The Effects of Light, Colour, and Print-Size on Reading Speed in the Visually Impaired

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ABSTRACT

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Reading is an essential component of daily life and it can be one of the most difficult tasks faced by individuals with low vision. A variety of factors, e.g., magnification, print-size, lighting, and colour, have been shown to improve reading speeds in the visually impaired, but there is no gold standard measure that can be used to assess optimal colour and illumination to facilitate reading. Increased print-size and luminance have consistently been shown to improve reading speed, and improved lighting has also been shown to improve the overall quality of life of the visually impaired. Conversely, colour manipulation, e.g., different coloured lighting, lens filters, plastic overlays, are controversial in their utility as there is contradictory evidence for their efficacy at improving reading speed. Additionally, there is a lack of research in the field examining at how both lighting and colour can be manipulated simultaneously, at various print-sizes, to examine their impact on reading speed in both the visually and non-visually impaired. Consequently, improved luminance and increased print-size are standard practices in low vision rehabilitation (LVR), however, the use of colour in LVR is likely to be more nuanced, individualistic, and/or not adequately assessed. Unfortunately, in the field of LVR there is no accepted and validated gold standard measure that can be used to determine optimal colour and illumination to facilitate reading at various print-sizes. Therefore, the purpose of this dissertation is to examine the effects of colour, illumination, and print-size on reading, and to compare/contrast the efficacy of novel assistive technology devices that may be used in the context of LVR to determine optimal colour and illumination to facilitate reading.

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This dissertation is composed of three separate research papers. The papers used original data collected throughout 2019-2020. In collaboration with Dr. Aaron Johnson, I conducted all statistical analyses and prepared manuscripts for submission. Dr. Caitlin Murphy collaborated on the preparation of the manuscript for Study 1, and Dr. Walter Wittich and Dr. Caitlin Murphy collaborated on the preparation of the manuscripts for Study 2 and Study 3. Funding for this research study was obtained by the Vision Health Research Network and FRQSC research grants awarded to Dr. Aaron Johnson and Dr. Walter Wittich.

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CHAPTER 1:
GENERAL INTRODUCTION

Age-related decline in vision can have profound effects on the physiological/ psychological wellbeing of older adults, with both complex tasks, e.g., independent living, and simple tasks, e.g., reading, becoming a challenge (Ctori et al., 2020; Geetanshu et al., 2019; Lange et al., 2021; Nayeni et al., 2020). Age-related visual decline can occur both naturally, the loss of elasticity of the lens, and/or pathologically, a leaky blood vessel that destroys a portion of the retina and distorts vision (Chader & Taylor, 2013; Stuen & Faye, 2003). These age-related/pathological changes in visual functioning often lead older adults to have poorer visual acuity and contrast sensitivity (Akutsu et al., 1991; Crassini et al., 1988; Long & Crambert, 1990). Severe enough impairments lead to a diagnosis of low vision, a visual acuity between 20/40 and 20/200 in the better eye, or legal blindness, classified as a visual acuity of 20/200 or worse in the better eye (Fontenot et al., 2018). Often these conditions can be effectively managed through low vision rehabilitation, with the most frequent reason for referral being difficulty reading (Brown et al., 2014; Owsley et al., 2009).

Low vision can compromise tasks of daily living that require reading, e.g., reading mail, bills, medication instructions, food labels, recipes, street signs, which in turn can reduce quality of life (Burmedi et al., 2002b, 2002a). Indeed, individuals seeking low vision rehabilitation often report lower quality of life, social wellbeing, and higher levels of depression/anxiety compared to age-matched controls of individuals without vision loss (Geetanshu et al., 2019; Lange et al., 2021; Miraftabi et al., 2020; Nayeni et al., 2020). Post-rehabilitation, those with low vision have been shown to see significant improvements in reading ability, social functioning, and overall quality of life (Ctori et al., 2020; Kavitha et al., 2020; Pyatova et al., 2020). Therefore, low vision rehabilitation is essential as it can substantially mitigate the psychological sequelae of visual impairments and reduce overall healthcare costs by effectively tracking and managing patient conditions. The purpose of this dissertation is to examine factors that influence reading, i.e., colour, illumination, and print-size, and to compare/contrast the efficacy of novel assistive technology devices used to determine optimal colour and illumination to facilitate reading.

Low vision rehabilitation consists of a variety of interventions, ranging from simple, such as psychoeducation, to complex, such as visual skills training and occupational therapy (Berger et al., 2013; Kaldenberg & Smallfield, 2020; Liu et al., 2013; Markowitz, 2006; Morrice et al., 2017; Smallfield & Kaldenberg, 2020; Steinkuller et al., 1999; Wittich et al., 2018; Zimmerman et al., 2010). Psychoeducation serves to validate a patient's experience and aims to reduce psychological distress, whereas complex interventions provide practical skills and tools to help those with low vision navigate their environment and lead meaningful lives. Skills can include eccentric viewing training, systematic scanning strategies, environment specific navigation training, and training on how to use assistive technology devices at home and at work. There are a variety of assistive technology devices, e.g., a white cane for navigation versus a handheld magnifier for spot reading, with which individuals in low vision rehabilitation can be trained and each device may be individualized to meet patient needs.

Assistive technology devices typically fall into two categories: low-tech and high-tech (Corn & Erin, 2010; Robinson, 2010; Zimmerman et al., 2010). Low-tech consist of generally inexpensive devices that are easy to use and may not require extensive training, e.g., handheld magnifiers, high illumination lamps, high contrast dishes. High-tech devices are generally more expensive, can still be easy to use but may require more training, e.g., electronic magnifiers, tablet computers, and retinal implants (Crossland et al., 2014; Gill et al., 2013; Latham, 2018; Morrice et al., 2017; Wittich et al., 2018). Both low and high-tech devices that aim to improve reading speed/ability generally do so by modifying text size through magnification, and/or optimizing lighting conditions to facilitate reading. There is a substantial body of evidence showing that increased text size improves reading speed in individuals with low vision, in those with and without central field loss (Bailey et al., 2003; Cheong et al., 2002; Lueck et al., 2003; Mansfield et al., 1996). While there is also considerable research showing that increased illumination improves reading speed in those with low vision, the effect of illumination colour is more nuanced (Bowers et al., 2001; Brunnström et al., 2004; Bullimore & Bailey, 1995; Eperjesi et al., 2004a, 2004b; Fosse & Valberg, 2004; Haymes & Lee, 2006; Ram & Bhardwaj, 2017; Veszeli & Shepherd, 2019; Wilkinson & Shahid, 2018; Wolffsohn et al., 2012).

Optimal lighting conditions to facilitate reading can be broken down into components of illumination (brightness) and colour (temperature/hue). Research has shown that there are generally concomitant increases in reading speed as brightness increases in individuals with low vision (Bowers et al., 2001). A possible mechanism of change may be the perceived change in contrast between the text and the page as brightness increases; conversely, as brightness/contrast increases, patients often report increased glare which can impede reading in addition to being uncomfortable or even painful for the reader (Hatton, 1977; Ludt, 1997). Lighting colour (temperature/hue) in this case may also be effective at improving reading speeds because different coloured lighting can modify perceived brightness/contrast without changing the brightness (Anstis, 2002; Barlow, 1957; Barlow et al., 1957). Importantly, while there is strong evidence for the effect of illumination on reading in individuals with low vision, there is contradictory evidence in the literature supporting the use of colour. There is also a gap in the literature as few studies have simultaneously investigated how both optimal colour and illumination can be varied to improve reading speed in the visually impaired.

There is clear physiological evidence as to why modifying the brightness and hue of a light source may improve reading speed in individuals with low vision; for example, light will have difficulty reaching the photosensitive layer of the eye (the retina) in those with age-related vision loss as the lens becomes occluded, loses elasticity, and the pupil narrows (Artal et al., 2003; Glasser & Campbell, 1998; Loewenfeld, 1979; Owsley, 2016; Paterson et al., 2020; Pokorny et al., 1987; Said & Weale, 1959). Therefore, increasing brightness also increases the likelihood that light will reach the retina and visual information can be processed accurately. For individuals with early-to-intermediate AMD (characterized by central field loss and the destruction of the photoreceptors in the fovea. i.e., cones), high luminance is beneficial for improving reading speed, conversely for those with severe AMD increased brightness may be less effective (Pondorfer et al., 2019; Thompson et al., 2018). This is due to the majority of photoreceptors in the periphery of the retina (the rods) being more sensitive to light then the cones, leading them to become overwhelmed with increased brightness and leaving the patient experiencing discomfort and glare (Hatton, 1977; Ludt, 1997; Stringham & Hammond, 2007). The reason the colour (temperature/hue) of a light source may be beneficial in low vision is due to a phenomenon known as the *Purkinje Shift*; at lower levels of illumination the blue end of the light spectrum is perceived as brighter than the red end of the spectrum, with rods mediating vision at low light levels (Anstis, 2002; Barlow, 1957; Barlow et al., 1957).

Simple interventions, such as optimizing light sources for individuals with low vision can have psychologically profound downstream effects; improved lighting conditions not only improves reading speed/ability but also knowledge acquisition, knowledge translation, and it can improve psychological wellbeing and quality of life (Amiri et al., 2020; Brunnström et al., 2004; Geetanshu et al., 2019; Kavitha et al., 2020; Lange et al., 2021; Miraftabi et al., 2020; Nayeni et al., 2020; Pyatova et al., 2020; Smallfield & Kaldenberg, 2020). Improved lighting conditions can support independent living, improve self-esteem, and lead to increased, or maintenance of, employment opportunities. Researchers have found that the colour temperature of light sources can also have positive impacts on mental alertness, concentration, and working memory (Kompier et al., 2020; Mills et al., 2007; Yang & Jeon, 2020). The benefits of improved lighting/colour conditions go beyond simply improving reading speed and therefore make them essential targets of low vision rehabilitation and serve as impactful mechanisms of change for individuals with low vision.

Currently, assessing optimal colour and illumination is an integral part of low vision rehabilitation, however, there is no gold-standard method that is used to assess the optimal conditions that will facilitate reading in individuals with low vision. In general, lighting needs are assessed using trial and error with the equipment available at individual low vision rehabilitation centers (Corn & Erin, 2010; Gendeman et al., 2010; Perlmutter et al., 2013; Wittich et al., 2018). There are, however, a variety of widely available assistive technology devices that can effectively modify optimal lighting and colour conditions that have also been found to be effective at improving reading speed in the visually impaired, e.g., the Apple iPad and the LuxIQ (Crossland et al., 2014; Morrice et al., 2017; Wittich et al., 2018). There are also novel devices, such as smart bulbs, that can easily modify lighting and colour conditions to suit a patient’s needs, but they have not been empirically investigated to determine their efficacy and effectiveness at improving reading speeds in the visually impaired. This gap in the literature and in clinical practice offers a rich field of research that can have a significant impact on the lives of those with visual impairments.

In summary, the existing literature suggests that optimal colour and illumination can significantly impact the lives of individuals with low vision at both the micro level, e.g., increasing task engagement and completion, and macro level, e.g., increase overall wellbeing and quality of life. However, there are several limitations in the existing literature; first, given the nuanced effect of coloured lighting there is contradictory evidence in the literature as to its effectiveness at improving reading speed in the visually impaired. Second, there are few studies that have experimentally investigated how both colour and illumination can be simultaneously varied to determine a patients optimal lighting needs to facilitate reading. Third, there lacks a standardized method that can be used to determine optimal lighting conditions to facilitate reading, and standardized measures that do exist, e.g., the LuxIQ, have yet to be empirically validated. Finally, there exist novel assistive technology devices that may be useful in improving reading speed in the visually impaired, but that either have not been empirically validated and/or have not had their functionality in modifying colour and illumination investigated.

Research Objectives

This dissertation consists of three studies that will add to the existing literature about the clinical utility of optimal lighting conditions for individuals with low vision and contribute to the broader understanding of the effectiveness of colour and illumination at improving reading. Specifically, this research will improve our understanding of how the efficacy of improved lighting conditions varies as a function of print-size in individuals with and without low vision, and how these improvements vary across devices. The purpose of this research is to determine how manipulating lighting and colour conditions of novel assistive technology devices effect the reading speed of individuals with and without visual impairments. This dissertation has five main objectives:

Objective 1*: Validate a standardized measure of reading speed in older adults (60+ years-old), to be used as reading material in this dissertation.*

Objective 2*: Determine the effectiveness of novel assistive technology devices at manipulating lighting conditions to improve reading speed in individuals with visual impairments.*

Objective 3*: Determine how the impact of lighting and colour effects reading speed in younger and older adults with normal/corrected to normal vision and with simulated reductions in visual acuity/contrast sensitivity.*

Objective 4*: Determine how the impact of lighting and colour effects reading speed in older adults with low vision.*

Objective 5*: Determine how the effects of lighting, colour, and device on reading speed vary as a function of print-size in participants with simulated and actual visual impairments.*

Study 1: *Validation of the International Reading Speed Texts in a Sample of Older (60+) Canadian Adults.*

This study addresses the first research objective. Specifically, this study investigated whether a standardized measure of reading, the International Reading Speed Texts (IReST), are valid in a sample of older adults. The IReST were specifically developed to assess continuous reading speed of individuals with visual impairments, however, they were only validated on a sample of 25 younger adults. This is a potentially confounding variable as individuals with visual impairments are likely to be older adults, and previous researchers have found that reading speed decreases in older adults with normal vision. Study 1 addresses the following research questions:

Question 1*: Are the standardized reading values provided by the IReST valid in older adults with normal/corrected to normal vision?*

Question 2*: If not, what are the expected age-related declines in reading speed for older adults with normal vision compared to the standardized values provided by the IReST?*

Study 2: *Assessing Optimal Colour and Illumination to Facilitate Reading.*

This study addresses the second, third, and fourth objectives of this dissertation; younger, older and visually impaired adults read standardized measures of reading using novel assistive technology devices and choosing their optimal lighting and colour conditions for reading. Participants with normal/corrected-to-normal vision read the standardized texts with and without simulated reductions in visual acuity/contrast sensitivity, and older adults with visual impairments read the texts using each device and choosing their optimal lighting conditions. Study 2 addresses the following research questions:

Question 1*: Do colour and illumination affect reading speed in individuals with and without visual impairments?*

Question 2*: Do colour and illumination differentially affect the reading speeds of young and older adults with normal vision compared to older adults with visual impairments?*

Question 3*: Are the novel assistive technology devices used in the study effective at manipulating lighting conditions to improve reading?*

Study 3: *Assessing Optimal Colour and Illumination to Facilitate Reading: An Analysis of Print-Size.*

This study addresses the fifth objective of this dissertation; younger, older, and visually impaired adults read standardized measures of reading using novel assistive technology devices, choosing their optimal lighting and colour conditions for reading at print-sizes that systematically decrease in size. Participants with simulated reductions in visual acuity/contrast sensitivity and actual visual impairments read the texts using each device and choosing their optimal lighting conditions. The lighting conditions remained constant and were not changed with the presentation of the texts that decreased logarithmically in size. Study 3 addresses the following research questions:

Question 1*: Are there differences in reading speed in participants with simulated and actual visual impairments at different print-sizes?*

Question 2*: Do the effects of lighting and colour at improving reading speed vary as a function of print-size?*

Question 3*: Does the efficacy of the assistive technology devices vary as a function of print-size?*

CHAPTER 2:
LITERATURE REVIEW

Reading is an essential component of daily life, yet it is one of the most difficult tasks faced by individuals with visual impairments (Brown et al., 2014; Elliott et al., 1997; Owsley, 2009; Rubin, 2013). Factors such as lighting and colour have been shown to effect reading speed in the visually impaired, but there is no gold standard measure that can be used by low vision rehabilitation specialists to assess optimal colour and illumination to facilitate reading (Eperjesi & Agelis, 2011; Eperjesi, Fowler, & Evans, 2002; Robinson, 2010; Zimmerman, Zebehazy, & Moon, 2010). Therefore, the goals of this dissertation are threefold: (1) to examine the efficacy of optimal lighting and colour conditions to facilitate reading in younger, older, and visually impaired adults; (2) to examine the effectiveness of novel assistive technology devices at manipulating optimal lighting and colour conditions to facilitate reading in younger, older, and visually impaired adults; and (3) to examine whether efficacy of optimal lighting and colour conditions vary as a function of print-size.

Physiological Basis for the use of Luminance, Colour, and Print-Size

There are clear physiological mechanisms that underpin the utility of luminance, colour, and print-size in low vision rehabilitation. For visual information to be processed, light must reach the photosensitive layer of the eye, i.e., the retina. In a healthy eye, light enters and is refracted via the cornea, the amount of light entering the eye is controlled by the iris which dilates to change the size of the pupil. The lens focuses light onto the retina, where a complex network of neurons will send information to the visual processing centers of the brain via the optic nerve (Hubel & Wiesel, 1962; Kuffler, 1953). In the retina there are two types of photosensitive cells called cones and rods; the majority of the cones are densely packed in the center of the retina, the fovea, whereas the rods are found in the periphery (Masland, 2001; Wässle, 2004). Cones are less sensitive to light compared to the rods and are responsible for mediating visual information processing under higher levels of illumination (photopic/mesopic conditions), providing a high level of visual acuity (Rushton, 1965; Stirling, 1965). Rods are more sensitive to light compared to cones and are therefore responsible for mediating visual information processing under low levels of illumination (scotopic/mesopic conditions); however, the neural process that makes them more sensitive to light also results in poor visual acuity (Rushton, 1965; Stirling, 1965). Taken together, in a healthy eye the cones and rods allow us to process visual information under high (photopic), medium (mesopic), and low (scotopic) lighting conditions. Due to age-related changes or pathological visual impairments, the visual system can be easily disrupted due to less light reaching the photosensitive layer of the eye. As we age the pupil shrinks in size (pupillary miosis), which results in less light entering the eye (Loewenfeld, 1979; Owsley, 2016). The lens also becomes occluded and loses its elasticity; the occluded lens results in more scattered light, whereas the loss of elasticity results in a reduction in the lenses ability to refract and properly focus light onto the retina (Owsley, 2016; Pokorny et al., 1987; Said & Weale, 1959). With less light entering the eye, it becomes difficult for the visual system to resolve contrast, resulting in decreased visual acuity (Artal et al., 2003; Glasser & Campbell, 1998; Owsley, 2016). Therefore, by simply increasing brightness levels (illumination), this increases the perceived contrast ratio, allowing the visual system to resolve fine details and process visual information accordingly.

The photoreceptors responsible for colour perception are the cones; there are three types of cones, S-Cones (short), M-Cones (medium), and L-Cones (long), with each type of cone being specialized in detecting short, medium, and long wavelengths of light, respectively (Brown & Wald, 1964; Stockman et al., 1993). The physiological specificity of these photoreceptors are the basis for trichromatic colour theory, which posits that the human visual system perceives colour by combining blue (short wavelength), green (medium wavelength), and red (long wavelength) light to perceive the colour spectrum (Brown & Wald, 1964). However, the trichromatic theory of colour does not account for the entire spectrum of visible light, and there is another neurophysiological process that occurs, opponent colour processing, that solves this problem. Opponent process theory is based on the complex neural networks that detect light (on/off center-surround receptive fields; see Kufler literature, e.g., (Kuffler, 1953) , whereby the receptive fields detect light in combinations of red/green light, yellow (red+green)/blue light, and rods detect luminance (Hurvich & Jameson, 1957; Johnson et al., 2008). Both age-related and pathological vision loss can impact how the visual system processes colour; as the lens becomes occluded and yellows with age, the visual system adapts and achieves/maintains colour constancy through cortical mechanisms that change the weighting attributed to different cone types in the retina (Wuerger, 2013; Xiao et al., 2011, 2013, 2015). While colour constancy perception appears to be less affected by aging, colour discrimination has been shown to decrease with age (Wuerger, 2013). In individuals with central field vision loss, e.g., AMD, the cones in the fovea are damaged/destroyed and this will severely impact their colour perception as it is the cones that discriminate different wavelengths (Cahill et al., 2005; Chowdhury, 2018; O'Neill-Biba et al., 2008). For both age-related and pathological vision loss, however, the use of different colour lighting to facilitate reading may be useful for a variety of reasons. For example, for those whose lenses have yellowed with age, it is conceivable that using blue lighting, or higher colour temperature lighting, may be less effective for reading due to the opponent colour process of vision whereby blue light will be neutralized through a yellow filter. If the blue light is neutralized through the yellow lens, then this will reduce the contrast and make it more difficult for the visual system to resolve fine details, such as text when reading. Conversely, blue/higher colour temperature lighting may improve reading ability in individuals with AMD; although they may also have yellowed lenses, with the loss of photoreceptors in the fovea (cones) vision becomes rod mediated and rods peak spectral sensitivity is to the short (blue) wavelength of light, i.e., the Purkinje shift.

To understand the impact of print-size on reading speed, one needs to understand how the visual system processes spatial information. While at the level of the retina visual information is processed as points of light that activate concentric circular on/off center-surround receptive fields, in the primary visual cortex light is processed as bars of light that activate on/off even/odd symmetric receptive fields (Hubel & Wiesel, 1962). In the primary visual cortex (area V1), there are neurons that respond preferentially to bars of light (spatial frequencies) of various sizes, orientations, and speeds; that is, in area V1 the human visual system has neurons that preferentially respond to either high, medium, or low spatial frequencies (Blakemore & Campbell, 1969; Bosking et al., 1997; Yacoub et al., 2008). Because the human visual system analyzes visual information in terms of spatial frequency, it is therefore also dependent on contrast, the difference in luminance between the black and white bars (Blakemore & Campbell, 1969). In the healthy eye, spatial frequency varies as a function of contrast such that low and medium spatial frequencies require less contrast to be resolved compared to high spatial frequencies. Therefore, high spatial frequency stimuli, such as a 12-point Times New Roman font, will require higher contrast and higher luminance to be resolved effectively by the visual system. As print-size increases the spatial frequency of the stimuli decreases, and therefore larger print-sizes will require less contrast and less luminance. However, as we age spatial contrast sensitivity at medium and high spatial frequencies decrease under photopic conditions and spatial contrast sensitivity at low spatial frequencies decrease under scotopic conditions (Derefeldt et al., 2009; Elliott et al., 1990; Kline et al., 1983; Owsley et al., 1983; Tulunay-Keesey et al., 1988). This means that even under high levels of illumination, older adults will still have difficulty reading at smaller print-sizes and will require either increased levels of illumination or text magnification to resolve the visual information correctly. Indeed, researchers have found that the critical print-size for reading increases with age, that is the smallest print-size that can be read at maximum reading speed gets larger with age (Calabrèse, Cheong, et al., 2016).

