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The Cognitive Effects of Light Color Temperature

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The Cognitive Effects of Light Color Temperature

A Dissertation Presented

by

LAUREN E. HARTSTEIN

Submitted to the Graduate School of the
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Psychological and Brain Sciences

The Cognitive Effects of Light Color Temperature

A Dissertation Presented

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DEDICATION

To Mark

For his limitless patience and support, and for carrying me through the toughest times.

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ABSTRACT

THE COGNITIVE EFFECTS OF LIGHT COLOR TEMPERATURE

MAY 2017

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The goal of the current studies is to explore the conditions by which light color temperature impacts cognitive abilities and the development of this relationship. Experiments 1 and 1A explored whether exposure to light fluctuating around a central color temperature leads to increases in attention in adult participants. Results showed that, under the dynamic lighting condition, participants' showed a significant decrease in reaction time on a measure of sustained attention, beyond those of a static light source at a cooler color temperature. Experiment 2 tested whether preschool-aged and 7-year-old participants would show increases in attention and cognitive flexibility after exposure to light set to a cooler color temperature, as has been previously seen in older children and adults. While 7-year-olds showed no effect of the lighting condition, preschool-aged children exposed to cooler color temperature light showed significantly greater improvements in cognitive flexibility than controls, demonstrating that the relationship between light and cognition is present from an early age. Taken together, these studies add to the growing literature demonstrating that the spectral composition of light can lead to improvements in cognitive abilities.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

In addition to allowing us to see, light impacts several non-visual domains, such as circadian rhythm, mood, and cognition. The mechanisms underlying these non-visual effects of light are even present in some blind individuals (Czeisler, et al., 1995), suggesting that they are independent of the visual system. Recent attention has turned to the ways in which light, specifically the spectrum and subsequent correlated color temperature (CCT) of light, impacts cognitive abilities. Light color temperature is typically measured in degrees Kelvin. As light wavelengths get shorter, the corresponding color temperature in Kelvin becomes higher. So white light consisting of light emitted in the blue portion of the visible spectrum (~480nm) will have a higher color temperature than light in the green portion of the spectrum (~550nm). Therefore, counter-intuitively, light that has a higher color temperature is considered to be a “cooler” color light. For example, white light measured at 5000K is a “cooler” color temperature and gives off a bluer appearance, whereas white light measured at 3000K is considered “warmer” and looks redder. This is similar to how stars in the sky that appear blue are actually much hotter than stars that look red. Similarly, when heating a metal, it initially glows red, but as the temperature increases, becomes “white hot”. In this dissertation, “cooler” will always refer to white light set to a higher, bluer, color temperature.

The mechanisms by which light CCT impacts non-visual domains, such as cognition, are beginning to be better understood thanks to the recent discovery of a third type of photoreceptor cell in the retina, in addition to the already known rods and cones (Berson, Dunn, & Takao, 2002; Hattar, Liao, Takao, Berson, & Yau, 2002) These cells were first hypothesized after researchers discovered that breeding mice without the known photoreceptors didn't impact their circadian response to light, but removal of the eyes did (Lucas, Freedman, Muñoz, Garcia-Fernández, & Foster, 1999), suggesting there must be some other photoreceptor in the eye regulating light's impact on the circadian rhythms. These intrinsically photosensitive retinal ganglion cells (ipRGCs) express the photopigment melanopsin and are maximally sensitive to light in the blue region of the visual spectrum, at wavelengths of approximately 480nm (Berson, et al., 2002; Foster, 2005). These cells seem programmed to be stimulated by the blue color of natural light, with daylight at noon emitting at approximately 5500K (Judd, MacAdam, & Wyszecki, 1964; Lighting Design Glossary, n.d.).

As light enters the eye and stimulates the ipRGCs, information is transmitted via the retinohypothalamic tract to the suprachiasmatic nucleus (SCN) in the hypothalamus, which is primarily responsible for the regulation of circadian rhythms (Gooley, Lu, Chou, Scammell, & Saper, 2001). Information from the ipRGCs is filtered into other, non-visual, brain regions, with fMRI studies with blind patients showing increased activity in the prefrontal cortex and thalamus following less than one minute of exposure to blue light (Vandewalle, et al., 2013). Following longer periods of exposure, blue light was found to modulate activation in a variety of regions, such as the intraparietal sulcus and right insula after 18 minutes of exposure, and the cingulate cortex, dorsolateral prefrontal cortex (dlPFC), and precuneus after 20 minutes of exposure (Vandewalle, Maquet, & Dijk, 2009).

The human ipRGCs system has a direct effect on circadian rhythms (Brainard & Hanafin, 2005), helping to regulate when the body feels sleepy or awake by modulating melatonin secretion. It also modulates brain regions associated with alertness, such as the hypothalamus and thalamus, and attention, such as the prefrontal cortex. And since the ipRGCs exhibit peak stimulation from light in the blue portion of the visible spectrum, it follows that exposure to blue light would have a positive impact on a person's alertness and attention, as measured behaviorally by their productivity or concentration on a task.

Adult Studies

Cognition

To date, the majority of studies looking at the impact of light color temperature on cognition have been conducted with adult participants. Studies exploring how light CCT impacts attention have indeed found improved performance in participants exposed to cooler color temperature light on go/no-tasks, a measure of sustained attention (Cajochen, et al., 2011; Chellappa, et al., 2011). Participants also reported higher subjective levels of alertness and less sleepiness following exposure to light set to a higher color temperature (Lehrl, et al., 2007; Lockley, et al., 2006; Rautkylä, Puolakka, Tetri, & Halonen, 2010; Viola, James, Schlangen, & Dijk, 2008). In the study conducted by Rautkylä, et al. (2010), effects of light were only found when participants were tested in spring and during the afternoon, with no effects found during autumn or testing in the morning, indicating that time of year and time of day can alter participant's susceptibility to the effects of cooler CCT light, possibly due to changes in melatonin level at different times of day or how much sunlight exposure they received. In addition to attention, higher CCT light has also been shown to have positive impacts on participants' task-switching ability (Ferlazzo, et al., 2014), memory (Hawes, Brunye, Mahoney, Sullivan, & Aall, 2012; Knez, 2001), and information processing (Lehrl, et al., 2007).

To further explore these effects, a previous study in our laboratory looked at the cognitive benefits of exposure to cooler color temperature light (Hartstein, Durniak, Karlicek, & Berthier, under review). In that study, undergraduate students were tested twice on measures of sustained attention, task switching, and mental rotation, after first being exposed to standard fluorescent 3500K office lighting and later under 5000K LED lights. Control participants were tested twice under the 3500K lights. To minimize sunlight exposure, participants were tested in the morning between 9:00 and 11:00 and during the winter months, between November and March. Results showed that, under the cooler color temperature 5000K lights, reaction time performance improved on the sustained attention task by males, but not females, and on the task switching task by females, but not males. Lighting condition had no effect on mental rotation performance. These results add to the growing literature showing improvements in concentration and attention following exposure to blue-enriched light at cooler color temperatures, and suggest the effects may be gender-specific.

Blue light's positive impact on attention can also be seen in physiological measures. In a recent study by Okamoto & Nakagawa (2015), participants completed an auditory oddball task under light set to three different wavelengths. While no behavioral differences were detected between the conditions, ERP measurements found the amplitude of the P300 component, which is said to reflect increased attention (Polich & Kok, 1995), was highest in the short-wavelength condition. A similar study found a larger contingent negative variation (CNV) component, related to attention and expectancy (Tecce & Scheff, 1969), in light set to a higher, cooler CCT (Deguchi & Sato, 1992).

Taken together, these findings demonstrate that artificial light, set to a cooler color temperature in an approximation of natural light, leads to improvements in cognitive domains, particularly attention.

However, artificial light sources are an imperfect simulation of natural daylight, as typical artificial light sources emit at a constant wavelength and intensity, whereas the color temperature and brightness of daylight is in constant flux throughout the day as the sun moves through the sky or passes behind clouds (Nayatani & Wyszecki, 1963; Judd, MacAdam, & Wyszecki, 1964). If the ipRGCs developed to be stimulated by natural daylight in order to regulate the circadian system, it follows that a better approximation of natural daylight would lead to greater stimulation and increased attention and concentration. With the rapid improvements in lighting technology, we now have greater control over the output from artificial light sources. Using a modern LED light source, we can now observe how small variations in light color temperature impact cognition. This is the aim of Experiment 1, in which participants were exposed to dynamic lighting, in which the color temperature of the light is constantly cycling around a fixed point, in this case ranging between 3700 and 4300K with a 50 second period.

Experiment 1 seeks to expand on the original findings by Hartstein, et al. (under review) by exploring whether cognitive performance will be enhanced by exposure to light set to a constantly changing color temperature similarly to the demonstrated enhancements seen in response to light at a static cooler color temperature light. Furthermore, in addition to greater stimulation, the dynamic nature of the light might reduce adaptation to the lighting condition, allowing increases in performance over a longer timeframe. Experiment 1 explores whether a more accurate approximation of natural light, which is in constant flux, would lead to greater stimulation of the ipRGCs and increased performance in tasks of attention and concentration, as measured by performance on a Go/No-Go and task-switching task.

Gender Differences

An interesting pattern to note in studies of how light color temperature impacts cognition is the high incidence of reported gender differences. Studies looking at the effects of lighting condition describe differences between males and females on how light color temperature impacts attention (Hartstein, et al., under review; Huang, Lee, Chiu, & Sun, 2014; Lehrl, et al., 2007), problem solving (Hygge & Knez, 2001; Knez, 1995), and memory (Knez 1995; Knez, 2001). In addition to the studies that report significant differences in the responses of each gender to changes in light color temperature, a number of studies recruited only male participants (Cajochen, et al., 2011; Chellappa, et al., 2011; Deguchi & Sato, 1992; Okamoto & Nakagawa, 2015; Rautkylä, et al., 2010), leaving open the possibility that gender differences would emerge had female participants been included.

Among the studies that reported differences between the genders, there is a lot of inconsistency in the nature of those differences. Hartstein, et al. (under review) found that males showed a larger positive change in performance on a go/no-go task under cooler color temperature light, while females showed no effect. But on a measure of task switching abilities, they found females to show greater improvements in the cooler CCT condition, while males showed no such change. Knez (2001) found that males performed worse on a long-term recall task in cooler CCT light, whereas females performed better in the cooler light condition.

Furthermore, although a number of studies report gender differences in their results, they offer little in suggestions as to the mechanisms underlying these differences. Cowan, et al. (2000) found gender differences in the BOLD response in participants' visual cortex, with males showing three-fold more activation to blue light than females, suggesting the differences could be based in physiologic responses to light color temperature, though these effects are possibly limited to the visual system. Another study found no differences between men and women in blood melatonin suppression after exposure to light set to different brightness levels (Nathan, Wyndham, Burrows, & Norman, 2000), suggesting melatonin suppression may not be the mechanism underlying the reported differences. Another possible reason for the differences seen between genders is the mood and subjective experience elucidated by different light conditions. Female participants rated warmer color temperature light as less clear than a cooler CCT light (Huang, et al., 2014) and rated lights at several color temperatures as more glaring, less soft, and more intense than males (Knez, 1995), suggesting that females may be more sensitive to changes in lighting condition than males. Finally, differences in how males and females' mood is impacted by light of different color temperatures has been reported, with female's negative mood found to decrease under light set to a warmer color temperature and increase under cooler color temperature light, with males reporting the opposite effect (Knez, 1995). While these findings suggest several mechanisms that could be at play in causing gender differences in cognitive responses to light color temperature, no clear evidence has emerged. One way to elucidate why men and women show different cognitive effects from exposure to cooler CCT light is to look at the development of these effects in children and see whether they are present from a young age, or unfold gradually throughout development. The timing of the emergence of these gender differences could help illuminate the mechanism underlying the differences in reactivity.

Child Studies

With the discoveries of the ipRGCs and their relationship to the non-visual system in the last decade, some attention has turned to understanding the development of these cells and pathways and whether they follow the same trajectory as development of the visual system. In human embryos, the photopigment melanopsin is evident in eye tissue as early as eight weeks post-conception (Tarttelin, et al., 2003). It is not clear from the presence of the photopigments when the full non-visual system comes online, but suggests that the foundation of the system is present from very early in development.

Results of studies with mice have shown that the ipRGCs are present and light sensitive from birth, with an active connection to the suprachiasmatic nucleus, regulator of circadian rhythm (Sekaran, et al., 2005; Tu, et al., 2005). The rods and cones don't become responsive to light until 10 days postnatal, suggesting that the non-image forming pathway of the ipRGCs comes online even before the visual pathway.

Looking at primates, one study found that the circadian rhythm of very premature baboon infants was impacted by exposure to bright light (Hao & Rivkees, 1999). If this finding holds true for human infants, it would suggest that at least some facet of the non-visual effects of light are present from birth. While one study by Mirmiran and Ariagno (2000) failed to find a connection between light set to a day/night cycle in the neonatal nursery and the onset of circadian rhythm in preterm human infants, other studies have shown that cycling light in the NICU leads to longer sleeping, improved feeding and more weight gain compared to controls (Brooks & Canal, 2013; Mann, Haddow, Stokes, Goodley, & Rutter, 1986).

