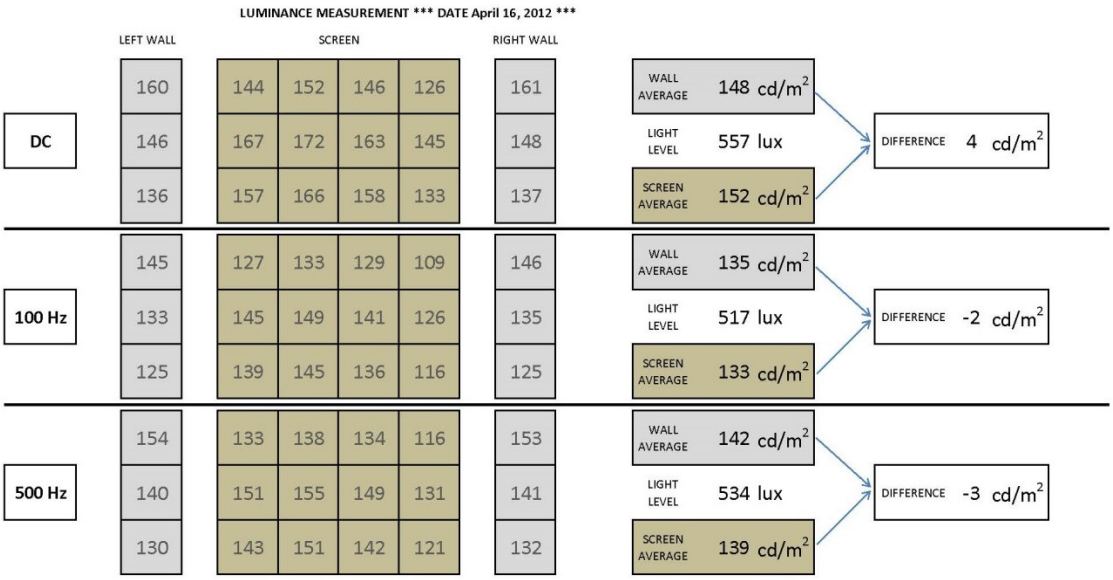


Figure 6: LED and monitor heat sink temperature comparisons for two days

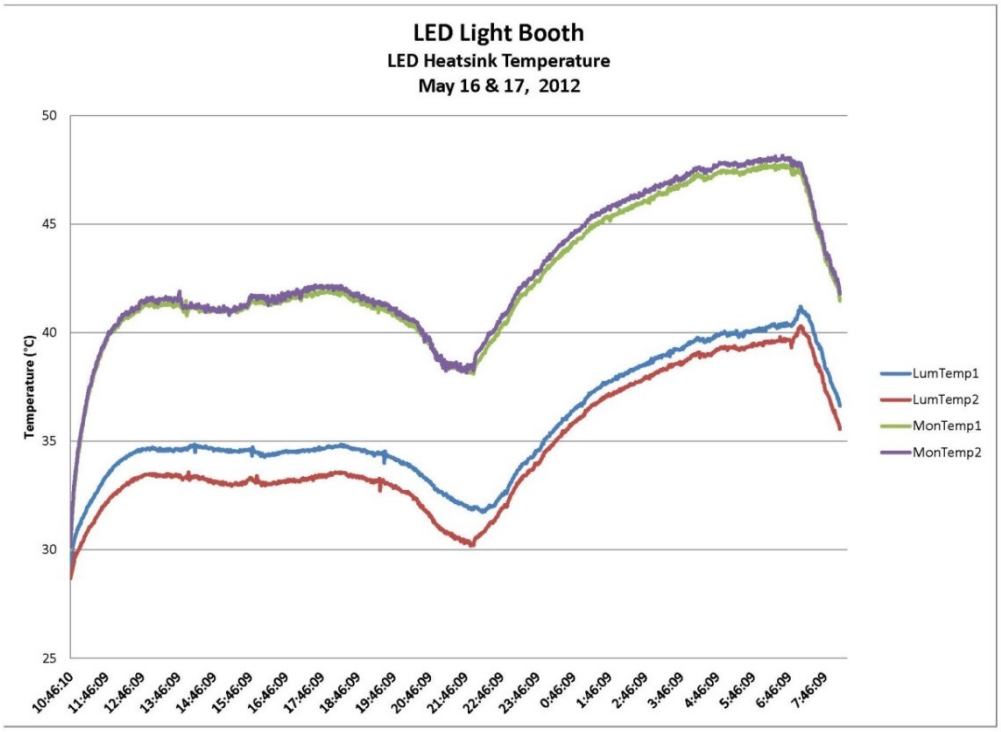


Figure 7: Computers and switching system diagrammatic representation of research facilities

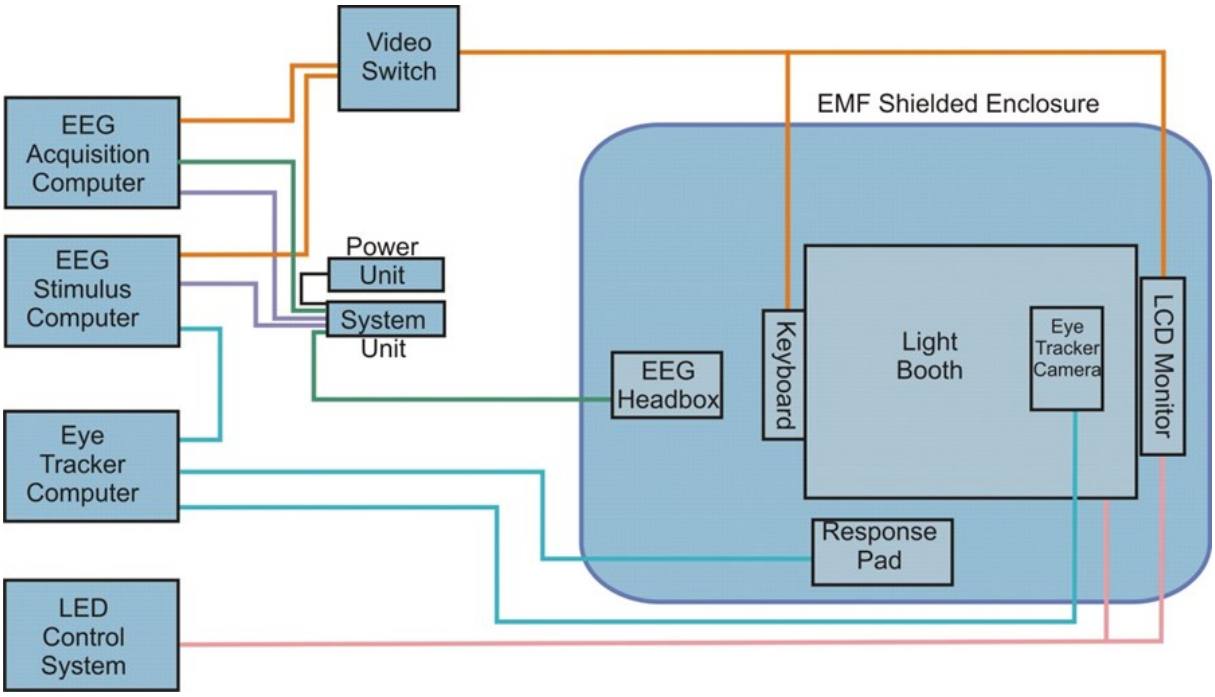


Figure 8: Laptop interface display of active LED illuminance values (yellow line) with luminance limitations (red lines) and 100 percent square wave modulation.

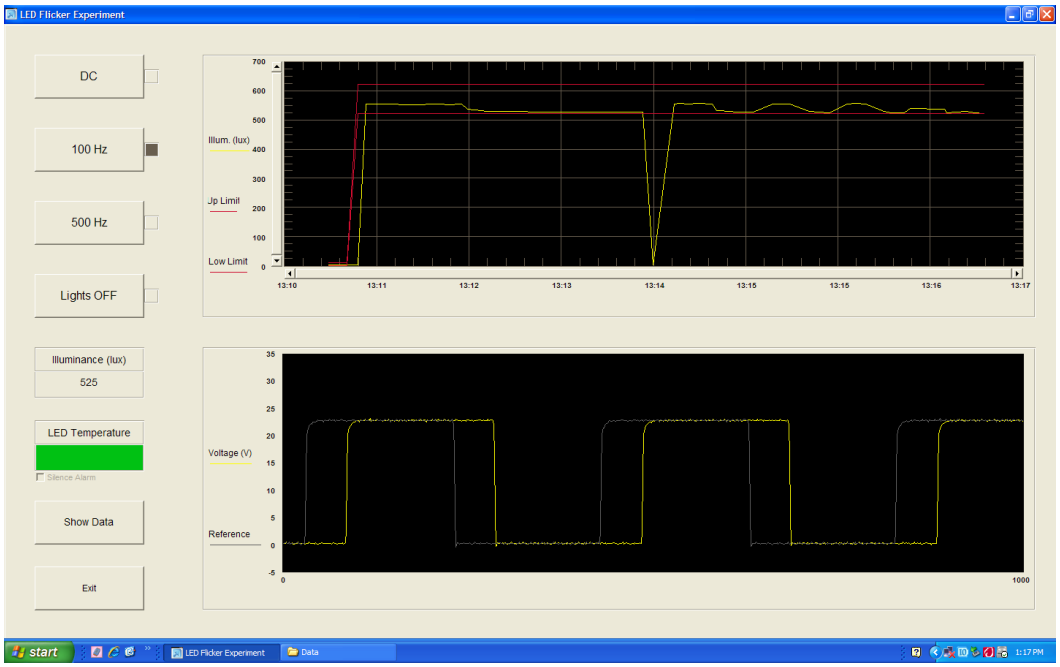
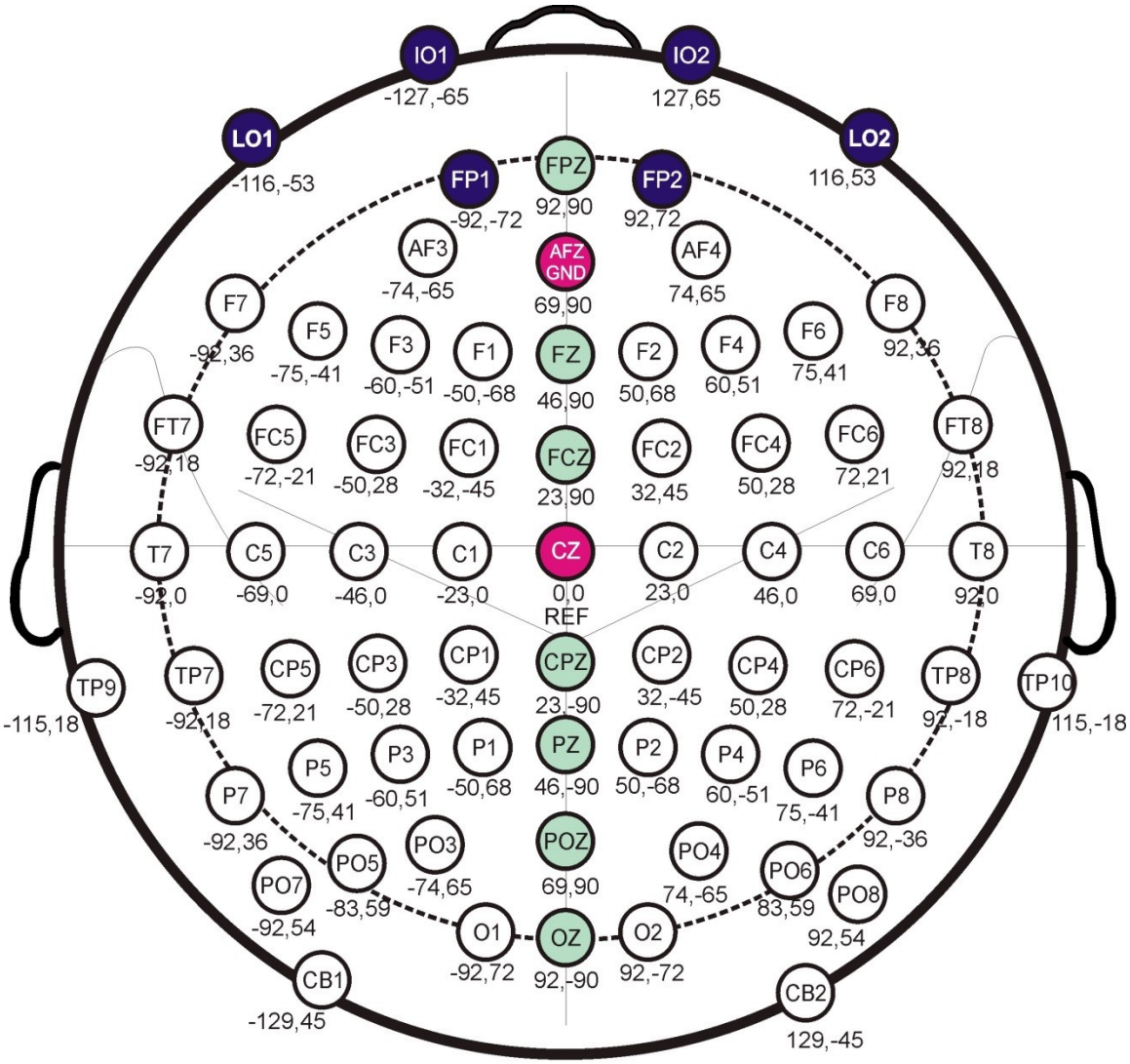
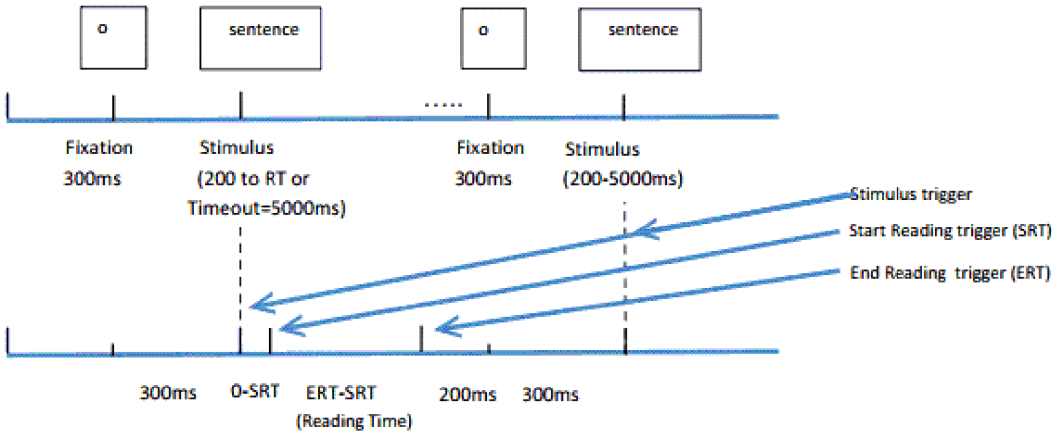


Figure 9: 70-channel Neuroscan Quik cap configuration



(REF IS SITUATED BEHIND Cz)

Figure 10: Sentence presentation stimulus and event timing



Stimulus trigger = X

Category (1-'A', 2-'The', 3-'There')

Start Reading trigger = XX

0

Category (1-'A', 2-'The', 3-'There')

End Reading trigger = XX

1

Category (1-'A', 2-'The', 3-'There')