Low Vision and Low Vision Rehabilitation

Generally, the term low vision refers to individuals with measurable visual abilities but who experience difficulty accomplishing visual tasks even while wearing corrective lenses (Corn & Lusk, 2010). More specifically, the American Academy of Ophthalmology categorizes low vision as a permanent visual impairment characterized by a visual acuity of 20/40 or worse in the better eye, a significant reduction in contrast sensitivity, and/or a reduced visual field (Fontenot et al., 2018). The World Health Organization estimates that globally 405.5 million individuals can be considered to have low vision, with the most frequent causes of low vision being age-related macular degeneration (AMD), cataracts, and glaucoma (Bourne et al., 2017; Flaxman et al., 2017; Fricke et al., 2018). While low vision represents a permanent loss in visual functioning, low vision rehabilitation (LVR) offers individuals with low vision a variety of techniques and assistive technology devices that can be used to improve functional vision (Steinkuller et al., 1999). Services and devices offered in LVR typically fall into two categories, high-tech, e.g., through the use of devices such as electronic magnifiers, closed circuit televisions, iPads, and retinal implants, and/or low tech, e.g., through the use of hand held magnifiers, lamps, and preferred retinal location training (Morrice et al., 2017; Robinson, 2010; Steinkuller et al., 1999; Wittich et al., 2018; Zimmerman et al., 2010).

The overall goal of LVR is to restore functioning and improve quality of life, but the most frequent reason individuals report actually seeking LVR is due to difficulty reading (Brown et al., 2014; Owsley et al., 2009). Therefore, a great deal of LVR focuses on providing services that improve individuals reading speed/ability by providing patients with devices to increase text size and improve lighting conditions (Cheong et al., 2002; Nguyen et al., 2009; Wilkinson & Shahid, 2018). Increased magnification and improved lighting have been shown to improve reading speed/ability in the visually impaired, however, lighting can be broken down into components of luminance and colour, the latter of which is more controversial in its utility (Alabdulkader & Leat, 2010; Bowers, Meek, & Stewart, 2001; Eperjesi, Maiz-Fernandez, & Bartlett, 2007; Eperjesi, Fowler, & Evans, 2004; Legge, Pelli, Rubin, & Schleske, 1985; Legge, Rubin, Pelli, & Schleske, 1985; Raasch & Rubin, 1993; Whittaker & Lovie-Kitchin, 1993). Luminance in this context refers to the brightness, intensity, and quality of the light source, whereas colour refers to the colour of the light that is produced and/or modified by an assistive device in terms of colour temperature/hue.

Luminance in Low Vision Rehabilitation

There are many studies that have examined the relationship between increased luminance and increased reading performance, e.g., Bullimore & Bailey (1995), Fosse & Valberg (2004) Haymes & Lee (2006), Ram & Bhardwaj (2017), and Seiple et al. (2018), however, one of the most frequently cited studies is that by Bowers et al. (2001). In this study, Bowers and colleagues asked participants with AMD to read 14 sentences from the MNread (Mansfield et al., 1993) under six different levels of illumination (lux) ranging from 50 to 5,000 lux. They found that as lux increased, there were also concomitant changes in reading speed and critical print-size, such that participants were able to read more quickly and were able to do so at smaller text sizes. Bowers et al. (2001) recommend that individuals with low vision, specifically those with AMD, will likely require task illumination of at least 2,000 lux to improve reading but that optimal illumination ought to be assessed with patients individually.

Improving task illumination has been shown to not only increase reading speed in individuals with low vision, but a study by Brunnström, Sörensen, Alsterstad, and Sjöstrand (2004) has shown that installing improved lighting throughout the home and providing a task illumination station improves overall quality of life in the visually impaired. In this study by Brunnström and colleagues, individuals with low vision were randomly assigned to two conditions: an intervention group and a comparison group. In both conditions, LVR specialists installed improved lighting in participants' kitchen, bathroom, and hallway. In the intervention condition, an additional task lighting station was also provided in participants' living rooms. The task lighting station in this study provided an area in which there was high intensity illumination to facilitate tasks such as reading or writing. Measures of quality of life examining general health, social support, and psychological well being, e.g., depressed mood, were taken at baseline and then again at 6 month follow-up. The researchers found that there were no significant differences in quality of life at 6-month follow-up for the comparision group, but there were significant improvements in quality of life for the intervention group across all categories. Thus providing improved task lighting, used for activities such as reading/writing, significantly improved the overall quality of life of individuals with low vision.

The results of these studies indicate that improving luminance conditions is an integral part of LVR, as it improves both individuals reading ability as well as their overal quality of life. Regrettably Brunnström et al. (2004) and other researchers, e.g., Cullinan, Gould, Silver, & Irvine (1979), and Bakker, Iofel, & Lachs (2004), have found that individuals with low vision frequently have poor lighting conditions at home, i.e., 20-30 lux, and they do not view improved lighting as importantly as other factors in LVR (Schuchard et al., 1999). Therefore, it is important for LVR specialists to provide assessments of optimal illumination to facilitate reading as this can have long lasting impacts on quality of life and well being. Unfortunately, there is no gold standard measure that can be used to determine optimal levels of illumination to facilitate reading in the field of LVR.

Colour in Low Vision Rehabilitation

Colour is used in a variety of ways in LVR, the most common method is through using assistive devices that use light sources of different colour temperatures/hues, coloured lens filters, and plastic coloured overlays for reading (Eperjesi et al., 2004b; Veszeli & Shepherd, 2019; Wilkinson & Shahid, 2018; Wolffsohn et al., 2012). However, the use of these colour devices is controversial as there is scant and often contradictory evidence for their efficacy. For example, a study by Wolffsohn and colleagues (2012) examined the effect of handheld magnifiers with embedded light emitting diodes of three colour temperatures (Kelvin; k), 2,700k, 4,500k, and 6,000k, on reading speed in individuals with AMD. Initial findings indicated that there were no significant differences in reading speeds across participants when reading using different colour temperatures. But researchers found significant improvements in reading speed across groups when they examined reading speeds associated with participants self-reported preferred colour temperature. In addition, when they further segregated the participants into experienced and novice assistive device users they found that experienced users read more quickly when using higher colour temperatures (6,000k) and slower when using lower colour temperatures (2,700k). The results of this study indicate that colour does seem to have some impact on reading speed in individuals with low vision, but that the effect is more nuanced and based on individuals colour preferences and user experiences.

Another study by Eperjesi et al. (2004a) examined the effect of different types of coloured filters on reading speed in individuals with normal vision and individuals with AMD. Specifically, the researchers compared participants reading speeds when using clip on yellow filters (CPF450s), a clip on neutral density filter, and a plastic coloured overlay derived from an Intuitive Colorimeter to participants reading speed while using a clear plastic filter. Eperjesi and colleagues found that there were no significant improvements in reading speeds across conditions except for when individuals with AMD read using the clip on CPF450s. However, the researchers noted that the CPF450s only increased reading speeds in individuals with AMD by 5% and therefore while the improvements were statistically significant, they may not be clinically relevant. This research again shows the conflicting evidence for the utility of colour in LVR; in this case yellow CPF450 colour filters do appear to improve reading speed, but the improvement is so small that it may not be relevant to all individuals.

Finally while there is a dearth of knowledge with respect to the effect of colour on reading in LVR, there are a variety of other fields of study that have examined the effect of colour on reading, e.g., research on reading disorders and research on early childhood education. However, even in these other fields there are contradictory findings with regards to whether or not colour can be used to improve reading speed/ability. In the reading disorders literature some studies find that there is no significant improvement in reading speed when using coloured filters, e.g., Denton & Meindl (2016), whereas others, e.g., Evans & Joseph (2002), Lightstone, Lightstone, & Wilkins (1999), and Wilkins, Jeanes, Pumfrey, & Laskier (1996), have consistently found that coloured reading filters can improve reading speeds in individuals with reading disorders by 5-25%. A recent study from the field of early childhood education by Veszeli and Shepherd (2019) found that the use of colour overlay filters significantly improved reading performance in younger children with less reading experience. Veszeli and Shepherd (2019) recorded reading times for participants self-reported most comfortable colour filter and objectively measured most effective colour filter, and found that both significantly improved reading times in younger readers but had less of an effect on older children. These findings are consistent with research that has been presented from the LVR literature, in that it appears that the effect of colour is more individualistic and depends on previous experience.

Taken together, the results of the studies presented here suggest that colour may have an effect on reading, but its effect is more nuanced compared to the effect of luminance and is likely to be more individualistic. That is to say, a red hued light source or colour filter may improve one patient with AMD's reading speed, but not improve another patient with AMD's reading speed. This inconsistency in the effect of colour on reading in individuals with visual impairments is, however, consistent with the heterogeneity of visual impairments whereby no two individual's visual impairment are exactly alike. Therefore, it is also important for LVR specialists to provide assessments of optimal colour, in addition to optimal illumination, to facilitate reading, as colour may improve a person with low vision's reading ability. Unfortunately, as with the assessment of optimal illumination, there is no gold standard measure that can be used to determine optimal colour to facilitate reading in the field of LVR.

Print-size in Low Vision Rehabilitation

Print-size is a crucial component of improving reading speeds of individuals with low vision and it has been found to interact with illumination (Bailey et al., 2003; Chung et al., 1998; Legge & Bigelow, 2011; Mansfield et al., 1996; Seiple et al., 2018; Whittaker & Lovie-Kitchin, 1993). Gordon Legge and his colleagues have extensively investigated the psychophysics of reading over the past four decades, e.g., see Psychophysics of Reading literature (I – XX; Gordon E. Legge, 2006), finding that there are a variety of factors that impact reading speed including print-size. Generally, they found individuals with normal and low vision have significantly slower reading speeds at small print-sizes and there is a ceiling effect, such that there are negligible differences in maximum reading speed across larger print-sizes. Moreover, each individual has a critical print-size, the smallest print-size that can be read at their maximum reading speed, whereby smaller print-sizes result in signifiicant reductions in reading speed. They also found that those with low vision have larger critical print-sizes and slower maximum reading speeds compared to individuals without visual impairments. Bailey et al. (2003) subsequently developped a theorteical framework to determine factors that impact optimal print-size for reading in individuals with and without low vision: visual skills, print layout, and cognitive/processing demands. Visual skills refer not only to an individual's visual acuity, but also their ability to control their eye movements, i.e., fixations, regressions, saccades, as print-size changes (Bullimore & Bailey, 1995; Legge, Pelli, et al., 1985; Legge, Rubin, et al., 1985; McConkie & Rayner, 1975; Schuchard & Fletcher, 1994; Virgili et al., 2004). Print layout refers to the choices in font, kerning, leading, and the number of rows per page, each of which can influence an individuals eye-movement patterns and change the ease with which reading material is processed (Arditi, 1996; J. Stephen Mansfield et al., 1996; Tinker, 1965). Finally, cognitive/processing demands refer to the linguistic complexity of the reading material, whether the text is being read silently or aloud, and whether the text is being read for comprehension versus speed. For example, when print-size is small and close to the limits of the visual system this will result in poorer visual acuity, more percise eye-movements, and will increase cognitive load, thereby significantly reducing reading speed. Conversely, when print-size is too large reading speed will also decrease as less information will fit on the page, which in turns reduces the visual span, and also increases cognitive load. Therefore, reading speed and print-size can be interpreted as a function of an individuals acuity reserve: the ratio of a given print-size to the reader's visual acuity. When a print-size is larger than a reader's visual acuity this results in a high acuity reserve, conversely, when a print-size is smaller than a reader's visual acuity this results in a low acuity reserve. However as noted above, either extreme (too high or too low) will result in significant reductions in reading speed. In general, those with low vision require an acuity reserve of 3:1 to achieve maximum or near maximum reading speeds (Lovie-Kitchin & Whittaker, 1999).

A factor not included in Bailey et al.'s (2003) framework is lighting conditions, however, there is research to suggest that optimal lighting conditions also interact with print-size and reading speed. A more recent study by Seiple et al. (2018) investigated the how optimial lighting conditions interact with print-size and reading speed in individuals with normal vision and AMD. Participants read sentences from the MNRead at print-sizes ranging from 0.0 to 1.3 logMAR and using illumination ranging from 3.5 to 696 cd/m^2. They found that under the lowest levels of illumination, reading speeds increased as print-size increased, however, when illumination increased to 30 cd/m^2 they observed significant improvements in reading speeds only at small print-sizes but not larger print-sizes. Interestingly, they found that any illumination greater than 30 cd/m^2 did not results in significant increases in reading speed for any print-size and the results were consistent for both participants with normal vision and with AMD. They conclude that optimal lighting conditions are essential to improve reading speeds at small print-sizes, however, the strength of the effect diminishes as text size increases in both individuals with normal and low vision. Of note is that in this study, the researchers did not investigate the use of coloured lighting and its impact on reading in those with and without visual impairments. Indeed, there appears to be a lack of literature that investigates how print-size, illumination, and colour interact with reading speed.

Assessing Optimal Colour and Illumination in Low Vision Rehabilitation

While there is no gold standard method of assessing optimal colour and illumination to facilitate reading, there are many ways in which lighting and colour needs are assessed using current LVR practices. Current methods of lighting/colour assessment include: light meters, home lighting assessment protocols e.g., the Home Environment Lighting Assessment (HELA), trial and error using a variety of lamps/light bulbs, and a new measure that attempts to standardize the process called the LuxIQ (Corn & Erin, 2010; Perlmutter et al., 2013; Wittich et al., 2018). Light meters can be used to measure specific luminance levels under controlled conditions, e.g., at a LVR centre, or to measure luminance levels in individuals home environments. The problem with light meters is that they are not available in all LVR centres, and when they are available studies have shown that few specialist will use them and many have not been trained in their use (Gendeman et al., 2010; Wittich et al., 2017). Perlmutter and colleagues (2013) attempted to remedy this by developing the HELA, a protocol for occupational therapist to assess lighting conditions in patient's home environments; however, the program has not yet been widely adopted and it requires the use of a light meter on which occupational therapists generally receive little to no training (Wittich et al., 2017). Thus, the more common way in which lighting is assessed in LVR settings is through a process of trial and error; whereby LVR specialists will attempt to identify optimal colour and illumination using a variety of lamps and light bulbs of different colour temperature/hues and intensities. This process is costly, inefficient, and requires the maintenance and storage of a large variety of lamps and bulbs. This has led to the development of a device, the LuxIQ (see figure 1; Jasper Ridge, 2019), that attempts to standardize the process of assessing optimal colour and illumination for individuals with low vision.

The LuxIQ is a small, portable device that can be used in both rehabilitation settings and home environments. It is simple to use: reading material is placed under the device, e.g., the IReST, and patients are then simply instructed to adjust the sliders on either side of the device to alter the luminance and colour temperature/hue output to their preference. Once the optimal luminance and colour settings have been determined, the luminance (lux) and colour

Figure 1. The LuxIQ. The LuxIQ is a standardized assessment tool that can be used to determine optimal colour and illumination to facilitate reading in individuals with low vision. Reading material, e.g., the MNread, is placed under the LuxIQ, then patients are instructed to adjust the sliders on the top of the device to their preference. The slider on the left controls luminance; luminance values range from 0 to 5000 lux. The slider on the right controls colour temperature and/or hue; colour temperature values range from 2700 to 4500 kelvin and colour hue values ranges from 525 to 625 nanometers.

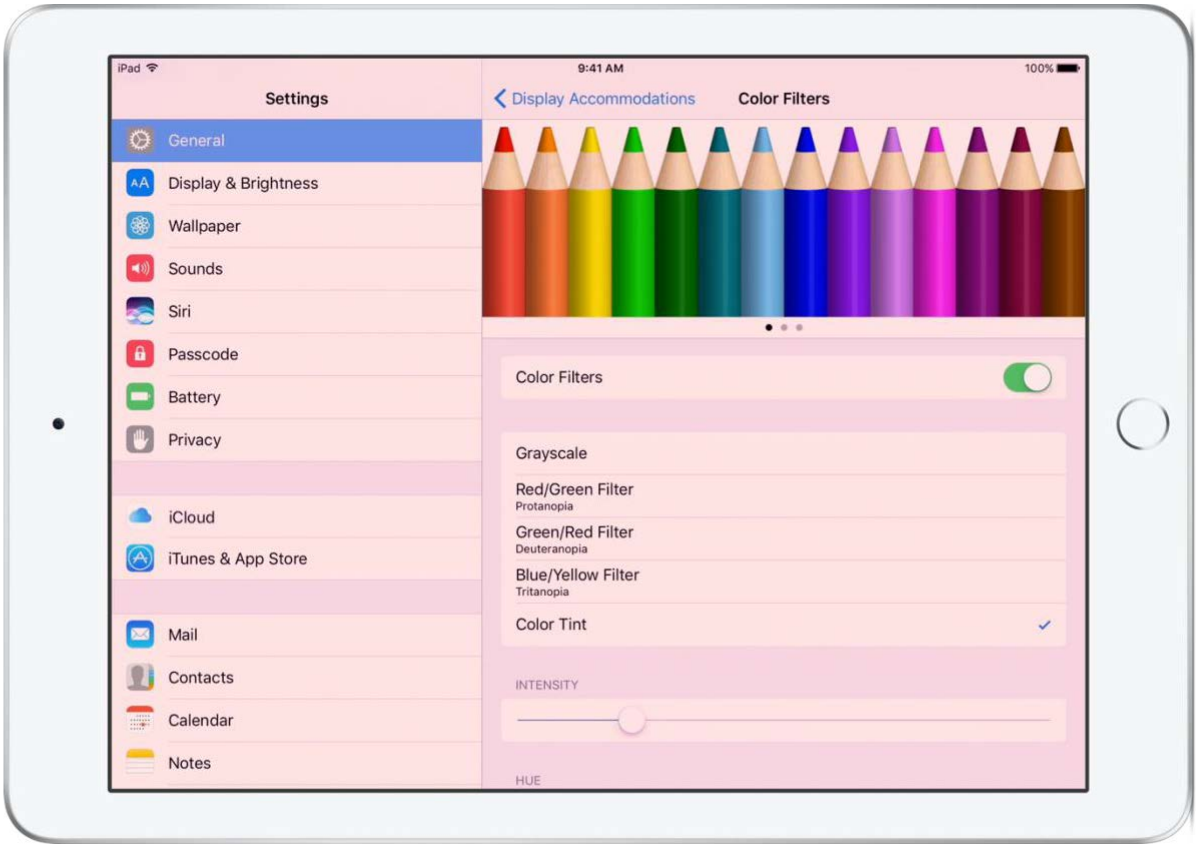
(kelvin/nanometer) values can be inputted into the Jasper Ridge website to find light sources that match the desired parameters. A criticism of the LuxIQ, however, is the poor test-retest reliability of the device; a study by Wittich et al. (2018) asked participants with normal/corrected to normal vision and individuals with low vision to adjust the luminance and colour temperature of the LuxIQ while viewing a sentence from a standardized text. The values were recorded, and then thirty minutes later the participants were asked to repeat the task. Wittich et al. (2018) found that differences in participants preferred lighting ranged more than 2600 lux and more than 2300 k in both normally sighted and low vision participants. In addition, thus far there have been no studies that have examined the validity of the device, i.e., does the preferred lighting and colour chosen by participants translate to improved reading speed and/or comprehension. Therefore, while the device standardizes the process of determining optimal colour and illumination to facilitate reading, there is no evidence that the preferred luminance and colour selected by individuals improves overall reading performance.

Present Research

As difficulty reading is the most frequent reason people seek LVR, and improved reading ability, through improved lighting/colour conditions, increases overall quality of life, it is essential that optimal lighting/colour needs for reading be assessed in LVR. However, LVR specialists lack valid and reliable assessment devices that can be used to determine optimal colour and illumination to facilitate reading. Therefore, the purpose of this dissertation is to examine the effects of colour, illumination, and print-size on reading, and to compare/contrast the efficacy of three devices that may be used in the context of LVR to determine optimal colour and illumination to facilitate reading. The devices that will be compared are: (1) the LuxIQ, (2), the Apple iPad, and (3) the MIPOW Smart bulb. The LuxIQ, as previously described, is a device currently used in the context of LVR that attempts to standardize the process of determining patients lighting/colour needs, but the device has been found to have poor test-retest reliability (Jasper Ridge, 2019; Wittich, et al., 2018). However, while the reliability of the device has been called into question, there have been no studies that have examined the validity of the device; i.e., do the lighting and colour settings chosen by participants actually result in improved reading speed and ability? Therefore, my dissertation will examine the validity of the LuxIQ in increasing reading speeds, by improving lighting and colour conditions, and compare participants reading performance when using two other devices, i.e., the Apple iPad and the MIPOW Smart bulb.

The Apple iPad is a tablet computer that individuals with low vision frequently report using as a reading aid, and previous research has found it to be an effective assistive technology device that can be used in the context of LVR (Crossland, Silva, & Macedo, 2014; Morrice et al., 2017; Wittich, et al., 2018). But previous studies have only examined the basic functionality of the iPad in the context of LVR, and there have been no studies looking at how accessibility options, specifically display accommodations, affect reading speed/ability in the visually impaired. The display accommodations on the iPad modify the way in which content is presented on the device, and the colour filter accommodation can change the colour hue/intensity of the devices display. For example, if a patient with low vision reads better using a red hued light, then they can modify the iPad's display using a red colour filter through the display accommodation options (see figure 2). In this way, the iPad colour filters can be used with digital media to achieve a similar effect that the LuxIQ temperature/colour settings have on print media, and therefore, this may result in increased reading speed in individuals with low vision. Thus, my dissertation will examine the efficacy of using the colour filter display accommodation on the iPad in the context of LVR, and compare participants reading speed/ability using the iPad to their performance using the LuxIQ and MIPOW Smart bulb.

The final device that will be assessed in this dissertation is the MIPOW Smart bulb; the MIPOW smart bulb is an inexpensive (30$ CAD), 5-watt, LED, light bulb that is controlled via Bluetooth connection from a mobile application installed on any smart device, e.g., cellular phone or tablet (MIPOW, 2019). Through the mobile application, a user can modify the intensity of the smart bulb's illumination and colour temperature/hue. According to the manufacturer, individuals can choose from one of 16 million different colour illuminations when using the MIPOW Smart bulb. Given the ability to change the colour and illumination of the device, the MIPOW Smart bulb may be an ideal and cost-effective tool that can be used in LVR. For example, in current LVR practices once a patient's optimal colour and illumination have been determined, they are provided with specifications for light bulbs to purchase so they can achieve those desired settings in their homes and workspaces. If, however, their visual impairment and lighting needs change, then they are required to purchase a whole new set of light bulbs; using the MIPOW Smart bulb would eliminate the necessity of going to purchase new bulbs, as



Color Filters ●

Grayscale
Red/Green Filter
Protanopia
Green/Red Filter
Deuteranopia
Blue/Yellow Filter
Tritanopia
Color Tint ✓

INTENSITY

HUE

Figure 2. The Apple iPad. The Apple iPad is a tablet computer that is frequently used by individuals with low vision as an assistive reading device. Using the accessibility features, individuals can apply colour filters to their reading material, achieving a similar effect with digital media as the LuxIQ achieves with print media.

patients could simply change the smart bulbs settings via the mobile application to reflect their new lighting needs. But there have been no studies that have examined the use of smart bulbs in the context of LVR, and no studies that have examined their effect on reading speed/ability in the visually impaired. Therefore, my dissertation will examine the efficacy of using the MIPOW Smart bulb in the context of LVR and compare participants reading speed/ability when using the smart bulb to their performance on the iPad and LuxIQ.