If we accept the findings from the adult literature, that exposure to blue light has an alerting effect and leads to improvements in cognitive skills like attention, then one question that arises is what the developmental trajectory of these effects looks like. Knowing that the ipRGCs are present and involved in regulating circadian rhythm from an early age suggests that an early relationship between light color temperature and cognition should also be seen. While only a handful of studies have been conducted looking at the cognitive effects of light color temperature on children, the work that has been done offers results consistent with the adult literature in showing positive effects after exposure to cooler temperature, blue-enriched light.

As in the adult literature, various studies have explored the effects of light color temperature on children's attention. A common measure across these studies was the d2 test of attention (Brickenkamp & Zilmmer, 2010), in which participants are given sheets of paper containing the letters "p" or "d" with either one or two lines next to them. The participant's task is to mark each letter "d" with two lines that is present on the page. It is purported to measure sustained attention and concentration, and seems roughly analogous to a go/no-go task in that participants must pay attention to features of the stimuli to know whether to react or inhibit reaction. Studies measuring children's performance on the d2 test found children committed fewer errors after exposure to cooler color temperature light at both age 16 to 17 years (Keis, Helbig, Streb, & Hille, 2014; Barkmann, Wessolowski, & Schulte-Markwort, 2012) and 10 years old (Sleegers, et al., 2012). For younger children, the results are less consistent. One study conducted with third graders (average age 8.3) found that children exposed to cooler color temperature light made fewer errors on the d2 test compared with children in a control condition (Barkmann, et al., 2012). However, another study of third graders using a similar setup found no differences on d2 test performance between children in the different lighting conditions (Mott, Robinson, Walden, Burnette, & Rutherford, 2012). One possible explanation for this discrepancy is that the d2 test is meant for individuals ages nine and older, and so may not be a valid measurement of attention in eight-year-olds.

The impacts of lighting condition on children's attention have also been measured through their level of fidgetiness during classroom activities. Ott (1976) replaced the standard fluorescents in one classroom of first graders with lights that resemble natural daylight. Time-lapse photographs of students were studied for signs of restless motion, with the results showing students in the experimental lighting condition settling down quicker and paying more attention to their teacher than those in the control condition.

One limitation of the studies to date that have been conducted with children is that all of them have been conducted in the classroom. In every case, the research design involved the comparison of students taught in a classroom with standard light compared with those taught under some form of blue-enriched enhanced lighting. Several of the studies even compared classrooms from different schools. There are many reasons why conducting studies only in the classroom is appealing to researchers, including the practicality of administering studies with many children at once and the marketability of results demonstrating improved test scores. But classroom studies lack the rigorous control of laboratory studies, and cannot control for outside influences, such as teacher effects. While the studies that have been conducted with children suggest that blue-enriched light does lead to similar positive effects as with adults on cognitive skills like attention, the true nature of these effects cannot be fully understood without conducting a more systematic evaluation of specific light conditions and measures in a laboratory environment. Furthermore, the scant literature that has studied these cognitive effects in children has only studied children ages 6 and older. No study to date has explored how different light color temperatures impact cognition in preschoolers or infants. But studying these populations is necessary in order to piece together the developmental story of these effects.

As such, Experiment 2 proposes to explore whether young children will show cognitive benefits in the domains of sustained attention and cognitive flexibility from exposure to cooler color temperature light, similar to those seen in adults and older children. Like Experiment 1, Experiment 2 builds on the original study by Hartstein, et al. (under review), aiming to replicate with young children the findings previously seen with adult participants. The original study found positive effects of exposure to cooler color temperature light on performance on tasks measuring sustained attention and task switching. Experiment 2 sought to replicate these effects in young children using the same color temperature settings as the original study, and child friendly versions of the original sustained attention and task switching tasks.

The study was conducted in a highly controlled, laboratory environment, in order to eliminate the possibility of outside influences, such as teacher effects. The study included two age ranges, 4.5-to-5.5-year olds, and 7-to-8-year olds. To date, only a couple of studies have examined cognitive effects of lighting in children under age nine, with inconsistent findings. The present study proposes to explore the effects of light color temperature on cognition in 7-year-olds, in an attempt to provide a clearer picture of the nature of the effects in this age group. Furthermore, no research has studied the cognitive effects of light in children under age six. Therefore, the proposed study aims to see whether preschool-aged children 4.5 to 5.5 years old, who are very much still developing their attention abilities, will show positive cognitive effects from exposure to cooler color temperature light.

Furthermore, although a number of studies in the adult literature have reported differences between males and females in their responses to cooler color temperature light in domains such as cognition and mood, these differences have not yet been explored in the child literature. Looking at whether gender differences are present in the development of the infant circadian rhythm, one study found girls show earlier development of circadian rhythm pertaining to temperature regulation than boys (Lodemore, Petersen, & Wailoo, 1992). However, they also found similar effects for infants who were breast fed rather than bottle fed, first born infants, infants from affluent families, and infants with older mothers, so it remains to be seen how important gender is to the development of the non-visual system and the establishment of circadian rhythm. The only child study to make mention of gender in regards to the cognitive effects of light exposure reported no differences between the genders on a measure of attention (Sleegers, et al., 2012). Experiment 2 also aims to explore whether 7-year-olds and preschool-aged children show gender differences in their cognitive response to cooler color temperature light. Knowing whether these gender differences are present in such a young age, and how they might change between the two age ranges studied, sheds light on whether these differences are caused by innate differences between the genders, or unfold later in development.

In sum, the present work builds on previous research findings by Hartstein, et al. (under review), in which exposure to light set to a cooler color temperature lead to faster reaction times on tasks of sustained attention and task switching, with possible differences between genders. Experiment 1 explores whether variations of daylight simulation lead to similar cognitive benefits. Experiment 1 measures whether fluctuations around a central color temperature, compared with the typical static output at one color temperature, provides greater stimulation to the ipRGCs and similar enhancements to cognitive performance. Experiment 2 aims to extend the findings from Hartstein, et al. (under review) to preschoolers and young children, to better understand the emergence of these cognitive reactions to light, and how they might benefit those who are still developing their attention skills.

CHAPTER II

EXPERIMENT 1

Experiment 1

Methods

Participants

Forty-eight undergraduate students participated in the study. Participants were excluded from participating if they had traveled across time zones in the last month, did not have normal or corrected-to-normal vision, had a history of psychological or neurological disorders, were taking psychotropic medication, or had consumed caffeine or smoked cigarettes the morning of testing. Four participants did not meet inclusion criteria, thus 44 participants (22 females) were included in the analyses. Participant ages ranged from 18-29, with an average age of 20 years. Sixty-one percent of participants identified as Caucasian, 22.7% as Asian, 9.1% as Hispanic, 2.3% as African American, and 4.5% as Other. Students received department extra credit as compensation for participating.

Apparatus and Setting

Testing took place in a small, windowless laboratory, with white ceiling and off-white painted walls. The testing room contained a desk covered with a white sheet. The decision to have the ceiling, walls, and table matte white was to reflect the light from the luminaires without glare. A Dell Inspiron 1501 laptop computer, used to administer the cognitive tasks, was placed on the desk. Study tasks were programmed using E-Prime Version 1.2. The testing room and set up are identical to those used by Hartstein, et al. (under review).

There were two LED luminaires in the ceiling, positioned above the desk. The lights were 2'x 2' 5-color channel (red, green, blue, amber, phosphor converted white) CREE LED color tunable fixtures. For the control lighting condition, the lights were set to a static 4000K. For the dynamic condition, the lights were set to fluctuate between 3700K and 4300K, at a frequency of .02hz, for a 50s period (See Figure 1).

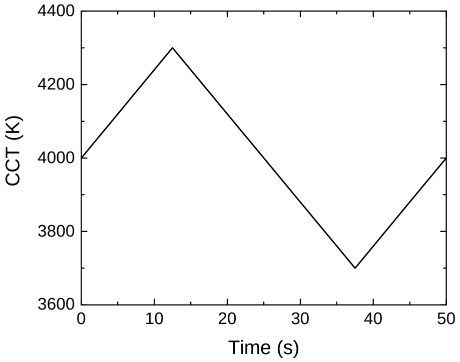

Figure 1: Change in color temperature in the dynamic light setting over the 50s period.

The size of the sweep for the dynamic condition was chosen to be the largest amplitude possible in the given frequency without participant's noticing the changes occurring. The spectra for the light source at 4000K and the range of spectra for the dynamic light condition can be seen in Figures 2a and 2b respectively.

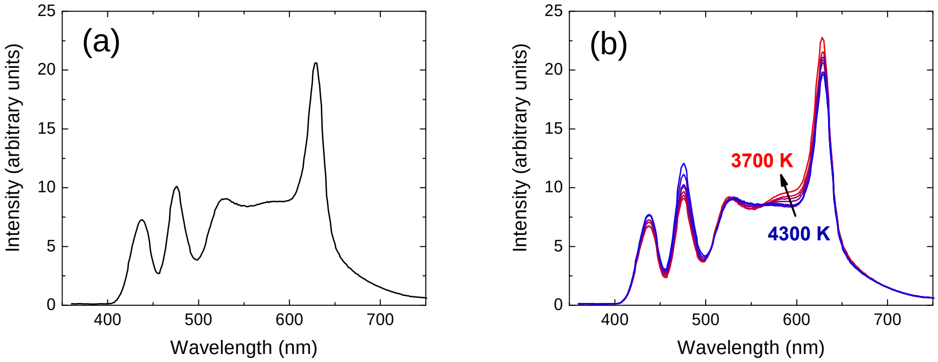

Figure 2: (a) Spectra of light emitted at 4000K. (b)Spectra of light emitted as light oscillates between 3700K and 4300K.

In order to determine how the different light settings stimulate each of the photoreceptive cells, relative lux values were calculated, based upon response curves presented by Lucas, et al. (2014). Table 1 shows the perceived lux values for each of the five photoreceptor types for the minimum, mean (also the baseline setting), and maximum values of the dynamic lighting condition, while Figure 3 shows the change in perceived lux values by each photoreceptor over time. As the color temperature increases, less stimulation of the L cones occurs and greater stimulation of the S cones and ipRGCs.

Photocell	Perceived lux		
	3700K	4000K	4300K
S Cone (blue)	336.68	367.38	405.78
ipRGC	446.42	467.70	508.06
Rod	492.78	505.73	534.05
M Cone (green)	582.26	576.25	585.74
L Cone (red)	664.40	639.24	634.25

Table 1: Effective lux perceived by photocells at the min, mean, and max values of the CCT range in Experiment 1, taken facing the light source.

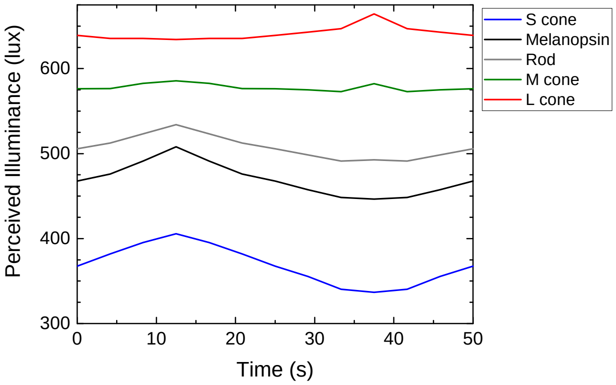

Figure 3: Change in perceived lux by each of the 5 photoreceptors across the 50s period in the dynamic light setting.

The illuminance of the lights at participant eye level remained the same throughout all lighting conditions. While the participants were exposed to light from the laptop as well as the luminaires, the laptop screen illuminance was held constant for all participants and across conditions, and therefore could not be responsible for any differences observed between participants in different lighting conditions. Furthermore, the laptop screen emitted only a trivial percentage of the total light reaching the participant's eye.

Procedure

All testing procedures were taken from Hartstein, et al. (under review). Testing was conducted between November and April in order to take advantage of less sunlight exposure during the winter months. All testing was done between 9:00 and 11:00am, to control for the amount of sunlight participants were exposed to before testing. Participants were randomly assigned to either the control or dynamic condition, ensuring an equal number of males and females in each condition and an equal number of participants in each group being tested at 9:00 or 10:00. When participants were consented, they were told that the study was about the effect of a delay on cognitive performance. There was no mention of lighting to the participant. The deception was necessary to ensure that participants in the dynamic group did not show enhanced performance due to their expectation of the effects of the lights.

After consenting, participants were brought into the testing room and seated at a desk in front of a laptop computer. They then completed the baseline assessment, consisting of two cognitive tasks: a Go/No-Go task measuring sustained attention and a task-switching task. The order of the tasks was counterbalanced across participants. After completing the two tasks, participants were asked to fill out the Profile of Moods (POMs) questionnaire, being instructed to only focus on how they were feeling at that moment. Upon completing the questionnaire, participants were taken out of the room to complete a brief questionnaire concerning general demographics, typical sleep/wake schedule, coffee and alcohol consumption habits, and video game habits. At this point, if the participant was in the dynamic condition, the experimenter switched the lights in the testing room to the dynamic setting without the participant's knowledge. The participant was then brought back into the testing room where they stayed for the remainder of the study. There was then a 20-minute adaptation period in which participants completed a filler task (Sudoku puzzles), while they adjusted to the lighting condition. Previous work has shown that 20 minutes is sufficient for the signal from the light to filter through a variety of cortical areas (Vandewalle, Maquet, & Dijk, 2009). Lastly, participants completed the same two computer tasks, in a different order than the baseline assessment, and the POMs questionnaire a second time. After completing the assessments, participants were asked what they though the study was about to ensure they had not guessed the study hypothesis, and whether they had noticed the changing lights. Finally, participants were fully debriefed as to the true purpose of the study, and given the opportunity to ask any questions.