Figure 11: Stroop stimulus and event timing

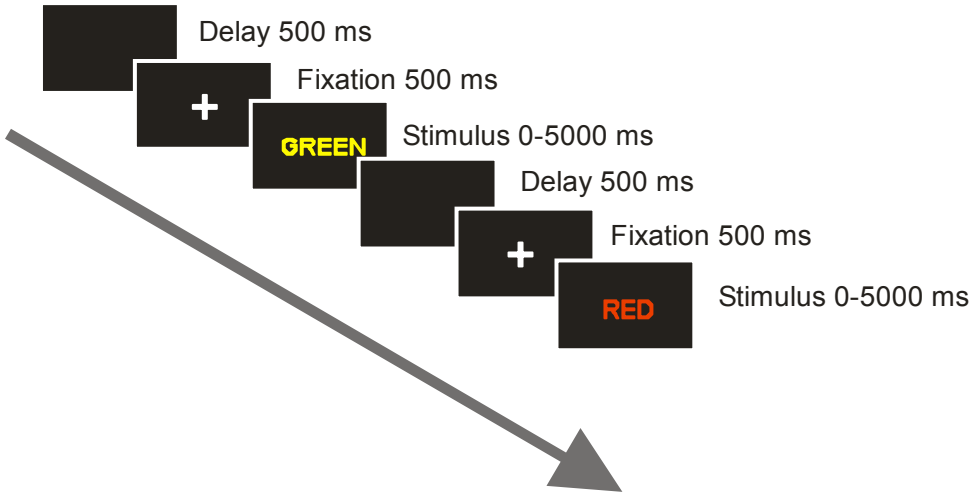
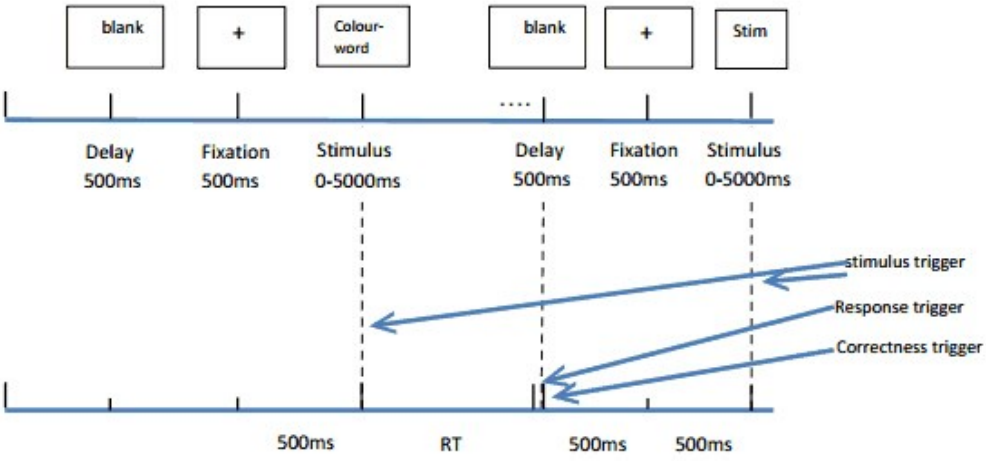


Figure 12: Stroop stimulus and response triggers and timing



Trigger Times for Stroop Task

Stimulus trigger = XXX

- 0
- Stimulus (1-red, 2-blue, 3-green, 4-yellow)
- Condition (1-word, 2-colour)

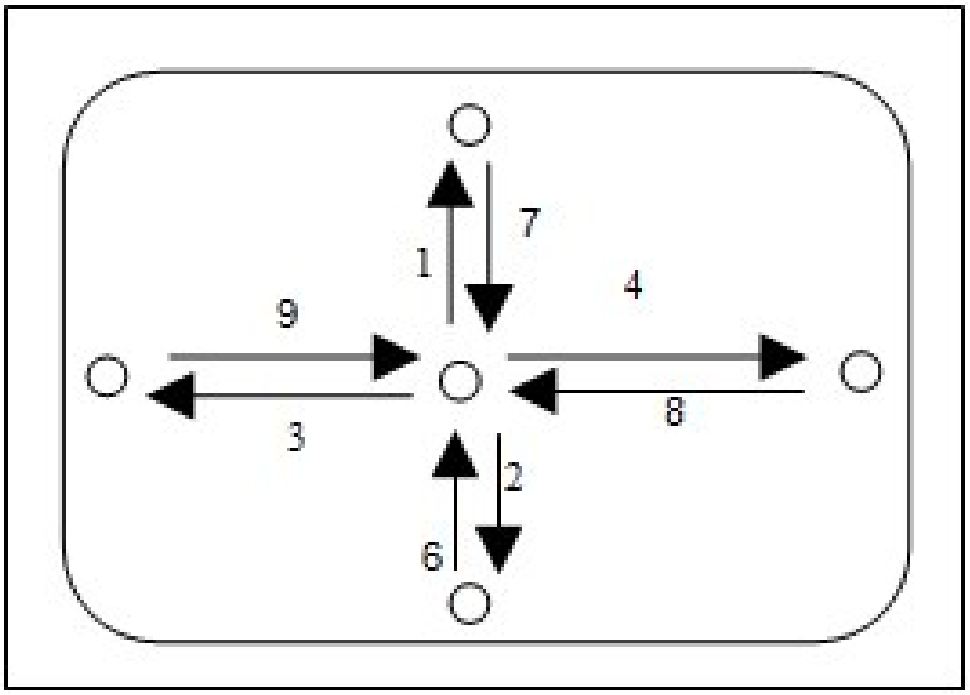
Response trigger = XXX

- Response (1-red, 2-blue, 3-green, 4-yellow)
- Stimulus (1-red, 2-blue, 3-green, 4-yellow)
- Condition (1-word, 2-colour)

Response Correctness = XX

- Correctness (0 – incorrect, 1-correct)
- 9

Figure 13: Eye movement calibration program showing trigger direction for saccades



*For experiment, stimulus was a white circle on a black background.

Figure 14: Neuroscan noise spectral analysis for 70 channel electrode configuration

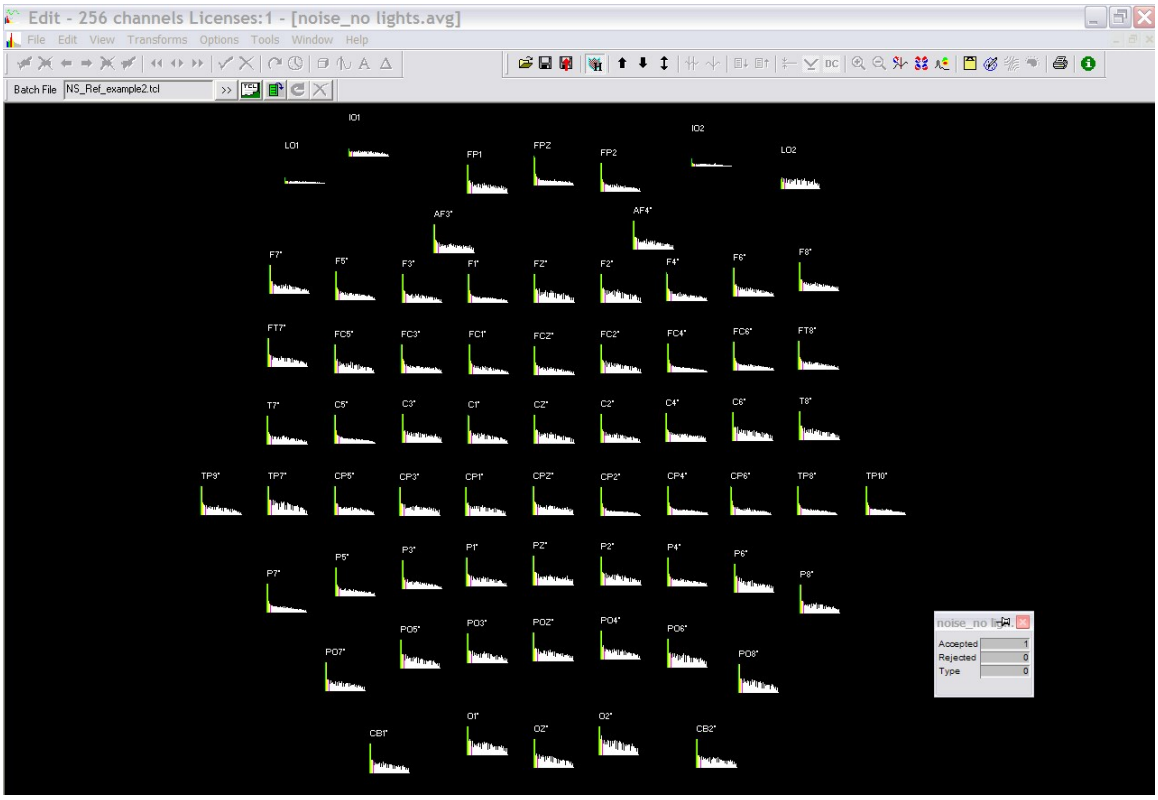


Figure 15: Eye tracker 9-point calibration screen

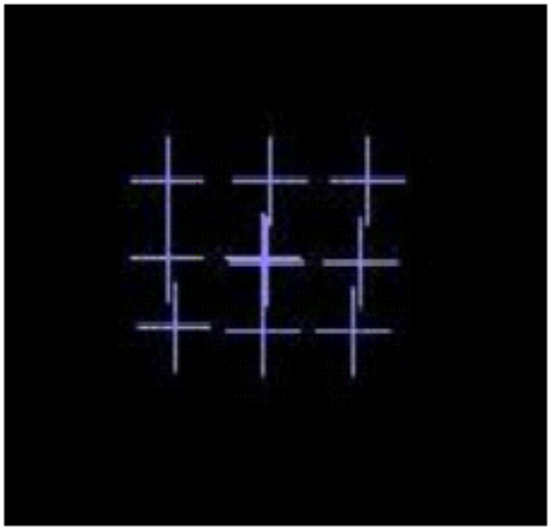


Figure 16: Eye tracker validation screen performed after initial calibration

An example of cross positions in a good calibration

Figure 17: Grand average waveform collapsed across colour conditions of right parieto-occipital electrode (PO8) for Strrop word and colur tasks (N=34)

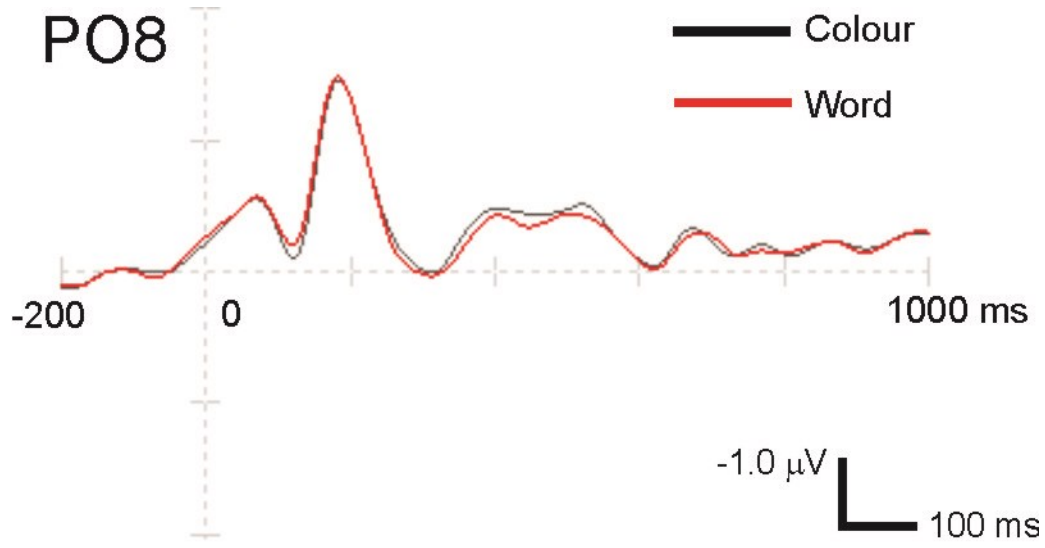


Figure 18: Electrode regions used in colour and word analyses

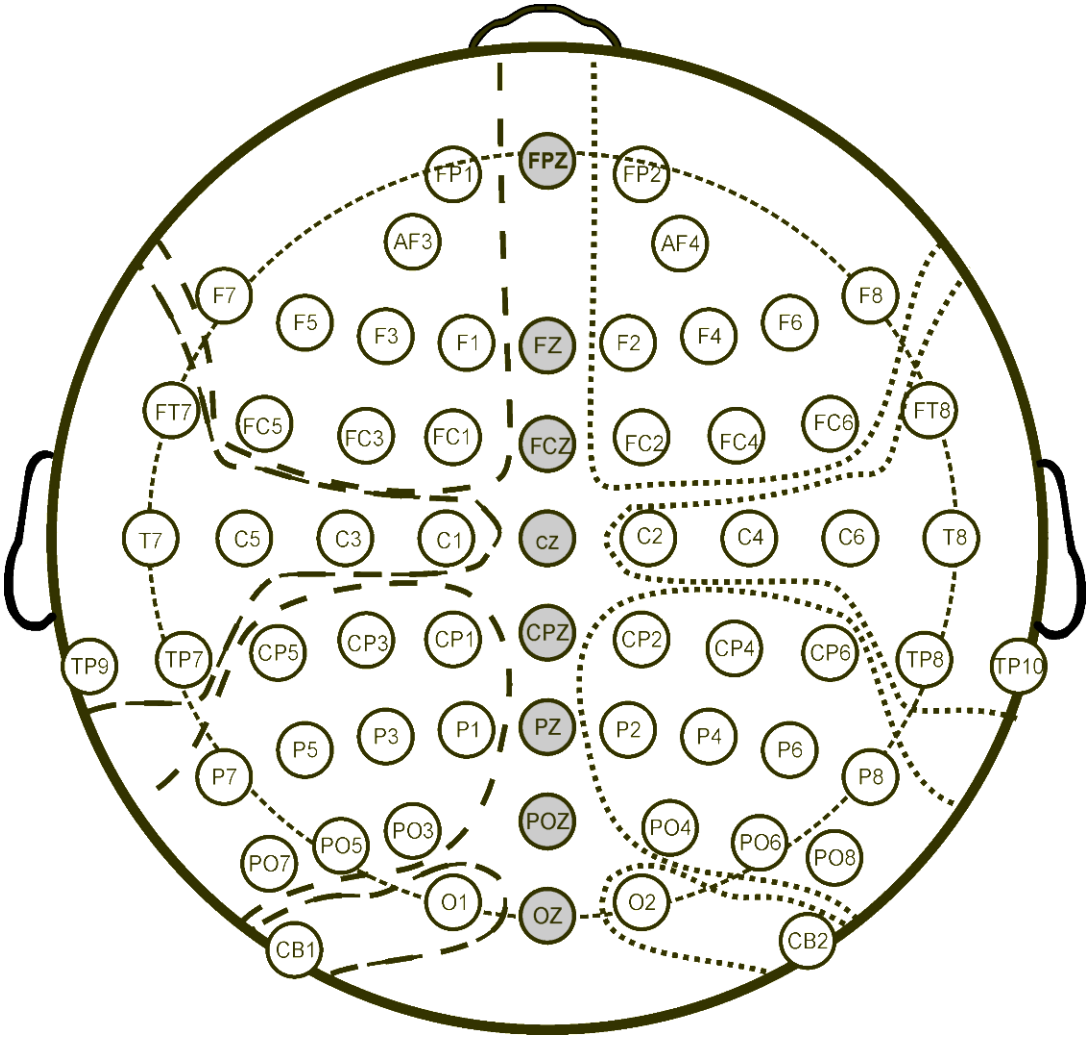


Figure 19: Average STAI scores for pre-test and experimental test blocks

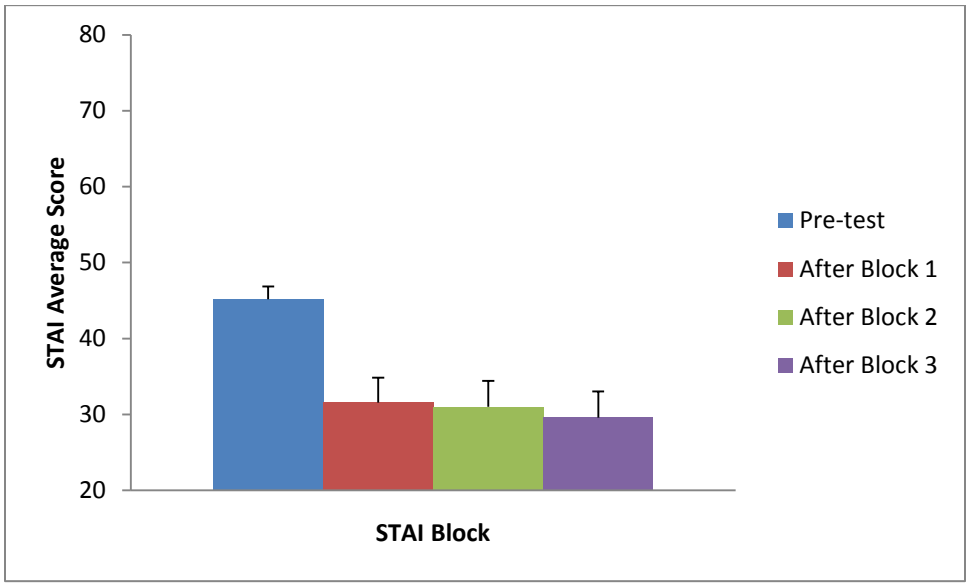
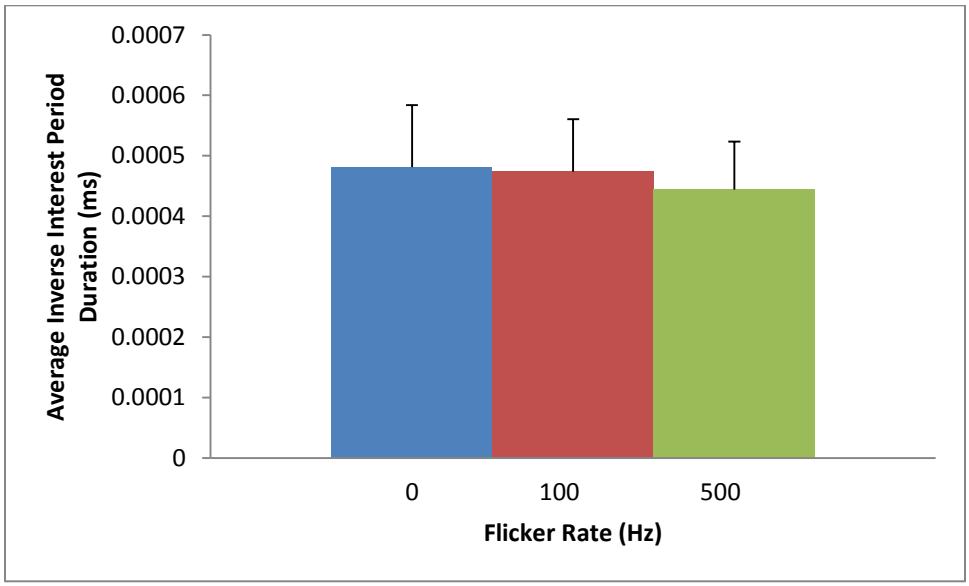