To examine which device will be best at determining optimal colour and illumination to facilitate reading, participants will read eight standardized texts, two texts per device in addition to two baseline measures of reading speed. Participants will select their optimal lighting and colour settings on the device and then read the text aloud. The lighting/colour settings will be recorded then reset between reading each text. Reading speed will be used as the outcome measure to determine which device results in participant's optimal lighting/colour to facilitate reading. Age, impairment severity, print-size, luminance (lux), and colour temperature (Kelvin) will be used as predictors of reading speed in younger, older, and visually impaired adults. A limitation of this design is that participants will be making different lighting/colour choices with each device, however, this is consistent with current low vision rehabilitation practices in determining optimal colour and illumination to facilitate reading. The present research consists of three studies that expand the current knowledgebase by investigating the impact of colour, illumination, and print-size on reading by examining the efficacy of three novel assistive technology devices at improving reading speeds in the visually impaired.

Study 1 (Chapter 3) investigated whether a standardized measure of reading speed, the IReST, is valid in a sample of older adults (60+) as this material will be used in subsequent experiments. The IReST is a measure of reading speed that consists of 10 short paragraphs that have been standardized for text difficulty, sentence complexity, and words per text (M=132 words). Each text is based on an encyclopaedia entry, is written at a 6th grade reading level, and has normative values, i.e., mean words per minute (WPM) and standard deviation, which can be used as a point of comparison. The IReST was developed in Europe, translated into 17 different languages, with the English language IReST being developed and normed in the United Kingdom on a sample of 25 young adults between the ages of 18-35 years old. The normative values of the IReST have been found to be valid in a sample of young adults with normal/corrected-to-normal vision in a Canadian sample, however, there have been no studies that have examined the validity of the measure in a sample of older adults (Morrice, Hughes, Stark, Wittich, & Johnson, In Review). Therefore, the purpose of the first experiment of this dissertation is to validate the IReST in a sample of older adults (60+ years-old) to determine if the normative values provided by the IReST can be used as a point of comparison in this population. The specific hypothesis of this study was:

Hypothesis 1.1*: Reading speeds of older adults will be significantly slower than the normative values provided by the IReST.*

Study 2 (Chapter 4) examined whether optimal colour and illumination predicted reading speeds in younger/older adults with normal vision/simulated reduction in visual acuity/contrast sensitivity and in older adults with visual impairments. This study also explored the efficacy of three novel assistive technology devices at improving reading: the LuxIQ, the Apple iPad, and the MIPOW Smart bulb. These devices were examined in a sample of younger (18+; *n*=15) and older adults (60+; *n*=15) with normal vision/simulated reductions in visual acuity/contrast sensitivity, and older adults (60+; *n*=15) with actual visual impairments. Due to the inherent differences in visual acuity, contrast sensitivity, and visual field loss caused by the heterogeneity of actual visual impairments, simulated visual impairments were used in this experiment to achieve a homogeneous reduction in visual acuity and contrast sensitivity across normally sighted participants. By using a simulated 20/80 (0.6 LogMAR) visual impairment, it was then determined what the average improvement in reading speed an individual might expect to experience when using either the LuxIQ, iPad, or Smart bulb. Participants were asked to read eight standardized texts under four different lighting and colour conditions with their normal/corrected-to-normal vision: two texts using baseline ambient room lighting, two texts using the LuxIQ, two texts using the Apple iPad, and two texts using the MIPOW Smart bulb. Before reading each text participants were asked to select their optimal lighting and colour settings on the device being used. The lighting/colour settings were recorded and then reset. One week later, participants returned to read standardized texts under the same four lighting conditions, however, they were asked to read the texts using a simulated visual reduction in visual acuity and contrast sensitivity. The order of the testing conditions and text presentation were counterbalanced to account for practice/learning effects. The differences in reading speed of older and younger adults with normal/corrected-to-normal vision and simulated visual impairments were then compared across devices to determine which device optimally improved lighting and colour conditions to facilitate reading. Older adults with actual visual impairments were then assessed following the same protocol used in the simulated impairment condition. Device efficacy was compared across groups, and we analyzed whether optimal colour and illumination could predict improvements reading speed. The specific hypotheses of this study were:

Hypothesis 2.1*: Increased illumination (lux) and higher colour temperatures (kelvin) will predict faster reading speeds in the simulated and actual impairment conditions.*

Hypothesis 2.2*:There will be no significant differences in reading speeds from baseline when using the LuxIQ, iPad, or Smart bulb in the normal vision condition*

Hypothesis 2.3*: Both the iPad and the LuxIQ will improve reading speeds from baseline in the simulated/actual impairment conditions, however, the iPad will be the most effective device.*

Study 3 (Chapter 5) used data obtained from the simulated impairment and actual impairment conditions of Study 2. Study 3 explored whether the association between colour, illumination, and reading speed in individuals with/without visual impairments remains constant at various print-sizes. The effectiveness of the assistive technology devices were also investigated to determine whether they remain effective at improving reading speeds across groups at various print-sizes.

Hypothesis 3.1*: There will be no differences in reading speed from baseline at large print-sizes, i.e., 1.2 LogMar, however, there will be significant improvements in reading speeds from baseline at smaller print-sizes, i.e., < 0.8 LogMar.*

Hypothesis 3.2*: The effect of colour and illumination will vary as a function of print-size.*

Hypothesis 3.3*:Device effectiveness will decrease at large print-sizes and increase at smaller print-sizes.*

CHAPTER 3:

STUDY 1

Validation of the International Reading Speed Texts in a Sample of Older (60+) Canadian Adults

Note: Copy edited version of this study was published in *Optometry and Vision Science*, August 2021

Abstract

On average, older adults (60+) with normal vision read the IReST 37.8 words per minute slower than the standardized values provided by the IReST manufacturer. When assessing reading speed in older adults, clinicians should bear in mind that the IReST norms do not account for these age-related differences. The purpose of this study is to validate the IReST in an English-speaking Canadian sample of older adults (aged 60+). Canadian English speaking older adults (n=25) read all 10 IReST aloud using the same protocol from the original IReST validation study. There were significant differences between the older adult sample and the published IReST values for each text (Mdiff = -37.84, 95% CI: [-41.34 to -34.34]). Reading speeds of older (60+) Canadian adults fell outside of the standardized values of the English language IReST. Researchers/clinicians who wish to assess older adults reading speed using the IReST ought to take this discrepancy into account.

Keywords: IReST, Validation, Older Adults, Reading Speed, Aging

Introduction

The International Reading Speed Texts (IReST) is a measure of reading speed that has been standardized for text difficulty, sentence complexity, words per text, and has previously been found to be valid in a sample of Canadian young adults (Hahn et al., 2006; Morrice et al., 2020; Trauzettel-Klosinski & Dietz, 2012a). However, previous researchers have demonstrated that reading speed decreases with age (Aberson & Bouwhuis, 1997; Akutsu et al., 1991; Calabrèse et al., 2016; Chen et al., 2019; R. Liu et al., 2017; Yu et al., 2010) and the normative values of the IReST have yet to be validated in a sample of older adults (aged 60+). Therefore, the purpose of this study is to validate the English language IReST in a sample of English-speaking older adults (aged 60+) with normal/corrected-to-normal vision.

The IReST was developed in Europe where it was linguistically adapted. and subsequently validated, into18 languages (Hahn et al., 2006; Trauzettel-Klosinski & Dietz, 2012). The IReST manufacturer provides standardized values of mean reading speed and variance, i.e., means and standard deviations in words per minute, to compare a reader's performance to these normative values. The English IReST, originally adapted and validated for British English, has been found to be valid in an age-matched English-speaking sample of Canadian young adults (Morrice et al., 2020). However, to the best of our knowledge there have been no studies that have investigated whether the normative values provided by the IReST manufacturer are valid in older adults (60+). While the original study used in the development of the IReST (Hahn et al., 2006) did include a sample of older adults (60 to 85-years-old), they reported reading speeds in characters per minute, as opposed to words per minute, and these reading speeds are not provided as part of the IReST normative values (Morrice et al., 2020). Other studies, e.g., Brussee, van Nipsen, and van Rens (2017); Morrice, Johnson, Marinier, and Wittich, (2017), have used the IReST to assess reading speed in older adults, but the purpose of these studies were not to validate these reading speeds in this population. Examining the impact of age on reading speed on the IReST is an important factor to consider when assessing older adults, as previous researchers have found that reading speeds decrease with age (Aberson & Bouwhuis, 1997; Akutsu et al., 1991; Calabrèse et al., 2016; Chen et al., 2019; R. Liu et al., 2017; Yu et al., 2010). In addition, the lack of normative values for older adults on the IReST could introduce a confounding variable when assessing individuals with visual impairments. As individuals with visual impairments are more likely to be above the age of 35-years-old (the maximum age range of the original IReST norms), it is presently unclear how much variability in this populations reading speeds as assessed by the IReST would be attributable to a visual impairment versus how much would be attributable simply to age-related changes in reading speeds.

The purpose of this study was to determine if the normative values provided by the IReST manufacturer are valid in older (60+) Canadian English speaking adults. It was hypothesized that the reading speeds of Canadian English speaking older adults (60+) will be significantly slower than the standardized values of the English language IReST. Participants in this study read all 10 English IReST aloud. The texts were read following the administration protocols provided by the IReST manufacturer.

Method

The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. In accordance with the Canadian Tri-Council Policy Statement of ethical conduct for research involving humans, (Canadian Institutes of Health Research et al., 2014) all aspects of the research protocol was approved by the human research ethics committee of Concordia University (certificate 30003975).

Participants

A sample of twenty-five adults (17 females), between the ages of 60 and 84 (M = 69.98, SD = 6.72), were recruited from the Concordia Vision Labs participant database. Inclusion criteria for this study required participants to have: (1) normal/corrected-to-normal vision; (2) they were required to be dominant English language speakers; and (3) they were required to have no reading/attention disabilities (Morrice et al., 2017; Morrice et al., 2020). The sample was chosen to match the original IReST validation experiment (*n*=25), as well as conform to an a priori power analysis. Using G*Power3.1 to test the difference from a constant, using a one-tailed test, a large effect size (*d* = .70), and an alpha of .05, a sample size of 24 was required to achieve power of .95 (Faul et al., 2007).

Procedure

Informed consent was obtained, then participants completed a language background questionnaire and measures of visual acuity/contrast sensitivity. Participants completed the **Concordia University Language Background Questionnaire** to obtain demographic information, health history, language background, and language proficiency (Morrice et al., 2017; Morrice et al., 2020). Participants visual acuity and contrast sensitivity were obtained using the **Freiburg Visual Acuity and Contrast Sensitivity Test** (Bach, 1996; Kurtenbach et al., 2013; Schulze-Bonsel et al., 2006a). Participants were then asked to read the IReST following the same protocols used in the original validation: participants read the texts aloud as a researcher recorded errors (Hahn et al., 2006; Trauzettel-Klosinski & Dietz, 2012). An exception in this study is that the order in which the IReST were read was counterbalanced to equally distribute carry-over effects (text presentation was randomized in the original experiment). The IReST were presented 40 cm away from participants and before reading each text participants were asked to "read the text aloud as quickly as possible and without going back and making corrections." Reading time and incorrect/omitted words were recorded. While error counts were not used in the original study the instructions from the IReST manufacturers state that errors should be counted and subtracted from the total number of words when calculating reading speed in words per minute. The formula used to obtain participants reading speed in words per minute was: (*words read correctly/seconds*) X 60 = *words per minute*.

Data Analysis

Difference scores (in words per minute) between the reading speeds of the older adult sample and IReST values were compared using planned directional one-sample t-tests. For each analysis, the alternative hypothesis stated that the mean was less than 0, with 95% confidence intervals around the mean difference, and Cohen's *d* as a measure of effect size. In addition, we also report Bayes factors to interpret the strength of evidence for the research (BF_{10}) and null hypothesis (BF_{01}; Dienes, 2011; Wetzels et al., 2011). Bayes factors were calculated using Jamovi 1.2 (The jamovi project, 2019), with the default Cauchy prior width of 0.707. As this choice of prior width may impact the results, we also conducted a robustness check of the posterior using two wider prior distributions (1.0, 1.5). Both of the wider prior distributions did not significantly impact the results.

Results

All anonymous data and subsequent analysis are available through the Open Science Framework (https://osf.io/chtfp/).

Table 1.

Participants' Self-Reported Language Fluency

	n	No Ability	Elementary	Moderate	Very Good	Fluent
English	25					
Speaking		0	0	0	0	25
Reading		0	0	0	0	25
Writing		0	0	0	1	24
Listening		0	0	1	1	23
French	23					
Speaking		1	5	9	6	3
Reading		2	4	12	4	2
Writing		4	9	7	3	1
Listening		1	5	7	6	4
Other	7					
Speaking		2	2	1	2	0
Reading		2	4	0	1	0
Writing		4	2	1	0	0
Listening		2	1	3	1	0

Note. Of the 7 participants with third languages, these languages included: Greek, Hebrew, Mandarin, Spanish, and Urdu.

Descriptive Statistics

Participants' dominant language was English, 92% of participants were bilingual, and 28% of participants were trilingual (see table 1). Participants had a mean visual acuity of 0.03 logMAR (20/21 Snellen; M = 0.03, SD = 0.11, 95% CI: [-0.02 to 0.08]), and a mean contrast sensitivity of 1.78 logCS (M= 1.78, SD= 0.15, 95% CI: [1.72 – 1.84]). The average number of errors/omitted words across texts was 1.36 words (*SD*= 1.89).

Canadian Older Adult Sample Compared to British IReST Values

Reading speeds of Canadian older adults were significantly slower than the standardized values provided by the manufacturer of the IReST (table 2). In all cases, the calculated *P-values* were less than .001, with the mean difference scores ranging from -47.7 words per minute to -27.3 words per minute, 95% confidence intervals ranging from -59.4 to -15.6 (Figure 1), and effect sizes ranging from -1.39 to -0.79. Bayes factor$_{10}$*'s* ranged from 121.12 to 2.16 x 10^{43}; such that the probability of the alternative hypothesis that the older adult sample would read slower than the published IReST was 121.12 to 2.16 x10^{43} times greater than the null hypothesis.

A one sample t-test was used to compare mean difference scores of participants overall reading speeds across the 10 IReST (*M*=190.4, *SD*=33.5) to the average of the reading speeds of the standardized values of the IReST (*M*=228.2; table 2). The overall mean reading speeds of Canadian older adults across the IReST were significantly slower than the standardized IReST values, *t*(249)=-17.8, *P*<.001, *Mdiff*=-37.84, *95% CI* [-41.3, -34.3], Cohen's *d* = -1.13, *95% CI* [-1.26, -0.99], *Bayes Factor*$_{10}$ = 2.17 x 10^{43}. The Bayes factor indicates the probability of the alternative hypothesis, i.e., older adult sample would read slower than the published IReST values, is 2.17 x 10^{43} times greater than the null hypothesis.

Discussion

The purpose of this study was to determine if the normative values provided by the IReST manufacturer are valid in older (60+) Canadian English speaking adults. As hypothesized, we found that older adults read the IReST significantly slower than the values provided by the IReST manufacturer. On average, older adults read the IReST 37.8 words per minute slower than the established values, and mean reading speeds consistently fell outside of the IReST measures of variability (Figure 1). The results of this study suggest that the standardized values provided by the IReST manufacturer do not capture the reading speeds of older English-speaking Canadian adults and are not valid in this population. It is recommended

Table 2.

Results of the One Sample t-tests Between Reading Speeds of British and Canadian Older Adults Samples on IReST.

IReST		British Sample	Canadian Sample			One Sample t-tests						
	n	*m*	*m*	*sd*	*Mdiff*	*df*	*t*	*P*	*95% CI:*	*Cohen's d*	*95% CI*	BF_{10}
1	25	236	192.9	38.7	-43.1	24	-5.57	< .001	[-56.3, -29.9]	-1.114	[-1.52, -0.68]	4368
2	25	243	200.7	38.6	-42.3	24	-5.48	< .001	[-55.5, -29.1]	-1.097	[-1.50, -0.66]	3588
3	25	227	190.0	29.5	-37.0	24	-6.26	< .001	[-47.1, -26.9]	-1.253	[-1.68, -0.80]	20975
4	25	244	196.3	34.3	-47.7	24	-6.95	< .001	[-59.4, -35.9]	-1.391	[-1.84, -0.91]	95942
5	25	229	195.5	29	-33.5	24	-5.77	< .001	[-43.4, -23.6]	-1.154	[-1.57, -0.71]	6852
6	25	197	165.0	26.5	-32.0	24	-6.05	< .001	[-41.1, -23]	-1.211	[-1.63, -0.76]	13091
7	25	232	192.6	30.5	-39.4	24	-6.44	< .001	[-49.8, -28.9]	-1.289	[-1.72, -0.83]	31245
8	25	237	197.3	31.7	-39.7	24	-6.26	< .001	[-50.6, -28.9]	-1.252	[-1.68, -0.80]	20722
9	25	226	198.7	34.1	-27.3	24	-3.99	< .001	[-39, -15.6]	-0.799	[-1.17, -0.41]	121
10	25	211	174.6	27.1	-36.4	24	-6.71	< .001	[-45.7, -27.1]	-1.342	[-1.78, -0.87]	56166
Mean	250	228.2	190.4	33.5	-37.8	249	-17.8	< .001	[-41.3, -34.3]	-1.13	[-1.26, -0.99]	2.17x10^{43}

Note. For all tests, the alternative hypothesis specifies that the mean is less than 0.

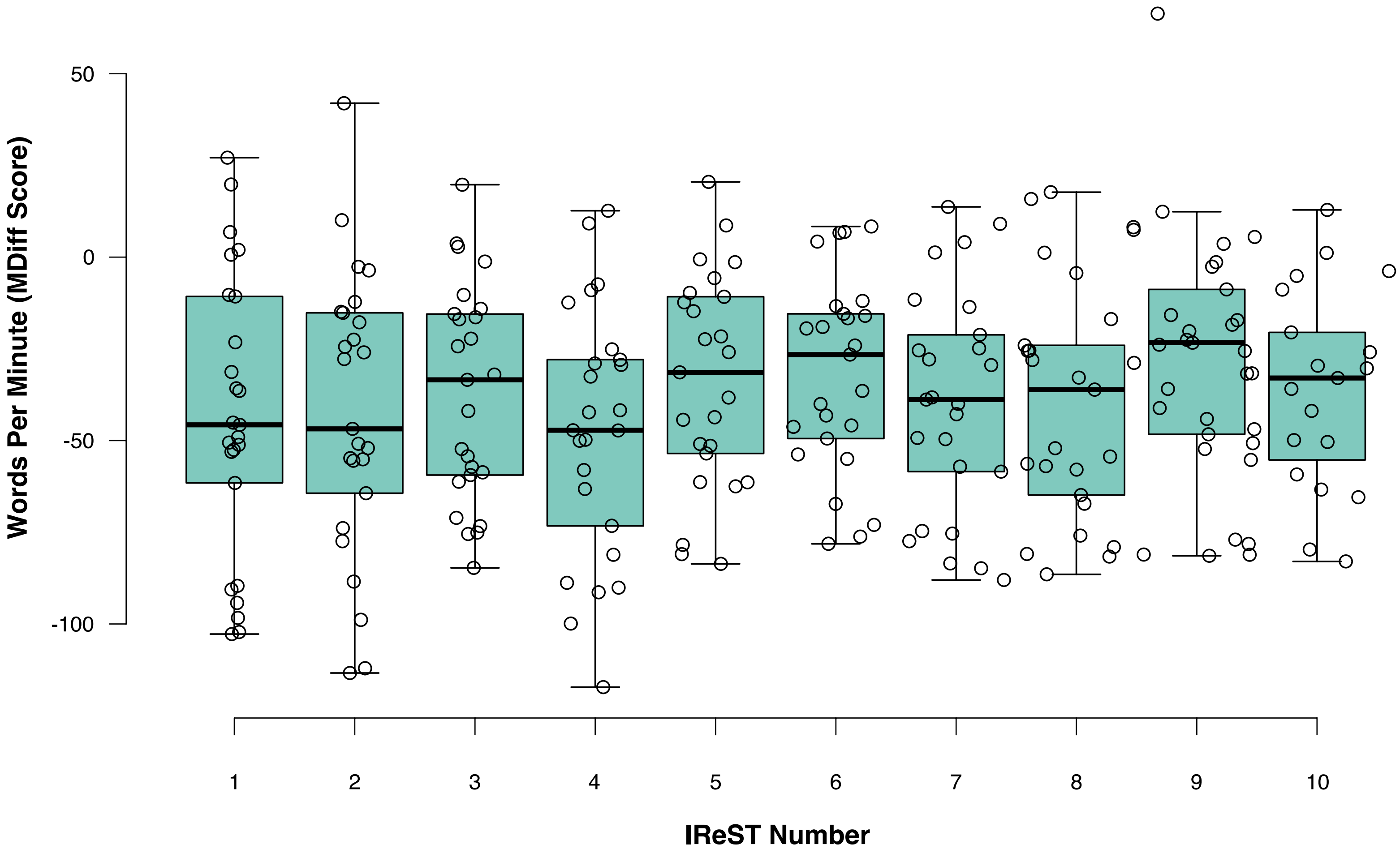


Figure 1. Mean difference scores in words per minute between Canadian Older Adults and British on the IReST. Boxplot of mean difference scores of reading speeds in words per minute on the International Reading Speed Texts (IReST) between the Canadian Older Adults and British English samples. Open circles represent data points, the medians are represented by the bold center lines, and the box limits are the 25th and 75th percentiles. The whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles.

that researchers and clinicians using the IReST to assess reading speeds in older adults use the values presented here (Table 2), as they will likely provide a more accurate estimate of this populations true reading speed. The results presented here are consistent with the original study used in the development of the IReST, Hahn et al. (2006), who found that on average older adults read the IReST at 951 characters per minute. If we assume that the average word in the English language has 5 characters, this results in older adults in the Hahn et al (2006) study having an average reading speed of 190.2 words per minute, which is comparable to the average reading speed of older adults in this study (M=190.4 words per minute). Using the baseline values reported here, the IReST can now be used to examine the impact of low vision rehabilitation pre/post intervention, e.g., before and after training using assistive technology devices, behavioural training, or improved lighting conditions, to examine how effective these interventions are at both the interpersonal and intrapersonal levels.

Previously, we have published data comparing Canadian young adults' reading speeds on the IReST to the published norms, whereby, young adults' (19 to 41-years-old) reading speeds fell within the standards established by the IReST (Morrice et al., 2020). A secondary analysis comparing reading speeds of Canadian young adults and older adults, indicates that Canadian older adults also read slower than Canadian young adults (M_{diff}=-40.42, 95% CI: [-44.49, -36.24]). It should also be noted that all of the young adults in our previous study were undergraduate students, whereas 88% of older adults in this study had at least an undergraduate degree, and 36% had graduate degrees as well. As only 3 participants in our sample did not have a university level education, it is unlikely that differences in education level were responsible for the observed differences in reading speed of Canadian older adults. In both younger and older adult samples, no participants reported any learning/attention disabilities, e.g., dyslexia, therefore these differences cannot be accounted for by learning or attention related difficulties. Other factors that may explain these differences in reading speeds could be age-related changes in reading habits, or alternatively pharmacological related side effects from medication, e.g., drowsiness, however, a limitation of this study is that these factors were not assessed.