Go/No-Go Task. The Go/No-Go task consisted of 140 trials. For each trial, participants saw a black fixation cross appear on a white screen for 500 ms, followed by either the letter "M" or the letter "W" in the center of the screen for 500 ms. Participants were instructed to press the right button whenever they saw an "M" appear ("go" trials), but to refrain from pressing any buttons when they saw a "W" ("no-go" trials). Trials were presented in random order, with approximately 80% "go" trials and 20% "no-go" trials. Results were recorded as the number of correct "no-go" trials, in which the participant successfully refrained from pressing the button, as well as the reaction time on correct “go” trials.

Task-Switching Task. All task stimuli and instructions were adapted from Davidson, Amso, Anderson, & Diamond (2006). The task consisted of a warm-up block, containing eight trials, two training blocks, each containing 16 trials, and a test block, containing 64 trials. In the warm-up block, participants were simply shown the different stimuli and trial types. For each of the succeeding trials, a letter “A” or “B” would appear on the computer screen on either the left or right side, during which participants had 2000 ms to respond, followed by the appearance of a fixation cross for 500 ms. Simultaneously, a voice on the computer would say either “what” or “where”, indicating whether they should answer based on what letter appears or where the letter appears. Participants were instructed that for “what” trials, they should press the left mouse button if they see an “A” and the right mouse button if they see a “B”. For “where” trials, they were instructed to press the left mouse button if the letter appears on the left side of the screen and the right mouse button if it appears on the right side of the screen. Each of the training blocks consisted of only one trial type (“what” or “where”), whereas the test block was a mix of both trial types, presented in equal number and in random order.

Participants’ accuracy and reaction time were recorded and analyzed by trial type. A trial that succeeded a trial of the same type was considered a “no-switch” trial, such as a “what” trial immediately following another “what” trial. Similarly, a trial was considered a “switch” trial if it succeeded a trial of the opposite type. Trials were also analyzed as either congruent or incongruent. A congruent trial consisted of an “A” appearing on the left side of the screen, or a “B” appearing on the right side of the screen, which has the same correct button press for both “what” and “where” trials.

Profile of Moods (POMs) Questionnaire. To assess participants’ mood in each lighting condition, the Profile of Moods was administered (McNair, Lorr, & Droppleman, 1971) For the POMs questionnaire, participants were given a list of 65 feeling words, and asked to indicate how much they were feeling each of those feelings in the present moment, by circling a number zero through four. A key was provided for each number choice stating the corresponding value in words (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, and 4 = extremely). Participants’ answers were compiled into subscales for a measure of tension, depression, anger, vigor, fatigue, and confusion, as well as a Total Mood Disturbance (TMD).

Results

See Table 2 for sleep habits as well as average alcohol and coffee consumption for each group. To look for differences between participants, 2-way 2x2 between-subjects ANOVAs were run to look at differences between participants assigned to each condition (Control, Dynamic), as well as any differences between genders (Male, Female), and any interaction between the two factors. Results showed a main effect of condition for average amount of alcohol consumed each week, with participants assigned to the control group reporting consuming 4.64 alcoholic drinks per week and participants in the dynamic group reporting 1.63 alcoholic drinks per week (F(1,40)=9.24, p=.004). There was also a significant main effect of gender for average bed time, with male participants reporting an average bed time of 12:42AM, with females going to bed on average at 11:31PM (F(1,40)= 8.76, p=.005). However, even though males reported going to bed an average of one hour later than female participants, there were no significant differences in the reported amount of sleep participants got the night before testing (F(1,40) = 1.19, p = .28), with males reporting an average of 7.42 hours of sleep and females reporting an average of 7.88 hours. No other significant differences were found.

	Control	Dynamic
Bed Time	23:50 (1h:18m)	00:14 (1h:16m)
Wake Time	08:09 (0:59m)	08:24 (1h:13m)
Alcoholic Drinks/Week	4.64 (4.09)	1.63 (2.16)
Coffee Drinks/Week	2.45 (3.38)	2.26 (3.80)
Hours Slept Previous Night	8.02 (1.74)	7.30 (1.18)

Table 2: Means and SD for various demographic components for participants of Experiment 1.

All task results were analyzed using a Group (Control, Dynamic) by Phase (Baseline, Test) by Gender (Male, Female) mixed model ANOVA. If the dynamic condition showed greater improvements in task performance over the control group, we would expect to see significant differences in the Group by Phase interaction coefficient.

Since a number of studies have demonstrated that light color temperature impacts both mood and cognition differently for men and women (Knez, 1995; Knez, 2001; Hygge & Knez, 2001; Huang, et al., 2014; Hartstein, et al., under review), the data were also analyzed to look for any interactions of participant gender.

Go/No-Go Task

<u>Accuracy.</u> Accuracy was scored as the number of "no-go" trials out of 28 in which participants correctly inhibited pressing the mouse button. See Table 3 for average accuracy on "no-go" trials across conditions.

	Baseline	Test	Difference
Control	18.05 (4.80)	19.81 (4.38)	1.76
Dynamic	19.17 (4.61)	19.17 (4.94)	0

Table 3: Means and standard deviations for number of correct "no-go" trials in Experiment 1.

Results of the ANOVA showed no significant effects of Phase (F(1,40) = 2.87, p = .10), Group (F(1,40) = .03, p = .85), or Group by Phase interaction (F(1,40) = 2.98, p = .09). Although the control group showed a larger improvement in accuracy than participants in the dynamic group, it was on the slight order of one or two more trials.

A main effect of gender was found (F(1,40) = 3.97, p = .05), with male participants showing overall higher accuracy than female participants. A marginally significant Group by Phase by Gender interaction was found (F(1,40) = 3.46, p = .07), suggesting that how much the two groups differed on their change in accuracy depended on their gender. See Table 4 for means and standard deviations separated by gender.

	Males		Females	
	Baseline	Test	Baseline	Test
Control	18.45 (4.08)	21.64 (2.54)	17.60 (5.68)	17.80 (5.18)
Dynamic	20.82 (4.12)	20.45 (4.72)	17.67 (4.68)	18.00 (5.05)

Table 4: Means and standard deviations for number of correct "no-go" trials for males and females in Experiment 1.

When analyzed separately, female participants showed no significant effects of Phase (F(1,20) = .12, p =.73), Group (F(1,20) = .004, p = .95), or Group by Phase interaction (F(1,20) = .01, p = .93). For male participants, significant effects were found for the main effect of Phase (F(1,20) = 5.07, p = .04) and Group by Phase interaction (F(1,20) = 8.03, p = .01). No significant differences were found for Group (F(1,20) = .14, p = .71). While male participants in the dynamic group showed consistent performance over time, with an average of 20.8 correct trials in the baseline and 20.5 correct trials in the test assessment, participants in the control group showed a larger improvement from baseline to test, improving from 18.5 correct trials to 21.6 correct trials. While participants in the control group showed larger improvements in performance, participants in the control group started off with a lower score than those in the dynamic group, and showed better performance in the test assessment by only one trial.

Reaction Time. See Table 5 for means and standard deviations for reaction time on correct "go" trials.

	Baseline	Test	Difference
Control	308.36 (31.46)	298.99 (34.86)	9.37
Dynamic	322.83 (30.28)	292.69 (36.95)	30.14

Table 5: Means and standard deviations for reaction time on correct "go" trials in Experiment 1.

Results of the statistical analysis showed a significant main effect of Phase (F(1,40) = 15.18, p < .001), with participants across both conditions showing significantly faster reaction times in the test assessment compared with the baseline. There was no significant main effect of Group (F(1,40) = .22, p = .64) or Gender (F(1,40) = 1.45, p = .24). A significant Group by Phase interaction was found (F(1,40) = 4.19, p =

.047), with participants in the dynamic group showing larger improvement in reaction time than participants in the control group (See Figure 4). While participants in the control group decreased their reaction time by an average of 3.05% (9.4ms), participants in the dynamic group showed a significantly larger average decrease in reaction time of 9.32% (30.1ms). No significant Group by Phase by Gender interaction was found (F(1,40) = .65, p = .43).

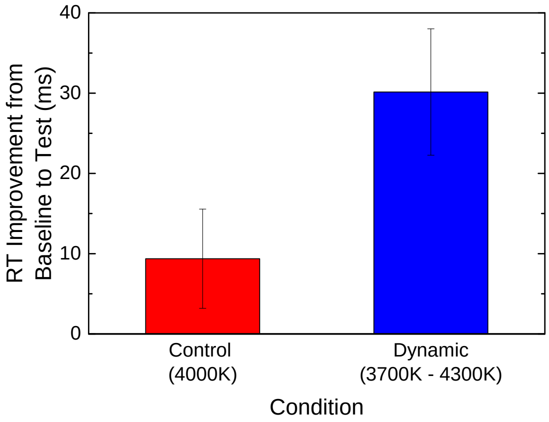

Figure 4: Change in reaction time (ms) on correct "go" trials from baseline to test in Experiment 1.

Although no significant effects of gender were found in the current analysis, previous work has suggested there might be. Hartstein, et al. (under review) found that male participants showed significantly greater improvement in reaction time on a go/no-go task after exposure to static cooler color temperature light compared with control participants. No such effect was found for female participants. As a comparison with the previous study, reaction times on the Go/No-Go task in Experiment 1 were also analyzed separately by gender, to look for any differences in how males and females' performance was impacted by the lighting condition. See Table 6 for average reaction times and standard deviations for each condition separated by gender.

	Males		Females	
	Baseline	Test	Baseline	Test
Control	306.28 (28.69)	305.38 (41.19)	310.65 (35.69)	291.96 (26.67)
Dynamic	331.14 (17.50)	301.69 (25.01)	315.21 (37.72)	284.44 (44.81)

Table 6: Means and standard deviations for reaction time on correct “go” trials in Experiment 1, separated by gender.

For female participants, a significant main effect of Phase was found (F(1,20) = 7.55, p=.01), with participants across conditions showing faster performance in the test assessment compared to baseline. No significant effects were found for Group (F(1,20) = .01, p = .91) or Phase by Group interaction (F(1,20) = .45, p = .51). For male participants, no significant main effect of Group was found (F(1,20)=.14, p= .71). However, similarly to females, a significant main effect of Phase was found (F(1,20) = 9.75, p = .005), with male participants across conditions showing faster performance in the test assessment. A significant Group by Phase interaction was also found (F(1,20) = 8.63, p = .008), suggesting that while both groups showed improved reaction times from the baseline to test assessment, the dynamic group showed greater improvement, mirroring the results seen in the overall group when both genders are included together. Males in the control group decreased their reaction time by an average of only .29% (.9ms) while males in the dynamic group showed an average decrease in reaction time of 8.89% (29.45ms). Female participants did show the same trend, with females in the dynamic group showing the same magnitude difference as males in the dynamic group (9.76% or 30.77ms), as well as larger decreases in reaction time than females in the control group (6.01% or 18.69ms). Unlike for males, these differences were not statistically significant, as females in the control group also showed some improvement over time. Male and female participants in the experimental group showed improved reaction times of the same magnitude (~30ms), confirming that the impact of the lighting condition on sustained attention reaction time did not differ by gender.

Task Switching Task

Accuracy. Accuracy on all trials was high, with participants answering correctly on 87.8% of trials across conditions and time points (See Table 7).

	Baseline	Test	Difference
Control	86.71 (7.25)	89.48 (5.74)	2.77
Dynamic	85.10 (6.86)	88.68 (6.38)	3.58

Table 7: Means and standard deviations for percent correct across all trials in Experiment 1.

Participants' accuracy showed a main effect of Phase (F(1,40)= 11.17, p = .002), Participants in both the control and dynamic groups showed improved accuracy from the baseline to test assessment. There were no significant effects for Group (F(1,40) = .48, p = .49) or Group by Phase interaction (F(1,40) = .27, p = .60). A significant Phase by Gender interaction was found (F(1,40) = 4.72, p = .04). Males showed a larger improvement in percent correct from baseline to test assessment than females, across conditions. Male participants' answered correctly on 85.4% of baseline trials and 89.4% of test trials, while females' percent correct went from 87.7% correct at baseline to 88.6% correct at test. There was no significant main effect of Gender (F(1,40) = .10, p = .75) or Group by Phase by Gender interaction (F(1,40) = .18, p = .67).

Reaction Time. Analyses of reaction times included only trials in which the participant answered correctly (See Table 8).

	Baseline	Test	Difference
Control	738.72 (127.16)	648.71 (105.80)	-90.01
Dynamic	745.01 (136.02)	692.76 (101.10)	-52.25

Table 8: Means and standard deviations of reaction time on correct trials in Experiment 1.