Figure 20: Inverse average sentence reading time (ms) for the interest period duration at three flicker rates (Hz)



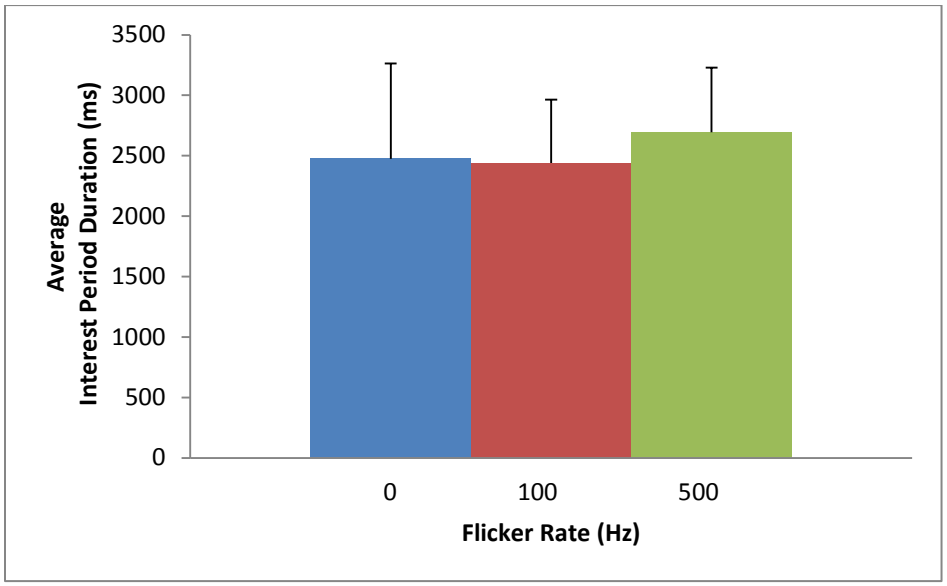
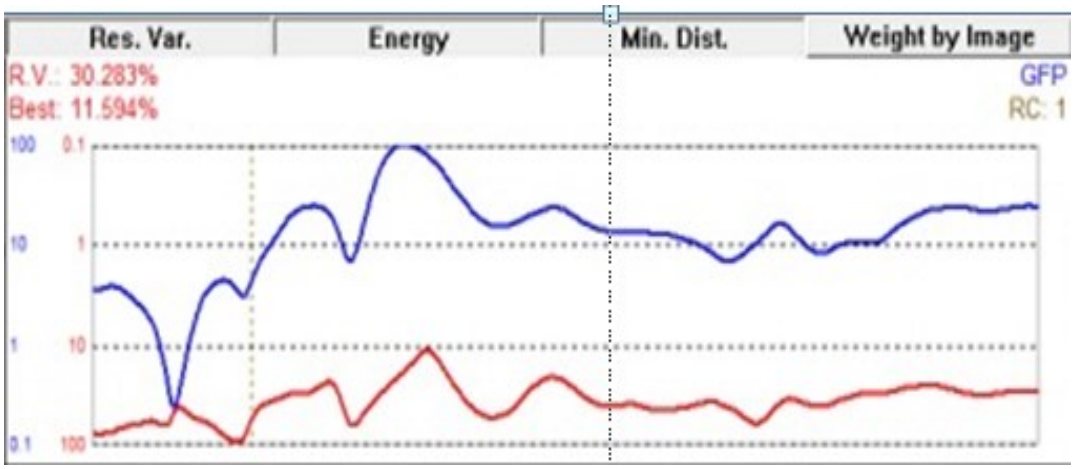
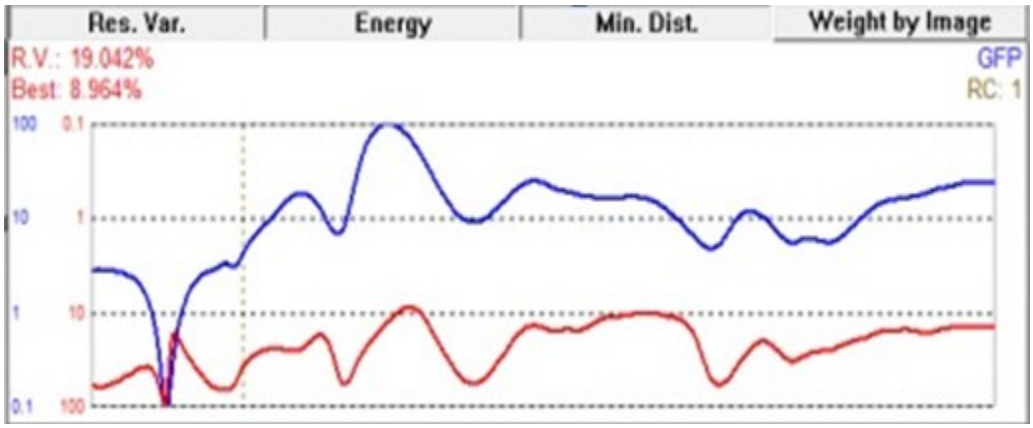


Figure 21: Residual variance (%) for grand average of Stroop colour and word tasks for -200 to 1000 ms



Stroop Colour



Stroop Word

Figure 22: Grand average response time difference (ms) of incongruent and congruent Stroop task at three flicker rates (Hz)

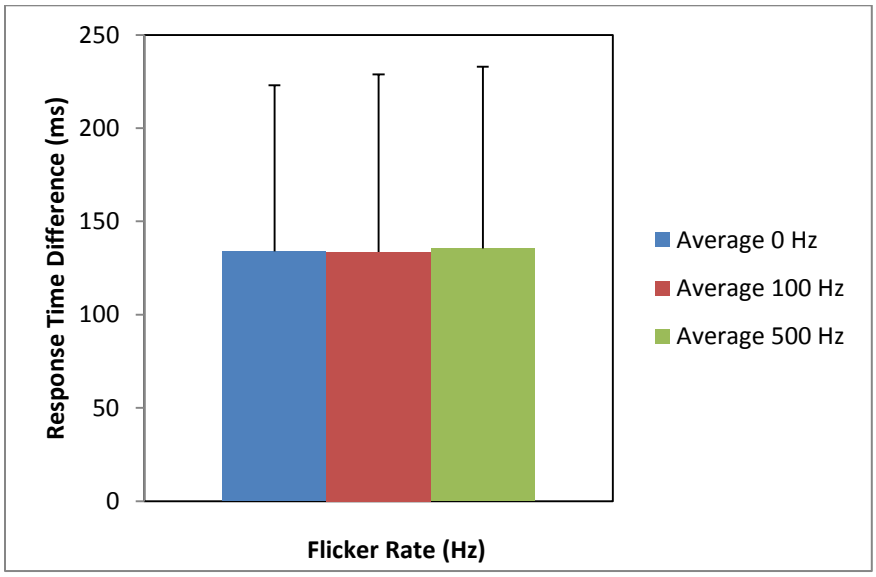
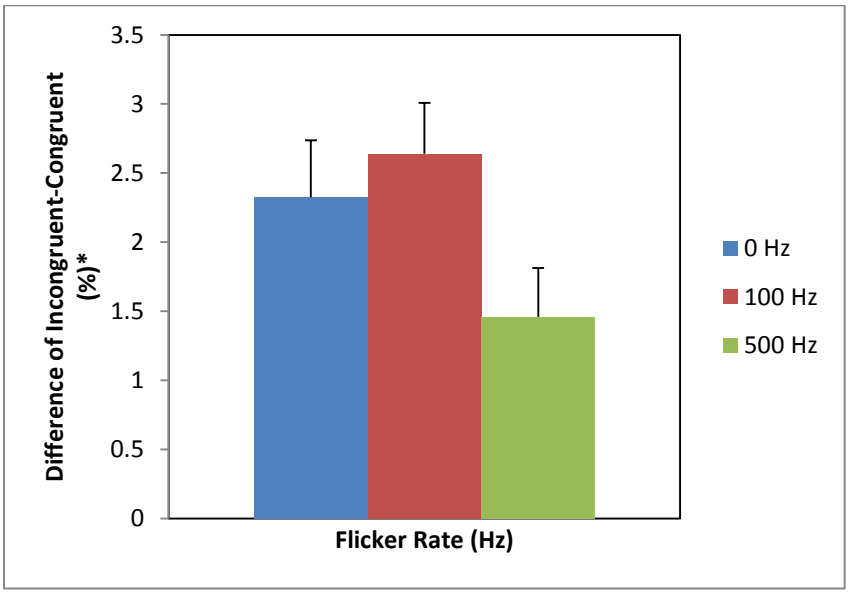
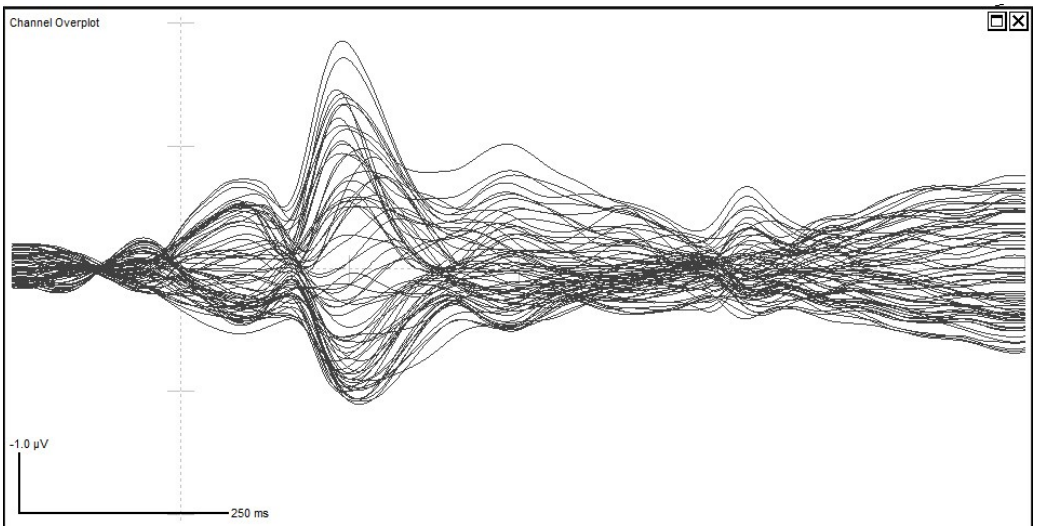


Figure 23: Grand average percent difference of incongruent and congruent Stroop tasks at three flicker rates (Hz)

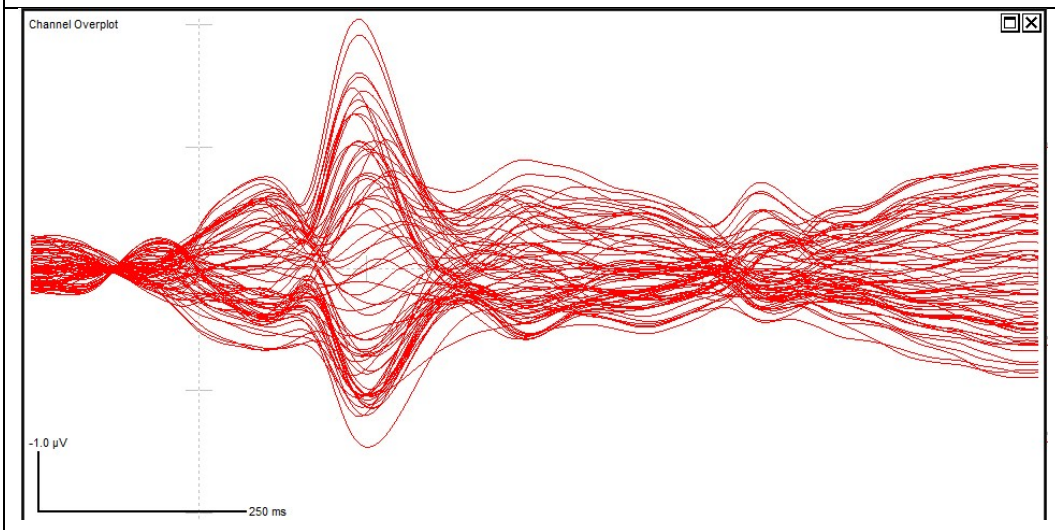


Difference of incongruent-congruent (%) was calculated as (100 (correct answers)/(total trials))for incongruent condition-(100*(correct answers)/(total trials)) for congruent condition

Figure 24: 70-Channel overplot electroencephalographic waveforms (μV) for Stroop colour and word tasks



Stroop Colour



Stroop Word

Figure 25: Regional mean peak amplitudes (μV) for four intervals (ms) in Stroop colour task