Although all of the participants in this study were dominant English language readers, one of the limitations of this study is the use of a multilingual sample. Although our previous research has found that the IReST is valid in a sample of younger Canadian adults (18 to 41-years-old), the Canadian sample had a larger variability in reading speeds (*SD* ranging from

31.80-44.83) compared to the values provided by the IReST (*SD* ranging from 22-32). Consistent with our previously published data, we found that this sample of older adults also had a higher variability in reading speed (*SD* ranging from 26.7-40.0), compared to the standards provided by the IReST. It is possible the higher variability may be linked to the high number of bilinguals (92%) and trilinguals (28%) participants in the study. This may be accounted for by the "weaker links" hypothesis, which suggests that bilinguals, compared to monolinguals, are subject to subtle differences in language-based processing speed even when using their dominant language (Gollan et al., 2008; Gollan & Goldrick, 2012). Conversely, an investigation (Cop et al., 2015) of the eye-movement patterns of monolingual and bilingual participants under naturalistic reading conditions (a 56,000 word novel) found that there were no differences in reading performance or patterns of monolingual and bilingual readers in their dominant language (L1). Whereas, bilingual participants showed significant differences in their reading performance and patterns in their second language (L2) compared to their dominant language (L1; Cop et al., 2015). It is possible that the subtle differences in language-based processing speed proposed by the "weaker links" hypothesis may only be apparent when multilinguals complete language based tasks aloud, e.g., oral reading, as was the case in this study. As only two participants in this study were monolingual, we were unable to investigate this as potential explanation for the increased variability observed in our sample.

Given the significant differences in reading speeds between the sample of older adults and the values provided by the IReST manufacturer, it is suggested that the IReST study group develop normative reading speed values for older adults across all languages of the IReST. As we previously found no difference between the normative values of the IReST in Canadian young adults, and that the average reading speed of our older adult sample is similar to the findings of Hahn et al (2006), we suspect that the observed differences in reading speed are most likely due to age. It is hypothesized that these age-related differences in reading speed will likely occur across languages, in both bilingual and multilingual individuals. Future studies should assess how the use of reading comprehension questions with the IReST impact reading speeds across ages/languages, as our previous research has found using reading comprehension questions reduces reading speed by an average of 25 words per minute.(Morrice et al., 2020) It would be beneficial to know how this might affect the reading speeds of older adults, as older adults who, for example seek low vision rehabilitation, are typically more concerned about improving their reading ability and comprehension, as opposed to just improving their reading speed. Finally, future studies should examine the impact of visual impairments on reading speeds on the IReST to determine what normative reading speeds values of this population would be. This would be beneficial to low vision rehabilitation specialist, as they would then have points of comparison to evaluate patients.

CHAPTER 4:
STUDY 2

Assessing Optimal Colour and Illumination to Facilitate Reading

Note: Copy edited version of this study was published in *Ophthalmic and Physiological Optics*, February 2021

Abstract

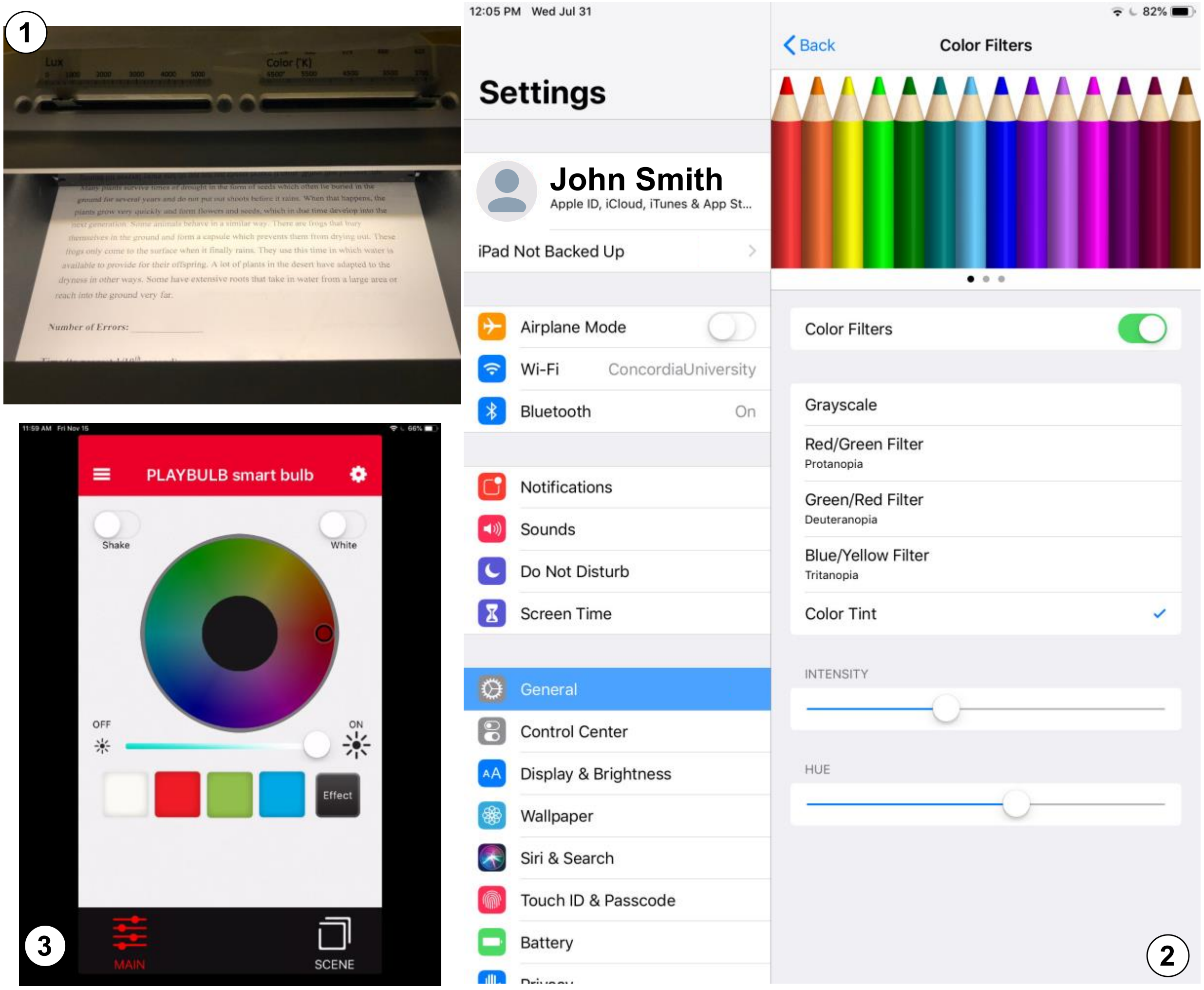
This study examined the effectiveness the LuxIQ, the Apple iPad, and a smart bulb in assessing optimal colour and illumination to facilitate reading in younger, older, and visually impaired adults. Participants read standardized texts at baseline (normal lighting/no device), then using the Apple iPad, LuxIQ, and smart bulb, with their normal vision (20/20 condition) and using a simulated reduction in visual acuity/contrast sensitivity (20/80 condition). Visually impaired participants followed the same procedure used in the 20/80 condition. There was a significant interaction between condition and device in younger ($F(1.5, 43.51) = 30.41$, $p < .001$, $\omega^2 = .34$) and older ($F(1.5, 4.51) = 4.51$, $p = .025$, $\omega^2 = .05$) adults with normal vision, and there was a significant effect of device ($F(2, 58) = 5.95$, $p = .004$, $\omega^2 = .12$) in visually impaired adults. In the 20/20 condition, age and colour predicted reading speed ($F(3,176) = 36.25$, $p < .001$, *Adj.* $R^2 = 0.37$), whereas age, lighting, and colour predicted reading speed ($F(3,176) = 36.25$, $p < .001$, *Adj.* $R^2 = 0.37$) in the 20/80 condition. In the visual impairment condition, lighting, colour, and impairment severity predicted reading speed ($F(3,85) = 10.10$, $p < .001$, *Adj.* $R^2 = 0.24$). The clinical implications of this study are that reading speeds improve in individuals with low vision under improved lighting conditions; specifically with higher levels of luminance and colour temperature. The effectiveness of the devices varied across groups, however, the LuxIQ was the only device to improve reading speeds from baseline in older adults with visual impairments.

Keywords: Reading, Low Vision, Lighting, Colour, Low Vision Rehabilitation

Introduction

Reading is an essential component of daily life, yet it is one of the most difficult tasks faced by individuals with visual impairments (Bown et al., 2014; D. B. Elliott et al., 1997; Owsley, 2009; Rubin, 2013). Factors such as magnification, lighting, and colour have been shown to improve reading speeds in the visually impaired, but there is no gold standard measure that can be used to assess optimal colour and illumination to facilitate reading (Brown et al., 2014; Cheong et al., 2002; Eperjesi et al., 2002; Eperjesi & Agelis, 2011; Nguyen et al., 2009; Owsley, 2009; Robinson, 2010; Wilkinson & Shahid, 2018; Zimmerman et al., 2010). Lighting can be broken down into three components: flicker, luminance, and colour. Flicker has been shown to impact in individuals with/without visual impairments, as well as reading disabilities, e.g., Dyslexia (Loew et al., 2015; Loew & Watson, 2012; Roberts & Wilkins, 2013; Wilkins, 2016; Yoshimoto et al., 2019). Increased luminance has consistently been shown to improve both reading speed and overall quality of life in the visually impaired (Bowers et al., 2001; Brunnström et al., 2004; Bullimore & Bailey, 1995; Fosse & Valberg, 2004; Haymes & Lee, 2006; Ram & Bhardwaj, 2017; Seiple et al., 2018). However, colour modifications through the use of assistive technology devices, e.g., different coloured lighting temperatures/hues, coloured lens filters, plastic coloured overlays, are controversial as there is scant and often contradictory evidence for their efficacy (Alabdulkader & Leat, 2010; Bowers et al., 2001; Brinker & Bruggeman, 1996; Denton & Meindl, 2016; Eperjesi et al., 2004a, 2004b, 2007; Bruce J. W. Evans & Joseph, 2002; Legge et al., 1985a, 1985b; Lightstone et al., 1999; Raasch & Rubin, 1993; Veszeli & Shepherd, 2019; Wilkins et al., 1996; Wilkinson & Shahid, 2018; Wolffsohn et al., 2012). Consequently, improved luminance is an essential component of low vision rehabilitation (LVR), while the effect of colour in LVR is likely to be more nuanced and individualistic. Unfortunately, in the field of LVR there is no accepted and validated gold standard measure that can be used to determine optimal colour and illumination to facilitate reading.

In LVR, lighting and colour needs are traditionally assessed in a variety of ways, e.g., light meters, home lighting assessment protocols, and trial and error using a variety of lamps/light bulbs (Corn & Erin, 2010; Gendeman et al., 2010; Perlmutter et al., 2013; Wittich et al., 2018). However, these methods are either unstandardized or not widely adopted. Novel measures, such as the LuxIQ, and/or mainstream technology devices, such as the Apple iPad and smart bulb, may



Wi-Fi ConcordiaUniversity

Bluetooth On

Color Filters ●

Color Tint ✓

Figure 1. Assistive technology devices: the LuxIQ, the Apple iPad, and the Playbulb smart bulb. The LuxIQ (1) is a portable device that can be used to assess optimal lighting and colour conditions for reading; material is placed under the device and the lighting and colour sliders are adjusted to the user's preference. The Apple iPad (2) is a tablet computer; display accommodations can be modified through accessibility options, such that intensity and hue of the device can be changed. The Playbulb (3) is an LED smart bulb that is controlled via Bluetooth connection using a mobile application, the lighting and colour output of the bulb can be changed based on user preferences.

be used as alternative methods for assessing optimal lighting/colour conditions to facilitate reading, and may offer a more standardized approach. The LuxIQ (Figure 1), is a small, portable device that can be used in both rehabilitation settings and home environments (Jasper Ridge, 2019). Reading material is simply placed under the device, and patients adjust the luminance and colour temperature/hue sliders to their preference. A criticism of the LuxIQ is that it has been found to have poor test-retest reliability in assessing lighting conditions in older adults with visual impairments (Wittich et al., 2018), and to our knowledge there have been no studies that have investigated the device's validity. The Apple iPad is an effective assistive technology device already used by individuals with low vision (Crossland et al., 2014; Morrice et al., 2017; Wittich et al., 2018). However, previous studies have only examined the basic functionality of the iPad, and there have been no studies looking at how the devices display accommodations effect reading speed/ability in the visually impaired. The display accommodations on the iPad modify the way in which content is presented on the device; such that colour filters change the colour hue/intensity of the display in a similar way to how the LuxIQ modifies the luminance and colour of print media. Display accommodations like these are not exclusive to the iPad, as they can be found on many tablet computers and mobile electronic devices; however, the iPad was used in this study given the previous research investigating the use of this device in individuals with low vision. Therefore the findings of this study may be generalizable other tablet computers that make use of display accommodation settings. Finally, a smart bulb is an inexpensive (~30$ CAD), LED light bulb controlled via Bluetooth connection from a mobile application on any smart device, e.g., cellular phone or tablet. Through the mobile application, a user can modify the luminance and change the colour temperature/hue of the light source. However, to our knowledge there have been no studies that have examined the use of smart bulbs in LVR, nor any studies that have examined their effect on reading speed/ability in the visually impaired. These devices were chosen as: (1) the LuxIQ is the only standardized measure currently used to assess lighting and colour conditions in LVR; (2) the iPad is an effective assistive technology device already used by individuals with low vision, however, lighting and colour capabilities of the device, to our knowledge, have not been assessed; and (3) the smart bulb may be a low cost alternative to the LuxIQ, but there have also, to our knowledge, been no studies investigating the effectiveness of smart bulb technology in the context of LVR . Therefore, the goal of this study was to examine the effectiveness of three assistive technology devices, the LuxIQ, the Apple iPad, and a smart bulb, as methods of assessing optimal colour and illumination to facilitate reading in younger, older, and visually impaired adults.

Method

The research followed the tenets of the Declaration of Helsinki. The research protocol was approved by the human research ethics committee of Concordia University (certificates 30003975 and 30006502) and the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal Research Ethics Board (CRIR-1401-0119) in accordance with the Canadian Tri-Council Policy Statement of ethical conduct for research involving humans (Canadian Institutes of Health Research et al., 2014).

Participants

Fifteen undergraduate students (11 female; 18-29 years-old; $M = 21.73$, $SD = 2.66$) and fifteen older adults (12 female; 62-75 years-old; $M = 68.67$, $SD = 3.92$) were recruited from the Concordia University Participant Pool and the Concordia Vision Labs participant database. Participants were required to have normal/corrected to normal vision. A sample of fifteen older adults with visual impairments (12 female; 70-96 years-old; $M = 82.73$, $SD = 9.66$) were recruited from the Lethbridge-Layton-Mackay Rehabilitation Centre. All participants were required to be dominant English language speakers. G*Power3.1 was used to determine the number of participants required to run a repeated measures ANOVA, testing within subject factors, for two groups with six measurements, using a large effect size ($f = .35$), a large correlation between measures ($r = 0.6$),and an alpha of .05, a total sample size of 14 was required to achieve power of .95.(Faul et al., 2007) A large effect and correlation was selected based on previously reported data examining the effect of simulated impairments on reading speed, and the impact of improved lighting conditions on reading performance (Bowers et al., 2001; Evans et al., 2010; Henry et al., 2020; Morrice et al., 2020; Smallfield et al., 2013). Two groups were selected, instead of three, as only two of the groups (younger/older adults) were in both the normal vision condition and simulated impairment condition. Whereas older adults with visual impairments could necessarily only be in the impairment condition. The six measurements were normal vision condition, LuxIQ, iPad, and smart bulb, and simulated impairment condition, LuxIQ, iPad, smart bulb. Theoretically there were 8 measurements when baseline is included, however, this resulted in a total sample size of 12. As reading speeds using each device were subtracted from baseline, and only six measurements were used in the analysis, this resulted in an increased sample size. Instead of using a total sample size of 14, we used 15 participants per condition for a total sample size of 45 (See OSF, https://osf.io/ekphj/).

Procedure

Pretest Battery and Materials

Informed consent was obtained from participants after explanation of the nature and possible consequences of the study, they then completed a pretest battery of questionnaires (~20 minutes) during which they adapted to the lighting conditions of the lab. The **Concordia University Language Background Questionnaire** was used to collect data on participants' first, second, and third languages, and self-reported speaking, reading, writing, and listening ability in English, French, and other languages (Segalowitz, 2009). Participants self-reported any visual/hearing impairments, and any known reading or attention disabilities. The **Montreal Cognitive Assessment (MoCA)** was used as a screener for mild cognitive impairment; participants completed the full MoCA (scored on 30 points), however, the MoCA-Blind (18 points) scoring procedure was used to better account for the cognitive abilities of the visually impaired sample (Dawes et al., 2019; Dupuis et al., 2015; Nasreddine et al., 2005; Wittich et al., 2010). The **Hardy, Rand, and Rittler (HRR) Pseudoisochromatic plates** were used to assess for the presence of colour blindness (Cole et al., 2006). Finally, participants completed the **Freiburg Visual Acuity and Contrast Sensitivity Test (FrACT)** (Bach, 1996; Kurtenbach et al., 2013; Schulze-Bonsel et al., 2006b).

Assessing Optimal Colour and Illumination

Younger and older non-visually impaired participants completed the normal vision condition (20/20 condition), then returned to the lab 1-week later to complete the simulated impairment condition (20/80 condition). In the 20/20 condition participants read eight texts from the **International Reading Speed Texts (IReST)** (Hahn et al., 2006; Trauzettel-Klosinski & Dietz, 2012). The IReST used were texts 1-5, and 7-9, a reading comprehension question was after reading reach text. Two IReST were read using the baseline lighting/colour conditions of the lab (217 lux, 3897 Kelvin); the remaining six texts were read using participants self-determined optimal lighting/colour preferences using the iPad Air (2013 edition: Apple, Cupertino, California), the LuxIQ (JasperRidge Inc., San Mateo, CA), and the Playbulb Smart bulb (MIPOW, Milpitas, CA), with two texts per device. When reading each text, other light sources in the room were turned off so that the only source of illumination came from the device. The order in which the texts were presented, and the order in which the devices were used were counter balanced to control for learning effects/fatigue. Before reading each text, participants were asked to “Choose the brightness and colour setting you find optimal for reading.” After reading each text participants reading speeds were noted, and their preferred brightness (lux) and colour settings (Kelvin) were recorded using a **HoldPeak-881C Digital Lux Meter** (HoldPeak, Zhuhai, China) and a **DataColor Spyder 3 Elite** (DataColor, Lawrenceville, New Jersey). The devices settings were reset after reading each text, and participants were again asked to choose their preferred brightness/colour settings.

One-week later participants returned to the lab to complete the 20/80 condition. In the 20/80 condition participants wore low vision simulator goggles, **Fork in the Road Goggles (20/80 [6/24]; WI, USA)**; when wearing these goggles (which are not tinted), participants experience a simulated reduction in visual acuity and contrast sensitivity across the entire visual field (Fork in the Road Vision Rehabilitation Services, n.d.). The goggles used in this study simulate a visual acuity of 0.60 logMAR (20/60 Snellen).[†] In the normal vision condition, participants wore the goggles with the lenses removed. As a manipulation check, participants completed the FrACT while wearing the goggles. Participants were then asked to read eight sets of **MNRead acuity charts** (Calabrèse et al., 2016, 2018; Mansfield et al., 1993; Mansfield et al., 2007). The MNRead were used in lieu of the IReST in the 20/80 condition, as participants were reportedly unable to read the small print-size of the IReST while wearing the goggles. The MNRead sentences used in this study were pulled from a recently published corpus of 9 million validated MNRead sentences (Mansfield et al., 2019). A non-linear mixed effect model from the *mnreadR* package in R was used to obtain participants predicted reading speeds at 0.4 logMAR (1 M size), the equivalent text size of the IReST (Calabrèse et al., n.d.; Cheung et al., 2008). Two MNRead charts were read using the baseline lighting/colour conditions of the lab, the remaining six charts were read using participants self-determined optimal lighting and colour preferences using the Apple iPad, the LuxIQ, and the smart bulb (two texts per device). The order in which the MNRead were presented, and the order in which the devices were used were counter balanced to control for practice effects/fatigue. Before reading each text participants were asked to “Choose the brightness and colour setting you find optimal for reading.” Participants reading

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[†] While there are no large scale studies investigating the effect of these goggles, we have a large unpublished data set (N=516) of younger and older adults indicating the goggles simulate a visual acuity of 0.57 logMar and contrast sensitivity of 0.93 logCS

speeds were noted after reading each sentence, when they could no longer read any of the sentences on the MNRead chart their preferred brightness (lux) and colour settings (Kelvin) were recorded. The devices settings were reset after reading each text, and participants were again asked to choose their preferred brightness/colour settings. Each participant completed an additional MNRead at baseline, without low vision simulator goggles, to determine if measure of reading speed were comparable to the IReST.

Participants with visual impairments (impairment condition) completed the same pretest measures as the 20/20 and 20/80 conditions, however, their visual acuity and contrast sensitivity were obtained from their medical chart. The impairment condition followed the same procedure used in the 20/80 condition.

Data Analysis

In younger and older adults with normal vision, two 2 (Condition) X 3 (Device) ANOVA's were used to assess device validity. In older adults with visual impairments, a one-way repeated measures ANOVA used to assess device validity. Difference scores in WPM were calculated between participants reading speeds for each device (Apple iPad, LuxIQ, and Smart bulb) and the average reading speed at baseline were compared across two conditions (20/20 and 20/80 conditions). Three multiple regressions (one per condition; 20/20, 20/80, Impairment) were used determine the impact of lighting and colour on reading speed. In the 20/20 and 20/80 conditions lux, Kelvin, and age (grouping variable: 1= young adult, 2 = older adult) were used as predictors, with reading speeds in WPM as the criterion. In the visual impairment condition lux, Kelvin, and acuity (grouping variable: 1 = acuity $\leq$0.6 logMAR, 2 = acuity >0.6 logMAR) were used as predictors, with reading speeds in WPM as the criterion. The data were analyzed using Kelvin, consistent with our literature review, and in order to make the results accessible to a clinical rehabilitation audience. However, the data is also available on OSF (https://osf.io/agsf5/) in CIE colour coordinates, should readers be interested in conducting analyses using these values.

Analyses were computed using traditional null hypothesis significance testing and Bayes factors (Dienes, 2011; Wetzels et al., 2011). Statistics were computed using JASP 0.13.1 (www.jasp-stats.org; JASP Team, 2020). Finally, 95% confidence intervals around the mean difference were used as a measure of the margin of uncertainty around the estimated difference between the two means, and ω^2 was used as a measure of effect size.

Results

All anonymous data and subsequent analysis are available through the Open Science Framework (https://osf.io/ekphj/).