Like accuracy, participant reaction time showed a significant main effect of Phase (F(1,40) = 29.04, p < .001). Participants demonstrated faster reaction times from baseline to test assessment across both conditions. Again, there were no significant effects for Group (F(1,40) = .88, p = .35) or Group by Phase interaction (F(1,40) = 2.08, p = .16). A significant main effect of Gender was found (F(1,40) = 7.88, p = .008). Female participants had faster average reaction times across conditions than male participants. There were no significant Phase by Gender (F(1,40) = .07, p = .80) or Phase by Group by Gender interactions (F(1,40) = .002, p = .97).

POMs Questionnaire

Scores for each subscale (tension, depression, anger, vigor, fatigue, and confusion) were calculated by adding the participant's circled response on each item in that category. A total mood disturbance (TMD) score was also calculated by adding the raw scores from the tension, depression, anger, fatigue, and confusion subscales, and then subtracting the vigor score. Any missing values were imputed as the average of that item across members of the participant's assigned group (Control or Dynamic). Each participant had two scores for each scale, having completed the POMs twice during testing, once in the baseline condition and once at test. Data from one participant in the control group was removed from analysis as that participant only completed half of the questionnaire in the test assessment. Means and standard deviations for each subscale can be seen in Table 9.

	Control		Dynamic	
	Baseline	Test	Baseline	Test
Tension	9.09 (5.32)	8.24 (6.13)	11.78 (7.91)	9.91 (7.76)
Depression	6.44 (6.63)	5.80 (7.83)	7.00 (8.82)	6.91 (11.35)
Anger	4.73 (5.30)	4.20 (5.58)	6.64 (7.65)	5.64 (8.13)
Vigor	13.10 (5.54)	12.80 (5.63)	13.31 (5.91)	11.35 (8.35)
Fatigue	8.00 (4.10)	6.95 (4.85)	9.43 (5.88)	9.12 (7.15)
Confusion	6.70 (3.47)	6.15 (3.61)	9.13 (5.00)	8.22 (5.18)
TMD	21.86 (20.24)	18.56 (22.78)	30.70 (30.66)	28.46 (35.31)

Table 9: Means and SD for each subscale of the Profile of Moods (POMs) in Experiment 1.

Results were again analyzed using a Group (Control, Dynamic) by Phase (Baseline, Test) by Gender (male, female) mixed model ANOVA. A significant main effect of Phase was found for the confusion subscale (F(1,41) = 6.45, p = .02). Participants across both groups reported less confusion in the test assessment than the initial baseline assessment. Marginally significant main effects of Phase were also found for the tension (F(1,41) = 3.87, p = .06) and vigor (F(1,41) = 3.48, p = .07) subscales. Participants across both groups reported less tension and less vigor in the test assessment compared with the baseline. No main effects of Group or Group by Phase interactions were found for any subscales. No significant effects of gender were found.

Experiment 1 Discussion

For the cognitive assessments, all reaction time analyses showed significant main effects of Phase, with participants' reaction times improving from baseline to test assessments, across gender, conditions, and tasks. This is likely due to practice effects, with participants having never before been exposed to these types of tasks improving with familiarity to the rules. For the task switching task, no Group by Phase interactions were found, indicating that there were no significant differences in the amount of improvement shown by the control or dynamic conditions. In other words, exposure to the dynamic lighting condition in the test assessment did not lead to greater improvements on the task switching task for participants in the dynamic group compared with those in the control group.

On the go/no-go task, a significant Group by Phase interaction was found, with participants in the dynamic group having greater improvement in their reaction time for correctly responding on “go” trials compared with participants in the control group. When analyzed separately be genders, it was found that the effect is stronger in males, with males in the dynamic group having showed significantly greater improvement in reaction time compared to male participants in the control group. These findings mirror those found by Hartstein, et al. (under review), in which males, but not females, showed significantly improved reaction times on a go/no-go task compared to a control group following exposure to cooler color temperature light. These findings support the prediction that exposure to the dynamic lighting condition leads to improvements in attention, as measured by reaction time on a sustained attention task. Furthermore, these results suggest possible gender differences in how males and females’ performance is impacted by the lighting condition, with males showing the stronger differences between conditions.

However, while both the control and dynamic groups were exposed to the same average color temperature (4000K), the dynamic group also received some exposure to light set to a cooler color temperature (up to 4300K). Since previous research has demonstrated that exposure to higher color temperature light leads to improvements in cognitive performance, one alternative explanation is that it was merely the exposure to the higher color temperature that lead to the greater performance, with no influence from the dynamic nature of the lighting. In order to explore this possibility, a follow-up condition is proposed (Experiment 1A). All procedures for Experiment 1A are identical to those of Experiment 1, with the exception that in the test assessment, the lights will be set to a static color temperature of 4300K. If the improvements in reaction time on the go/no-go task seen in the dynamic condition of Experiment 1 were due only to the exposure to higher color temperature light, we would expect to see the same improvements for participants in this condition. However, if the dynamic nature of the lighting condition in Experiment 1 is driving the reaction time improvements in the dynamic group, we would expect to see no significant improvements for participants in Experiment 1A compared with the control group.

Experiment 1A

Methods

Participants

Twenty-five undergraduate students participated in the study. All eligibility requirements, consent procedures, and participant compensation will be identical to those used in Experiment 1. Two participants were excluded, one for failing to meet eligibility requirements and one because of computer error. Therefore, 23 participants (11 female) were included in the analyses. Participant ages ranged from 18 to 23, with an average age of 20.25 years. Fifty-two percent of participants identified as Caucasian, 26.1% as African American, and 21.7% as Asian.

Apparatus and Setting

All equipment and the testing setting were identical to those used in Experiment 1.

Procedure

All procedures were identical to those used in Experiment 1, with the exception of the light setting in the test assessment. Following the baseline assessment, the light setting was changed to a static 4300K.

Results

See Table 10 for a comparison of demographics between participants from the Control condition and participants in the Static condition from Experiment 1A. Two-way 2x2 between subjects ANOVAs were run to look for demographic differences between participants in each group (Control, Static), as well as differences by gender (Male, Female). A significant main effect of Group was found for average bed time, with participants in the static condition going to bed an average of one hour later than participants in the control condition ($F(1,40) = 6.23$, $p = .02$). No other significant differences between the two groups were found.

	Control	Static
Bed Time	23:50 (1h:18m)	00:52 (1h:31m)
Wake Time	08:09 (0:59m)	08:32 (0:58m)
Alcoholic Drinks/Week	4.64 (4.09)	2.98 (4.68)
Coffee Drinks/Week	2.45 (3.38)	2.54 (3.36)
Hours Slept Previous Night	8.02 (1.74)	7.14 (1.92)

Table 10: Means and standard deviations of demographic variables in Experiment 1A.

Just like in Experiment 1, all task results were analyzed using a Group (Control, Static) by Phase (Baseline, Test) by Gender (male, female) mixed model ANOVA.

Go/No-Go Task

Accuracy. See Table 11 for a comparison of accuracy scores out of 28 trials for both groups of participants.

	Baseline	Test	Difference
Control	18.05 (4.80)	19.81 (4.38)	1.76
Static	21.65 (4.17)	22.43 (2.84)	0.78

Table 11: Means and standard deviations for raw accuracy scores on go/no-go task in Experiment 1A.

The results from the ANOVA showed a significant main effect of Phase (F(1, 40) = 5.40, p = .03), with participants across conditions showing significant improvement from the baseline to test assessments, as well as a significant main effect of Group (F(1,40) = 8.44, p = .01), with participants in the static condition showing better performance than the control condition across both assessments. A marginally significant main effect of Gender was also found, (F(1,40) = 2.99, p = .09), with male participants demonstrating higher accuracy than female participants, across conditions and time points. No significant interactions were seen for Group by Phase (F(1,40) = .62, p = .44), Group by Gender (F(1,40) = .20, p = .66), or Phase by Gender (F(1,40) = .05, p = .83).

A significant Group by Phase by Gender interaction was found (F(1,40) = 6.36, p = .02), suggesting that the ways in which the lighting condition impacted the change in accuracy depends on gender. See Table 12 for means and standard deviations of each condition separated by gender.

	Males		Females	
	Baseline	Test	Baseline	Test
Control	18.45 (4.08)	21.64 (2.54)	17.60 (5.68)	17.80 (5.18)
Static	22.92 (3.94)	22.50 (3.63)	20.27 (4.15)	22.36 (1.80)

Table 12: Means and standard deviations for number of correct “no-go” trials for males and females in Experiment 1A.

When analyzed separately, female participants showed no significant main effect of Phase (F(1,19) = 1.73, p = .20) or Group by Phase interaction (F(1,19) = 1.18, p = .29), but did show a significant main effect of Group (F(1,19) = 4.45, p = .05), with females in the static condition showing overall higher accuracy than females in the control condition. For male participants, a significant main effect of Phase was found (F(1,21) = 4.26, p = .05), suggesting an average overall improvement in accuracy over time. However, a significant Group by Phase interaction was also found (F(1,21) = 7.21, p = .01), showing that males in the control group in fact demonstrated an increase in accuracy over time while males in the static group had little change. Nevertheless, a marginally significant main effect was condition was also found (F(1,21) = 3.89, p = .06), indicating that males in the static group performed significantly better overall than participants in the control group.

Reaction Time. A significant main effect of Phase was found (F(1,39) = 6.13, p = .02), with participants in both conditions showing significantly faster reaction times in the test compared with baseline assessment (See Table 13). A significant main effect of Group was also found (F(1,39) = 5.34, p = .03), with the control group demonstrating faster reaction times across both time points. No significant Group by Phase interaction was found (F(1,39) = .40, p = .53), indicating no differences between the two conditions on how the light setting impacted changes in reaction time. No significant gender effect or interactions with gender were found (F < 1).

	Baseline	Test	Difference
Control	308.36 (31.46)	298.99 (34.86)	-9.37
Static	336.58 (30.28)	320.11 (36.95)	-16.47

Table 13: Means and standard deviations for reaction time on correct "go" trials in Experiment 1A.

Task Switching Task

Accuracy. Data from one participant was removed from analysis of the task-switching task for not reaching the minimum criteria of at least 60% correct on all trials. Accuracy on all trials continued to be high for the static condition, with participants answering correctly on 87.1% of trials across assessments, consistent with the 87.8% average accuracy found in Experiment 1 (See Table 14).

	Baseline	Test	Difference
Control	86.71 (7.25)	89.48 (5.74)	2.77
Static	84.42 (8.08)	88.26 (8.32)	3.84

Table 14: Means and standard deviations for percent correct across all trials in Experiment 1A.

Results for accuracy on the task-switching task showed a main effect of Phase (F(1,39) = 16.00, p < .001), with participants across both conditions showing significant improvement from baseline to test. Similarly to accuracy on the go/no-go task, a marginally significant Group by Phase by Gender interaction was found (F(1,38) = 3.57, p = .07), suggesting that the effect of lighting condition on changes in accuracy over time is impacted by gender. See Table 15 for means and standard deviations of accuracy on the task-switching task separated by gender.

	Males		Females	
	Baseline	Test	Baseline	Test
Control	85.04 (8.43)	90.15 (5.46)	88.54 (5.56)	88.75 (6.25)
Static	83.62 (8.84)	86.84 (9.32)	85.23 (7.59)	89.68 (7.36)

Table 15: Means and standard deviations for percent accuracy on task-switching task in Experiment 1A, separated by gender.

When analyzed separately, male participants demonstrated a significant main effect of Phase (F(1,20) = 11.51, p = .003), such that male participants in both conditions showed significantly greater accuracy on the task switching task in the test compared to baseline assessment. There was no significant effect for Group or for Group by Phase interaction (F < 1). Female participants showed a similar significant main effect of Phase (F(1,19) = 4.91, p = .04), with more accurate performance in the test assessment. Female participants also demonstrated a marginally significant Group by Phase interaction (F(1,19) = 4.07, p = .06), with female participants in the static group showing greater improvements in accuracy over time than female participants in the control group. Finally, there was no significant main effect of Group for female participants (F(1,19) = .19, p = .67).

Reaction Time. See Table 16 for a breakdown of means and standard deviations across condition for overall reaction time on the task-switching task.

	Baseline	Test	Difference
Control	738.72 (127.16)	648.71 (105.80)	-90.01
Static	745.26 (149.18)	680.87 (94.24)	-64.39

Table 16: Means and stand deviations for overall reaction time on task-switching task in Experiment 1A.

A significant main effect of Phase was found (F(1,39) = 37.88, p < .001), with participants across conditions showing significantly faster reaction times in the test assessment compared with the baseline. A significant Group by Gender interaction was also found (F(1,39) = 5.50, p = .02). While females in the control group demonstrated faster reaction times across time points than females in the static group, male participants in the static group were faster overall than males in the control group. No other significant effects were found.

POMS Questionnaire

As in Experiment 1, subscales were calculated for participants in the static condition for each of the mood categories (tension, depression, anger, vigor, fatigue, confusion, and total mood disturbance (TMD)). Any missing values were imputed from the average of that item across participants in that condition. Data from one participant in the static condition was removed from analyses for not completing a third of the items during the test assessment. Means and standard deviations for each subscale can be seen in Table 17.