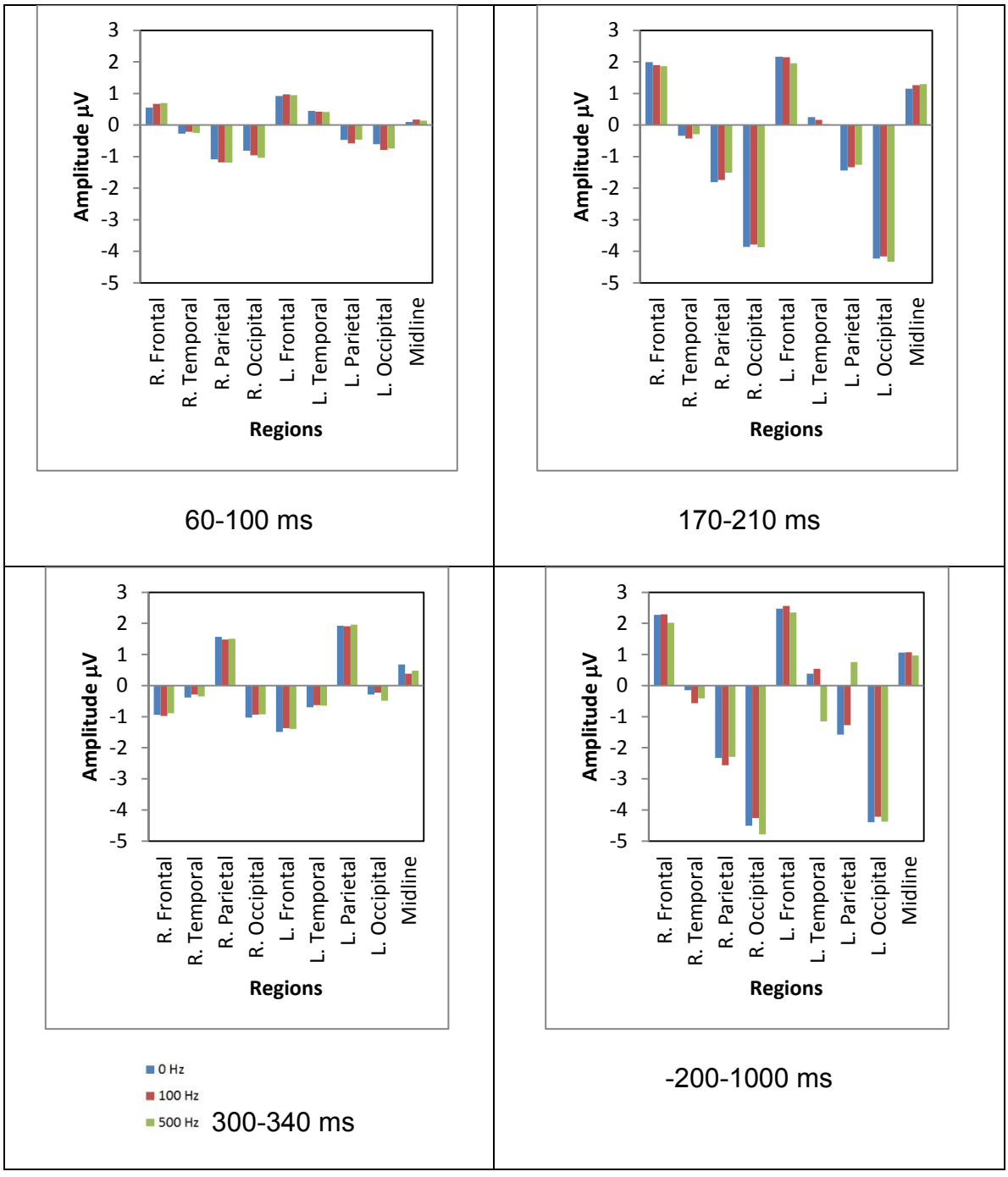


Figure 26: Regional mean peak amplitudes (μV) for three intervals (ms) in Stroop colour task for right and left hemispheres and midline region

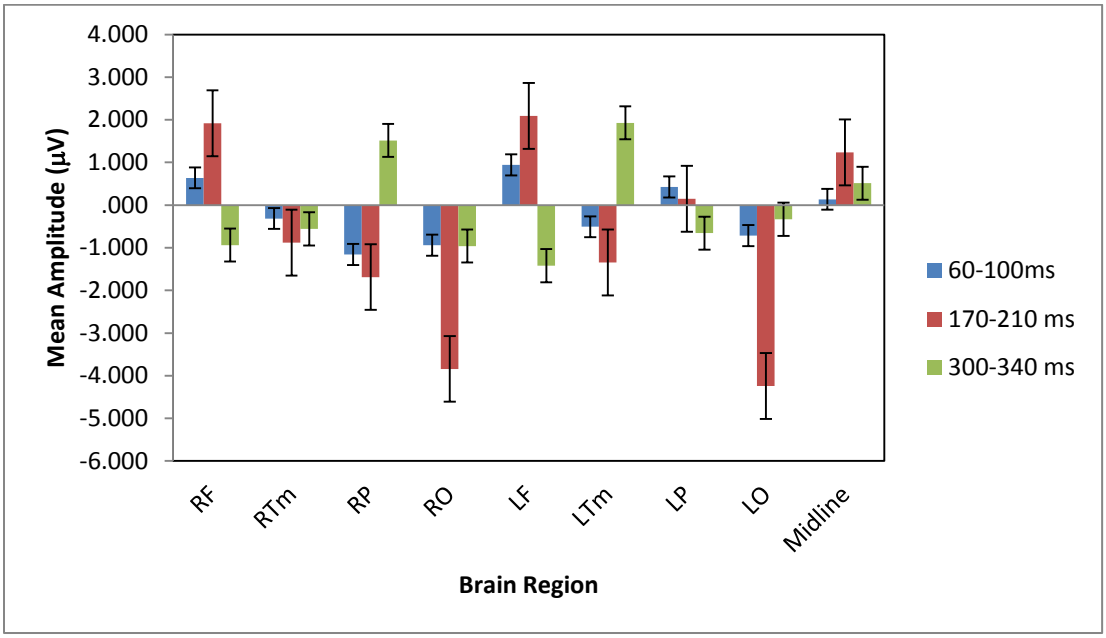


Figure 27: Regional mean peak amplitude (μV) for three intervals (ms) in Stroop word task for right and left hemispheres and midline region

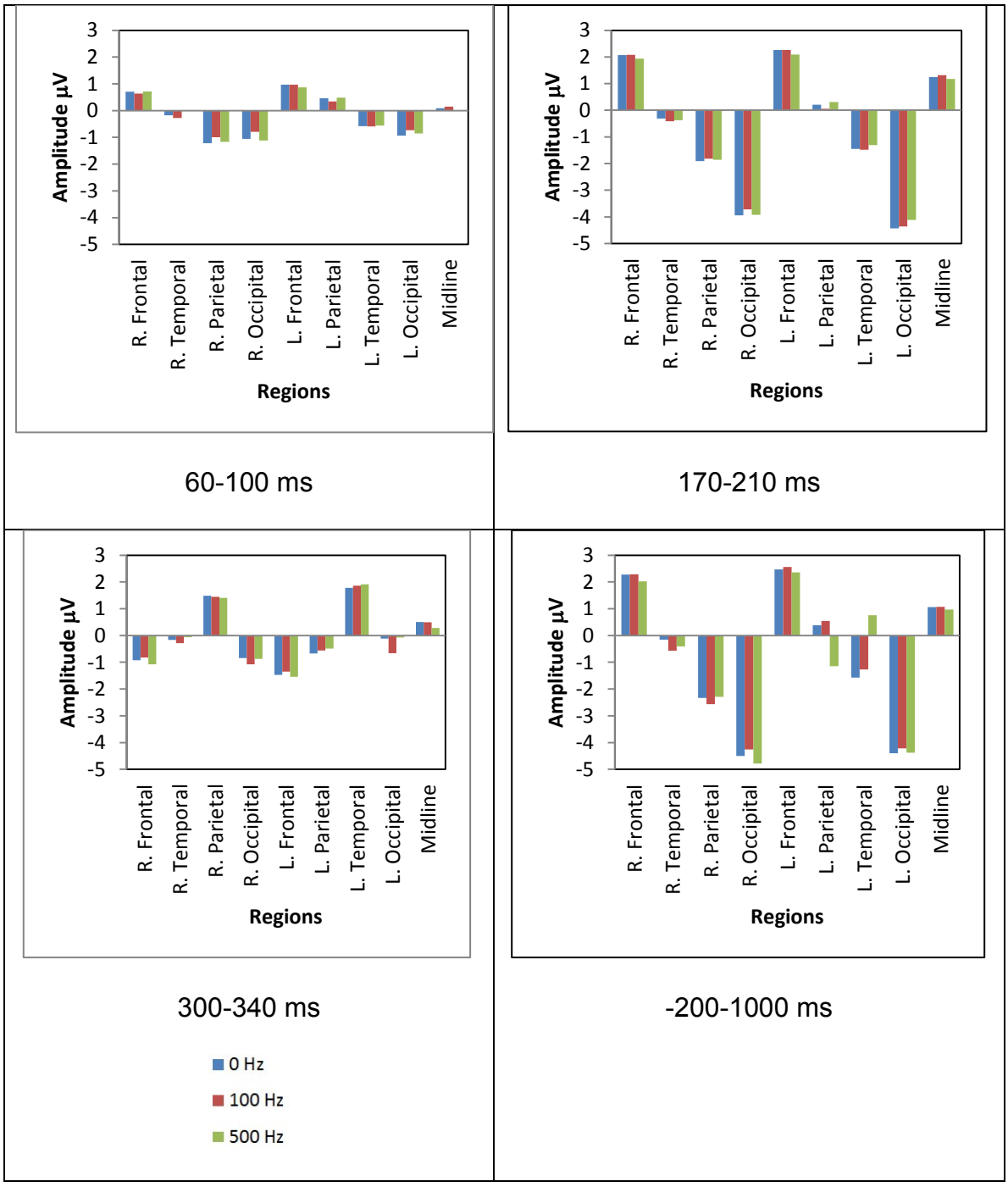


Figure 28: Regional mean peak amplitudes (μV) for three intervals (ms) in Stroop word task for right and left hemispheres and midline region

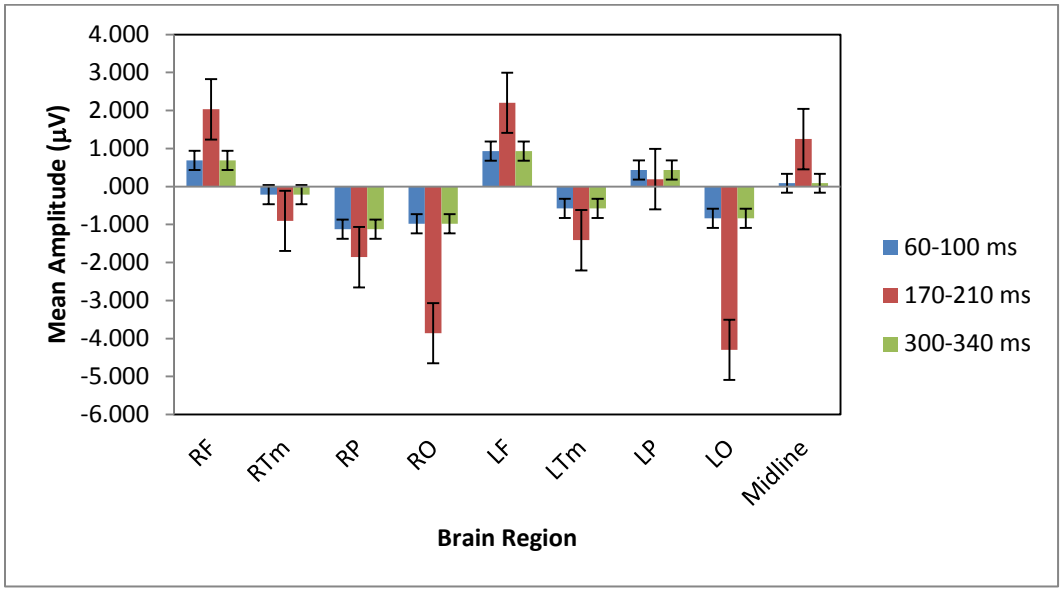
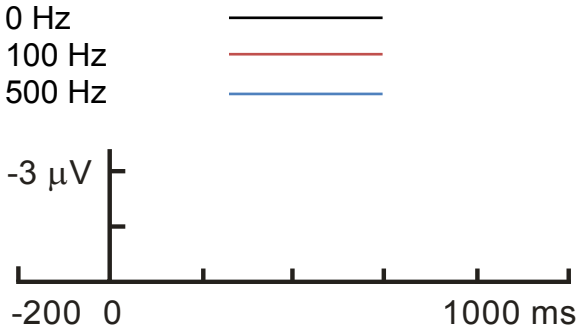
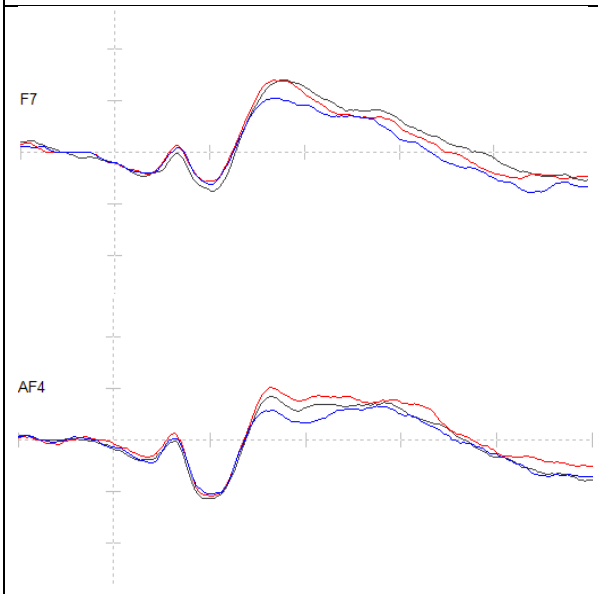


Figure 29: Grand average waveforms (μV) at selected electrodes for Stroop colour

Waveform for Stroop Colour	Observations
	For all peak and latency figures, negative was plotted upwards.
 Frontal	F7 and AF4, showed a more positive deflection for the 500 Hz response at 330 ms.

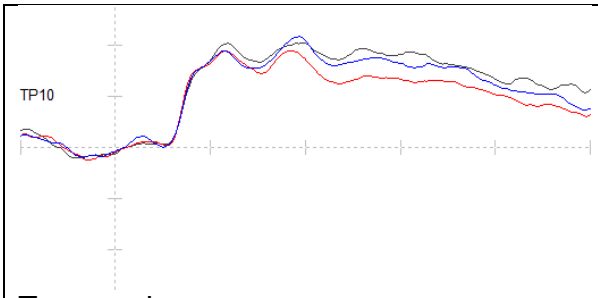
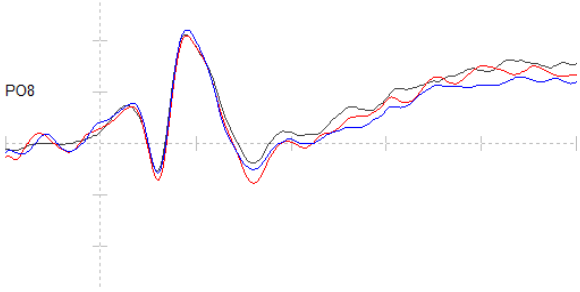
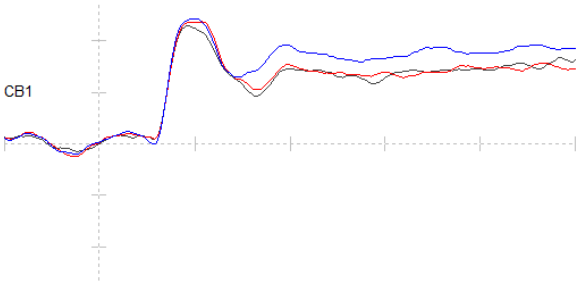
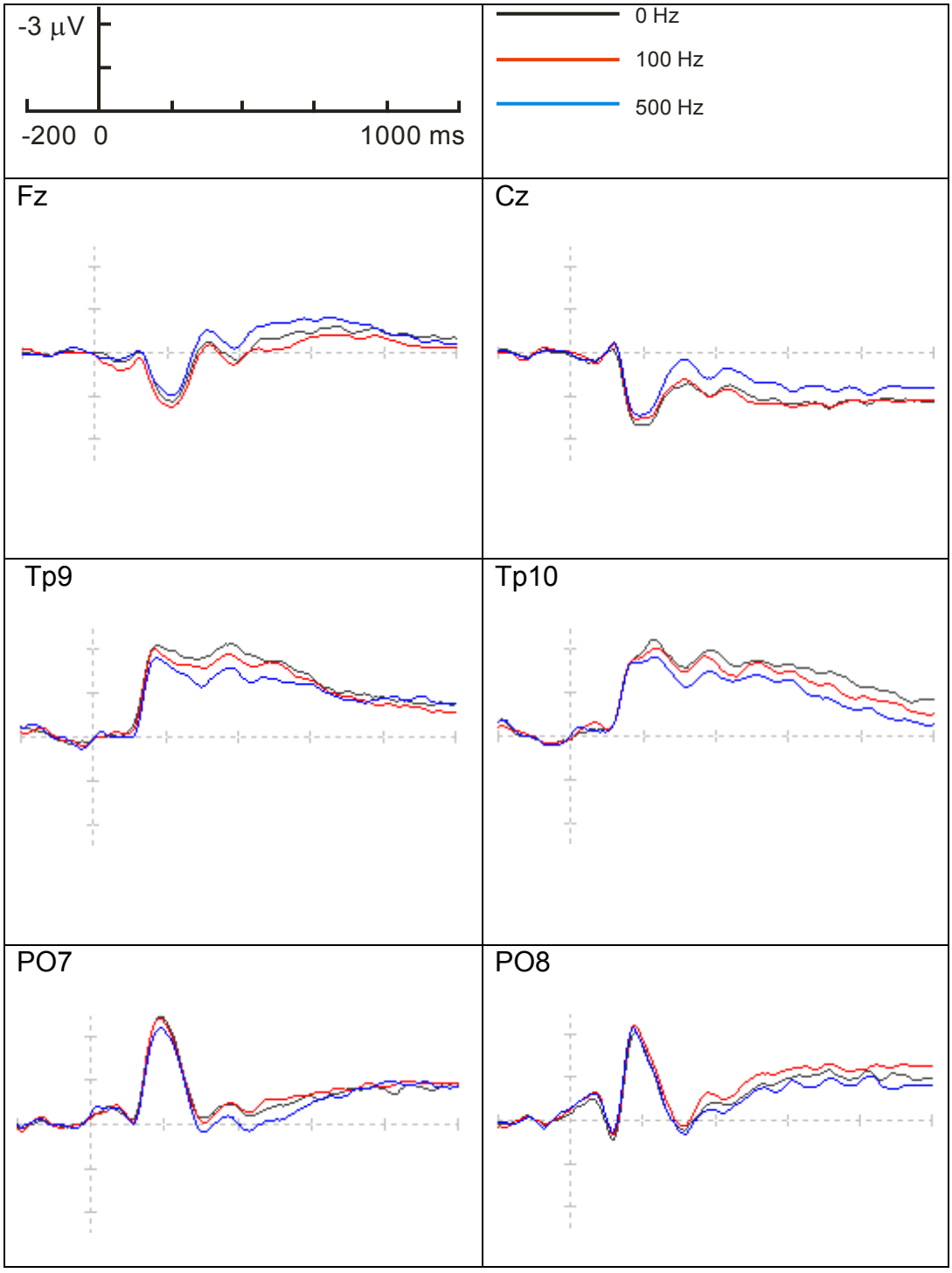
 Temporal	TP10, showed a more positive deflection for 100 Hz as compared to 0 and 500 Hz flicker at the 460 ms latency.
 Parietal	The 100Hz positive deflection for 310 ms latency was slightly larger than 0 and 500 Hz. Negative was plotted upwards for all peak and latency figures.
 Cerebellar	CB1, showed a more sustained negative deflection for 500 Hz than the 0 or 100 Hz for latencies at 330 ms and 390 ms.