Descriptive Statistics

See table 1 for a breakdown of participants self-reported language fluency and table 2 for participants visual acuity/contrast sensitivity, ocular pathology, and scores on the MoCA. There were significant differences in the ages of older adults with and without visual impairments ($t(28) = -5.22$, $p < .001$, *Cohen's d* = -1.91). All non-visually impaired participants completed the HRR screener without error. Only two of the visually impaired participants completed the colour blindness screener successfully. It is likely that visually impaired participants were unable to complete the HRR plates due to the visual acuity required to complete this task.

Manipulation Check

The low vision simulator goggles were effective at simulating a visual acuity of 0.6 logMAR in both younger (M_{logMAR}=0.54, SD=0.10, 95%CI [0.48, 0.60]; M_{logCS}=0.97, SD=0.18, 95%CI [0.87, 1.08]) and older adults (M_{logMAR}=0.69, SD=0.17, 95%CI [0.59, 0.79] M_{logCS}=0.83, SD=0.27, 95%CI [0.72, 1.02]). Reading speeds at baseline on the MNRead were comparable to reading speeds on the IReST in both younger (*Mdiff*=-10.37, t_{14}=-1.43, p=.18, *Cohen's d*=-0.37, 95% CI [-25.93, 5.19], BF_{10}=0.61) and older adults (*Mdiff*=-5.14, t_{14}=-0.59, p=.56, *Cohen's d*=-0.16, 95% CI [-23.55, 13.27], BF_{10}=0.31). In young adults the MNRead was compared to published IReST values with reading comprehension questions.(Morrice et al., 2020) As no published values exist of the IReST with comprehension questions for older adults, reading speeds were compared to older adults' own baseline IReST values.

Young Adults Device Validity – Repeated Measures 2 X 3 ANOVA

A 2 (Condition) X 3 (Device) repeated measures ANOVA was used to examine the validity of each device in young adults (table 3). Mauchly's test of sphericity was violated (χ^2_2=11.35, p=.003), and so degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ε=0.75). Results indicate that there was a significant interaction between Acuity and Device, $F_{1.5, 43.51}$= 30.41, p<.0001, ω^2=.34, BF_{10}=1.043x10^{20}, *error%*=5.06). Marginal means were compared to 0 (baseline) as post-hoc comparison. No devices were effective at improving reading speeds from baseline in the 20/20 condition (figure 2), however, in the 20/80 condition the LuxIQ and the smart bulb significantly improved reading speeds from baseline (table 4).

Table 1.

Self-Reported Language Fluency

		n	Group	No Ability	Elementary	Moderate	Very Good	Fluent
English	Speaking	15	YA	0	0	0	1	14
		15	OA	0	0	0	1	14
		15	AI	0	0	0	0	15
	Reading	15	YA	0	0	1	1	13
		15	OA	0	0	0	1	14
		15	AI	0	0	0	1	14
	Writing	15	YA	0	0	0	2	13
		15	OA	0	0	0	1	14
		15	AI	0	1	0	0	14
	Listening	15	YA	0	0	0	0	15
		15	OA	0	0	0	2	13
		15	AI	0	0	0	0	15
French	Speaking	14	YA	0	2	4	6	2
		14	OA	0	1	4	7	2
		13	AI	1	2	3	4	3
	Reading	14	YA	1	2	4	6	1
		14	OA	0	2	3	6	3
		13	AI	2	4	2	3	2
	Writing	14	YA	2	4	4	3	1
		14	OA	1	4	4	3	2
		13	AI	4	4	1	3	1
	Listening	14	YA	0	3	1	5	5
		14	OA	0	1	3	8	2
		13	AI	3	2	3	1	4
Other	Speaking	8	YA	1	1	3	0	3
		9	OA	0	6	0	3	0
		6	AI	1	1	1	0	3
	Reading	8	YA	1	4	1	2	0
		9	OA	1	3	2	2	1
		6	AI	1	2	0	0	3
	Writing	8	YA	4	3	1	0	0
		9	OA	3	3	1	2	0
		6	AI	1	2	0	0	3
	Listening	8	YA	1	0	1	4	2
		9	OA	0	3	1	1	4
		6	AI	1	1	0	1	3

Note. YA: Young Adult, OA: Older Adult, AI; Actual Impairment.

Table 2.
Descriptive Statistics

Visual Acuity and Contrast Sensitivity by Group		LogMAR (OU) M (SD)	LogCS (OU) M (SD)
Young Adults		-0.15 (0.03)	2.02 (0.13)
Older Adults (Normal Vision)		0.12 (0.15)	1.83 (0.23)
Older Adults (Visual Impairment)		0.89 (0.60)	1.21 (0.42)
Ocular Pathology of Older Adults with Visual Impairments		LogMAR (OU)	LogCS (OU)
AMD (Dry)		0.78	1.2
AMD, Glaucoma		1.3	0.84
AMD (Dry), Retinal Detachment		0.36	1.56
AMD (Dry-OD, Wet-OS)		1	0.96
AMD (Dry-OS, Wet OD), Glaucoma		0.9	1.28
AMD (Wet)		0.84	1.28
AMD (Wet)		0.48	0.78
AMD (Wet), Corneal Scarring (OS)		1.16	0.72
AMD (Wet), Pre-Glaucoma		1.08	0.96
AMD (Wet), Pre-Glaucoma		0.44	1.16
Cataracts, OU		0.41	1.62
Myopic Degeneration		0.8	0.96
Myopic Degeneration (Choroidal Neovascularization, Lamellar Formation)		0.1	1.44
Retinitis Pigmentosa		2.7	0
Trauma (OS), Occipital aneurysm (OD)		1	0.56
MoCA by Group		MoCA M (SD)	MoCA Blind M (SD)
Young Adults		25.93 (1.94)	19.67 (1.84)
	Pass/Fail Ratio =	1.5	6.5
Older Adults (Normal Vision)		25.93 (1.39)	19.60 (1.35
	Pass/Fail Ratio =	2	14
Older Adults (Visual Impairment)		20.53 (5.07)	16.00 (4.12)
	Pass/Fail Ratio =	0.26	0.667

Note. OD: Oculus Dexter (Right Eye), OS: Oculus Sinister (Left Eye), OU: Oculus Uterque (Both Eyes), MoCA: Montreal Cognitive Assessment.

Table 3

Mean reading speeds per condition, per device.

Condition	Device	n	M	SD	95% CI	Mdiff	95% CI
YA 20/20	Baseline	30	215.13	29.89	[203.97, 226.30]	-	-
	iPad	30	212.49	31.11	[200.87, 224.10]	-2.65	[-7.87, 2.57]
	LuxIQ	30	207.35	29.37	[196.38, 218.31]	-7.79	[-14.14, -1.44]
	Smart Bulb	30	212.78	28.74	[202.05, 223.52]	-2.35	[-7.17, 2.47]
YA 20/80	Baseline	30	38.58	25.34	[29.12, 48.04]	-	-
	iPad	30	42.62	30.24	[31.33, 53.91]	4.04	[-4.89, 12.97]
	LuxIQ	30	105.64	59.57	[83.39, 127.88]	67.06	[47.32, 86.80]
	Smart Bulb	30	57.06	34.01	[44.36, 69.75]	18.48	[7.09, 29.87]
OA 20/20	Baseline	30	153.20	38.23	[138.93, 167.48]	-	-
	iPad	30	169.14	24.36	[160.05, 178.24]	15.94	[5.51, 26.37]
	LuxIQ	30	172.42	28.73	[161.70, 183.15]	19.22	[9.05, 29.39]
	Smart Bulb	30	168.69	24.47	[159.55, 177.83]	15.49	[5.92, 25.06]
OA 20/80	Baseline	30	8.76	14.41	[3.38, 14.14]	-	-
	iPad	30	20.80	35.13	[7.68, 33.92]	12.04	[2.41, 20.35]
	LuxIQ	29[†]	50.81	46.84	[32.99, 68.62]	42.52	[28.71, 56.33]
	Smart Bulb	30	25.56	40.14	[10.57, 40.55]	16.81	[2.30, 33.44]
VI	Baseline	30	46.02	62.28	[22.80, 69.31]	-	-
	iPad	30	46.62	60.07	[24.19, 69.05]	0.56	[-5.48, 6.60]
	LuxIQ	30	57.62	80.06	[27.72, 87.51]	11.56	[2.92, 20.20]
	Smart Bulb	30	39.44	59.37	[17.27, 61.61]	-6.62	[-12.61, -0.63]

Note: [†]Data missing on one participant due to power outage during testing.

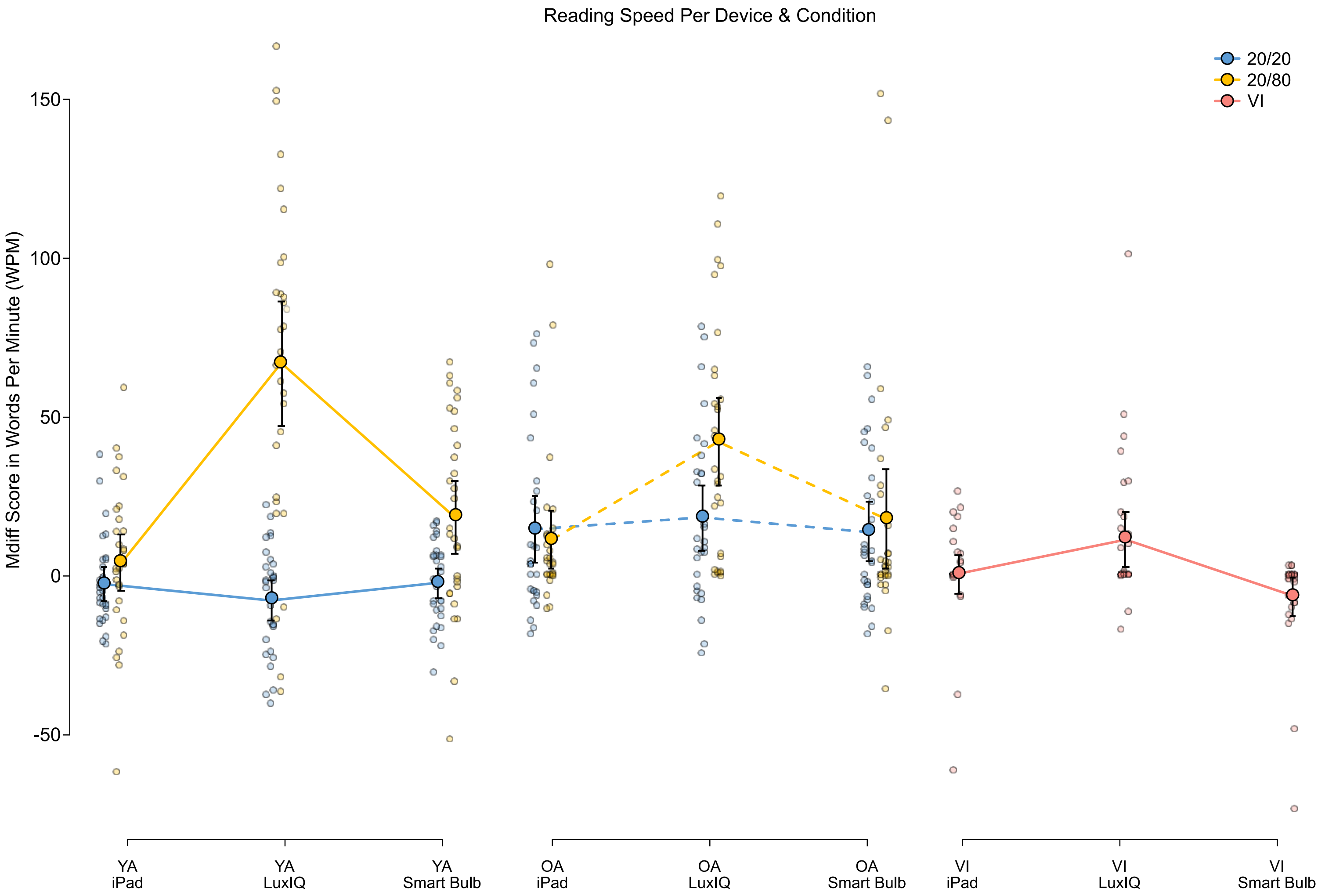

Figure 2. Mean difference scores of reading speeds in words per minute across conditions and devices. Mean difference scores between reading speeds at baseline and when using each device across conditions in young, old, and visually impaired adults. Error bars represent bootstrapped 95% confidence intervals around the mean difference (table 3). Note. YA = Young Adults, OA = Older Adults, VI = Older Adults with Visual Impairment.

Table 4.

Post Hoc Comparisons: Marginal Means compared to 0 (Baseline)

Condition	Device	Marginal Mean[†]	95% CI	SE	t	df	p	Cohen's d	95% CI	BF 10	Error %
YA 20/20											
	iPad	-2.65	[-13.01, 7.71]	5.24	-0.51	152.65	0.614	-0.19	[-0.55, 0.17]	0.318	0.002
	LuxIQ	-7.79	[-18.15, 2.58]	5.24	-1.49	152.65	0.139	-0.46	[-0.83, -0.08]	2.758	3.424 x10^{-6}
	Smart Bulb	-2.35	[-12.71, 8.01]	5.24	-0.45	152.65	0.655	-0.18	[-0.54, 0.18]	0.306	9.651 x10^{-4}
YA 20/80											
	iPad	4.043	[-6.31, 14.40]	5.24	0.77	152.65	0.442	0.17	[-0.19, 0.53]	0.288	1.194 x10^{-4}
	LuxIQ	67.06	[56.70, 77.41]	5.24	12.79	152.65	< .001	1.27	[0.78, 1.75]	124308.198	3.856 x10^{-8}
	Smart Bulb	18.48	[18.48, 28.83]	5.24	3.53	152.65	< .001	0.61	[0.21, 0.99]	15.12	1.954 x10^{-6}
OA 20/20											
	iPad	14.66	[3.40, 25.93]	5.70	2.57	144.09	0.011	0.57	[0.18, 0.95]	9.826	2.204 x10^{-6}
	LuxIQ	18.34	[7.07, 29.61]	5.70	3.22	144.09	0.002	0.71	[0.30, 1.10]	54.217	1.372 x10^{-4}
	Smart Bulb	13.91	[2.64, 25.17]	5.70	2.44	144.09	0.016	0.60	[0.21, 0.99]	14.85	1.963 x10^{-6}
OA 20/80											
	iPad	11.38	[0.11, 22.65]	5.70	1.99	144.09	0.048	0.51	[0.13, 0.89]	5.046	2.725 x10^{-6}
	LuxIQ	42.52	[31.26, 53.79]	5.70	7.46	144.09	< .001	1.17	[0.70, 1.64]	21599.896	1.450 x10^{-7}
	Smart Bulb	17.87	[6.60, 29.14]	5.70	3.14	144.09	0.002	0.41	[0.04, 0.78]	1.75	4.138 x10^{-6}
VI											
	iPad	0.56	[-6.25, 7.37]	3.42	0.16	80.46	0.87	0.04	[-0.32, 0.39]	0.198	0.012
	LuxIQ	11.56	[4.75, 18.37]	3.42	3.38	80.46	0.001	0.50	[0.12, 0.89]	4.305	2.884 x10^{-6}
	Smart Bulb	-6.62	[-13.43, 0.20]	3.42	-1.93	80.46	0.057	-0.41	[-0.78, -0.04]	1.737	4.150 x10^{-6}

Note: [†]Marginal Mean estimates represent mean difference scores from baseline reading speeds. YA = Young Adult, OA = Older Adults, VI = Older Adults with Visual Impairments.

Older Adults Device Validity – Repeated Measures 2 X 3 ANOVA

A 2 (Condition) X 3 (Device) repeated measures ANOVA was used to examine the validity of each device at improving reading speed in older adults (table 4). Mauchly's test of sphericity was violated (χ^2_2= 9.56, p=.008), and so degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ε=0.77). Results indicate that there was a significant interaction between Acuity and Device, $F_{1.5,\ 4.51}$= 4.51, p=.025, ω^2=.05, BF_{10}=20.90, *error%*=1.49). Marginal means were compared to 0 (baseline) as post-hoc comparisons. Each deice, the Apple iPad, LuxIQ, and smart bulb improved reading speeds from baseline in both the 20/20 and 20/80 conditions in older adults without visual impairments (table 4).

Older Adults (Visual Impairment) Device Validity – One Way Repeated Measures ANOVA

A one-way repeated measures ANOVA was used to examine the validity of each device in older adults with visual impairments (table 4). Results indicate that there was a significant effect of Device, $F_{2,\ 58}$=5.95, p=.004, ω^2=.12, BF_{10}=36.69, *error%* = 0.89). Marginal means were compared to 0 (baseline) as post-hos comparison. Only the LuxIQ significantly improved reading speeds from baseline in older adults with visual impairments.

Multiple Regression - Effect of Lighting and Colour (20/20 Condition)

A multiple regression was used to predict reading speed (WPM) from luminance (lux), colour temperature (Kelvin), and age (grouping variable: 1=young adults, 2=older adults) in individuals without visual impairments. The data were screened for assumptions and outliers, and no outliers were found. The assumptions of linearity, normality, homoscedasticity, and multicollinearity were met. The model significantly predicted reading speed, $F_{3,176}$=36.25, p<.0001, $Adj.\ R^2$=0.37, BF_{10}=2.264 x 10^{15} (table 5). Only Kelvin and Age were significant predictors in the model, whereby Age (b=-.54, t=-8.42, p<.0001) and Kelvin (b=-.16, t=-2.62, p=.010]) indicated significant reductions in reading speed (figure 3).

Multiple Regression - Effect of Lighting and Colour (20/80 Condition)

A multiple regression was used to predict reading speed (WPM) from luminance (lux), colour temperature (Kelvin), and age (grouping variable: 1=young adults, 2=older adults) in individuals with simulated reductions in visual acuity/contrast sensitivity. The data were screened for assumptions and outliers. Two outliers were identified (standard residual > 3) but were retained for the analysis. All assumptions of linearity, normality, homoscedasticity, and

Table 5.

Regression coefficients for the three regressions.

20/20 Condition – Younger and Older Adults Model Coefficients

			95% Confidence Interval					95% Confidence Interval	
Predictor	**Estimate**	**SE**	**Lower**	**Upper**	**t**	**p**	**Stand. Estimate**	**Lower**	**Upper**
Intercept	260.68	7.28	246.314	275.047	35.81	< .0001			
Lux	-0.003	0.002	-0.006	$5.675*10^{-4}$	-1.65	0.100	-0.11	-0.23	0.02
Kelvin	-0.002	$9.036*10^{-4}$	-0.004	$-5.828*10^{-4}$	-2.62	0.010	-0.16	-0.29	-0.04
Age	-36.77	4.364	-45.390	-28.159	-8.42	< .0001	-0.54	-0.66	-0.41

20/80 Condition – Younger and Older Adults Model Coefficients

			95% Confidence Interval					95% Confidence Interval	
Predictor	**Estimate**	**SE**	**Lower**	**Upper**	**t**	**p**	**Stand. Estimate**	**Lower**	**Upper**
Intercept	118.63	13.04	92.90	144.36	9.10	< .0001			
Lux	0.01	0.002	0.006	0.015	4.60	< .0001	0.31	0.18	0.45
Kelvin	-0.003	0.002	-0.006	$-1.095*10^{-4}$	-2.04	0.042	-0.14	-0.27	-0.005
Age	-43.07	6.65	-56.19	-29.96	-6.48	< .0001	-0.43	-0.56	-0.23

Impairment Condition - Model Coefficients

			95% Confidence Interval					95% Confidence Interval	
Predictor	**Estimate**	**SE**	**Lower**	**Upper**	**t**	**p**	**Stand. Estimate**	**Lower**	**Upper**
Intercept	48.88	26.50	-3.81	102.77	1.88	0.063			
Lux	0.02	0.005	0.01	0.03	4.20	< .0001	0.41	0.22	0.61
Kelvin	0.005	0.002	$2.06*10^{-4}$	0.01	2.08	0.040	0.19	0.001	0.39
Impairment Severity	-31.54	12.72	-56.90	-6.23	-2.48	0.015	-0.24	-0.43	-0.05

Noye. Age (1 = Young Adults, 2 = Older Adult) and Impairment Severity (1 = ≤ 0.6 logMAR, 2 = > 0.6 logMAR) are grouping variables.

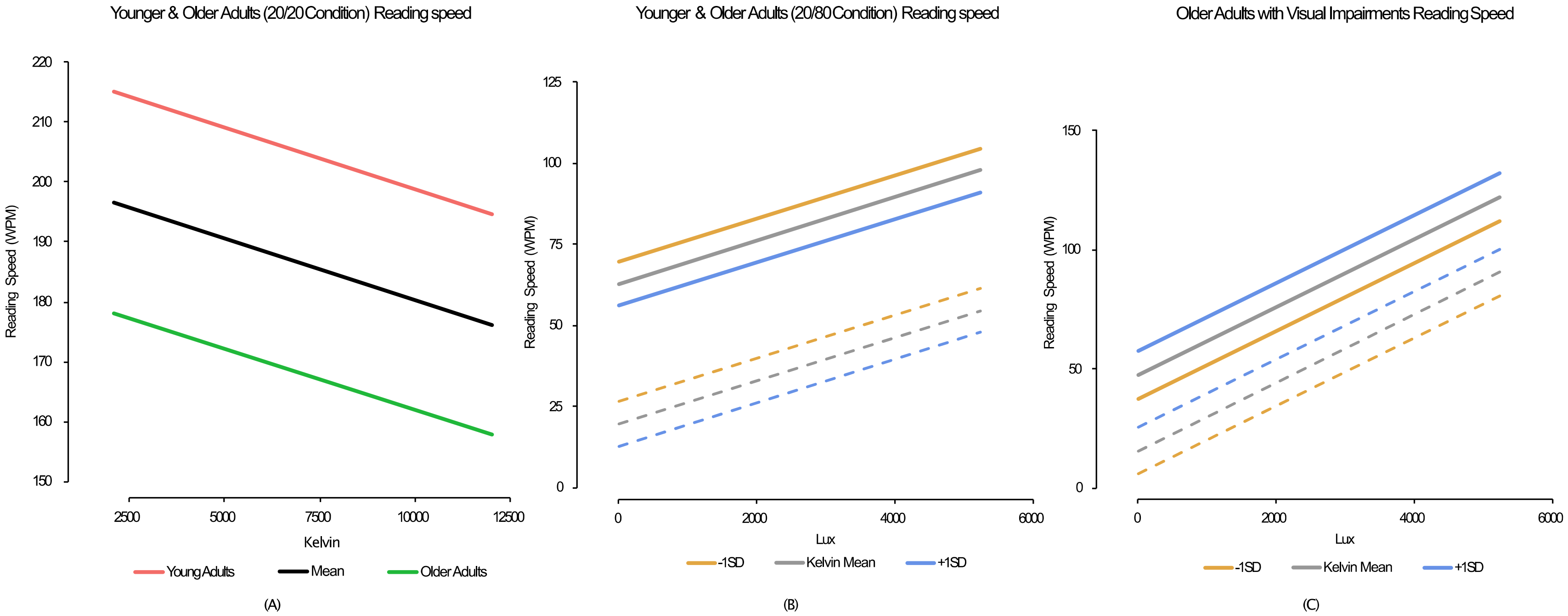

Figure 3. Predicting reading speed using Age, Lux, and Kelvin. (A) Predicting reading speeds in younger and older adults (20/20 condition). (B) predicting reading speeds in younger and older adults 20/80 condition; solid lines represent predicted reading speeds of younger adults, whereas dashed lines represent reading speeds of older adults. (C) Predicted reading speeds of older adults with visual impairments; solid lines represent participants with visual acuities ≤ 0.6 logMAR, whereas dashed lines represent participants with visual acuities > 0.6 logMAR.

multicollinearity were met. The model significantly predicted reading speed, $F_{3,175}=20.59$ $p<.0001$, *Adj.* $R^2=0.25$, $BF_{10}=5.266 \text{ x } 10^8$ (table 5). All predictors added significantly to the model; such that as Lux ($b=.31$ $t=4.60$, $p < .0001$) increased reading speed increased, and as Age ($b=-.43$, $t=-6.48$, $p<.0001$) and Kelvin ($b =-.14$, $t=-2.04$, $p =.042$) decreased reading speed increased. This is consistent with the ANOVA, such that the assistive technology devices improved reading speeds from baseline in both younger and older adults, however, younger adults saw greater improvements in reading speed compared to older adults.