	Control		Static	
	Baseline	Test	Baseline	Test
Tension	9.09 (5.32)	8.24 (6.13)	10.45 (8.98)	9.18 (7.49)
Depression	6.44 (6.63)	5.80 (7.83)	8.27 (11.98)	7.86 (11.72)
Anger	4.73 (5.30)	4.20 (5.58)	6.09 (6.38)	5.63 (5.91)
Vigor	13.10 (5.54)	12.80 (5.63)	11.64 (6.73)	9.20 (6.78)
Fatigue	8.00 (4.10)	6.95 (4.85)	8.77 (6.43)	8.77 (6.29)
Confusion	6.70 (3.47)	6.15 (3.61)	7.59 (5.35)	7.72 (4.54)
TMD	21.86 (20.24)	18.56 (22.78)	29.55 (36.14)	29.97 (33.63)

Table 17: Means and standard deviations for ratings on the POMs questionnaire in Experiment 1A.

Results of the ANOVA revealed a significant Phase by Gender interaction for the tension subscale, F(1,38) = 4.87, p = .03, with female participants reporting much higher tension at the baseline and a larger decrease across time points than males. For the vigor subscale, significant main effects were found for Phase, F(1,38) = 7.48, p = .01, and Gender, F(1,38) = 4.41, p = .04, with male participants reporting more vigor than female participants across conditions and time points, and all participants reporting a decrease in vigor from the baseline to test assessments. A significant Group by Phase interaction was also found, F(1,38) = 4.50, p = .04, with participants in the static condition reporting a larger decrease in vigor over time. For the confusion subscale, a significant Phase by Gender interaction was found, F(1,38) = 6.39, p = .04, with female participants reporting less confusion between baseline and test assessments and male participants reporting an increase in confusion. A significant 3-way Phase by Group by Gender interaction was also found, F(1,38) = 7.12, p = .01, prompting follow up comparisons separately for male and female participants. For female participants, a significant main effect of Phase was found, F(1,18) = 6.12, p = .02, with female participants across conditions reporting a decrease in confusion between baseline and test assessments. For male participants, a significant Group by Phase interaction was found, F(1,20) = 5.02, p = .04, with males in the control group reporting a decrease in confusion over time, whereas males in the static group reported an increase. Lastly, for total mood disturbance, a significant Phase x Gender interaction was found, F(1,38) = 4.51, p = .04, with female participants reporting large decreases in mood disturbance over time, whereas male participants reported a small increase. No other significant main effects or interactions were found for any of the subscales. Given the high incidence of gender effects, Tables 18 and 19 show the POMs scores separately for males and females.

	Control		Static	
	Baseline	Test	Baseline	Test
Tension	8.10 (4.86)	8.40 (5.64)	8.33 (6.37)	8.75 (7.34)
Depression	6.90 (7.75)	7.00 (9.83)	5.17 (7.11)	6.17 (9.49)
Anger	5.30 (5.08)	4.60 (5.68)	5.00 (4.65)	6.08 (6.16)
Vigor	14.30 (6.57)	13.40 (6.65)	14.50 (7.17)	11.50 (7.59)
Fatigue	7.90 (4.04)	7.40 (4.70)	6.75 (5.67)	7.75 (5.28)
Confusion	7.40 (4.03)	6.79 (3.32)	5.42 (4.34)	7.42 (4.23)
TMD	21.30 (19.01)	20.79 (20.58)	16.17 (26.44)	24.67 (30.97)

Table 18: Means and standard deviations for ratings on the POMs questionnaire for male participants in Experiment 1A.

	Control		Static	
	Baseline	Test	Baseline	Test
Tension	10.07 (5.80)	8.13 (6.84)	13.00 (11.20)	9.70 (8.04)
Depression	6.00 (5.66)	4.60 (5.44)	12.00 (15.65)	9.90 (14.21)
Anger	4.16 (5.70)	3.80 (5.75)	7.40 (8.07)	5.10 (5.88)
Vigor	11.90 (4.31)	12.20 (4.66)	8.20 (4.34)	6.44 (4.62)
Fatigue	8.10 (4.38)	6.50 (5.21)	11.20 (6.71)	10.00 (7.42)
Confusion	6.00 (2.83)	5.50 (3.95)	10.20 (5.47)	8.08 (5.08)
TMD	22.42 (22.42)	16.33 (25.72)	45.60 (40.85)	36.34 (37.21)

Table 19: Means and standard deviations for ratings on the POMs questionnaire for female participants in Experiment 1A.

Experiment 1A Discussion

As in Experiment 1, all reaction time analyses showed a significant main effect of Phase, indicating that, across all conditions, participants' reaction times decreased from the baseline to test assessments. These results were expected as participants became more comfortable with the tasks with practice.

Gender differences were found for accuracy on the two tasks, with male participants in the control group showing larger improvement in go/no-go accuracy than males in the static group, and female participants in the static group showing larger improvement in task-switching accuracy than females in the control group. The previous study by Hartstein, et al. (under review) found similar task specific inconsistencies in gender differences. On a go/no-go task, male participants in that study showed larger reaction time improvement after exposure to a cooler color temperature light source than those in the control group, but female participants showed no such effect. But the reverse was true on a task switching task, in which female participants in the cooler CCT light condition showed larger reaction time improvements compared with controls, but male participants showed no effect. Together, the findings of these two studies suggest that gender differences in how light color temperature impacts cognitive performance may be dependent on the particular task.

The results of Experiment 1 found that participants in the dynamic group showed a significantly greater decrease in reaction time on correct "go" trials in the go/no-go task than participants in the control group. Participants in the control group improved their reaction times by an average of 3.04%, compared with participants in the dynamic group, whose reaction times improved by an average of 9.34%. Experiment 1A sought to show whether exposure to light set to a static 4300K, giving participants a small increase in exposure to shorter-wavelength blue light, would lead to the same differences in performance improvement. The results of Experiment 1A showed no such difference between participants in the control and static groups, with participants in the static condition improving their reaction times on the go/no-go task by an average of 4.89%. Figure 5 illustrates the change in reaction time between the baseline and test assessments for each of the three lighting conditions.

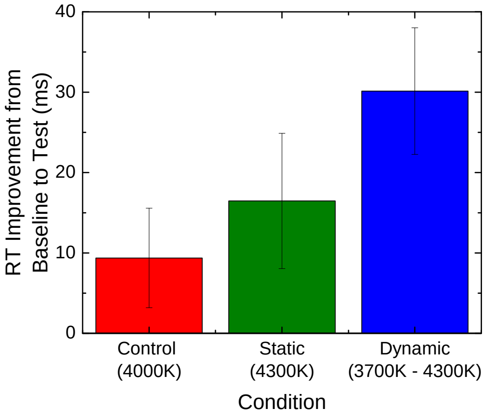

Figure 5: Change in reaction time (ms) on correct "go" trials from baseline to test across all three lighting conditions.

Taken together, these findings suggest that it was not just the increased exposure to blue light in the dynamic condition that lead to better performance on the go/no-go task. If that were true, the same, if not greater, effects would have been seen from participants in the static condition. Rather, the results suggest that it is the constant, slow changes in lighting in the dynamic condition that lead to the observed improvements in performance.

CHAPTER III

EXPERIMENT 2

Experiment 2 aimed to see whether preschool aged and 7-year-old children showed the same cognitive benefits of exposure to cooler color temperature light, as previously seen in studies with adults and older children.

Methods

Participants

Forty-five children aged 4.5-to-5.5 years and 25 7-to-8-year-olds were brought into the laboratory for a single experimental session lasting approximately one hour. Eligibility requirements for participation were no history of psychological or neurological disorders, not taking any psychotropic medication, and not having travelled across time zones for one month prior to testing. One participant was excluded for failing to meet the eligibility requirements, three for experimenter error, and four fussed out of the study, leaving 38 4.5-to-5.5-year-olds (21 female) and 24 7-year-olds (9 female) in the data set. Participant ages in the younger group ranged from 4 years, 6.6 months to 5 years, 5.5 months, with an average of 4 years, 8.9 months, while participants in the older age group had an age range of 7 years, 0.5 months to 7 years, 11.9 months, with an average age of 7 years, 6.6 months. Parents were asked to answer a number of questions regarding the child’s sleep patterns, including their typical bed time, wake time, and napping habits. Participants were contacted through e-mail and phone after being identified from state birth records. Children received a small toy as a token of appreciation for their participation.

Apparatus and Setting

The testing room, setting, lights, and computer were all identical to those used in Experiments 1 and 1A. For the warm lighting condition, the lights were set to 3500K. For the cool lighting condition, they were set to 5000K. Figure 6 shows the spectra for each of the light settings.

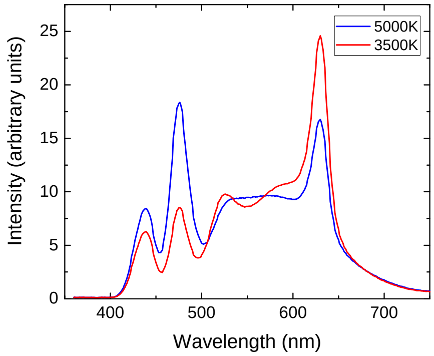

Figure 6: Spectra of the room lights taken at 3500K and 5000K.

Changing the light settings from 3500K to 5000K reduces the red light and increases the blue light put out by the LED light source. This effect is also seen in the effective lux perceived by each type of photoreceptor in the eye (See Table 20). Compared with the baseline setting of 3500K, the 5000K light setting leads to a reduction in stimulation of the L cones, corresponding to the decrease in red light emitted by the light source, and a large increase in stimulation of the S cones and, critically, the ipRGCs, maximally stimulated by light in the blue portion of the visible spectrum.

Photocell	Perceived lux	
	3500K	5000K
S Cone (blue)	318.01	519.10
ipRGC	450.59	650.09
Rod	507.32	646.97
M Cone (green)	615.81	665.88
L Cone (red)	713.88	685.97

Table 20: Effective lux perceived by photocells for each lighting condition in Experiment 2, taken facing the light source.

Procedure

Participants were randomly assigned to either the control or experimental group, ensuring that the groups contained an equal number of each gender. While adult participants in Experiments 1 and 1A were run at a consistent time in the morning, the difficulties of recruiting child participants necessitated scheduling appointments for whatever time parents were able to bring their children to the laboratory. As such, participants were run throughout the day, with the time of appointment recorded for comparison across groups. Informed consent was obtained from the parent while the child participant acclimated to the researchers and played with some toys. For the 7-year-old participants, verbal assent was obtained. The researcher discussed the study procedures with the child, make clear that they could stop the study at any time without consequence, and answered any questions they had prior to asking for their verbal assent to participate. While the parent was fully informed of the purpose of the study and whether the lights were going to be changed, the details of the study were not discussed with the child so that they did not tune into any possible changes in lighting condition, and were not influenced by any preconceived notions of how the lighting might impact their performance. After consent, and assent when relevant, the participant and their parent were brought into the testing room and seated at the desk in front of the laptop computer.

During the baseline assessment, the lights in the room were set to 3500K for all participants. Participants completed two computer tasks: a Go/No-Go task measuring selective attention and a Hearts and Flowers task, which measured their cognitive flexibility, or the ability to switch between rules. While the d2 test of attention has been used in much of the previous work exploring the cognitive effects of light in children, the test is suggested for children ages nine and older, and was therefore not appropriate for participants in the present study. The order of task presentation was counter-balanced across participants. Following the first completion of the tasks (baseline assessment), participants were briefly taken out of the testing room in order to choose storybooks to read during the subsequent 20-minute adaptation period. While the participant was out of the room, if they were in the experimental condition, the researcher covertly changed the light in the testing room from 3500K to 5000K. For the control condition, the light settings were not changed.

Participants were then brought back into the testing room, where they stayed for the remainder of the study. They then read age-appropriate storybooks with the researcher for 20 minutes, which served as an adaptation phase during which participants in the experimental condition adjusted to the new lighting environment. Following the adaptation period, participants completed the two computer tasks a second time (test assessment), in the reversed order from which they completed them previously.

Go/No-Go Task

Participants were told that they are going to play a game about going to the zoo. They were shown an image of a cartoon zookeeper, who they were introduced to as Emily the zookeeper. They were then told that “one day, Emily wasn’t paying attention and all the animals escaped from the zoo!” Children were then told that their job is to help Emily re-catch the animals. In order to do that, they need to press the right mouse button whenever they see an animal appear. They were then shown a picture of a monkey and told that the monkey is their friend, who is helping them to catch the animals, so they don’t want to catch him. So when they see the monkey, they don’t want to press any buttons. The child was then asked to repeat the instructions to confirm their comprehension. If the child did not understand, the instructions were repeated until the child demonstrated a sufficient grasp of the instructions. The task was composed of 64 trials, in a semi-random order. The task consisted of 75% “go” trials and 25% “no-go” trials. “Go” trials consisted of images of six different animals: a flamingo, a tiger, a tortoise, a hippopotamus, a zebra, and an antelope. Each image was presented for 800 ms, with a white slide with a fixation cross being presented for 500 ms between each trial. Results were recorded as the number of correct “no-go” trials, in which the child successfully inhibited responding to the image of the monkey, as well as latency on correct “go” trials, in which the child correctly caught one of the other six animals.