Figure 30: Grand average waveforms at selected electrode sites for Stroop word



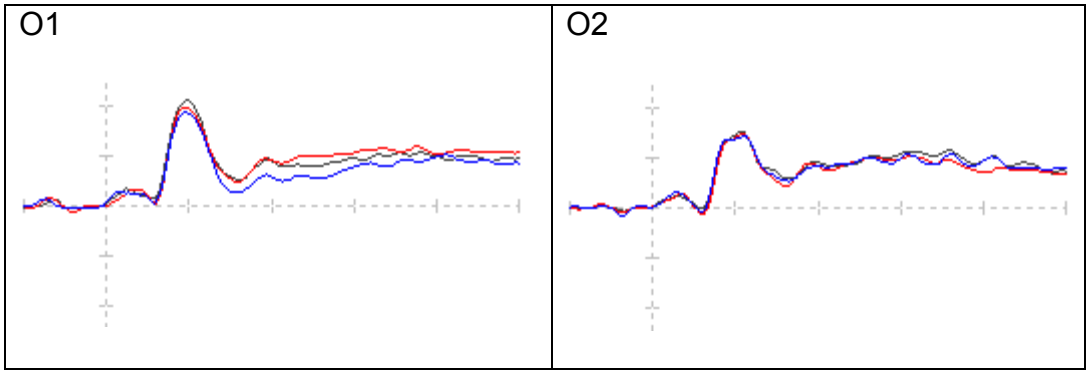
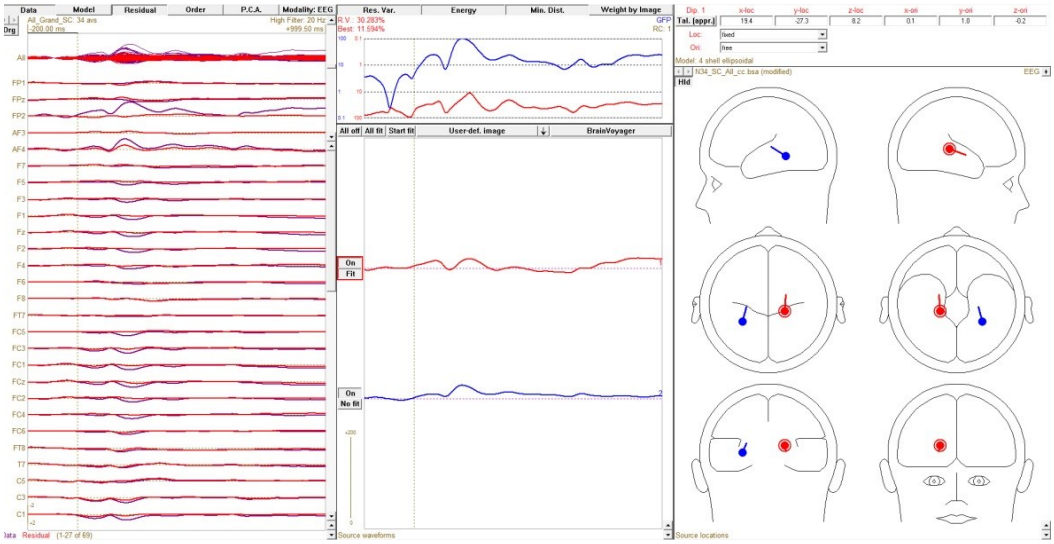

O1
O2

Figure 31: Stroop colour rand average source analysis showing electrode waveforms on the left, source waveforms in the centre with residual variance (top), and source dipoles on the right

Stroop Colour



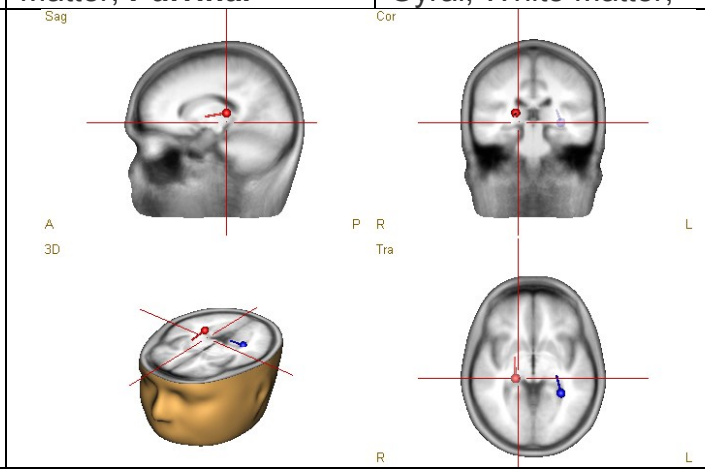
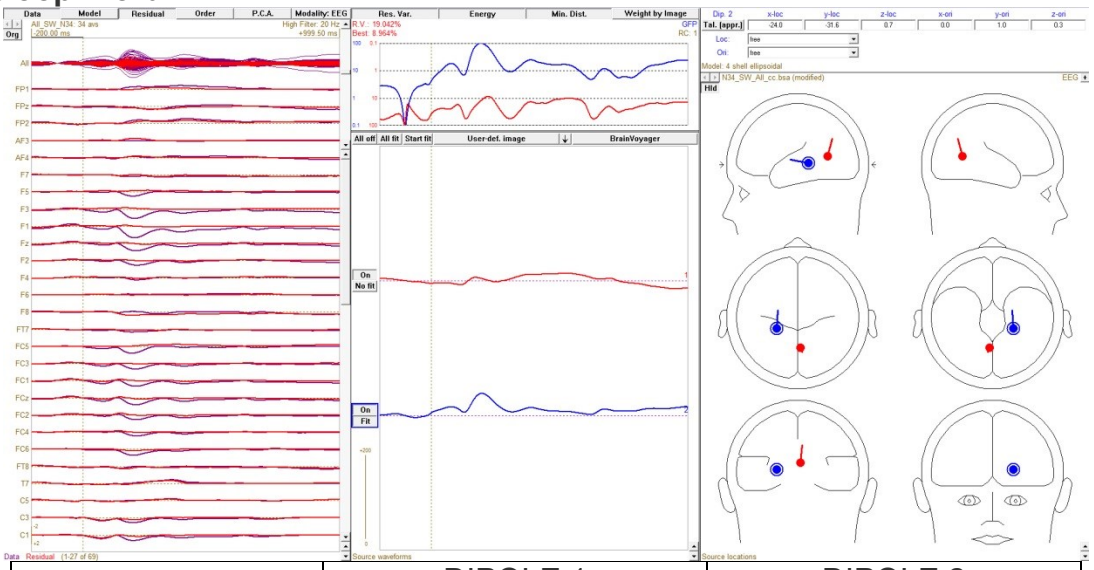
Besa Dipole	DIPOLE 1			DIPOLE 2		
x,y,z coordinate	19.4	-27.3	8.2	-30.2	-41.9	-2.4
x,y,z orientation	0.1	1.0	-0.2	0.2	0.8	0.6
Talairach coordinates	19.0	-27.0	8.0	-30.0	-42.0	-2.0
Localization	Right Cerebrum, Sub-lobar, Thalamus, Gray Matter, **Pulvinar**			Left Cerebrum, **Temporal Lobe**, Sub-Gyral, White Matter, *		
Localization Image Red = Dipole 1 Blue = Dipole 2						

Figure 32: Stroop word grand average source analysis showing electrode waveforms on the left, source waveforms in the centre with residual variance (top), and source dipoles on the right

Stroop Word



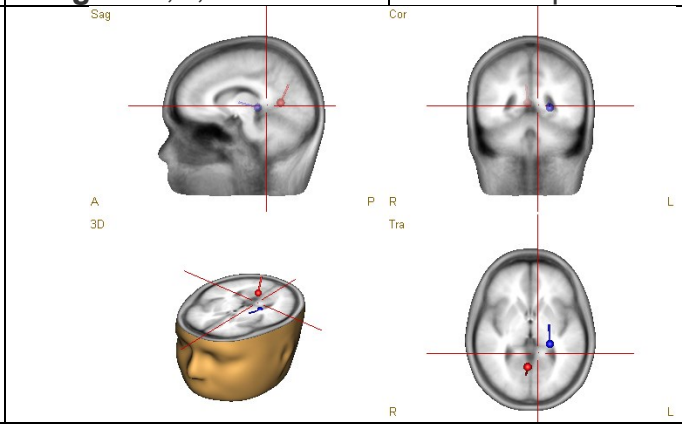
	DIPOLE 1			DIPOLE 2		
Besa Dipole x,y,z coordinate	3.2	-59.8	6.5	-24.0	-31.6	0.7
Besa Dipole x,y,z orientation	0.1	-0.4	0.9	0.0	1.0	0.3
Talairach.org coordinates	3.0	-60.0	7.0	-24.0	-32.0	1.0
Localization	Right Cerebrum, Limbic Lobe, **Posterior Cingulate**, *, *			Left Cerebrum, Sub-lobar, Lateral Ventricle, Cerebro-Spinal Fluid, *		
Localization Image Red = Dipole 1 Blue = Dipole 2						

Figure 33: Source localizations for Stroop colour and word at 60-100 ms

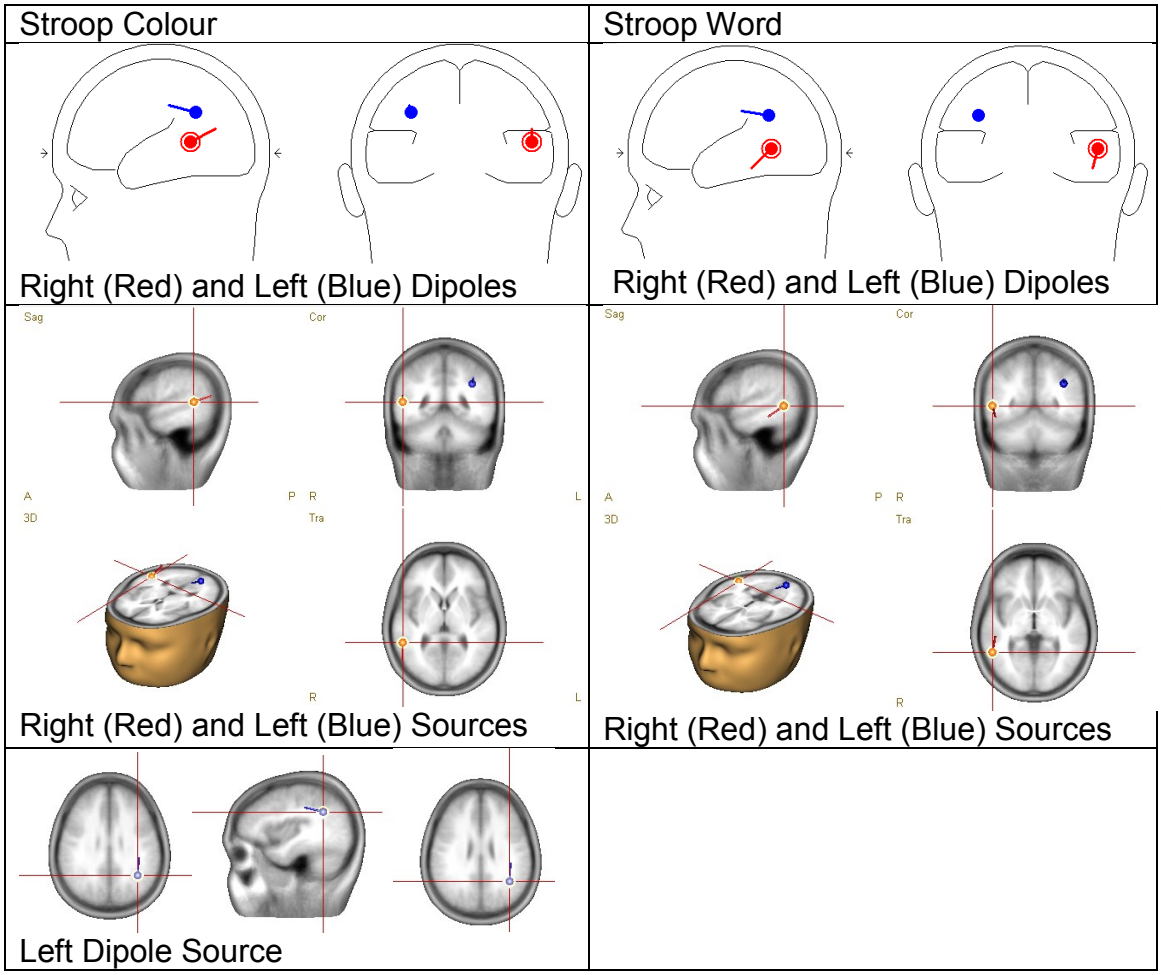


Figure 34: Source localizations for Stroop colour and word at 170-210 ms

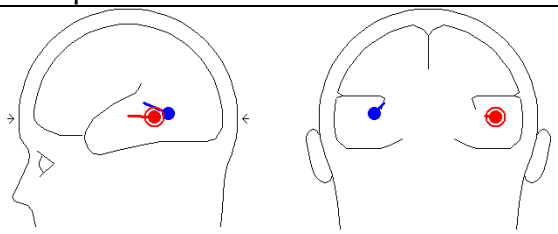
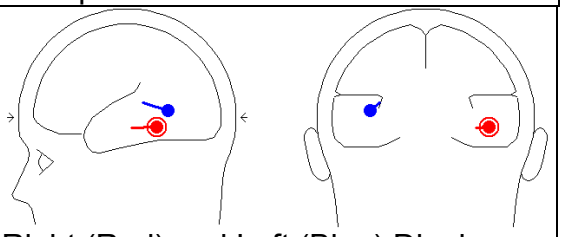
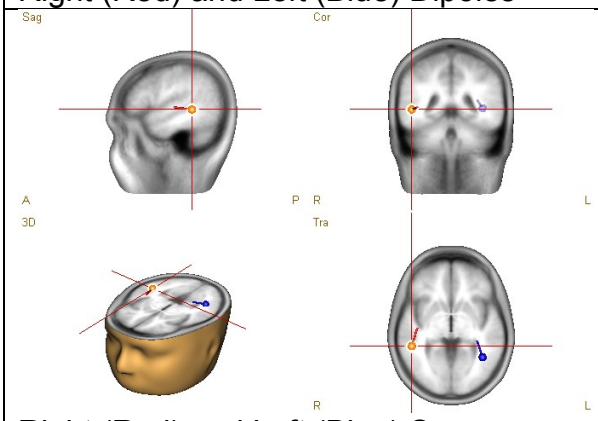
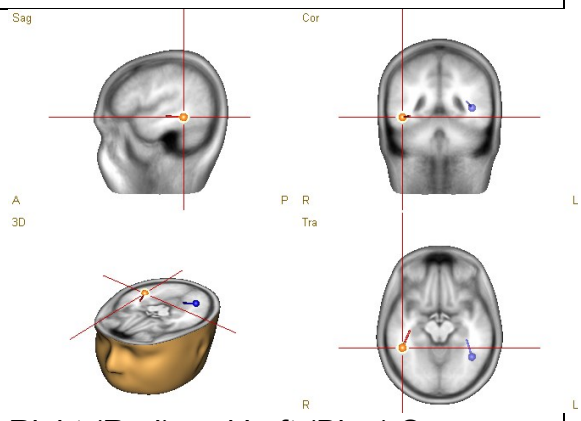
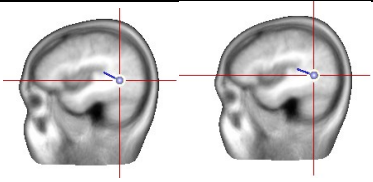
Stroop Colour	Stroop Word
 Right (Red) and Left (Blue) Dipoles	 Right (Red) and Left (Blue) Dipoles
 Right (Red) and Left (Blue) Sources	 Right (Red) and Left (Blue) Sources
 Right (Red) and Left (Blue) Sources	