Multiple Regression - Effect of Lighting and Colour (Impairment Condition)

A multiple regression was used to predict reading speed (WPM) from luminance (lux), colour temperature (Kelvin), and severity of impairment (grouping variable: 1 = ≤ 0.6 logMAR, 2 = > .06 logMAR) in individuals with visual impairments. The data were screened for assumptions and outliers, no outliers were found. The assumptions of linearity, homoscedasticity, and multicollinearity were met, however, the assumption of normality was violated. The violation of the assumption of normality was expected given the inherent variability in reading speeds of individuals with visual impairments, therefore the results should be interpreted with caution. The model significantly predicted reading speed, $F_{3,85}=10.23$, $p<.0001$, *Adj.* $R^2=0.27$, $BF_{10}=2{,}490.13$ (table 5). All predictors added significantly to the model, whereby Lux ($b =.41$, $t=4.18$, $p<.0001$) and Kelvin ($b=.2$, $t=2.08$, $p=.040$) increased as reading speed increased, and, as impairment severity ($b=-.24$, $t=-2.48$, $p=.015$) increased, reading speed decreased.

Discussion

The purpose of this study was to investigate the effectiveness of the LuxIQ, the Apple iPad, and the Smart bulb, as methods of assessing optimal colour and illumination to facilitate reading in younger, older, and visually impaired adults. Devices equally improved reading speeds in older adults in the 20/20 condition by an average of 17 WPM. In the 20/80 condition, the LuxIQ (+67 WPM) and the smart bulb (+15 WPM) improved reading speeds in young adults. Whereas each device, the LuxIQ (+43 WPM), the smart bulb (+18 WPM), and the iPad (+11 WPM) improved reading speeds in older adults in the 20/80 condition. Finally, older adults with visual impairments only saw significant improvements in reading speeds when using the LuxIQ (+11 WPM).

The effect of luminance, colour, age, and impairment severity were investigated as predictors of reading speed. In younger and older adults (20/20 condition), colour temperature and age were significant predictors of reading speed; such that younger adults read faster than older adults, and both younger and older adults read significantly faster at lower colour temperatures (2,673 Kelvin). In younger and older adults (20/80 condition), luminance, colour temperature, and age were significant predictors of reading speed, whereby participants read significantly faster at higher lux and lower colour temperatures and younger adults in the 20/80 condition read faster than older adults. Finally, in older adults with visual impairments (impairment condition), luminance, colour temperature, and impairment severity were significant predictors of reading speed, whereby participants read significantly faster at higher lux values, higher colour temperatures, and when their visual impairment(s) were less severe.

The findings of this study suggest the LuxIQ is most effective at improving reading speeds at small print-sizes, i.e., newspaper print (10-point times new roman font), across all conditions. This is consistent with the literature that suggest that increased luminance improves reading speed in individuals with visual impairments (Eperjesi et al., 2004a; Wolffsohn et al., 2012). The reason the LuxIQ may been the most successful device at improving reading speeds in this study is due to participants low acuity reserve at this print-size (Mohammed & Dickinson, 2000). In general, individuals with low vision require an acuity reserve of 3:1 in order to achieve near maximum reading speed, and when acuity reserves are low, they require increased illumination to compensate.(Lovie-Kitchin & Whittaker, 1999; Seiple et al., 2018) Interestingly, older adults with visual impairments read significantly faster at higher colour temperatures, whereas younger/older adults in the 20/80 condition read faster at lower colour temperatures. These findings are in line research by Wolffsohn et al. (2012) who found that individuals with visual impairments who have more experience using assistive technology devices read faster at high colour temperatures. These findings are also consistent with a recent study which found older adults with visual impairments preferred higher colour temperatures and illumination for reading (Henry et al., 2020). Given that participants in the impairment condition were recruited from a low vision rehabilitation center, it is conceivable they may have received previous training in selecting lighting and colour conditions that provide the maximum illumination with the highest contrast. Whereas younger and older would not have received this training, and therefore may have selected a colour temperature based on preference/comfort and less on functionality. Previous research has shown that high luminance contrast improves reading performance in individuals with low vision, therefore, it is conceivable that higher versus lower colour temperatures would lead to lead to greater luminance contrast (Knoblauch et al., 2008; Legge et al., 1990; Sinoo et al., 2011). This would explain how even at lower levels of illumination, higher colour temperatures lead to greater reading speeds as this would lead to greater luminance contrast. If individuals with low vision prefer reading with lower levels of illumination due to glare, then using higher colour temperatures at low illumination may help to improve reading speeds. It should also be noted that under normal clinical service conditions, the client is allowed to choose their light colour preference that they feel leads to an improvement in reading. In the current study we replicated this instruction to assess if this lead to a measurable improvement in reading speed. In our initial analysis of the colour data, we find no trend in the selection of colour temperature. A larger sample size could potentially allow us to explore this preference, but it was not the primary aim of the study. By providing the colour temperature information in the OSF repository, this will allow other researchers to view these data, and potentially use them in a meta analysis to answer this question.

The majority of participants with visual impairments in this study were diagnosed with age-related macular degeneration; therefore, researchers and clinicians should be cautious in generalizing the findings of this study to other ocular pathologies. The differences in the effectiveness of each device and the lighting/colour settings chosen by participant between the actual impairment sample and the simulated impairment sample should also be considered. The simulated impairment condition is the result of a degraded input of visual information before reaching an intact retina, whereas individuals with actual impairment experience distorted visual input caused by a damaged retina. A limitation of this study is that we only examined the effectiveness of devices at improving reading speed at 10-point font (0.4 logMAR/1.0 M size); however, individuals with visual impairments would likely read at larger text sizes, e.g. 18-point font (0.7 logMAR/ 2.0 M size). As the MNRead was used in the 20/80 condition, in the future we will examine whether device effectiveness varies as a function of print-sizes. Additionally, this study was completed under scotopic conditions; under photopic conditions these effects may be diminished. A conceptual limitation of the study was in comparing digital versus print media; on the iPad, participants read from a uniformly backlit display screen, whereas when using the LuxIQ and MIPOW Smart bulb, the illumination is subtractive and not necessarily uniform. Furthermore, at baseline we were unable to compare the colour gamut producible by each device, as we could not obtain this information for the smart bulb used in this study. Also, in this study chromaticity is represented as colour temperature (Kelvin) as this is often used to describe the light from low vision devices, however, it is acknowledged that the Kelvin scale does not fully describe chromaticity. Therefore, the data are available online (https://osf.io/agsf5/) in alternative formats that fully characterize the chromaticity (e.g., LUV). Finally, there were significant differences in the ages of older adults with normal vision and those with visual impairments; as a convenience samples were used. It is conceivable that part of the variability in device effectiveness at improving reading speeds in older adults with visual impairments may be accounted for by age-related effects.

In future studies we will examine the impact of these devices at improving reading speeds at a variety of print-sizes. This will allow us to compare the validity of each device at improving reading speeds at more ecologically valid print-sizes. Future studies will also examine the reliability of each device; while assessing the validity of each device at improving reading speed is important, it is equally important that the devices do so reliably.

CHAPTER 5:

STUDY 3

Assessing Optimal Colour and Illumination to Facilitate Reading: An Analysis of Print-size

Note: Copy edited version of this study was accepted to *Ophthalmic and Physiological Optics* in July 2021

Abstract

This study examined how optimal colour/illumination conditions and the efficacy of the Apple iPad, LuxIQ, and smart bulb varied as a function of print-size in younger, older, and visually impaired adults. Participants read standardized texts from the MNRead at baseline, then using the Apple iPad, LuxIQ, and smart bulb in the simulated low vision (SLV) condition. Visually impaired participants followed the same procedure (impairment condition). At 1.2 LogMAR (SLV) no light source improved reading speeds from baseline. In the impairment condition, the Apple iPad (*M*=9.49, *95% CI* [3.18, 19.42]) and LuxIQ (*M*=15.95 *95% CI* [9.54, 24.86]) improved the reading speeds. At a print-size of 0.8 LogMAR (SLV), the LuxIQ (*M*=13.04, *95% CI* [3.21, 21.27]) improved reading speeds of younger adults, whereas the Apple iPad (*M*=28.70, *95% CI* [14.65, 42.51]), LuxIQ (*M*=49.63, *95% CI* [30.04, 69.68]), and smart bulb (*M*=23.11, *95% CI* [3.33, 42.11]) improved the reading speeds of older adults. In the impairment condition, the Apple iPad (*M*=5.54, *95% CI* [0.31, 12.13]) and LuxIQ (*M*=13.90, *95% CI* [7.88, 23.49]) improved the reading speeds. In the SLV condition, only age was a significant predictor of reading speed at a print-size of 1.2 LogMAR ($F_{3,164}=10.74$ $p<.001$, *Adj.* $R^2=0.16$), while age and luminance, but not colour, were significant predictors at a print-size of 0.8 LogMAR ($F_{3,164}=52.52$ $p<.001$, *Adj.* $R^2=0.49$). In the visual impairment condition, both age and lux were significant predictors of reading speed at a print-size of 1.2 ($F_{3,85}=7.14$ $p<.001$, *Adj.* $R^2=0.20$) and 0.8 LogMAR ($F_{3,85}=7.97$ $p<.001$, *Adj.* $R^2=0.22$), but colour was not. These findings indicate that light source effectiveness and optimal colour/illumination vary as a function of print-size. Moreover, it appears that print-size is the most important factor at improving reading speeds, as print-size decreases luminance becomes crucial, and only at the smallest print-sizes does the effect of colour become useful.

Keywords: Reading, Print-size, Lighting, Colour, Low Vision

Introduction

Individuals with low vision often seek low vision rehabilitation services due to difficulty reading (Brown et al., 2014; Elliott et al., 1997; Fraser et al., 2015; Massof, 1995; Owsley et al., 2009; Rubin, 2013). Low vision rehabilitation specialists generally prescribe assistive magnification devices and/or provide behavioural training (e.g., preferred retinal locus or eccentric viewing training) aimed at improving reading speed (Brunnström et al., 2004; Corn & Erin, 2010; Gendeman et al., 2010; Lange et al., 2021; Nayeni et al., 2020; Perlmutter et al., 2013; Wittich et al., 2017; Zimmerman et al., 2010). Assistive devices often improve the reading speed and ability of those with visual impairments by modifying print-size and lighting conditions, i.e., luminance and colour. While there is substantial evidence showing the increased luminance and print-size improve reading, there has been contradictory evidence in the field with regards to the effects of coloured lighting on reading (Bowers et al., 2001; Brunnström et al., 2004; Denton & Meindl, 2016; Eperjesi et al., 2004a, 2004b, 2007; Bruce J.W. Evans & Allen, 2016; Lightstone et al., 1999; Lueck et al., 2003; Seiple et al., 2018; Veszeli & Shepherd, 2019; A. J. Wilkins et al., 1996; Arnold Wilkins, 2002; Wolffsohn et al., 2012). We have previously found that novel assistive technology or assessment devices, such as the Apple iPad, the LuxIQ, and the smart bulb, can be used to improve reading speed in individuals with and without visual impairments (Morrice et al., 2021). Additionally, we found that for reading at near with a small print-size (0.4 LogMAR; 1 M-Size), the optimal lighting and colour conditions to facilitate reading were light sources with a high brightness (lux) and colour temperature (Kelvin). A limitation of our previous study was that we did not examine how the effectiveness of the devices (light sources) and lighting conditions varied as a function of print-size. Here we examine how reading speeds of younger and older adults with simulated visual impairments and older adults with actual visual impairments vary as a function of print-size, light source, and lighting/colour conditions.

Increased print-size has been found to be a reliable predictor of improved reading speeds in the visually impaired (Bailey et al., 2003; Chung et al., 1998; Legge & Bigelow, 2011; J. Mansfield et al., 1996; Seiple et al., 2018; Whittaker & Lovie-Kitchin, 1993). IIn practice, print-size can be increased using larger fonts, e.g., large print books (18-point font; 2M size), closer viewing distance, or through the use of assistive technology devices such as handheld magnifiers, CCTV, and/or iPad (Morrice et al., 2017; Robinson, 2010; Wittich et al., 2018;

Zimmerman et al., 2010). Print-size is a significant predictor of reading speeds in individuals with normal vision a study by Calabrèse and colleagues (2016) has shown that critical print-size, defined as the smallest print-size that can be read at an individual's maximum reading speed, increases with age. Younger adults can read smaller print-sizes at a faster reading speed compared to older adults; however, this difference decreases as the print-size increases. Indeed, it has been found that, at a small print-size (0.4 LogMAR; 1 M-Size), older adults (60+) read on average 38 words per minute slower than younger adults (Morrice et al., *In Press*). For individuals with visual impairments, there is a significant increase in critical print-size when compared to both younger and older adults with normal vision (Calabrèse et al., 2016; Legge et al., 1985; Legge et al., 1985). A number of factors can influence the critical print-size of individuals with visual impairments, with reductions in contrast sensitivity associated with vision loss being one of the most important factors (Legge et al., 1987; Owsley, 2016; Rubin & Legge, 1989).

Researchers have demonstrated that modifying luminance contrast can have a profound impact on the reading speeds of individuals with both normal vision and visual impairments (Legge et al., 1987; Rubin & Legge, 1989). In those with normal vision, reduced contrast at small print-sizes, i.e., < 0.5 LogMAR, resulted in significant and marked reductions in reading speed. Whereas at larger print-sizes, such as 0.8 LogMAR, the visual system was able to tolerate reductions in contrast such that participants were able to maintain reading speeds greater than 200 words per minute until contrast dropped below 0.10. (Legge et al., 1987). Conversely, the visual systems of individuals with visual impairments were less tolerant to reductions in contrast, and generally required four times the amount of contrast to maintain reading performance (Rubin & Legge, 1989). One way to increase perceived contrast, and thereby improve reading speed, is through increased luminance, i.e., brightness.

A study by Seiple et al. (2018) investigated how increased brightness interacts with print-size and reading speed in individuals with and without visual impairments. Participants read sentences from the MNRead at print-sizes ranging from 1.3 to 0.0 LogMAR and using illumination ranging from 3.5 to 696 cd/m^2. At 3.5 cd/m^2, they found that reading speeds increased as print-size increased; however, when illumination increased to 30 cd/m^2, they observed significant improvements in reading speeds only at small but not larger print-sizes. Interestingly, they found that any illumination greater than 30 cd/m^2 did not result in significant increases in reading speed for any print-size, and these results were consistent for both participants with normal vision and those with age related macular degeneration (AMD). They concluded that optimal lighting conditions are essential to improve reading speeds at small print-sizes; however, the strength of the effect diminishes as text size increases in both individuals with normal and low vision. Of note is that in this study, the researchers did not investigate the use of coloured lighting and its impact on reading in those with and without visual impairments. There appears to be a lack of literature that investigates how print-size, illumination, and colour interact with reading speed.

One reason for the diminished effect of illumination at larger print-sizes may be due to a reader's acuity reserve; defined as the ratio of the print-size to the reader's visual acuity (Mohammed & Dickinson, 2000). When a print-size is larger than a reader's visual acuity, this results in a high acuity reserve. Conversely, when a print-size is smaller than a reader's visual acuity this results in a low, or absent, acuity reserve. Researchers have found that individuals with low vision require an acuity reserve of 3:1 to achieve maximum or near maximum reading speeds (Lovie-Kitchin & Whittaker, 1999). Therefore at large print-sizes, where acuity reserve is high, the impact of lighting may be diminished. Conversely, at small print-sizes when acuity reserve is low, the impact of lighting may be crucial.

The purpose of this study is to investigate how optimal colour/illumination and the effectiveness of the Apple iPad, the LuxIQ, and the smart bulb vary as a function of print-size to facilitate reading in individuals with simulated and actual visual impairments. This study is a follow-up to our previous work, Morrice et al., 2021, where participants read standardized texts from the International Reading Speed Texts(IReST; normal vision condition) and the MNRead (simulated low vision/actual impairment conditions) using the iPad, LuxIQ, and smart bulb. Previously, (Morrice et al., 2021), we examined how these light sources and conditions influenced reading speeds at a fixed print-size of 0.4 LogMAR (1 M-size; 10-point Times New Roman font). Here, we conduct additional analyses on the data from the simulated low vision and actual impairment conditions collected previously[28] to examine how lighting, colour, and reading speed varies as a function of print-size; more specifically we (1) examine how reading speeds compared to baseline varied across light sources and conditions from print-sizes ranging from 1.3 to 0.0 LogMAR on the MNRead; (2) compared mean differences in reading speeds from baseline across light sources and conditions at print-sizes of 1.2, 0.8, and 0.4 LogMAR on the MNRead; and (3) conduct four additional multiple regressions using age, impairment severity, lux, and Kelvin as predictors of reading speed at print-sizes of 1.2 and 0.8 LogMAR in comparison to our previously reported regressions in Morrice et al. (2021) at a print-size of 0.4 LogMAR. It was hypothesized that the effectiveness of the light sources at improving reading speed would be greatest at lower print-sizes, and their effectiveness would decrease at larger print-sizes.

Method

The research followed the tenets of the Declaration of Helsinki. The research protocol was approved by the human research ethics committee of Concordia University (certificates 30003975 and 30006502) and the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal Research Ethics Board (CRIR-1401-0119) in accordance with the Canadian Tri-Council Policy Statement of ethical conduct for research involving humans (Canadian Institutes of Health Research et al., 2014b).

Participants

A total of 45 participants took part in this study: fifteen undergraduate students 11 female; 18-29 years-old; M = 21.73, SD = 2.66), fifteen older adults with normal vision (12 female; 62-75 years-old; M = 68.67, SD = 3.92), and fifteen older adults with visual impairments (12 female; 70-96 years-old; M = 82.73, SD = 9.66). Undergraduate students were recruited from the Concordia University Participant Pool, older adults with normal vision were recruited from the Concordia Vision Labs participant database, and older adults with visual impairments were recruited from the Lethbridge-Layton-Mackay Rehabilitation Centre. All participants were dominant English language speakers. The sample size conformed to an *a priori* power analysis for planned comparisons reported in Morrice et al. (2021): using G*Power3.1 to achieve power of .95 a total sample size of 14 was required to run a repeated measures ANOVA (within subject factors), with two groups, six measurements, using a large effect size (f = .35), a large correlation between measures (r = 0.6), and an alpha of .05 (Faul et al., 2007).

Procedure

The procedure reported here is the same that can be found in Morrice et al. (2021); however, the procedure for the normal vision condition (20/20 condition) is omitted as we do not conduct any new analyses on this condition.

Pre-test Battery

After an explanation of the nature of the study, participants provided informed consent. They then completed a pre-test battery of questionnaires, that took approximately 20 minutes, during which they adapted to the lighting conditions of the testing space. The pre-test battery consisted of the Concordia University Language Background Questionnaire (Segalowitz, 2009), the Montreal Cognitive Assessment (MoCA; Dawes et al., 2019; Dupuis et al., 2015; Nasreddine et al., 2005; Wittich et al., 2010), the Hardy, Rand, and Rittler (HRR) Pseudoisochromatic plates (B. L. Cole et al., 2006), and the Freiburg Visual Acuity and Contrast Sensitivity Test (FrACT) (Bach, 1996; Kurtenbach et al., 2013; Schulze-Bonsel et al., 2006b). These measures were used to assess participant language background, health history, cognitive functioning, colour blindness, and their visual acuity and contrast sensitivity.

Assessing Optimal Colour and Illumination

Participants with normal vision wore low vision simulator goggles (un-tinted) in the simulated low vision condition (SLV), Fork in the Road Goggles (WI, USA). While wearing the goggles, participants experience a simulated reduction in visual acuity and contrast sensitivity across the entire visual field. The goggles used in this study simulate a visual acuity of 0.60 LogMAR (20/60 Snellen).[†] Participants were then asked to read eight sets of MNRead acuity charts, with the sentences used in this study pulled from the validated online database of nine million MNRead sentences (Mansfield et al., 2019). A non-linear mixed effect (NLME) model from the *mnreadR* package in R was used to obtain participants predicted reading speeds across print-sizes of 1.3 to 0.0 LogMAR (Calabrèse et al., 2017; Cheung et al., 2008). Using the NLME model has been found to be a more precise and reliable way of estimating the MNRead reading parameters (Atilgan et al., 2020; Baskaran et al., 2019; Calabrèse, Cheong, et al., 2016; Calabrèse et al., 2018) The MNRead was used following the administration protocols: participants were asked to "*read each sentence aloud, as quickly and accurately as possible*," while the experimenter followed along with a stopwatch and marking any words that are omitted or read incorrectly. Participants were instructed to read each sentence, until they could no longer make out any of the words. Two MNRead charts were read using the baseline lighting/colour conditions of the lab (217 lux, 3897 Kelvin), and the remaining six charts were read using participants self-determined optimal lighting/colour preferences using the iPad Air (2013 edition:

[†] While there are no large-scale studies investigating the effect of these goggles, we have a large unpublished data set (N=516) of younger and older adults indicating the goggles simulate a visual acuity of 0.57 logMar and contrast sensitivity of 0.93 logCS

Apple, Cupertino, California), the LuxIQ (JasperRidge Inc., San Mateo, CA), and the Playbulb Smart bulb (MIPOW, Milpitas, CA), reading two charts per light source. When using the devices, i.e., iPad, LuxIQ, and smart bulb, the overhead lighting in the lab was turned off. Participants read each text under scotopic lighting conditions, with the only source of illumination coming from the device itself. The order of presentation of the MNRead charts and light sources were counterbalanced to control for practice effects/fatigue. Participants were instructed to "Choose the brightness and colour setting you find optimal for reading" before reading each chart. Reading speeds were recorded after reading each sentence, participants preferred brightness (lux) and colour settings (Kelvin) were recorded using a HoldPeak-881C Digital Lux Meter (HoldPeak, Zhuhai, China) and a DataColor Spyder 3 Elite (DataColor, Lawrenceville, New Jersey) once they were no longer able read any of the sentences on the chart. The settings on each light source were reset after reading each chart, and before reading the next chart participants were again asked to choose their optimal lighting and colour settings. Participants with visual impairments (impairment condition) completed the same pre-test measures and followed the same procedure used in the SLV condition.