Hearts and Flowers

Task components and procedures were adapted from Davidson, et al. (2006). The Hearts and Flowers task consisted of two practice blocks, each with 16 trials, followed by a test block with 40 trials. In each trial, an image of a heart or a flower appeared on either the left or right side of the screen (see Figure 7). The child was told that when they see a heart, they should press the mouse button that matches the same side where the heart appears on the screen, and when they see a flower, they should press the mouse button that is on the opposite side of where the flower appears on the screen.

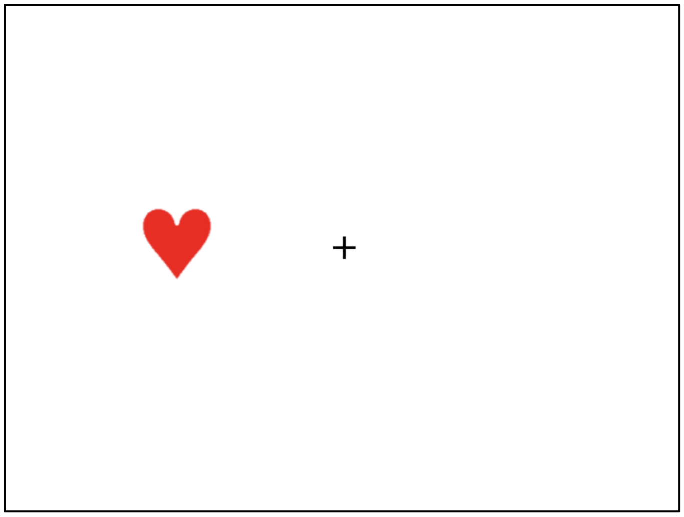

Figure 7: Example of stimulus from Hearts and Flowers task.

The first practice block consisted of only heart trials, the second practice block consisted of only flower trials, and the test block consisted of both types of trials together. Before each block began, the instructions for that block were reviewed with the child, who was asked to demonstrate which button they would press for each possible trial. During each trial, a fixation cross appeared for 500 ms, followed by the trial stimulus. For the 7-year-old participants, the stimulus appeared for 2000 ms. For the preschool aged participants, the stimulus appeared onscreen for 2500 ms. The test block consisted of 40 trials, 20 of each type of stimulus, 10 appearing on each side of the screen, presented in a random order. Trials were broken down into “no-switch” trials, in which two of the same type of stimulus appeared in a row (i.e. a heart followed by another heart), and “switch” trials, in which the trial followed a trial of the opposite stimulus type (i.e. a heart followed by a flower). Participants' accuracy and reaction times were recorded and analyzed by trial type.

Results

4.5-to-5.5-year-olds

See Table 21 for a comparison of demographics between participants in the control and experimental groups. T-tests were conducted to look for any significant differences between the two groups. A marginally significant difference was found for the number of hours participants slept the previous night, t(36) = -1.82, p = .09, with participants in the experimental group having slept an average of 37 minutes more the previous night than participants in the control group. Significantly more participants in the control group reported taking daily naps than those in the experimental group, t(36) = 2.78, p = .01. No other significant differences between the two groups were found.

	Control	Experimental
Bed Time	20:15 (0:44m)	20:11 (0:46m)
Wake Time	06:54 (0:32m)	07:05 (0:47m)
Hours Slept Previous Night	10.19 (1.29)	10.81 (0.77)
Percent Taking Daily Naps	55.6	15.0
Age	4yrs, 11.4mos (3.3mos)	4yrs, 10.5mos (3.1mos)

Table 21: Means and standard deviations of demographic variables for participants aged 4.5-to-5.5 years.

Results on each task were analyzed with 2-way 2x2 mixed ANOVAs to look for differences between the two conditions (Control, Experimental) and across the two testing time points (Baseline, Test).

Go/No-Go Task

Accuracy. Accuracy was scored as the correct number of "no-go" trials out of 16, in which participants correctly inhibited pressing the mouse button upon seeing the picture of the monkey (See Table 22).

	Baseline	Test	Difference
Control	12.63 (1.89)	13.05 (2.74)	0.42
Experimental	12.53 (2.48)	12.68 (2.81)	0.15

Table 22: Means and standard deviations for accuracy on correct "no-go" trials out of 16 total trials, for participants aged 4.5 to 5.5 years.

Both the control and experimental groups showed only minor improvements between the baseline and test assessments. The analysis indicated no significant effects of Phase, F(1,36) = .55, p = .46, Group, F(1,36) = .11, p = .74, or Group by Phase interaction, F(1,36) = .11, p = .74.

Reaction Time. Reaction time was calculated in ms for correct "go" trials, in which participants correctly pressed the mouse button in response to a "go" stimulus. A significant main effect of Phase was found, F(1,36) = 7.08, p = .01, with participants in both groups showing decreased reaction times from the baseline to test assessments (See Table 23). No significant effects were found for Group, F(1,36) = .60, p = .45, or Group by Phase interaction were found, F(1,36) = .04, p = .83.

	Baseline	Test	Difference
Control	596.03 (50.83)	570.89 (48.30)	-25.14
Experimental	582.91 (49.30)	561.45 (60.47)	-21.46

Table 23: Means and standard deviations for reaction time (in ms) on correct “go” trials, for participants aged 4.5 to 5.5 years.

Hearts and Flowers Task

In order to be included in the analysis, participants needed to demonstrate understanding of the rules for each trial type, by scoring approximately 70% or higher on the preliminary “hearts only” and “flowers only” blocks. Out of 38 participants who completed the task, 12 failed to meet the threshold for demonstrating comprehension of the individual trial types, and were subsequently removed from analysis for this task. Of those 12 participants, no pattern is evident in group assignment (six control, six experimental) or gender (five male, seven female). Their ages ran the full range of the study, from 4 years, 6 months to 5 years, 5 months, with a mean of 4 years, 11 months. They participated in the study in a variety of times throughout the morning and afternoon. As such, there is no evidence of systematic differences between participants who demonstrated understanding of the hearts and flowers trial types and those who did not.

Therefore, data from 26 participants was used in the final analyses of the Hearts and Flowers Task[1]. Only trials in which the participant answered correctly were included in the analyses. Results were analyzed by overall performance across the 40 trials in the mixed block as well as performance on “switch” trials, in which participants had to rapidly switch between the two types of trials.

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[1] To explore how the removal of those 12 participants affected the data analysis, separate analyses were run including the data from all 38 participants. Conclusions of the analyses remained the same, with or without the data from those 12 participants included.

Accuracy. Overall accuracy was calculated as the percent of correct trials out of the 40 trials given in the mixed block. See Table 24 for means and standard deviations for each group in the baseline and test assessments.

	Baseline	Test	Difference
Control	76.92 (14.33)	83.85 (14.99)	6.93
Experimental	73.65 (13.64)	87.12 (7.83)	13.47

Table 24: Means and standard deviations for percent correct on the hearts and flowers task, for participants aged 4.5 to 5.5 years.

A significant main effect of Phase was found, F(1,24) = 32.07, p < .001, such that participants across both groups showed improvements in accuracy between the baseline and test assessments. No significant main effect of Group was found, F(1,24) = .00, p > .99. A marginally significant Group by Phase interaction was found, F(1,24) = 3.30, p = .08. Although both groups of participants showed improved accuracy between the baseline and test assessments, the experimental group showed a larger improvement (13.47%) than participants in the control group (6.93%) (See Figure 8).

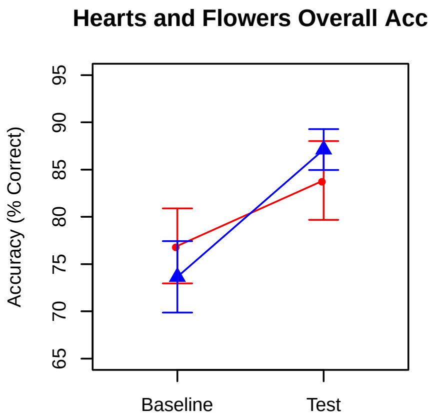

Figure 8: Percent correct on the hearts and flowers task for participants in the control (red) and experimental (blue) groups, for participants aged 4.5 to 5.5 years.

For switch trials, results showed a significant main effect of Phase, F(1,24) = 29.08, $p < .001$, such that participants in both groups showed improvements in accuracy on switch trials between the baseline and test assessments (See Table 25). There was no significant main effect of Group, F(1,24) = .07, p = .80. A significant Group by Phase interaction was found, F(1,24) = 4.65, p = .04.

	Baseline	Test	Difference
Control	76.12 (13.69)	82.65 (15.40)	6.53
Experimental	70.51 (13.83)	85.75 (9.44)	15.24

Table 25: Means and standard deviations for percent correct on switch trials on the hearts and flowers task, for participants aged 4.5 to 5.5 years.

Just like in the overall trials, while both groups of participants showed improved accuracy on switch trials between the baseline and test assessments, participants in the experimental group showed a significantly larger improvement (15.24%) than participants in the control group (6.53%) (See Figure 9). These results indicate that, following exposure to the cooler color temperature lights, participants in the experimental group showed a significantly larger improvement in their ability to switch between trial types than participants in the control group.

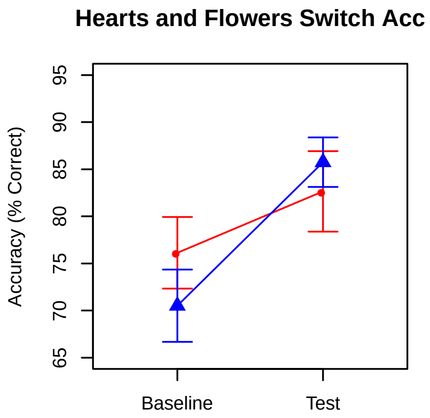

Figure 9: Percent correct on "switch" trials on the hearts and flowers task for participants in the control (red) and experimental (blue) groups, for participants aged 4.5 to 5.5 years.

Reaction Time. Reaction time was calculated as the average reaction time (in ms) for correct trials across the 40 total trials in the mixed block. See Table 26 for means and standard deviations for each group across the two time points.

	Baseline	Test	Difference
Control	1397.18 (202.74)	1272.58 (254.33)	-124.60
Experimental	1336.80 (263.10)	1210.11 (163.02)	-126.69

Table 26: Means and standard deviations for reaction time (in ms) across all correct trials on the hearts and flowers task, for participants aged 4.5 to 5.5 years.

A significant main effect of Phase was found, F(1,24) = 10.47, p = .004, such that participants in both the control and experimental groups showed decreased reaction times between the baseline and test assessments. There was no significant main effect of Group, F(1,24) = .60, p = .45, or Group by Phase interaction, F(1,24) = .001, p = .98.

The results for switch trials mirror those for the overall block of trials, with a significant main effect of Phase, F(1,24) = 12.45, p = .002, but no significant effects of

Group, F(1,24) = .24, p = .63, or Group by Phase interaction, F(1,24) = .06, p = .81 (See Table 27).

	Baseline	Test	Difference
Control	1478.74 (236.65)	1336.52 (250.83)	-142.22
Experimental	1446.92 (310.75)	1283.49 (169.74)	-163.43

Table 27: Means and standard deviations for reaction time (in ms) across switch trials on the hearts and flowers task, for participants aged 4.5 to 5.5 years.

7-year-olds

See Table 28 for a comparison of demographics between participants in the control and experimental groups. Unlike the younger participants, none of the 7-year-old participants reported taking daily naps and so no information on naps was included in the demographics table. Sleep habits between the two groups differed very little. T-tests revealed no significant differences between the two groups.

	Control	Experimental
Bed Time	20:21 (0:41m)	20:24 (0:27m)
Wake Time	07:04 (0:41m)	06:59 (0:28m)
Hours Slept Previous Night	10.42 (0.69)	10.40 (0.80)
Age	7yrs, 5.7mos (4.5mos)	7yrs, 7.5mos (2.9mos)

Table 28: Means and standard deviations of demographic variables for 7-year-old participants.

Go/No-Go Task

Accuracy. Similarly to the younger participants, neither group showed a large improvement between baseline and test assessments (See Table 29). Results of the ANOVA indicated no significant effects of Phase, F(1,22) = .21, p = .65, Group, F(1,22) = 1.29, p = .27, or Group by Phase interaction, F(1,22) = .21, p = .65.

	Baseline	Test	Difference
Control	12.08 (2.75)	12.08 (1.98)	0
Experimental	12.75 (1.96)	13.17 (1.99)	0.42

Table 29: Means and standard deviations for accuracy on correct “no-go” trials out of 16 total trials, for 7-year-old participants.

Reaction Time. See Table 30for means and standard deviations for reaction time on the go/no-go task. As with accuracy, very little improvement was seen for either group between the baseline and test assessments. No significant differences were found (F < 1).

	Baseline	Test	Difference
Control	518.86 (44.67)	512.79 (40.19)	-6.07
Experimental	515.46 (41.95)	506.66 (41.89)	-8.80

Table 30: Means and standard deviations for reaction time (in ms) on correct “go” trials, for 7-year-old participants.

Hearts and Flowers Task

Accuracy. All participants reached the established minimum threshold and demonstrated clear understanding of the task, and were thus included in the analyses.