Figure 35: Source localizations for Stroop word at 300-340 ms

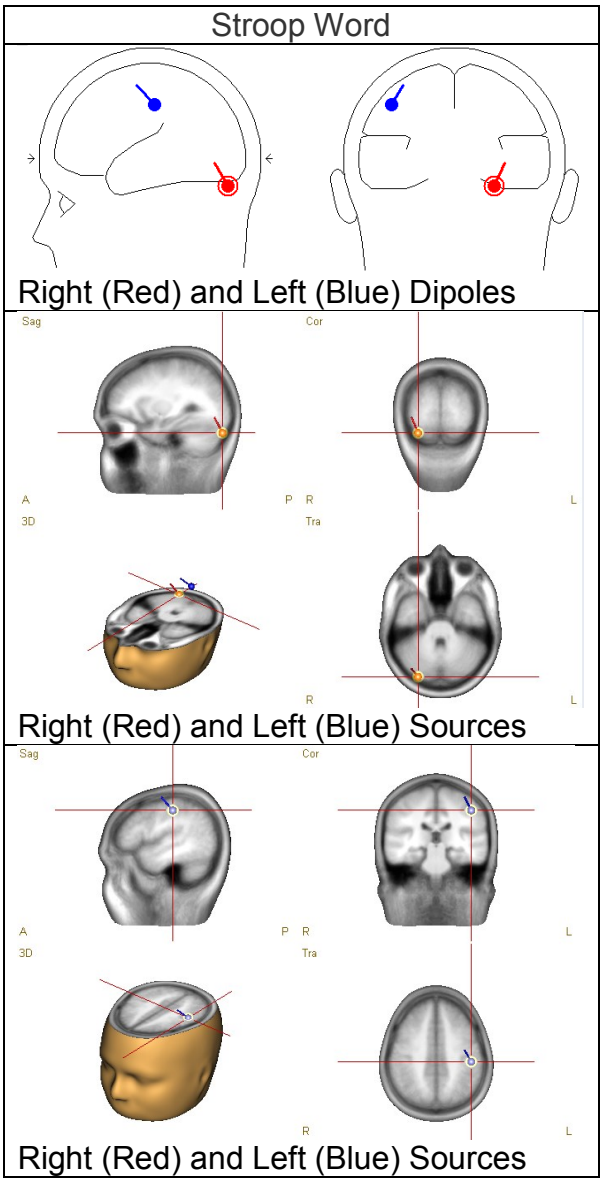


Figure 36: Source localizations for Stroop colour and word at -200-1000 ms

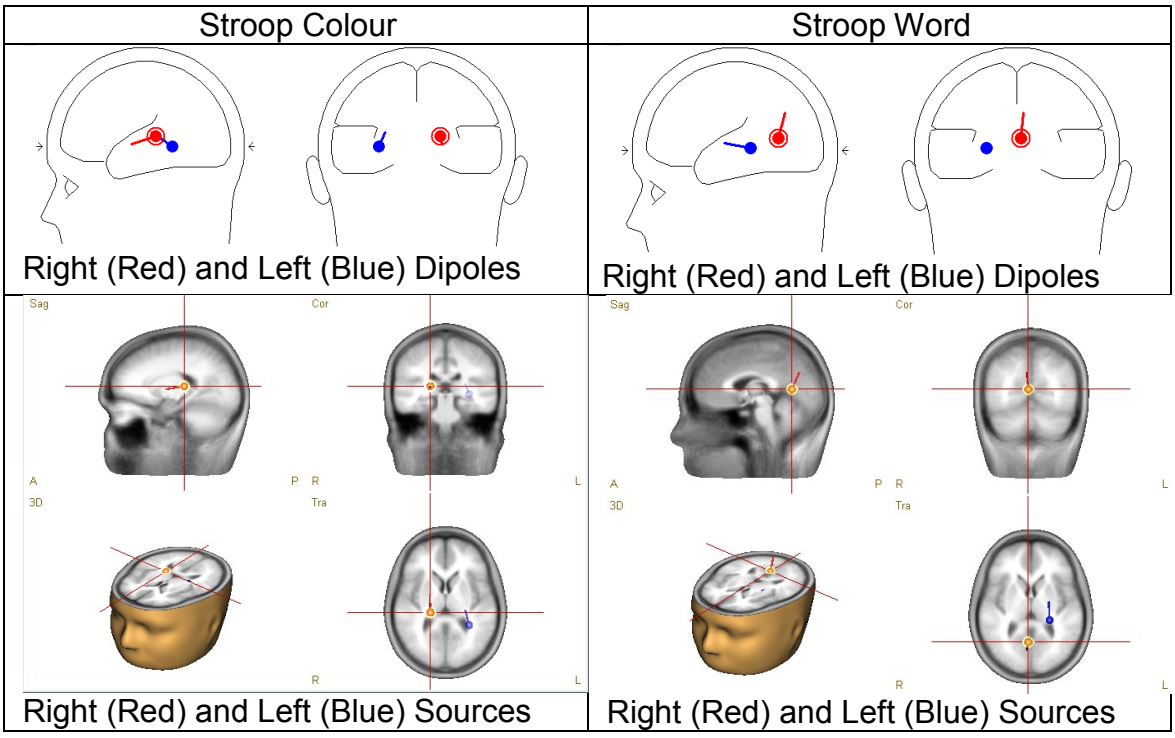


Figure 37: Activation in each hemisphere for Stroop colour of the difference between incongruent and congruent at three flicker rates

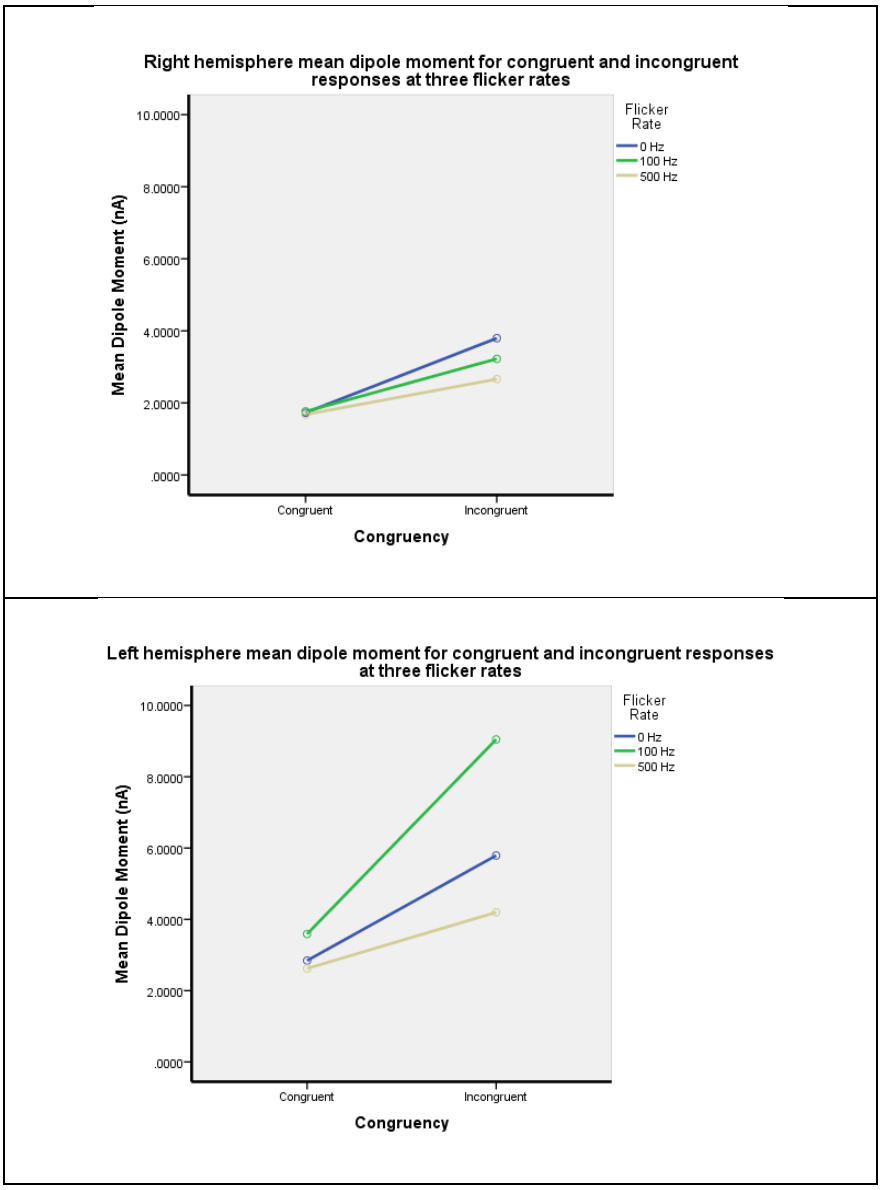
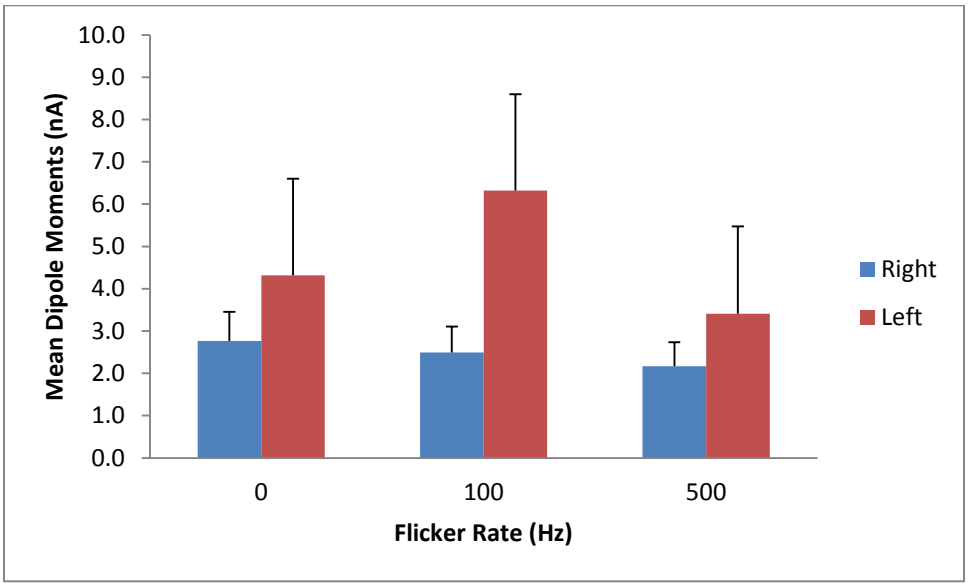


Figure 38: Average activation in each hemisphere for Stroop colour showing dipole by flicker rate interaction



Appendices

Appendix A: Definitions, Symbols, and Abbreviations

A.1 Sub-Appendix: Definitions

1. asthenopia: weakness or rapid fatigue of the eyes often accompanied by pain and headache (http://www.merriam-webster.com/medlineplus/asthenopia); subjective symptoms of ocular fatigue, discomfort, lacrimation, and headaches arising from use of the eyes. (http://medical-dictionary.thefreedictionary.com/asthenopia).

2. Candela: SI base unit for photometry: luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that had a radiant intensity in that direction of 1/683 Watts per steridian ($W\cdot sr^{-1)}$; Symbol: cd = $lm\cdot sr^{-1}$; NOTE Defined by the 16th General Conference of Weights and Measures, 1979.

3. flicker (http://eilv.cie.co.at/term/443) or luminous modulation: impression of unsteadiness of visual perception induced by a light stimulus whose luminance or spectral distribution fluctuates with time

4. illuminance (http://eilv.cie.co.at/term/550) (at a point of a surface) [Ev; E] 1. quotient of the luminous flux $d\Phi_v$ incident on an element of the surface containing the point, by the area dA of that element; 2. integral, taken over the hemisphere visible from the given point, of the expression $L_v\cos\theta d\Omega$, where Lv is the luminance at the given point in the various directions of the incident elementary beams of solid angle dΩ, and θ is the angle between any of these

beams and the normal to the surface at the given point $E_v = \frac{d\Phi_v}{dA} = \int_{2\pi} L_v \cos\theta \, d\Omega$; Unit: lx = lm·m-2

5. lumen (http://eilv.cie.co.at/term/704): An SI unit of luminous flux; Symbol: lm; luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 cd (defined by 9th General Conference of Weights and Measures, 1948); equivalent definition: luminous flux of a beam of monochromatic radiation whose frequency is 540 × 1012 Hz and whose radiant flux is 1/683 Watt.

6. luminance (the amount of light in a given direction, at a given point of a real or imaginary surface) [L_v; L] (http://eilv.cie.co.at/term/711): quantity defined by the formula: $L_v = \frac{d\Phi_v}{dA \cos\theta \, d\Omega}$; where $d\Phi_v$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle, dΩ, containing the given direction; dA is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam; Unit: cd·m^{-2} = lm·m^{-2}·sr^{-1}; NOTE 1 The above equation does not represent a derivative (i.e. a rate of change of flux with solid angle or area) but rather the quotient (i.e. a result obtained by dividing one quantity by another) of an element of flux by an element of solid angle and an element of area. In strict mathematical terms the definition could be written:

$L_v = \lim_{A,\Omega \to 0} \frac{\Phi_v}{A \cdot \Omega \cdot \cos\theta}$; in practical measurements, A and Ω should be small enough

that variations in Φ_v do not affect the result. Otherwise, the ratio $\frac{\Phi_v}{A \cdot \Omega \cdot \cos\theta}$ gives the average luminance and the exact measurement conditions must be specified.