Data Analysis

Descriptive statistics, i.e., mean, standard deviations, and 95% confidence intervals, for mean differences in reading speed from baseline are reported. Mean difference scores of reading speeds on each light source compared to baseline at print-sizes of 1.2, 0.8, and 0.4 LogMAR were analysed using 95% confidence intervals calculated using the bias-corrected accelerated bootstrap method based on 5,000 bootstrap samples (Haukoos, 2005; Henderson, 2005). Bootstrapping is a statistical method that estimates the sampling distribution by resampling one's own data. The key mechanism of the bootstrap is the random resampling with replacement, this allows for some of the original observations to be sampled more than once, in contrast other observations may not be resampled at all (Efron, 1979; Efron & Tibshirani, 1986; Haukoos, 2005; Henderson, 2005; Rousselet et al., n.d.). Therefore, there will be variation across the means of the bootstrapped samples, representing the variation that would be expected if we had collected data from a new sample of participants. Each resample is the same size (*N*) as the original, and a greater number of resamples provide a more precise estimate of the sampling distribution. Confidence intervals around the median of the bootstrap distribution can then be constructed. The bootstrapped confidence interval method was used to limit the inflation of alpha, as the a priori power analysis was based on planned comparisons reported in Morrice et al. (2021), and this will allow for a more meaningful interpretation of the results. Four additional multiple regressions were used to determine the effects of lighting, colour, age, and impairment severity on reading speeds at print-sizes of 1.2 and 0.8 LogMAR; this same analysis is reported in Morrice et al. (2021) for reading speeds at a print-size of 0.4 LogMAR. In the simulated impairment condition, lux, Kelvin, and age (grouping variable: 1= young adult, 2 = older adult) were used as predictors of reading speeds in words per minute at print-sizes of 1.2 and 0.8 LogMAR. In the visual impairment condition, lux, Kelvin, and acuity (1 = acuity ≤0.6 logMAR, 2 = acuity >0.6 logMAR) were used as predictors of reading speeds in words per minute at print-sizes of 1.2 and 0.8 LogMAR. Post-hoc power analyses for each regression were conducted and are reported in the results; however, in all cases power was greater than 0.98. Regressions were computed using traditional null hypothesis significance testing and Bayes factors, and R^2 was used as a measure of effect size (Dienes, 2011; Wetzels et al., 2011). Statistics were computed using JASP 0.14 (JASP Team, 2020).

Results

All anonymous data and subsequent analysis are available through the Open Science Framework (https://osf.io/9zk47/).

Descriptive Statistics

All participants in the simulated impairment conditions had normal or corrected-to-normal vision. Participants visual acuity, contrast sensitivity, and ocular pathology can be found in Morrice et al. (2021), and are included here as supplemental material. Participants mean difference scores of reading speeds with each light source compared to baseline across conditions at all print-sizes (1.3 to 0.0 LogMAR) can be found in table 1 and are visually presented in figure 1.

Effect of Device at 1.2, 0.8, and 0.4 LogMAR

Bootstrapped bias-corrected accelerated 95% confidence intervals based on 5,000 bootstrap samples were constructed around participants mean difference scores from baseline when using each light source at print-sizes of 1.2, 0.8, and 0.4 LogMAR (see table 2; see figure 2). No light source led to significantly improved reading speeds from baseline in younger and older adults with simulated impairments at a print-size of 1.2 LogMAR. On the other hand, in

Table 1.
Mean differences in reading speed across conditions, device, and print-sizes

Condition	LogMAR													
YA (SLV) *n* = 30	1.3	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
iPad														
Mdiff (SD)	5.2 (13.26)	5.35 (16.43)	5.5 (15.04)	5.56 (14.12)	5.33 (15.68)	4.41 (21.78)	2.38 (31.13)	-0.15 (38.58)	-0.19 (37.63)	4.04 (30.72)	7.68 (18.32)	3.76 (7.99)	0.93 (2.62)	0.15 (0.62)
95% CI	[0.25, 10.15]	[-0.78, 11.48]	[-0.11, 11.11]	[0.29, 10.83]	[-0.52, 11.18]	[-3.72, 12.54]	[-9.24, 14]	[-14.55, 14.25]	[-14.24, 13.86]	[-7.43, 15.51]	[0.84, 14.52]	[0.78, 6.74]	[-0.04, 1.91]	[-0.08, 0.38]
LuxIQ														
Mdiff (SD)	5.99 (16.95)	6.49 (17.66)	7.37 (17.32)	8.91 (17.62)	11.59 (19.49)	16.17 (23.94)	23.81 (31.21)	35.88 (40.23)	52.18 (47.63)	67.05 (55.67)	68.66 (54.82)	45.56 (42.92)	20.68 (28.76)	7.57 (16.02)
95% CI	[-0.34, 12.32]	[-0.09, 13.08]	[0.91, 13.83]	[2.33, 15.49]	[4.31, 18.87]	[7.23, 25.11]	[12.16, 35.46]	[20.86, 50.9]	[34.4, 69.96]	[46.27, 87.83]	[48.19, 89.13]	[29.54, 61.58]	[9.94, 31.42]	[1.59, 13.55]
Smart Bulb														
Mdiff (SD)	1.56 (17.82)	1.84 (18.5)	2.36 (17.2)	3.3 (16.27)	4.93 (17.13)	7.65 (21.37)	11.76 (28.37)	16.77 (34.76)	20.1 (38.02)	18.47 (37.5)	12.95 (24.47)	5.21 (10.12)	1.28 (2.94)	0.22 (0.73)
95% CI	[-5.09, 8.21]	[-5.06, 8.74]	[-4.06, 8.78]	[-2.77, 9.37]	[-1.46, 11.32]	[-0.33, 15.63]	[1.17, 22.35]	[3.79, 29.75]	[5.91, 34.29]	[4.47, 32.47]	[3.81, 22.09]	[1.43, 8.99]	[0.19, 2.37]	[-0.05, 0.49]
OA (SLV) *n* = 26														
iPad														
Mdiff (SD)	2.81 (22.49)	6.21 (22.07)	11.19 (23.28)	17.64 (27.34)	24.33 (33.17)	28.58 (37.3)	27.9 (36.89)	22.25 (31.25)	13.7 (21.25)	5.61 (10.36)	1.27 (2.94)	0.12 (0.35)	0 (0.01)	0 (0)
95% CI	[-6.27, 11.89]	[-2.7, 15.12]	[1.79, 20.59]	[6.6, 28.68]	[10.94, 37.72]	[13.52, 43.64]	[13, 42.8]	[9.63, 34.87]	[5.12, 22.28]	[1.43, 9.79]	[0.08, 2.46]	[-0.02, 0.26]	[0, 0]	[0, 0]
LuxIQ														
Mdiff (SD)	-1.43 (39.34)	3.88 (39.34)	11.96 (40.69)	23.18 (44.36)	36.68 (49.39)	49.52 (52)	57.64 (49.64)	58.4 (45.43)	51.31 (42.09)	37.91 (36.87)	22.64 (28.14)	10.73 (18.02)	4.03 (9.49)	1.16 (3.87)
95% CI	[-17.32, 14.46]	[-12.01, 19.77]	[-4.47, 28.39]	[5.26, 41.1]	[16.73, 56.63]	[28.52, 70.52]	[37.59, 77.69]	[40.05, 76.75]	[34.31, 68.31]	[23.02, 52.8]	[11.28, 34]	[3.46, 18]	[0.2, 7.86]	[-0.4, 2.72]
Smart Bulb														
Mdiff (SD)	0.32 (35.24)	3.27 (34.29)	7.56 (34.83)	13.12 (38.67)	18.93 (45.46)	23 (51.02)	23.88 (50.65)	22.05 (43.48)	17.97 (32.92)	11.86 (22.27)	5.72 (11.88)	1.68 (3.88)	0.22 (0.56)	0 (0.02)
95% CI	[-13.91, 14.55]	[-10.58, 17.12]	[-6.51, 21.63]	[-2.5, 28.74]	[0.57, 37.29]	[2.39, 43.61]	[3.43, 44.33]	[4.49, 39.61]	[4.68, 31.26]	[2.87, 20.85]	[0.92, 10.52]	[0.11, 3.25]	[0, 0.44]	[0, 0]
OA (VI) *n* = 30														
iPad														
Mdiff (SD)	8.07 (19.02)	8.54 (19.81)	8.91 (20.72)	8.04 (19.89)	6.1 (18.16)	3.74 (16.61)	1.91 (14.64)	0.65 (13.74)	0.04 (14.59)	0.56 (16.98)	1.4 (20.27)	0.07 (20.36)	-0.23 (13.25)	-1.36 (7.5)
95% CI	[0.97, 15.17]	[1.14, 15.94]	[1.18, 16.64]	[0.6, 15.47]	[-0.68, 12.88]	[-2.46, 9.94]	[-3.55, 7.37]	[-4.48, 5.78]	[-5.4, 5.48]	[-5.78, 6.9]	[-6.17, 8.97]	[-7.53, 7.67]	[-5.17, 4.71]	[-4.16, 1.44]
LuxIQ														
Mdiff (SD)	16.23 (19.74)	16.83 (19.14)	17.25 (18.94)	16.58 (19.18)	15.23 (19.65)	13.51 (19.37)	11.41 (18.67)	9.63 (19.05)	9.42 (20.42)	11.55 (23.01)	15.26 (28.7)	17.53 (33.38)	15.46 (28.82)	8.15 (17.87)
95% CI	[8.86, 23.6]	[9.69, 23.97]	[10.18, 24.32]	[9.42, 23.74]	[7.9, 22.56]	[6.28, 20.74]	[4.44, 18.38]	[2.52, 16.74]	[1.8, 17.04]	[2.96, 20.14]	[4.55, 25.97]	[5.07, 29.99]	[4.7, 26.22]	[1.48, 14.82]
Smart Bulb														
Mdiff (SD)	1.59 (16.97)	1.9 (17.97)	2.12 (18.98)	1.27 (19.5)	-0.49 (19.4)	-2.69 (17.86)	-4.45 (14.47)	-5.66 (13.76)	-6.4 (15.67)	-6.61 (17.68)	-5.05 (16.26)	-2.15 (14.28)	-0.62 (11.05)	-0.41 (5.93)
95% CI	[-4.74, 7.92]	[-4.81, 8.61]	[-4.96, 9.2]	[-6.01, 8.55]	[-7.73, 6.75]	[-9.36, 3.98]	[-9.85, 0.95]	[-10.79, -0.53]	[-12.25, -0.55]	[-13.21, -0.01]	[-11.12, 1.02]	[-7.48, 3.18]	[-4.74, 3.5]	[-2.62, 1.8]

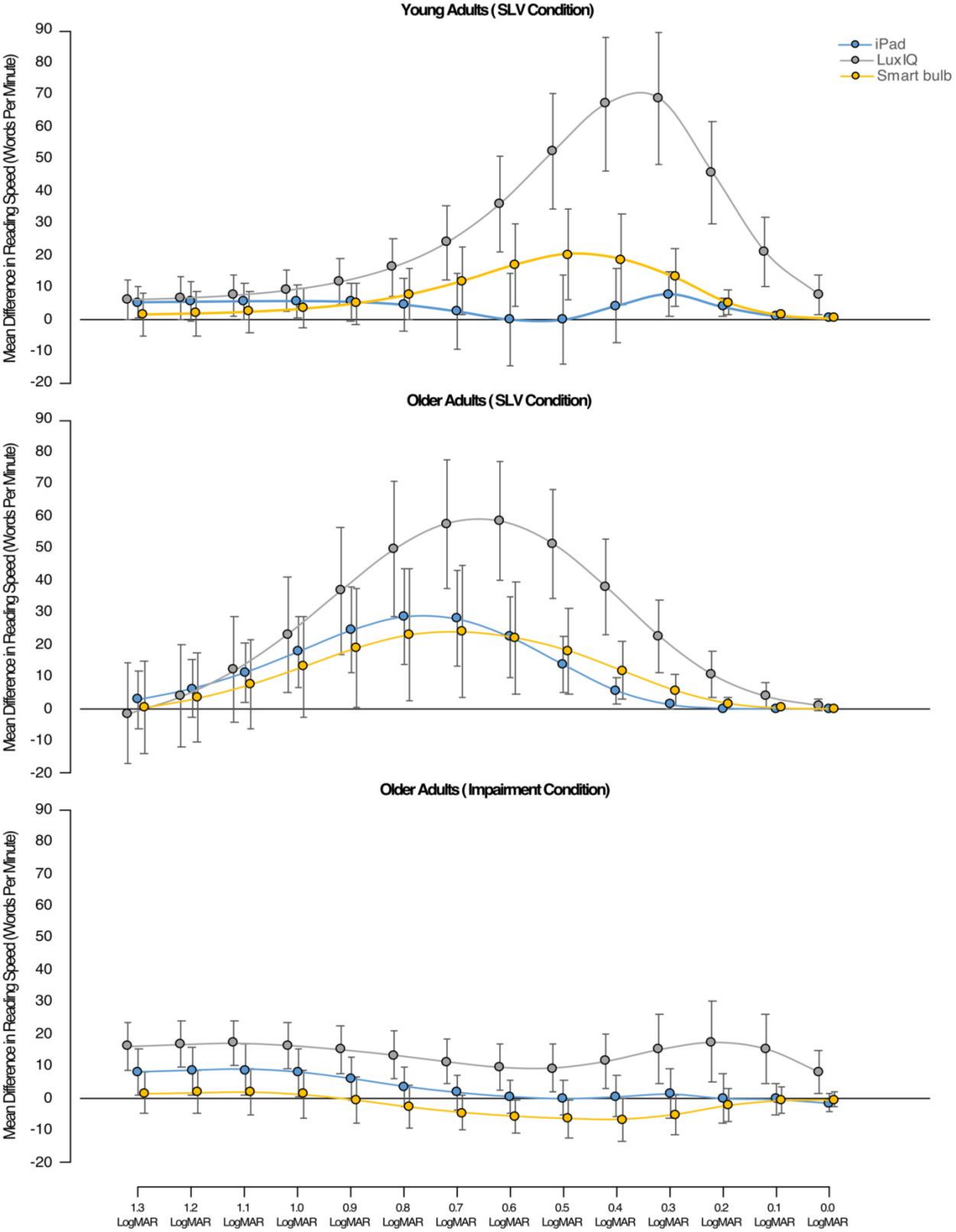

Figure 1. Mean reading speeds on each device, for each condition, across print-sizes. Participants means reading speeds and 95% confidence intervals from 1.3 to 0.0 LogMAR.

Table 2.
Marginal Means and bootstrapped 95% confidence intervals

Condition/ Light Sources		**Marginal Mean**	**bias**	**95% bca* CI**	
				Lower	**Upper**
1.2 LogMAR					
YA	iPad	5.14	-0.07	-0.37	11.98
	LuxIQ	3.96	-0.09	-2.05	10.94
	Smart Bulb	2.86	-0.08	-3.72	10.56
OA	iPad	6.12	-0.06	-1.81	15.07
	LuxIQ	3.89	-0.009	-11.005	18.95
	Smart Bulb	3.23	-0.03	-9.38	16.35
VI	iPad	9.49	-0.07	3.18	19.42
	LuxIQ	15.95	-0.09	9.54	24.86
	Smart Bulb	2.02	-0.0003	-5.29	8.781
0.8 LogMAR					
YA	iPad	4.22	0.001	-4.36	12.98
	LuxIQ	13.04	-0.03	3.21	21.27
	Smart Bulb	7.39	0.01	-0.19	15.54
OA	iPad	28.70	0.01	14.65	42.51
	LuxIQ	49.63	0.10	30.04	69.68
	Smart Bulb	23.11	0.10	3.33	42.11
VI	iPad	5.54	-0.009	0.31	12.13
	LuxIQ	13.90	-0.05	7.87	23.49
	Smart Bulb	-2.10	0.01	-10.04	4.45
0.4 LogMAR					
YA	iPad	-0.58	-0.01	-13.30	8.79
	LuxIQ	65.84	-0.06	44.87	85.40
	Smart Bulb	17.34	-0.03	3.28	29.84
OA	iPad	5.58	0.01	2.18	10.01
	LuxIQ	37.68	0.05	26.75	51.70
	Smart Bulb	11.81	0.05	5.95	19.94
VI	iPad	0.66	-0.03	-8.09	6.08
	LuxIQ	12.32	0.007	6.05	24.80
	Smart Bulb	-6.20	0.02	-18.43	-1.55

* Bias corrected accelerated.

Note. Bootstrapping based on 5000 successful replicates.

Note. Marginal Means estimate is based on the median of the bootstrap distribution.

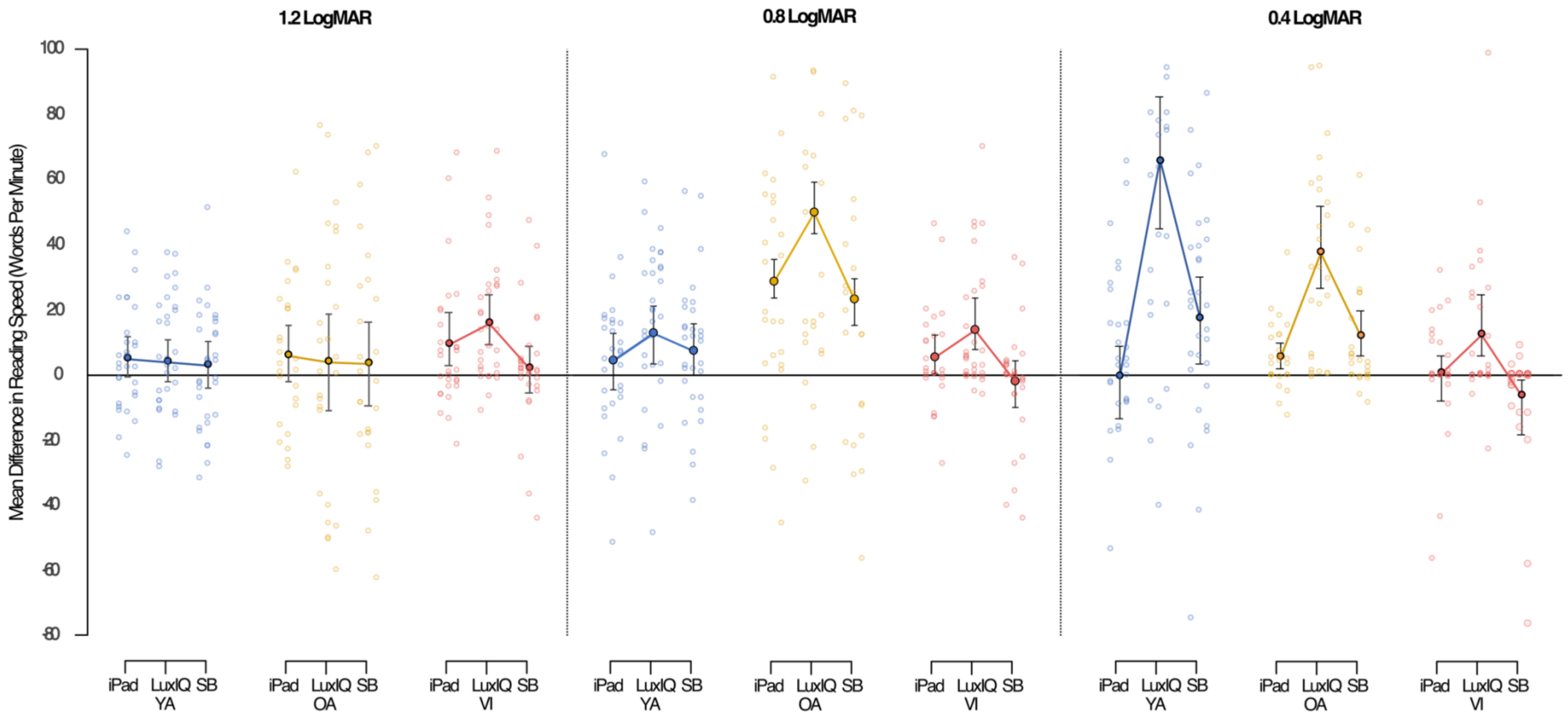

Figure 2. Mean difference scores of reading speeds in words per minute across conditions and light sources at print-sizes of 1.2, 0.8, and 0.4 LogMAR. Mean difference scores between reading speeds at baseline and when using each light source across conditions in young, old, and visually impaired adults .Marginal mean estimates and 95% confidence intervals were calculated using the bias-corrected accelerated bootstrap method based on 5,000 bootstrap samples. Note. SB = Smart bulb, YA = Young Adults, OA = Older Adults, VI = Older Adults with Visual Impairment.

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older adults with visual impairments both the iPad (*M*=9.49, *95% CI* [3.18, 19.42]) and the LuxIQ *M*=15.95 *95% CI* [9.54, 24.86]) improved reading speeds from baseline, however, the smart bulb had no effect. At a print-size of 0.8 LogMAR, the LuxIQ improved reading speeds from baseline in younger adults with simulated impairments (*M*=13.04, *95% CI* [3.21, 21.27]). Conversely all light sources, the iPad (*M*=28.70, *95% CI* [14.65, 42.51]), LuxIQ (*M*=49.63, *95% CI* [30.04, 69.68]), and smart bulb (*M*=23.11, *95% CI* [3.33, 42.11]) improved reading speeds of older adults with simulated impairments from baseline. The iPad (*M*=5.54, *95% CI* [0.31, 12.13]) and LuxIQ (*M*=13.90, *95% CI* [7.88, 23.49]) improved reading speeds from baseline at a print-size of 0.8 LogMAR in older adults with visual impairments. Finally, consistent with the findings reported in Morrice et al. (2021), in the simulated impairment condition the LuxIQ (*M*=65.84, *95% CI* [44.87, 85.40]) and smart bulb (*M*=17.34, *95% CI* [3.28, 29.84]) improved reading speeds of young adults from baseline, whereas each light source, the iPad (*M*=5.58 *95% CI* [2.18, 10.01]), LuxIQ (*M*=37.68, *95% CI* [26.75, 51.70]), and smart bulb (*M*=11.81, *95% CI* [5.95, 19.80]) improved reading speeds of older adults. In the visual impairment condition only the LuxIQ improved reading speeds from baseline (*M*=12.32, *95% CI* [6.05, 24.80]). Thus, generally for younger and older adults with simulated visual impairments, light source effectiveness at improving reading speed from baseline increased as print-size decreased. Comparatively, for old adults with visual impairments a broad range of light sources were effective at larger print-sizes, whereas only the LuxIQ was effective at the smallest print-size of 0.4 LogMAR.