Participants in both groups exhibited very similar levels in improvement in percent correct across the overall block of trials (See Table 31).

	Baseline	Test	Difference
Control	82.08 (10.97)	87.50 (12.39)	5.42
Experimental	80.00 (11.73)	85.63 (13.06)	5.63

Table 31: Means and standard deviations for percent correct on the hearts and flowers task, for 7-year-old participants.

Results showed a significant main effect of Phase, F(1,22) = 6.41, p = .02, but no effects of Group, F(1,22) = .20, p = .66 or Group by Phase interaction, F(1,22) = .002, p = .96. These findings indicate that both groups improved significantly from the baseline to test assessments, but there were no differences between the groups in how the lighting condition impacted their change in performance.

Mirroring the results for the overall trials, when looking at switch trials, a significant main effect of Phase was found, F(1,22) = 8.11, p = .01, but no significant effects of Group, F(1,22) = .20, p = .66, or Group by Phase interaction, F(1,22) = .20, p = .66. Again, participants in both groups significantly improved on their ability to switch between the rules of each trial type, but no differences were seen between the groups on their change in performance (See Table 32).

	Baseline	Test	Difference
Control	78.17 (12.85)	86.46 (12.88)	8.29
Experimental	77.18 (13.96)	83.23 (13.07)	6.05

Table 32: Means and standard deviations for percent correct on switch trials on the hearts and flowers task, for 7-year-old participants.

Reaction Time. For overall reaction time, participants in the control group started off slower than participants in the experimental group at baseline (See Table 33). However, this difference between the two groups was not significant, t(22) = 1.67, p = .11.

	Baseline	Test	Difference
Control	1010.14 (162.61)	863.79 (176.52)	-146.35
Experimental	896.57 (180.02)	795.68 (170.06)	-100.89

Table 33: Means and standard deviations for reaction time (in ms) across all correct trials on the hearts and flowers task, for 7-year-old participants.

Results of the ANOVA showed a significant main effect of Phase, F(1,22) = 33.44, p < .001, with both groups of participants showing significantly decreased reaction times between the baseline and test assessments. No effects were found for Group, F(1,22) = 1.89, p = .18, or Group by Phase interaction, F(1,22) = 1.13, p = .30.

For reaction time on switch trials, a significant main effect of Phase was found, F(1,22,) = 72.35, p < .001, with participants in both the control and experimental groups showing significantly decreased reaction times when switching between trial types between the baseline and test assessments (See Table 34). No effects were found for Group, F(1,22) = 1.84, p = .19 or Group by Phase interaction, F(1,22) = 2.76, p = .11.

	Baseline	Test	Difference
Control	1089.53 (182.11)	889.85 (175.30)	-199.68
Experimental	958.46 (201.16)	824.01 (176.41)	-134.45

Table 34: Means and standard deviations for reaction time (in ms) across switch trials on the hearts and flowers task, for 7-year-old participants.

Gender

Gender was not included as a factor in the ANOVAs because of the large imbalance between male and female participants in the 7-year-old group. However, mixed effects models were run to see whether gender played a role in how the lighting condition impacted participants' task performance over time. Results of the mixed effects models can be seen in Appendix A. Results indicated no significant gender differences in the lighting condition's effect on task performance.

Experiment 2 Discussion

While the lighting condition did not impact the 4.5-to-5.5-year-old participants' change in performance on the go/no-go task, on the hearts and flowers task, participants in the experimental group showed a significantly larger improvement in their ability to switch between tasks than participants in the control group. Following exposure to the cooler color temperature lighting condition, participants in the experimental group showed an average increase in their ability to switch between tasks an average of 15.24%, compared with participants in the control group who improved on average by 6.53%.

For the 7-year-old participants, no group differences were seen for improvement on either task. On the hearts and flowers task, main effects of Phase were found for accuracy and reaction time, indicating that the 7-year-old participants in both groups showed significant improvement from the baseline to test assessments. However, there were no significant interactions between Group and Phase, suggesting that the lighting condition did not impact the 7-year-old participants' task performance over time.

CHAPTER IV

GENERAL DISCUSSION

Experiments 1 and 1A

In Experiment 1, undergraduate adult participants were tested to see whether exposure to small, slow fluctuations in light color temperature around a fixed central point (3700-4300K) would lead to greater improvements over time on measures of sustained attention and task switching compared with control subjects (4000K). While no group differences were seen on the task switching task, participants in the experimental group showed significantly greater reaction time improvement on a go/no-go task, measuring sustained attention, following exposure to the dynamic lighting. In order to explore whether these effects were driven by the exposure to a slight increase in color temperature, as higher color temperatures have been previously shown to lead to cognitive benefits, Experiment 1A exposed participants to light at the upper color temperature extreme of the dynamic settings (4300K). However, participants in Experiment 1A did not show the same benefits to the lighting condition as participants in the dynamic lighting condition of Experiment 1, suggesting that it was not the increase in blue light exposure alone that lead to these effects. It is important to note that, of all the participants in both the dynamic and static groups, in which a change in lighting setting occurred, none reported noticing any changes in the lights, nor guessed the study hypothesis. This allows us to conclude that participants' performance was not influenced by preconceived expectations of how the light settings would affect them.

The general consensus of research to date is that exposure to white light set to a higher color temperature, emitting more light in the blue portion of the visible spectrum, leads to increased alertness and better performance on a variety of cognitive tasks. This is believed to be accomplished after stimulation of the ipRGCs, maximally sensitive to light emitted at about 480nm, which impacts the circadian rhythm through melatonin suppression. However, the results of Experiments 1 and 1A suggest that there may be additional mechanisms underlying how light influences attention.

Recent work from one group suggests that exposure to red light can also lead to increases in alertness, further calling in to question whether the circadian system is the only mechanism underlying these effects. In a series of studies, participants were exposed to light boxes of short-wavelength blue (470nm) or long-wavelength red (630nm) light following exposure to extremely dim light. Results showed exposure to both light sources lead to reduced alpha power measured on EEG, suggesting increases in alertness (Figueiro, Bierman, Plitnick, & Rea, 2009; Sahin & Figueiro, 2013).

As participants in the studies by Figueiro, et al. (2009) and Sahin & Figueiro (2013) were exposed to light from a single color LED, in a narrow wavelength band, following exposure to an almost dark condition, the implications of their results are unclear for more real world scenarios in which someone might be exposed to warmer or cooler color temperature ambient white lighting. However, if the results of these two studies were to hold up in support of the benefits of exposure to white light at a warmer, color temperature emitting more red light, it would support the current findings of Experiments 1 and 1A that mild fluctuations in color temperature, both warmer and cooler, can lead to cognitive benefits in attention beyond those seen from exposure to slightly more blue light alone. Participants in Experiments 1 and 1A were also tested in the morning, when melatonin levels should already be low (Nussey & Whitehead, 2001), further suggesting that melatonin suppression is not the only mechanism underlying the relationship between light and alertness.

If melatonin suppression is not the only mechanism by which light impacts attention, what other mechanisms might underlie these effects? While ipRGCs were initially thought to be a collection of identical cells, recent evidence suggests that they consist of several subtypes differing in physiology (Schmidt, Chen, & Hattar, 2011), suggesting stimulation of these cells by light might project to other brain regions and impact processes other than melatonin suppression. It is difficult to draw firm conclusions from the measures of the present studies, which includes only the two lighting conditions and no measures of physiological response. However, the findings of Experiments 1 and 1A do suggest that one possible mechanism for light's impact on attention could be a response to changes in the lighting environment. With a constantly fluctuating color temperature, there is less opportunity for adaptation of the photoreceptors, possibly leading to greater stimulation of attention and alertness related brain regions.

In order to better understand how dynamic changes in light color temperature impact cognitive processes, future studies should explore the conditions and tasks in which these effects occur. Testing participants at various times of day, at different points in the daily melatonin cycle, would offer insight into whether melatonin suppression mediates the cognitive effects of dynamic lighting. Manipulating the spectrum of the lights to have greater or lesser impact across the different photoreceptors would serve to investigate how the rods, cones, and ipRGCs contribute to the observed results. Furthermore, testing participants across a variety of psychological tasks would build an understanding of what specific abilities are impacted by dynamic changes in lighting, suggesting pathways by which the lighting condition impacts behavior.

Subjective mood ratings, as measured by scores on the POMs questionnaire, showed no impacts of the lighting condition in Experiment 1. In the follow up condition in Experiment 1A, differences were found for only one subscale, with participants in the static condition reporting a large decrease in vigor over time, compared with controls. Overall, no consistent effect of lighting condition on subjective mood rating was found. If small changes in mood occurred, a lack of power or insensitivity of the measure could account for the failure to find such changes. Furthermore, perhaps if participants were aware of the changes in lighting, their conscious opinions of the conditions might have had a greater influence on their moods. However, the lack of differences in participants' mood ratings suggests that the reaction time differences measured on the Go/No-Go task between participants in the control and dynamic groups cannot be explained by large changes in participants' moods as a result of the lighting condition.

Experiment 2

In Experiment 2, preschool aged and 7-year-old children were tested to see whether previous findings in adults, that exposure to cooler color temperature light improves performance on cognitive tasks, extended to young children. Participants were tested to see whether 20 minutes of exposure to cooler color temperature light (5000K) would lead to greater improvements over time on measures of sustained attention and task switching compared with control subjects only exposed to the warmer color temperature baseline lights (3500K). Seven-year-olds showed no group differences on either task, indicating no benefits from exposure to the cooler color temperature light.

However, while 4.5 to 5.5 year olds showed no group differences on the go/no-go task, they did demonstrate significantly greater improvement in their ability to switch between tasks following exposure to the experimental lighting condition. These findings replicate previous findings with adult participants, that exposure to cooler color temperature light improves task switching performance (Ferlazzo, et al., 2014; Hartstein, et al., under review).

The results of Experiment 2 are the first to our knowledge to show that the relationship between light color temperature and cognition is present in children as young as 4-and-a-half. Children at this age are just developing their executive function abilities, with cognitive flexibility, or switching between rules, having a particularly long progression over development. One study testing children aged 4 to 13 on a rule switching task found that even 13-year-olds didn't perform at adult levels (Davidson, et al., 2006). The Hearts and Flowers task is challenging, as it requires participants to remember the rules of each trial type and rapidly switch between them. But the results of Experiment 2 suggest that cognitive flexibility, in preschool-aged children, can be enhanced following exposure to light set to a cooler color temperature. These results can inform parents and teachers about creating an optimal learning environment for young children in homes and schools, using light at a higher color temperature to enhance children's executive functioning abilities from a young age.

The results of Experiment 2 demonstrate that the color temperature of light can have an impact on cognitive abilities, specifically cognitive flexibility, from a young age. However, even at 4-and-a-half, children have experienced hundreds of days worth of day/night cycles, allowing time for experience to shape the connections with the ipRGCs.

To truly understand whether these non-visual effects of light are present from birth or how they develop over time with experience, future studies should look at how light color temperature affects arousal and attention in infants, through either looking time tasks or physiological measures such as heart rate.

While preschool aged participants demonstrated greater improvements in task switching after exposure to light set to a cooler color temperature, 7-year-olds showed no such benefits from the lighting condition. It is unclear from the present results whether 7-year-olds really derive no benefit to sustained attention and task switching abilities from exposure to cooler color temperature light or if limitations in the present study failed to elicit those effects. Previous work by Huiberts, Smolders, & de Kort (2015) suggests that light's impact on cognition may depend on the difficulty level of the task being measured. The tasks in Experiment 2 were originally chosen to be appropriate for the younger participants and were then extended to the 7-year-old participants. Although the response window for the Hearts and Flowers task was reduced for the 7-year-olds, requiring faster reactions, it may not have been challenging enough for the older participants to elicit enough variability to show an effect of the lighting condition. Furthermore, the sample size of 24 may be insufficient to detect a small effect. More participants need to be added to the sample to ascertain whether the lighting condition truly failed to impact 7-year-olds' performance on these particular tasks.

Gender

Unlike previous work by Hartstein, et al. (under review), the present studies did not find clear gender differences in how lighting condition impacted participants' cognition. In Experiments 1 and 1A, lighting condition was found to impact accuracy on the go/no-go task differently for male and female participants, with male participants in the control group improving significantly more than those in the dynamic or static groups, and female participants showing no effect of the lighting condition. In Experiment 1A, female participants in the static group showed a significantly larger improvement in overall accuracy on the task-switching task than did females in the control group, whereas male participants showed no effects of the lighting condition. These inconsistent findings do not help to clarify the specific nature of the previously seen gender differences or suggest what might be underlying them.

In Experiment 2, no gender differences were seen in how the lighting condition impacted children's task performance over time. These results support findings from a study by Sleegers, et al. (2012), which reported no gender differences in how light color temperature affected concentration in elementary school students. Taken together, the results of these two studies indicate that the mechanisms leading to gender differences in how light impacts cognition, seen in adults throughout several studies, is not yet present in preschool or elementary school aged children. This suggests that the gender differences seen in adults may be due to hormonal differences occurring after the onset of puberty or differences in preference for different lighting condition that develop overtime.