7. luminous efficacy (of a source) [η_v; η_v] (http://eilv.cie.co.at/term/729): quotient of the luminous flux emitted by the power consumed by the source; Unit: $lm \cdot W^{-1}$;

8. luminous efficacy (of radiation) [K] (http://eilv.cie.co.at/term/730): quotient of the luminous flux, Φ_v, by the corresponding radiant flux, Φ_e; Unit: $lm \cdot W^{-1}$; NOTE 1 Luminous efficacy depends on a number of factors, particularly the state of visual adaptation and the size and position of the source in the visual field. For this reason it is possible to define a number of spectral luminous efficacy functions, for specific visual conditions. Unless otherwise indicated, the luminous flux referred to in the definition above is that determined using the CIE standard photometric observer i.e. using the V(λ) and V'(λ) functions for photopic and scotopic vision respectively.; NOTE 2 For any spectral luminous efficacy function, K(λ),the luminous efficacy for monochromatic radiation at a frequency 540×1012 Hz, which corresponds to the wavelength λ = 555,016 nm in standard air, is defined as 683 $lm \cdot W^{-1}$.; NOTE 3 The maximum value of K(λ) is denoted by the symbol Km. For photopic vision Km = 683 V(555 nm) / V(555,016 nm) lm·W-1 = 683,002 lm·W-1 ≈ 683 $lm \cdot W^{-1}$ and for scotopic vision

$K'_m = 683\ V'(507\ nm) / V'(555{,}016\ nm)\ lm \cdot W^{-1} = 1\ 700{,}05\ lm \cdot W^{-1} \approx 1\ 700\ lm \cdot W^{-1}$; For other wavelengths: $K(\lambda) = K_m V(\lambda)$ and $K'(\lambda) = K'_m\ V'(\lambda)$

9. luminous flux [Φ_v; Φ] (http://eilv.cie.co.at/term/738): The quantity derived from the radiant flux, Φ_e, by evaluating the radiation according to its action upon

the CIE (Commission Internationale de L'Eclairage, International Commission of Illumination) standard photometric observer; Unit: lm; NOTE: For photopic vision $\Phi_v = K_m \int_0^\infty \frac{d\Phi_e(\lambda)}{d\lambda} V(\lambda)\, d\lambda$ where $\frac{d\Phi_e(\lambda)}{d\lambda}$ is the spectral distribution of the radiant flux and V(λ) is the spectral luminous efficiency illuminance: the amount of luminous flux (light energy) that reaches a given surface area.

10. luminous modulation: see flicker above

11. lux (http://eilv.cie.co.at/term/744): An SI unit of illuminance; the illuminance produced on a surface of area 1 m^2 by a luminous flux of 1 lumen uniformly distributed over that surface; Symbol: lx = lm·m-2; NOTE: Non-metric, non-SI units: lumen per square foot (symbol: $lm \cdot ft^{-2}$), footcandle (symbol: fc) (US); 1 $lm \cdot ft^{-2}$ = 1 fc = 10,764 lx.

12. photon (http://eilv.cie.co.at/term/918): quantum of electromagnetic radiation considered as a particle of energy hv, where h is the Planck constant and v the frequency of the radiation; NOTE A photon is an elementary particle of spin 1 and having zero rest mass.

13. photopic vision (http://eilv.cie.co.at/term/938): vision by the normal eye in which cones are the principle active photoreceptors; NOTE 1 Photopic vision normally occurs when the eye is adapted to levels of luminance of at least 5 $cd \cdot m^{-2}$.; NOTE 2 Colour perception is typical of photopic vision.

14. scotopic vision (http://eilv.cie.co.at/term/1142): vision by the normal eye in which rods are the principle active photoreceptors; NOTE 1 Scotopic vision normally occurs when the eye is adapted to levels of luminance of less than ~10^{-3} $cd \cdot m^{-2}$.; NOTE 2 In comparison to photopic vision, scotopic vision is

characterized by the lack of colour perception and by a shift of the visual sensitivity towards shorter wavelengths.

15. starting voltage (http://eilv.cie.co.at/term/1264): the voltage between the electrodes (located within a lamp) which is needed to start the discharge in the lamp; Unit: V

16. steradian: (http://eilv.cie.co.at/term/1266) SI unit of solid angle; solid angle that, having its vertex at the centre of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere; Symbol: sr.

17. Watt: (http://oxforddictionaries.com/definition/english/watt) the SI unit of power, equivalent to one joule per second, corresponding to the power in an electric circuit in which the potential difference is one volt and the current one ampere.

A.2 Sub-Appendix: Symbols and Abbreviations

(http://en.wikipedia.org/wiki/Luminous_energy)

Quantity		Unit		Dimension	Notes
Name	Symbol	Name	Symbol	Symbol	
Luminous energy	Q_v	lumen second	lm·s	T·J	units are sometimes called talbots
Luminous flux	Φ_v	lumen (= cd·sr)	lm	J	also called luminous power
Luminous intensity	I_v	candela (= lm/sr)	cd	J	an SI base unit, luminous flux per unit solid angle
Luminance	L_v	candela per square metre	cd/m^2	L^{-2}·J	units are sometimes called nits
Illuminance	E_v	lux (= lm/m^2)	lx	L^{-2}·J	used for light incident on a surface
Luminous emittance	M_v	lux (= lm/m^2)	lx	L^{-2}·J	used for light emitted from a surface
Luminous exposure	H_v	lux second	lx·s	L^{-2}·T·J	
Luminous energy density	ω_v	lumen second per $metre^3$	$lm·s·m^{-3}$	L^{-3}·T·J	
Luminous efficacy	η	lumen per watt	lm/W	M^{-1}·L^{-2}·T^3·J	ratio of luminous flux to radiant flux
Luminous efficiency	V			1	also called luminous coefficient
See also: SI · Photometry · Radiometry · (Compare)					

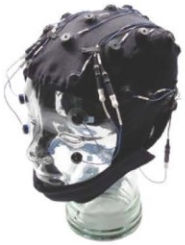
Appendix B: Advertisement, Informed Consent, and Debriefings

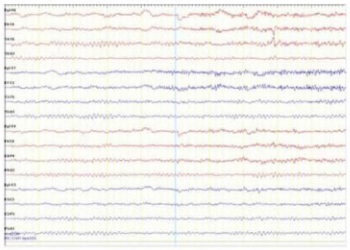
B.1 Sub-Appendix: Advertisement

IRB Approval Code: **Ethics Expiry Date:**

RESEARCH PARTICIPANTS NEEDED!

Neurophysiological correlates of arousal and visual performance effects of luminous modulation





Carleton University Neuroscience Department NICER Lab together with the National Research Council of Canada is conducting a study examining brain activity elicited by different lighting conditions while reading.

Why is the study being conducted?

To help determine what aspects of brain functioning are affected under different lighting conditions.

Who can participate?

Participants must be between 18-25 years of age, right-handed, normal or correct-to-normal vision, with no history of neuropsychological problems, not taking neuroleptic drugs, and no personal or familial history of epilepsy.

What is involved?

Participation will involve completing some questionnaires and a vision test, followed by recording of electric brain activity while completing reading tasks. One visit to the NICER Lab is required for this experiment.

Compensation

Participants will receive (one) 1 course credit per hour of participation to a maximum of 3 credits.

To refer or find out more information, please contact:

Patricia Van Roon, Research Assistant
(613) x 3097
pvanroon@connect.carleton.ca

This study has received clearance from the Carleton University Ethics Committee for Psychological Research (reference #11-176) and been approved by the National Research Council of Canada Research Ethics Board (Protocol 2011-29)

B.2 Sub-Appendix: Informed Consent

Informed Consent Form

Experiment Title: Neurophysiological correlates of arousal and visual performance effects of luminous modulation

Faculty Sponsor:

Dr. Amedeo D'Angiulli,

Department of Neuroscience

Carleton University

2202A Dunton Tower

(613) 520-2600 x 2954

The purpose of this informed consent form is to ensure that you understand both the purpose of the study and the nature of your participation. The informed consent must provide you with enough information so that you have the opportunity to determine whether you wish to participate in the study. Please ask the researcher to clarify any concerns that you may have after reading this form.

Research Personnel:

In addition to the Faculty Sponsor named above, the following people are involved in this research and may be contacted at any time should you require further information about this study:

Principal Investigator: Patricia Van Roon (pvanroon@connect.carleton.ca)

Collaborators:

Dr. Jennifer Veitch (National Research Council of Canada, Ottawa)

Dr. Brad Lehman (Northeastern University, Boston, USA)

Dr. Arnold Wilkins (University of Essex, Colchester, UK)

Purpose:

This study examine how the human brain responds to variations in light intensity, and whether this can affect a person's reading performance, subjective experience, and brain activity.

Task:

At the start of the session, you will complete some visual acuity tasks to measure how well you can see with both eyes at near and far points and a colour blindness test. You will also answer some simple computerized questionnaires about your personal well-being. The questionnaires are designed to measure mood and anxiety. You will also be asked to complete a general/health questionnaire and a handedness inventory. Participants must achieve certain scores on these tasks to continue. If your scores show that you are not a candidate to participate, you will be excused from the rest of the experiment. You will still receive your course credit for the number of hours in which you participated.

The brain activity recordings that we take are similar to those of routine clinical electroencephalography (EEG). To record the brain responses, electrodes are placed on your scalp and around the eyes. The electrodes on the scalp are kept in place with an elastic cap that fits over your head like a bathing

cap. The ones around the eyes will be kept in place with double-sided washers and some medical tape. The skin beneath the electrodes is rubbed slightly with a prep pad or Nu-Prep, which contain pumice, to remove any dirt or oil before the electrodes are connected to the skin with a double-sided washer. When the electrodes are taken off, any residue can be removed with water. The skin under the electrodes may be slightly red for a little while after the recording but this soon returns to normal.

The recording session will last approximately one hour. The recording session has three blocks, separated by rest periods. During each block we will measure brain activity and eye movements while you read short sentences and answer questions about words presented on a computer screen in the light booth. After these two tasks we will ask you to repeat a questionnaire before the rest period.

When you have completed the three blocks, you will receive information about the experiment and given the opportunity to ask any questions and provide feedback to the researcher. You will also be allowed another rest break for up to 10 minutes.

Duration & Locale:

The experiment will take place in the NICER Laboratory located in the Visualization and Simulation Centre (VSIM) building of the Neuroscience Department at Carleton University. You will only need to come on one occasion to the laboratory. The whole session will take about 2-3 hours.

Remuneration:

You will be given one (1) course credit per hour for your participation to a maximum of 3 credits for 3 hours of participation.

Potential Risks/Discomfort:

There are no known risks with the procedure. The electrodes for the EEG recordings can be mildly uncomfortable (the skin is rubbed slightly with pumice to remove any dirt or oils that can interfere with the measurements) and the experiment may seem a bit dull because of the repetitive measurements. If, however, you should feel uncomfortable at any time and wish to end your participation in the experiment, please notify the researcher and the session will be discontinued.

Anonymity/Confidentiality:

Your name appears only on this consent form. All other records are identified by an arbitrary identification number, making them anonymous. The consent forms are kept in a locked file cabinet accessible only to project personnel. After all the data have been collected, the consent forms will after which they will be destroyed in accordance with the policies set by Library and Archives Canada. Any personal information collected about you during this study will be kept anonymous be stored in a locked file cabinet at the National Research Council of Canada for seven (7) years, and strictly confidential, and will only be used for the purposes of this research. In any publications or presentations that derive from this research, you will not be referred to in any way that will allow your identification. Furthermore, all data gathered from this experiment will only be made accessible to the researchers involved with this

study and to duly authorized authorities at Carleton University and the National Research Council of Canada.

Right to Withdraw:

Your participation in this experiment is completely voluntary. You can withdraw your consent and stop participation in this experimental study at any time and for any reason. Such withdrawal from the study will not prejudice in any way your treatment at Carleton University. If you are receiving course credit for your participation, your withdrawal will not constitute any academic penalty and you will still attain the credits for participation in this study. If there is anything with which you are uncomfortable providing information, you have the right to omit these items without affecting your participation in the study.

The results of these experiments will not provide any direct benefit to you. However, these results may help us in developing guidance for effective lighting systems

Approval:

This study has been approved by and received clearance from the Carleton University Ethics Committee for Psychological Research (reference #11-176).

For additional information, please contact Dr. Amedeo D'Anguilli at (613) 520-2600 ext. 2954.

Should you have any ethical concerns regarding this study then please contact: Monique Sénéchal, (Department Chair, Carleton University Ethics Committee for Psychological Research, 520-2600, ext. 1155).

Should you have any other concerns about this study then please contact Dr. Shawn Hayley (Department Chair, Department of Neuroscience 327 LSRB, 613 520-2600 x6314).

The National Research Council of Canada is supporting this study, which has been reviewed and approved by the NRC Research Ethics Board. Any questions or concerns about the ethics of this study may be directed to Ms. Lea Maloney, Assistant to the NRC Research Ethics Board, at (613)-993-8872 (NRC-REB@nrc-cnrc.gc.ca), referring to Protocol No. 2011-29 [NRC Project No. 44-B3249].

Consent:

I have been provided with a description of the experimental procedures and any possible risks or benefits that might be associated with these procedures. I have been told that confidentiality will be maintained.

I have also been given an opportunity to ask questions concerning these procedures and any questions that I have asked have been adequately answered. I shall be given a copy of this informed consent.

I have been told that I can withdraw my consent and stop my participation in this experimental study at any time and for any reason. Such withdrawal from the study will not prejudice, in any way, my treatment at Carleton.

I understand the information that I have been provided and I voluntarily consent to participate in this experimental study.

Participant's Name

Signature

Date

Researcher's Name

Signature

Date

B.3 Sub-Appendix: Debriefing For Participants

Experiment Title: Neurophysiological correlates of arousal and visual performance effects of luminous modulation

The experiment in which you just participated was looking at the effect of flicker on physiological arousal and visual performance to determine optimal lighting frequencies. When operated on magnetic ballasts, i.e. with a frequency of 100 or 150 Hz, fluorescent lighting systems were associated with asthenopia in some individuals. Changes were made, primarily to improve energy-efficiency, from magnetic ballasts to electronic ballasts (which operate at ~ 40 kHz) during the late 1990s largely ended these problems. Research into the neurological and visual effects of luminous modulation (flicker) was no longer a priority. New development into light-emitting diode (LED) light sources, promoted for their potential to save lighting energy, has brought back the need for more precise information about these effects because these sources can be operated with almost any characteristics depending on the design of the electronics for power supplies and drivers. With this information, it should be possible to achieve energy savings without causing unintended side effects. Do you have any questions?

If you experienced any discomfort during this experiment, please alert the researcher and you will be given contact information for resources that can assist you. If you are experiencing an unpleasant mood, please alert the researcher and she will direct you to the appropriate resources or if you prefer, you may contact the Carleton Health & Counselling Services (website: http://www.carleton.ca/health) at 2600 Carleton Technology & Training Centre, by telephone at 613-520-6674 or by email at hcs@carleton.ca.

This project is in collaboration with researchers at Carleton University, the National Research Council of Canada (NRC), Northeastern University and the University of Essex. The project also falls under the authority of the NRC Research Ethics Board, which has assigned it protocol number 2011-29. This study has received clearance by the Carleton University Psychology Research Ethics Board (reference #11-xxx).

Thank you for your participation in this research! Your time and effort are greatly appreciated!

Should you have any ethical concerns regarding this study then please contact:

Dr. Monique Sénéchal, Chair, Carleton University Ethics Committee for Psychological Research, (613) 520-2600, x. 1155.

Ms. Lea Maloney, Ethics Assistant, National Research Council of Canada, (613)-993-8872, e-mail: NRC-REB@nrc-cnrc.gc.ca.

Should you have any other concerns about this study then please contact:

Dr. Shawn Hayley, Chair, Department of Neuroscience, (613) 520-2600, x. 2648

or any of the following individuals:

Patricia Van Roon, Principal Researcher, (613) 520-2600 x. 3097

Dr. Amedeo D'Angiulli, Faculty Advisor, (613) 520-2600 x. 2954

B.4 Sub-Appendix: Debriefing For Non-Participants

Experiment Title: Neurophysiological correlates of arousal and visual performance effects of luminous modulation

The experiment for which you volunteered was looking at the effect of flicker on physiological arousal and visual performance to determine optimal lighting frequencies. When operated on magnetic ballasts, i.e. with a frequency of 100 or 150 Hz, fluorescent lighting systems were associated with asthenopia in some individuals. Changes were made, primarily to improve energy-efficiency, from magnetic ballasts to electronic ballasts (which operate at ~ 40 kHz) during the late 1990s largely ended these problems. Research into the neurological and visual effects of luminous modulation (flicker) was no longer a priority. New development into light-emitting diode (LED) light sources, promoted for their potential to save lighting energy, has brought back the need for more precise information about these effects because these sources can be operated with almost any characteristics depending on the design of the electronics for power supplies and drivers (refer to Appendix D for information on how lighting systems work). With this information, it will be possible to achieve energy savings without causing unintended side effects. Do you have any questions?

You will still receive course credit equivalent to the number of hours of participation or a minimum credit of 0.25 upon completion of the informed consent and questionnaires.