Applications

Thanks to computers, cell phones, and e-readers, people are getting more blue light exposure than ever before. Studies have shown nighttime use of electronic devices is prevalent and related to instances of insomnia and unrefreshing sleep (Fossum, Nordnes, Storemark, Bjorvatn, & Pallesen, 2014; Gradisar, et al., 2013). Technology manufacturers are beginning to pay attention to the findings on the strong relationship between ipRGC activation by cooler light color temperatures and circadian rhythm, mood, and cognition. Applications and products are being created to help consumers take advantage of the cognitive benefits of blue light exposure while minimizing the risks associated with exposure at night.

F.lux, on the market since 2009, adjusts the color temperature of a user's computer screen, cycling the color temperature between warmer and cooler based on the wake up time set by the user. Apple's similar application, Night Shift, is included in the operating system of all new phones and has just been announced to be included in upcoming Mac computers. Philips is selling Philips Hue, a personal home lighting kit that lets users control lights remotely and set color temperature to their mood and activity, with settings like "Relax, Concentrate, Energize, Reading" (Philips, n.d. -b). Given the market's interest in applying research findings on the non-visual effects of light to consumer products, it is important to continue exploring how variable color temperatures affect mood, sleep, and cognition in order to understand the benefits and risks of such technologies and keep consumers informed on the science behind the products being advertised to them.

In addition to personal use, dynamic lighting fixtures are being marketed towards schools to influence student behavior in the classroom. For several years, Philips has been marketing a dynamic lighting system for classrooms called SchoolVision (Philips, n.d. -a). SchoolVision allows teachers to select the lighting environment from four pre-programmed options of varying brightness and light color temperature: Normal, Focus, Energy, and Calm. Most relevant to the present research is the Focus setting, advertised by Philips as “highest light intensity and a cool color tone, supports concentration for tests”, and the Energy setting, a “high intensity level, very cool color tone, makes children alert during mornings and after lunch” (Philips, n.d. -a). Experiment 2 in the present study supports these claims by Philips that, in the case of preschool-aged children, exposure to light set to a cooler color temperature leads to improvements in cognition, specifically the ability to switch between tasks. Further studies should be conducted looking at the effects of light color temperature on cognition for these young children, to better substantiate claims by Philips and similar companies that these lighting systems can promote learning in schools without negative consequences to health or sleep. The results of Experiment 1 join several other studies in demonstrating positive effects of lighting condition on attention in undergraduate students (Ferlazzo, et a., 2014; Hartstein, et al., under review; Huang, et al., 2014; Rautkylä, et al., 2010), demonstrating the applicability of this research to students across a wide range of ages.

Studies implementing some form of SchoolVision in the classroom reported a decrease in fidgetiness and observed aggressive behaviors and increase in oral reading fluency and concentration in elementary school students (Barkmann, et al., 2012; Mott, et al., 2012; Wessolowski, Koenig, Schulte-Markword, & Barkmann, 2014). While products like Philips Hue and SchoolVision allow for variation in color temperature depending on the cognitive demands of the situation, further work should be done to expand on the preliminary findings from Experiment 1 showing that small fluctuations in color temperature can produce cognitive benefits and how that might be applied to classrooms and workspaces.

Light therapy, as a simulation of daylight, has long been used as an effective treatment for Seasonal Affective Disorder (Terman, et al., 1989). However, more recent attention has turned to whether light therapy is useful to treat other clinical populations. Given light's connection with alertness and attention, it might be used to help those who struggle to concentrate. For adult participants with ADHD, one study found that three weeks of morning bright light exposure lead to a significant decrease in both subjective and objective measures of ADHD symptoms (Rybak, McNeely, Mackenzie, Jain, & Levitan, 2006). Further work is needed to confirm light therapy as an effective treatment for ADHD and extend these findings to children with the disorder. In addition to morning bright light therapy, would individuals with ADHD receive short-term benefits to attention from brief exposure to cooler color temperature light? Could this therapy be applied to children with ADHD to help them concentrate in school? While research suggests that light spectral composition can increase performance on measures of cognitive abilities, specifically attention and cognitive flexibility, supported by the findings of Experiments 1 and 2, each new answer seems to raise even more questions about this relationship between light and cognition and the ways in which it can be applied.

Health Concerns

With the high volume of artificial light humans are exposed to each day, there is concern whether these long-term exposures pose any risks to the structures of the eye. In rodent studies, photoreceptor damage was found after exposure to light resembling natural sunlight (415-455nm) (Arnault, et al., 2013) and blue light at 464nm (Kuse, Ogawa, Tsuruma, Shimazawa, & Hara, 2014). However, no significant photoreceptor damage was found following exposure to blue light at 474 nm (Ferguson, Melton, Li, Park, & Tosini, 2008; Tosini, Ferguson, & Tsubota, 2016). Work in this field also suggests a circadian rhythm to the dangers of retinal damage such that, in rats, the risk of retinal damage is greater following nighttime light exposure as opposed to during the day (Organisciak, Darrow, Barsalou, Kutty, & Wiggert, 2000; Vaughan, Nemke, Fliesler, Darrow, & Organisciak, 2002). Studies on the development of age-related macular degeneration (AMD) in humans have mixed results, with some indicating long-term exposure to blue light may contribute to the development of AMD (Algvere, Marshall, & Seregard, 2006; Taylor, West, & Muñoz, 1992), while others find no association (Darzins, Mitchell, & Heller, 1997).

From a recent review of the current literature, Tosini, et al. (2016) conclude that short term exposure to blue light from LEDs with peak emission of 470-480nm should not contribute to increased risk for ocular pathologies, but further studies need to be conducted to determine any risks associated with long-term exposure. Given the increase in exposure to blue light emitting devices, like computers and cell phones, and especially the prevalence of late night use of these devices, future research should carefully explore what risks, if any, this exposure might pose to eye physiology. These concerns highlight the importance of the results of Experiment 1, showing that cognitive benefits from artificial light exposure can be obtained without the need for high intensity blue light, but rather light cycling through a range of color temperatures. Using dynamic lighting systems, cognitive benefits could be achieved with limited exposure to potentially damaging blue light. Future work should expand on these findings to find the optimal color temperature settings to give the largest cognitive boost, while ensuring safe levels of exposure to avoid any potential retinal damage.

Limitations

Our full understanding of the effects in the two experiments presented here is limited by elements of the methodology. Participants were only tested once after exposure to the experimental lighting condition, following 20 minutes of adaptation. As a result, no claims can be made as to the duration of the effects, and whether they would still be present after the participant left the testing room and entered a new lighting environment. There are also unaccounted for external factors that could lead to individual differences in response to the lighting condition. An individual's prior light history can impact melatonin suppression and the alerting effects of light (Chang, Scheer, Czeisler, & Aeschbach, 2013; Hébert, Martin, Lee, & Eastman, 2002). While Experiments 1 and 2 collected data on participants' recent sleep habits and the level of sunlight at time of testing, no detailed information on light history was collected. As such, individual differences in light history and how that may have impacted performance cannot be gleaned from the present data.

In addition to the specific light settings that lead to the greatest activation of the ipRGCs, results across a variety of studies suggest there is still much to parcel out in order to fully understand the mechanisms of these non-visual effects and how to optimize parameters for commercial use. Previous work suggests the effects largely depend on factors such as type of task and level of task difficulty (Chellappa, et al., 2011; Huiberts, Smolders, & de Kort, 2015), as well as time of day and season (Rautkylä, Puolakka, Tetri, & Halonen, 2010). Experiments 1 and 1A aimed to control some of these factors by testing participants only in the winter months during a 2-hour morning block. However, future work is needed to systematically examine the best settings to maximize cognitive benefits throughout the day and year, as well as determine the types of tasks most susceptible to improvement following light exposure.

Conclusions

In sum, the research presented in this dissertation adds to a growing body of work demonstrating the profound ways light can impact non-visual domains, such as cognition. In Experiment 1, exposure to a light source slowly fluctuating around a central color temperature lead to significantly faster reaction time on a measure of sustained attention, calling into question the specific route by which light impacts cognition and suggesting possible alternatives to increased blue light exposure. The results of Experiment 2 provide the first evidence that the relationship between light and cognition is evident in children as young as 4.5-years-old, with exposure to light at a cooler color temperature leading to greater improvements in cognitive flexibility. These findings can help inform parents and teachers about the possibility of using light as a tool to aid in young children's learning.

While there is still much work to be done in this field, in terms of identifying the optimal settings for improved performance and how to minimize any possible risks, the emerging consensus of the relationship between light color temperature and skills like attention and cognitive flexibility opens up a wide array of possibilities. From improving productivity in workspaces and classrooms, to helping those with clinical disorders like ADHD, there are many ways in which our knowledge of how light impacts cognition could be applied to make everyday lives a little brighter.

APPENDIX

RESULTS OF MIXED EFFECTS MODELS FOR EXPERIMENT 2

Variables	F value	*p*-value
Group	.18	.67
Gender	4.72	.04
Phase	.31	.58
Group x Gender	3.14	.09
Group x Phase	.03	.87
Gender x Phase	1.84	.18
Group x Gender x Phase	.94	.34

Table 35: Results of the mixed effects models for accuracy on the Go/No-Go task for participants aged 4.5-to-5.5.

Variables	F value	*p*-value
Group	.51	.48
Gender	4.91	.03
Phase	6.77	.01
Group x Gender	.08	.78
Group x Phase	.02	.89
Gender x Phase	.17	.68
Group x Gender x Phase	.71	.41

Table 36: Results of the mixed effects models for reaction time on the Go/No-Go task for participants aged 4.5-to-5.5.

Variables	F value	*p*-value
Group	.03	.86
Gender	.07	.79
Phase	27.98	< .001
Group x Gender	3.05	.09
Group x Phase	3.20	.09
Gender x Phase	.07	.79
Group x Gender x Phase	.11	.74

Table 37: Results of the mixed effects models for overall accuracy on the Hearts and Flowers task for participants aged 4.5-to-5.5.

Variables	F value	*p*-value
Group	.20	.66
Gender	.08	.78
Phase	26.14	< .001
Group x Gender	3.02	.10
Group x Phase	5.39	.03
Gender x Phase	1.47	.24
Group x Gender x Phase	.15	.70

Table 38: Results of the mixed effects models for accuracy on switch trials on the Hearts and Flowers task for participants aged 4.5-to-5.5.

Variables	F value	*p*-value
Group	.38	.55
Gender	.79	.38
Phase	9.90	.005
Group x Gender	.002	.97
Group x Phase	.01	.91
Gender x Phase	.78	.39
Group x Gender x Phase	.32	.58

Table 39: Results of the mixed effects models for overall reaction time on the Hearts and Flowers task for participants aged 4.5-to-5.5.

Variables	F value	*p*-value
Group	.09	.77
Gender	1.41	.25
Phase	11.45	.003
Group x Gender	.00	.996
Group x Phase	.13	.72
Gender x Phase	.91	.35
Group x Gender x Phase	.11	.74

Table 40: Results of the mixed effects models for reaction time on switch trials on the Hearts and Flowers task for participants aged 4.5-to-5.5.

Variables	F value	*p*-value
Group	1.74	.20
Gender	4.43	.03
Phase	.10	.76
Group x Gender	.06	.81
Group x Phase	.10	.76
Gender x Phase	.10	.76
Group x Gender x Phase	.10	.76

Table 41: Results of the mixed effects models for accuracy on the Go/No-Go task for 7-year-old participants.

Variables	F value	*p*-value
Group	.01	.94
Gender	1.31	.27
Phase	1.61	.22
Group x Gender	1.34	.26
Group x Phase	.03	.86
Gender x Phase	2.79	.11
Group x Gender x Phase	.27	.61

Table 42: Results of the mixed effects models for reaction time on the Go/No-Go task for 7-year-old participants.

Variables	F value	*p*-value
Group	.11	.74
Gender	.72	.41
Phase	5.48	.03
Group x Gender	.002	.96
Group x Phase	.02	.89
Gender x Phase	.03	.86
Group x Gender x Phase	.60	.45

Table 43: Results of the mixed effects models for overall accuracy on the Hearts and Flowers task for 7-year-old participants.

Variables	F value	*p*-value
Group	.17	.68
Gender	.62	.44
Phase	7.46	.01
Group x Gender	.08	.79
Group x Phase	.33	.57
Gender x Phase	.24	.63
Group x Gender x Phase	.60	.45

Table 44: Results of the mixed effects models for accuracy on switch trials on the Hearts and Flowers task for 7-year-old participants.

Variables	F value	*p*-value
Group	1.45	.24
Gender	2.19	.15
Phase	27.28	< .001
Group x Gender	.00	.996
Group x Phase	1.02	.32
Gender x Phase	.67	.42
Group x Gender x Phase	.05	.83

Table 45: Results of the mixed effects models for overall reaction time on the Hearts and Flowers task for 7-year-old participants.

Variables	F value	*p*-value
Group	1.31	.27
Gender	2.58	.12
Phase	61.99	< .001
Group x Gender	.04	.85
Group x Phase	2.14	.16
Gender x Phase	.52	.48
Group x Gender x Phase	.40	.54

Table 46: Results of the mixed effects models for reaction time on switch trials on the Hearts and Flowers task for 7-year-old participants.

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