This project is in collaboration with researchers at Carleton University, the National Research Council of Canada (NRC), Northeastern University and the

University of Essex. The project also falls under the authority of the NRC Research Ethics Board, which has assigned it protocol number 2011-29.

Thank you for your interest in this research! Your time and effort are greatly appreciated!

Should you have any ethical concerns regarding this study then please contact:

Dr. Monique Sénéchal, Chair, Carleton University Ethics Committee for Psychological Research, (613) 520-2600, x. 1155.

Should you have any other concerns about this study then please contact: Dr. Shawn Hayley Chair, Department of Neuroscience, and (613) 520-2600, x. 2648

or any of the following individuals:

Patricia Van Roon, Principal Researcher, (613) 520-2600, x. 3097

Dr. Amedeo D'Angiulli, Faculty Advisor, (613) 520-2600 x2954

Appendix C: Verbal Instructions for Participants

C.1 Sub-Appendix: STAI Verbal Instructions

Although most of the instructions for the task were viewed on the computer monitor by the participant while the researcher read them, the following instructions were provided verbally for the STAI. Some participants misconstrued this task regardless of the available instructions in that they incorrectly perceived the task to have a memorization component and attempted to match their answers for each presentation of the STAI. For this reason, the following instructions were added verbally.

- "Do you understand the instructions you have read? This is not a memory experiment. We are interested in how you are feeling at this moment in time. When you respond to these statements, please answer them from how you are feeling right now."

C.2 Sub-Appendix: Sentence Reading Verbal Instructions

The following instructions were provided verbally to each participant before reading the first set of sentences and re-iterated in each block:

"Please read each sentence in full from left to right. Make sure your eyes hit every word. An eye tracker (refer to Appendix E for eye tracker information) is being used to track if you have read the sentence. If you get to the end of the sentence and the next sentence does not appear, please re-read the sentence from the start and make sure your eyes hit every word. The eye tracker will automatically advance to the next sentence when you have done this. Pay particular attention to focusing on the first word of the sentence as most people miss this word."

If the participant had any difficulty with this, which sometimes happened when the participant had difficulty focusing on the first and/or last words, the following instructions were added:

"Try to focus a little before the first word and a little after the last word. Make sure that your eyes every word in the sentence."

No participants had any difficulty with these instructions and were able to complete this task.

Appendix D: How LED, Fluorescent and Incandescent Lights Work

In order to understand how different lighting systems effect the visual systems, It is necessary to understand how these different lighting systems function and how the various components of the system can contribute to flicker.

D.1 Sub-Appendix: Incandescent

The energy source to energize atoms in an incandescent light is electricity (the movement of free electrons). The filament at the centre of the oxygen-free argon or krypton-filled vacuum lamp is made of tungsten wire because of its very high melting point. The argon is needed to prevent the tungsten from evaporating under high temperatures. The electrical current heats the very tightly coiled tungsten filament. The starting size of a filament is about 50 cm but this is coiled down until it is about 2 cm. The electrons moving through the filament collide and cause the filament to heat up. As the filament heats, the tungsten begins to glow. When incandescent lights are powered by AC, the power through them isn't constant and there are surges that heat the filament slightly above equilibrium, followed by decreases when the filament cools slightly. The incandescent output varies slightly over a half-cycle. Incandescent lights do not flicker if the light is powered by constant DC voltage or when powered by direct current (e.g., battery power), and very little flicker when powered by alternating current (i.e. mains power).

D.2 Sub-Appendix: Fluorescent

Fluorescent tube lights work by using electrodes, usually positioned at the end of the tube, argon and mercury vapour within the tube, and fluorescent powder or phosphorescent compound which coats the inside of the tube. The different phosphor coatings produce different colours of light. Older fluorescent lamp systems consisted of the tube, the ballast (or choke) and a starter switch. The ballast controls the amount of current so that the lamp does not short. The AC power switches every $1/60^{th}$ of a second (in America, $1/50^{th}$ in Europe) and the magnetic field in the ballast grows and shrinks with the AC cycle. The filament inside the tube heats up as the current goes through. In the starter, a small neon lamp heats up the bimetallic starter. Once this is heated, it switches to the off position. The magnetic field collapses causing an induction kick or spike in voltage. This voltage kick forces electrons through the vapours within the tube. The electrons collide with the mercury electrons which forces them into a higher unstable energy state. When they drop down to their original state, an ultraviolet (UV) photon is produced which collides with an electron in the phosphor coating of the tube. When the UV photon strikes the phosphor coating, the phosphor coating releases a photon in the visible range of the spectrum. The spectral power distribution of this output depends on the chemical composition of the phosphor.

D.3 Sub-Appendix: LEDs

With the increase in computer use, hand-held devices, text messaging, 3D television and increased demand for energy efficiency, there had been an increase in importation and sale of SSL technology. LEDs are more versatile, environmentally friendly, and longer lasting which makes them attractive alternatives to current lighting systems.

In general, there are two methods used by lighting companies to manufacture the full colour spectrum of LEDs: AlInGaP (Aluminum, Indium, Gallum and Phosphorus) technology which creates light in the red, orange, and yellow spectrum and InGaN (Indium, Gallium, and Nitrogen) technology which creates light in the blue, green, and white spectrum. An LED is a semiconductor device with positive P-type (or holes) and N-type (negatively charged electrons) semiconductor materials which together create a diode. A diode conducts an electrical current only in one direction. When a current is applied to the diode the negatively charged electrons and the holes move towards each other to the P-N junction. When a free electron and a hole contact each other, a photon is produced because the holes exist at a lower energy level than the electrons. In order to lose the energy, the photon is produced. The amount of energy produced by the photon determines the frequency or colour of the light. The type of material and process used to create the semiconductors defines the colour of the photons, efficiency, and performance characteristics of the LED. This is then processed into an LED chip and installed into a housing that allows electrical connection and the desired amount of light to be output. To produce the LED, a

substrate is used (e.g., sapphire for InGaN LEDs, gallium arsenide for AlInGaP LEDs). Layers of various materials are grown on a round wafer-like substrate under precise pressure and temperature controls to make up the N- and P-layers as well as the N-P junction in a process called epitaxial or epi-growth. The brightness, colour, and intensity of the final LED product are determined by the quality and consistency of this epitaxial process. Individual LED chips are then defined on the wafer and the wafer is cut into several individual LEDs. These LEDs are then tested for colour and other electrical characteristics. The LED is installed into a casing and wires are added to incorporate the electrical connections. A lens is added to the top of the casing to direct the light.

****See Figure xxx – How LEDs work

The electrical connection to the chip is through a device called a driver and it is this device that determines if flicker will be present in the final product (Wilkins, Lehman, & Veitch, 2010).

D.4 Sub-Appendix: Summary

Incandescent lamps flicker at twice the mains frequency (i.e. 50 or 60 Hz) because the filament grows hotter each time the current peaks but the thermal inertia of the filament means that the modulation amplitude is very low.

The older model fluorescent lamps flicker at twice the mains frequency if they use magnetic ballasts driven directly from the AC. Modern fluorescent lamps use electronic ballasts that operate at about 20–40 kHz. The electrons stay excited for longer than the switching frequency and the light output appears constant. Flicker can still exist in these lamps if they degrade or malfunction; however, under normal operation they are less likely to affect an individual biologically.

SSLs and LEDs appear constant but high power SSLs normally have their own driver chip which carefully controls the current and voltage of the diode so it is less sensitive to the supply power. However, ones that are sensitive to the power supply will flicker at the mains frequency.

Appendix E: Eye Tracker Information

The researcher outlines the participant's pupil and adjusts the corneal reflection for each eye prior to running the calibration program. If this is changed during the experiment, the participant is required to perform the tracking calibration again to re-assess the centroid and ellipse fittings. To calibrate locus-of-gaze centroid and ellipse, two 9-point grids are used and the calibration procedure is repeated until the average error is below 0.5°. Once the pupil threshold is determined, the centroid calibration measures the mid-pupil using a centre of mass algorithm which defines the pupil's coordinates by calculating the distribution of mass and the average of the weighted position coordinates. The ellipse calibration determines the pupil's centre by fitting an ellipse to the pupil mass. The researcher uses the host software to outline the ellipse fitting solution to determine pupil position. Ellipse-fitting decreases drift potential and manages pupil occlusion but may result in higher noise levels. The eye positions assist in the assessment of the Sentence Reading data by providing event synchronization of the first and last words presented within their corresponding invisible boundary box. This information will provide the exact sentence reading time under each lighting condition and, therefore, a measure of visual arousal.

(***Insert Figure 9 and 10 – eye tracking calibration about here***)

The second calibration tests for accuracy by using a white circle moving on a black background and randomly appearing on the screen at a rate of 1000 ms (i.e. when one circle disappears in one location, a new circle appears in the next location). The researcher's monitor displays the location of each eye, the

steadiness of gaze on the circle based on the calibration settings, and the angle of deviation from the centre of the circle to the location of the participant's eye.

SR Research (Mississauga, Ontario) describes the purpose of eye tracking as follows:

"Eye tracking assesses how well a participant fixates, whether there is head movement during a calibration, and whether there is head movement between two successive runs of calibration. The primary purpose of the eye tracker is to detect significant amounts of drift by asking the participant to fixate on one or more fixed location(s). System drift, if it occurs, is likely due to head movement, forehead slippage, lower eyelid occlusion, etc., but not due to the calibration itself.

To assess drift in the tracker recording, each calibration is validated by presenting several fixed locations on the screen, and checking the participant's fixation accuracy on those targets. The eye tracker software records this information and saves a summary of the errors across various locations as well as mean and maximum gaze errors."

Appendix F: Incidence Rates of Asthenopia

Technological changes (e.g., laser eye surgery) and advancements (e.g., hand-held electronic devices) make the assessment of the incidence of asthenopia highly challenging. The number of symptoms associated with asthenopia also makes this condition difficult to assess. Assessments only examining one or two of the symptoms will likely under-estimate the incidence rate. In addition, the majority of people faced with this condition will likely not report it as such previous reports have indicated no resolution to the problem. Furthermore, many individuals may feel this is the likely result of near vision work and the symptoms will go away eventually. Finally, the condition is difficult to localize due to the wide range of symptoms. The only method for effectively assessing the incidence rates of asthenopia is to review related research into the condition.

Sheedy et al. (2003) performed a behavioural experiment where participants rated the magnitude of asthenopic conditions after reading each of eight different reading conditions (e.g., mixed astigmatism, close viewing, distance, etc.). Their results indicate a pathway for the external symptoms related to dry eye (e.g., tearing, itching, burning, etc.) and another internal pathway (e.g., headaches, eye strain, eye pain) related to accommodative vision stress (Sheedy, 2003) assessed using principal factor analyses with orthogonal varimax rotation to test symptom by condition relationships.

Maino and Chase (2011) graphically interpreted the prevalence, frequency and impact of asthenopia of a study conducted by Saks et al., (2011) which

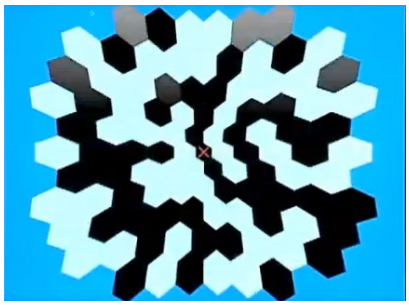
surveyed 3,800 patients from eight countries including China, Japan, Korea, Italy, France, the United States, and the United Kingdom. Maino and Chase show the incidence levels of asthenopia as 58% for eye strain, 69% for tired eyes, 29% for headaches, and 19% for pain behind the eyes with a high proportion of these individuals indicating that these symptoms were bothersome.

In addition, occupations requiring sustained near vision work will have a higher rate of asthenopic symptoms compared with similar control groups. Specific incidence rates for asthenopia have not been calculated on a local, national, or international level. However, research into this condition can provide some guides for incidence levels of asthenopia (i) Tiwari et al. (2011) found a predominance of eyestrain in child labourers of 32.2% significantly higher than a comparison group. Female children were also significantly more likely to report eyestrain. (ii) Among 419 computer operators in a Bhanderi et al. (2008) study, 194 (46.3%) suffered from asthenopia during or after computer work. Again, females reporting the condition in a marginally higher proportion compared with males, (iii) Agarwal, et al., (2012) analyzed ocular complaints from 150 computer users and found eyestrain (53%), occurrence of eye strain, (53.8%), itching (47.6%) and burning (66.7%) as the predominant complaints. Bhanderi et al. recommended methods to alleviate the symptoms including reducing the number of hours in front of the computer monitor, increasing the distance between the monitor and the eyes, using antiglare screens, increasing the number of rest breaks, changing the type of monitor, and adjusting the brightness of the monitor.

These recommendations can alleviate the symptoms of some types of asthenopia, however, the symptoms can return.

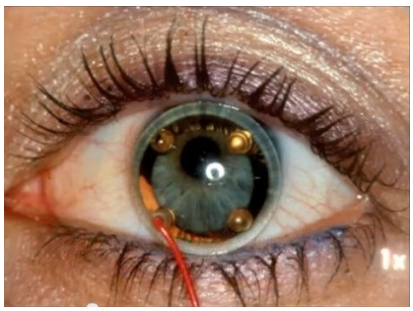
Appendix G: Electroretinogram

The electroretinogram uses contact lens-like electrodes placed on the surface of the eye. Usually eye drops are used to increase the dilation the pupil (usually 7 mm pupil to obtain central 40° of retina). Patching the other eye helps the patient only use the eye that is being tested (i.e. prevents dominant eye effects). This is usually followed by 30 minutes of dark adaptation which allows the retina to produce its strongest responses. Current ERGs use computer video displays. Older versions used mirrors and flashing lights. Most researchers use a stimulus that flashes randomly over all the individual black and white shapes.



(http://www.youtube.com/watch?v=dvWvywkV2G8)

Depending on the type of lens used, you may need to add a ground (usually the earlobe) and a negative reference (usually the middle of the forehead) for recording the ERG. The ERG lens comes with the wires already attached to the lens.



http://www.youtube.com/watch?v=dvWvywkV2G8

The eye is usually prepared with a general anesthetic (e.g. proparacaine). These drops are place in the eye before the lens is inserted. The lens has to be inserted carefully so as to avoid scratching the cornea. The head is usually stabilized to minimize movements. The display is positioned directly in front of the eye containing the lens.

http://www.youtube.com/watch?v=dvWvywkV2G8

The knob at the upper left of the display unit is an adjustable focus that the patient can use to make the images clear.

http://en.wikipedia.org/wiki/File:Electroretinogram.jpg

Appendix H: Detailed Screening Variables

The Keystone Ophthalmic vision tests were used to screen participants for vision problems including gross suppression, vertical imbalance, lateral posture and postural stability, fusion facility, stereoscopic vision, monocular discrimination under fusion, depth awareness, and colour deficits. The results indicate that all participants had normal or corrected to normal vision for far and near point tests. All participants could discriminate the colours in two colour vision tests indicating no red-green colour blindness.

The average BDI score was 4.06 (SD=5.5). Scores of 10 or more indicate at least mild depression. Most healthy normal adults would have scores less than 9 indicating minimal depression (N=30); participant scores greater than 9 but less than 18 (N=2) indicate individuals experiencing mild depression, and scores greater than or equal to 19 and less than or equal to 29 corresponding to moderate depression (N=2). There were no individuals whose scores were greater than 29 and, therefore, no indications of severe depression.

The cutoff scores for the BDI are based on clinical ratings of depression corresponding to mean BDI total scores of 10.9 (SD=8.1) for minimal, 18.7 (SD=10.2) for mild; 25.4 (SD=9.6) for moderate, and 30.0 (SD=10.4) for severe (Beck, 1967, p. 196). With normal populations, BDI total scores greater than 15 may detect possible depression; however, Oliver and Simmons (1984) suggest that only a trained clinician would be able to confirm this. Since the population was considered average normal controls and the participants did not respond to key questions (e.g. suicidal ideation) with higher depression scores, this was not

considered necessary. The concern with respect to event-related potentials is that these individuals show increased latencies and reduced amplitudes during cognitive tasks (Kaiser et al., 2003; Singh et al., 2000). This was not the case when the ERPs were examined.

The right-handedness scores of the participants (mean=76.2, SD=18.4) were subjected to an independent samples t-test grouped by Gender was found to be not significant (t_{32}>0.05) indicating there were no differences in right-handedness between genders.