Multiple Regression – Effect of lighting and colour at a print-size of 1.2 LogMAR (Simulated Low Vision Condition)

Note that for this and all subsequent regressions, data were screened for assumptions and outliers. No outliers were found, and all assumptions of linearity, normality, homoscedasticity, and multicollinearity were met. A multiple regression was used to predict reading speed in words per minute (WPM) at a print-size of 1.2 LogMAR from luminance (lux), colour temperature (Kelvin), and age (grouping variable: 1=young adults, 2=older adults) in individuals with simulated reductions in visual acuity/contrast sensitivity. The model significantly predicted reading speed, $F_{3,164}$=10.74 *p*<.001, *Adj.* R^2=0.16 BF_{10}=8348 (table 3). Age was the only significant predictor in the model, whereby increased Age (*b*=-.40, *t*=-5.44, *p*<.001) indicated a

Table 3.

Regression coefficients for the four regressions.

			95% Confidence Interval					95% Confidence Interval	
Predictor	**Estimate**	**SE**	**Lower**	**Upper**	**t**	**p**	**Stand. Estimate**	**Lower**	**Upper**
1.2 LogMAR - SLV Condition – Younger and Older Adults Model Coefficients									
Intercept	214.69	6.95	200.95	228.43	30.85	< .001			
Lux	0.00002	0.001	-0.002	0.002	0.01	0.987	0.001	-0.14	0.14
Kelvin	-0.0008	0.0008	-0.002	0.0008	-0.98	0.324	-0.072	-0.21	0.07
Age	-19.86	3.65	-27.07	-12.66	-5.44	< .001	-0.399	-0.54	-0.25
0.8 LogMAR - SLV Condition – Younger and Older Adults Model Coefficients									
Intercept	225.7	8.5	208.90	242.51	26.52	< .001			
Lux	0.005	0.001	0.002	0.008	3.08	0.002	0.180	0.06	0.29
Kelvin	0.00001	0.001	-0.002	0.002	-0.14	0.885	-0.008	-0.12	0.10
Age	-55.9	4.46	-64.72	-47.09	-12.52	< .001	-0.717	-0.83	-0.60
1.2 LogMAR - Impairment Condition – Older Adults Model Coefficients									
Intercept	144.07	29.18	86.06	202.08	4.93	< .001			
Lux	0.01	0.006	0.00004	0.023	1.99	0.049	0.204	0.0006	0.4
Kelvin	0.002	0.002	-0.003	0.006	0.63	0.525	0.063	-0.13	0.26
Impairment Severity	-51.02	14.00	-78.87	-23.18	-3.64	< .001	-0.362	-0.55	-0.16
0.8 LogMAR - Impairment Condition – Older Adults Model Coefficients									
Intercept	105.61	30.29	45.38	165.83	3.48	< .001			
Lux	0.018	0.006	0.005	0.029	2.89	0.005	0.292	0.09	0.49
Kelvin	0.003	0.003	-0.002	0.008	1.29	0.198	0.128	-0.06	0.32
Impairment Severity	-46.38	14.54	-75.27	-17.48	-3.19	0.002	-0.313	-0.50	-0.11

Note. Age (1 = Young Adults, 2 = Older Adult) and Impairment Severity (1 = ≤ 0.6 logMAR, 2 = > 0.6 logMAR) are grouping variables.

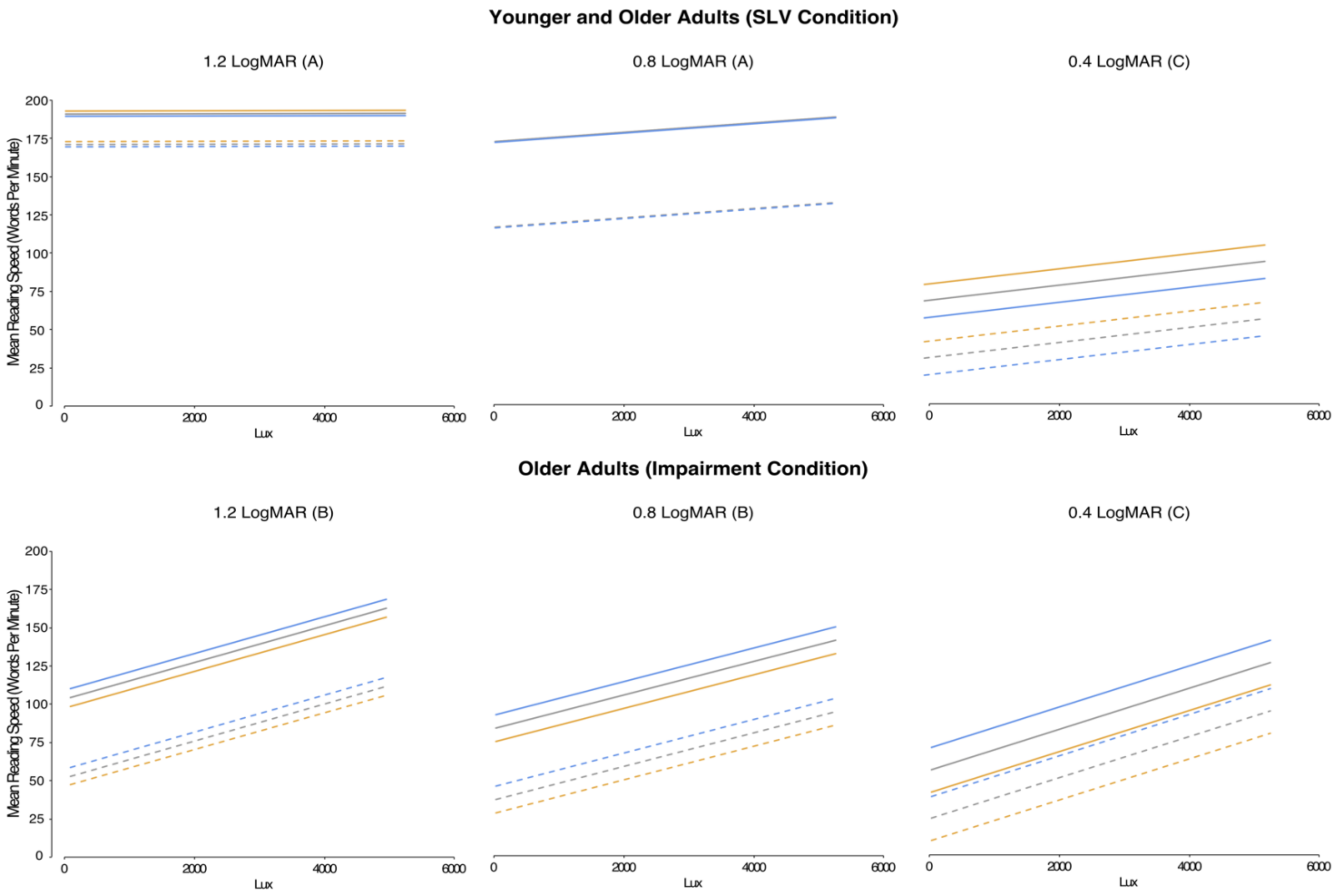

Figure 3. Predicting reading speed using Age, Impairment Severity, Lux, and Kelvin. (A) Predicting reading speeds in younger and older adults (SLV condition) at print-sizes of 1.2, 0.8, and 0.4 LogMAR: solid lines represent predicted reading speeds of younger adults, whereas dashed lines represent reading speeds of older adults. (B) Predicted reading speeds of older adults with visual impairments; solid lines represent participants with visual acuities ≤ 0.6 logMAR, whereas dashed lines represent participants with visual acuities > 0.6 logMAR. (C) Results for 0.4 LogMAR are reported in Morrice et al. (2021) and are present here for comparison.

significant reduction in reading speed (figure 3). A post hoc power analysis using G*Power3.1 with R^2=0.16, α=0.05, n=168, and 3 predictors, indicate power of 0.99 (Faul et al., 2007).

Multiple Regression – Effect of lighting and colour at a print-size of 0.8 LogMAR (Simulated Low Vision Condition)

A multiple regression was used to predict reading speed (WPM) at a print-size of 0.8 LogMAR from luminance (lux), colour temperature (Kelvin), and age (grouping variable: 1=young adults, 2=older adults) in individuals with simulated reductions in visual acuity/contrast sensitivity. The model significantly predicted reading speed, $F_{3,164}$=52.52 p<.001, *Adj.* R^2=0.49 BF_{10}=6.113 x 10^{20} (table 3). Only Age and lux were significant predictors in the model, whereby as Age increased (b=-.72, t=-12.53, p<.001) reading speed decreased and as lux increased (b=.18, t=-3.08, p=.002) reading speed increased (figure 3). A post hoc power analysis using G*Power3.1 with R^2=0.49, α=0.05, n=168, and 3 predictors, indicate power of 1.00 (Faul et al., 2007).

Multiple Regression – Effect of lighting and colour at a print-size of 1.2 LogMAR (Impairment Condition)

A multiple regression was used to predict reading speed (WPM) at a print-size of 1.2 LogMAR from luminance (lux), colour temperature (Kelvin), and impairment severity (grouping variable: 1 = ≤ 0.6 logMAR, 2 = > .06 logMAR) in individuals with visual impairments. The model significantly predicted reading speed, $F_{3,85}$=7.14 p<.001, *Adj.* R^2=0.20 BF_{10}= 101.48 (table 3). In this model, only impairment severity and lux were significant predictors. In the impairment condition at a print-size of 1.2 LogMAR as impairment severity increased (b=-.37, t=-3.64, p<.001) reading speed decreased, and as lux increased (b=.20 t=-1.99, p=.049) reading speed increased (figure 3). A post hoc power analysis using G*Power3.1 with R^2=0.20, α=0.05, n=89, and 3 predictors, indicate power of 0.98 (Faul et al., 2007).

Multiple Regression – Effect of lighting and colour at a print-size of 0.8 LogMAR (Impairment Condition)

A multiple regression was used to predict reading speed (WPM) at a print-size of 0.8 LogMAR from luminance (lux), colour temperature (Kelvin), and impairment severity (grouping variable: 1 = ≤ 0.6 logMAR, 2 = > .06 logMAR) in individuals with visual impairments. The model significantly predicted reading speed, $F_{3,85}$=7.97 p<.001, *Adj.* R^2=0.22 BF_{10}=245.76 (table 3). Consistent with the regression at a print-size of 1.2 LogMAR, only impairment severity and lux were significant predictors in this model at a print-size of 0.8 LogMAR. Here as impairment severity increased (*b*=-.31, *t*=-3.19, *p*=.002) reading speed decreased and as lux increased (*b*=.29 *t*=-2.89, *p*=.005) increased reading speed increased (figure 3). A post hoc power analysis using G*Power3.1 with R^2=0.22, α=0.05, *n*=164, and 3 predictors, indicate power of 0.99 (Faul et al., 2007).

Discussion

Previously, we have demonstrated that at a small print-size (0.4 LogMAR; 1 M-Size), high brightness (lux) and colour temperature (Kelvin) can facilitate reading (Morrice et al., 2021). Here we expand on these findings to explore how these results varied as a function of print-size to facilitate reading in individuals with simulated and actual visual impairments. As hypothesized, light source effectiveness varied as a function of print-size, such that the Apple iPad, the LuxIQ, and the smart bulb were generally most effective at lower print-sizes and less effective at higher print-sizes. Specifically, in younger and older adults (SLV condition; figure 2) there were no significant differences in light source effectiveness at improving reading speeds from baseline at a print-sizes of 1.2 LogMAR. At smaller print-sizes in younger and older adults (SLV condition), the LuxIQ consistently outperformed both the iPad and smart bulb at improving reading speeds at print-sizes of 0.8 and 0.4 LogMAR, with no differences in the effectiveness between the iPad and smart bulb. In older adults with real visual impairments, both the iPad and LuxIQ were effective at improving reading speeds at print-sizes of 1.2 and 0.8 LogMAR, however, at a print-size of 0.4 LogMAR only the LuxIQ significantly improved reading speeds from baseline. This latter finding is consistent with our previous findings. In general, see figure 1, all of the light sources were less effective at improving reading speeds from baseline in younger and older adults (SLV condition) at larger print-sizes, > 1.0 LogMAR, and were more effective at smaller print-sizes, ≤1.0 LogMAR. Whereas in the visual impairment condition devices were differentially effective at almost all print-sizes. Consistently across conditions, the LuxIQ was the most effective at improving reading speeds at smaller print-sizes (<1.0 LogMAR), while the iPad and smart bulb were generally equally effective and adequate at improving reading speeds from baseline at small print-sizes (≥ 1.0 LogMAR). It is important to note that the LuxIQ is generally used as an assessment device in low vision clinics to determine optimal lighting and colour conditions for reading, as opposed to an assistive technology device aimed to improve reading speed/ability. While the LuxIQ improved reading speeds at small print-sizes, future studies ought to examine the validity of the LuxIQ as an assessment device given that the optimal lighting/colour conditions chosen by participants across devices differed from those chosen using the LuxIQ.

The effects of age, impairment severity, lux, and Kelvin were also investigated as predictors of reading speed at print-sizes of 1.2 and 0.8 LogMAR. In younger and older adults (SLV condition) the only significant predictor of reading speed at a print-size of 1.2 LogMAR was age, such that older adults read slower than younger adults, this is consistent with our previous findings and the literature (Carver, 1992; Morrice et al., n.d., 2021). Whereas at a print-size of 0.8 LogMAR both age and lux significantly predicted reading speeds, such that as age increased reading speed decreased and as lux increased reading speeds increased. However, colour temperature (Kelvin) was not a significant predictor. These findings are consistent with the acuity reserve hypothesis, such that luminance is less effective at larger print-sizes in the SLV condition (Bailey et al., 2003; Lovie-Kitchin & Whittaker, 1999; Mohammed & Dickinson, 2000). As the average acuity of the SLV condition was 0.6 LogMAR, at a print-size of 1.2 LogMAR acuity reserve would equal 2 ($1.2 \div 0.6 = 2$) and therefore luminance would be less effective at improving reading speeds. Conversely, at a print-size of 0.8 LogMAR, acuity reserve would equal 1.33 ($0.8 \div 0.6 = 1.33$), and therefore increased luminance may be beneficial. In older adults with actual visual impairments (impairment condition) at a print-size of 1.2 LogMAR both impairment severity and lux were significant predictors, but Kelvin was not. As impairment severity increased reading speed decreased and as lux increased reading speed increased. The same results were found at a print-size 0.8 LogMAR, where again impairment severity and lux predicted reading speeds of older adults in the impairment condition. We again observed that as impairment severity increased reading speed decreased and as lux increased reading speed increased. These findings are again consistent with the acuity reserve hypothesis. However, in this case the luminance was effective at both larger and smaller print-sizes in the impairment condition. As the average acuity of the impairment condition was 0.9 LogMAR, at a print-size of 1.2 LogMAR acuity reserve would equal 1.33 ($1.2 \div 0.9 = 1.33$) and at a print-size of 0.8 LogMAR, acuity reserve would equal 0.89 ($0.8 \div 0.9 = 0.89$). Therefore, in the impairment condition luminance would be effective at improving reading speeds at almost all print-sizes presented to this sample. Interestingly colour temperature had no effect at larger print-sizes (1.2 and 0.8 LogMAR) in both conditions; compared to the findings of Morrice et al.

(2021) where at a small print-size of 0.4 LogMAR colour temperature was also a significant predictor of reading speed in both the SLV and impairment conditions (see figure 3). The differences between the SLV and impairment conditions is also an important avenue for future research as there are a variety of reasons why the impairment condition behaves differently than the SLV condition; e.g., cognitive deficits, reduced processing speed, abnormal eye movement patterns, compensatory strategies, age related decline, physiological differences/abnormalities (Frank et al., 2006; Paik et al., 2020; Rubin & Feely, 2009; Schacknow & Samples, 2010; Seiple et al., 2005; Whitson et al., 2013). In contrast, the SLV condition represents the impact of degraded visual input in the absence of the aforementioned factors, therefore in the future it may be relevant to compare the findings from the SLV conditions to individuals with early on-set low vision. The marked difference between data from participants with SLV compared with participants with a visual impairment highlights that it is not appropriate for researchers to use data from participants with SLV to predict the effect of a variable or intervention on patients with a visual impairment.

Taken together, these findings may provide an explanation for the inconsistencies in the literature for the effectiveness of the use of colour at improving reading speeds in the visually impaired. It may be that print-size is the most important factor at improving reading speeds, followed by luminance as print-size decreases, and the effect of colour only becomes useful at small print-sizes/acuity reserve, e.g., 10-12 point font (0.4 LogMAR; 1 M-size). This hypothesis would be consistent with the findings of Seiple et al. (2018) with regards to the effect of luminance and print-size on reading speed, and there may be also physiological and psychological evidence as to why coloured lighting is useful at smaller print-sizes. More recently (Morrice et al., 2021) it was found that individuals with visual impairments read faster with higher luminance and higher colour temperature lighting, which would be lighting closer to the shorter wavelength (blue) of the light spectrum. Physiologically, for those with central field loss caused by age related macular degeneration (the majority of this sample) visual functioning begins to rely more heavily on peripheral photoreceptors, of which the majority are rods. Rods are more sensitive to shorter wavelengths of light and therefore bluer light is then perceived as perceptually brighter (see literature on Purkinje shift; Anstis, 2002; Barlow, 1957; Barlow et al., 1957). Alternatively, research has found that rod dysfunction is one of the earliest bio-markers of AMD, and consequently although rods will perceive blue light as perceptually brighter they will still have difficulty resolving the visual detail (Owsley et al., 2016). Psychologically, clients at low vision rehabilitation centres (the majority of this sample) are taught to choose brightness and colour settings that provide maximum perceived contrast, i.e., a bright light with a high colour temperature. Therefore, optimal lighting conditions for reading in the visually impaired may be high brightness at larger print-sizes and high brightness and colour temperature for small print-sizes and future research is warranted on the underlying mechanisms.

A limitation of this study was that participants were required to use the same level of illumination/colour at each print-size to systematically examine the effect of print-size and device effectiveness. Under more ecologically valid conditions, participants would have been able to modify the lighting and colour conditions at each print-size. The testing was also completed under scotopic lighting conditions, it is conceivable that under photopic conditions the effects of print-size, lighting/colour conditions, and device may be less pronounced. As previously discussed (Morrice et al., 2021), a conceptual limitation of this study was in comparing digital versus print media; when using the iPad participants read using additive light from a uniformly backlit display, comparatively when using the LuxIQ and smart bulb the light source is subtractive and not necessarily uniform. Methodologically, the power analysis used to select the sample size in this study was based on planned comparisons reported in our earlier work (Morrice et al., 2021); however, post-hoc power analyses on the results from this study indicate power was greater than 0.98 for each analysis used here. Additionally, chromaticity is represented here as colour temperature; this is because Kelvin is frequently used to describe the light from low vision devices, however, it is noted that Kelvin does not fully describe chromaticity. The data have been made available online in alternative formats that fully characterize chromaticity (e.g., LUV, LAB, XYZ; https://osf.io/49ftr/). In future studies we will examine MNRead parameters not assessed here, including maximum reading speed, critical print-size, and the reading accessibility index (Calabrèse, Owsley, et al., 2016). Researchers and clinicians ought to be cautious when comparing these findings to other tablet and digital devices. While there are other digital devices, tablets, and PCs available on the market and used by individuals with low vision, the Apple iPad was chosen for use in this study due to previous research that has investigated its efficacy for use in low vision rehabilitation (Crossland et al., 2014; Mednick et al., 2017; Morrice et al., 2017; Wittich, Jarry, et al., 2018; Wu et al., 2020). Indeed, the display accommodation settings used in this study are not exclusively available on the iPad as they can be found on other devices, however, each digital device is unique in its luminance output capability and the type of display accommodations that are available. Therefore, while the findings of this study may be generalizable to other tablet computers and digital devices, comparisons ought to be made with caution. Finally, most participants in the impairment condition were diagnosed with age related macular degeneration; therefore, clinicians and researchers ought to be thoughtful in generalizing these findings to other forms of visual impairment. Comparisons between the SLV and impairment condition ought also be cautious, given that the simulated impairment is the result of degraded input of visual information before reaching an intact retina compared to distorted visual input caused by a damaged retina. In the future, we plan to examine the test re-test reliability of the light sources used in this study, while the light sources appear to be valid at improving reading speeds in the visually impaired it is important that they do so reliably.

In conclusion, it appears that at larger print-sizes, there are no significant differences between the effectiveness of the light sources at improving reading speeds. Therefore, those with visual impairments ought to choose a light source that they find most suitable for their individual needs; however, if they will be using the light source to read smaller print media, they would do well to consider a source that provides maximum brightness and colour temperature outputs. Additionally, for larger print-sizes where acuity reserves are higher, increased illumination may not be as beneficial; however, as print-sizes/acuity reserves decrease higher illumination and colour temperature lighting may be more beneficial to facilitate reading.

CHAPTER 6:
GENERAL DISCUSSION

The overall goal of this dissertation was to investigate the effects of lighting, colour, and print-size on reading through the use of three novel assistive technology devices. More specifically, it examined how the effectiveness of optimal levels of colour and illumination varied as a function of print-size and device in younger and older adults with normal vision/simulated reductions in visual acuity/contrast sensitivity and older adults with visual impairments. This was accomplished through three studies. Study 1 (Chapter 3) validated a standardized measure of reading speed, the IReST, to be used as reading materials in subsequent studies. The standardized value of the IReST are based on a sample of younger adults, and there are no published values for expected reading speeds of older adults. Study 2 (Chapter 4) explored how optimal lighting and colour conditions affected reading speeds in younger, older, and visually impaired adults at small print-sizes, 10-point Times New Roman Font. This study also examined the effectiveness of three novel assistive technology devices, the iPad, LuxIQ, and Smart Bulb, at manipulating optimal lighting and colour conditions to facilitate reading. Finally, Study 3 (Chapter 5) investigated how the effect of optimal colour and illumination varied as a function of print-size, from 1.3 LogMAR to 0.0 LogMAR. This study also investigated how the effectiveness of the devices varied as a function of print-size.

Summary of Research Findings

The findings of this research provide a deeper understanding of the impact of optimal lighting conditions on reading and accomplished the stated objectives of this dissertation. The first objective was to validate a standardized measure of reading speed in older adults (60+ years-old) to be used as reading material in this dissertation. Study 1 established that reading speeds of older adults were slower than the standardized values reported by the IReST manufacturer. These findings are consistent with the literature, showing that reading speeds decrease as age increases, and are actually consistent with the original study used to develop the IReST. The original study that reports the development of the IReST, Han et al. (2006), included a sample of older adults, however, they only reported reading speeds in characters per minute and these values are not provided by the IReST manufacturer. Han et al. (2006) found that older adults read on average 951 characters per minute; assuming that in English the average word has

5 characters, this equates to a reading speed of 190.2 words per minute, with the average reading speed of older adults in this study being 190.4 words per minute. This study achieves the first objective of this dissertation and has significant implications for both clinical and research practices: clinically, this will allow low vision rehabilitation specialists to accurately assess the reading speeds of older adults compared to age-matched controls with normal vision and thereby have an accurate assessment of patients reading ability. For researchers, the results of this study will allow them to have standardized values for comparison when using the IReST to investigate factors that influence reading speeds in older adults.

The second objective of this dissertation was to determine the effectiveness of novel assistive technology devices at manipulating lighting conditions to improve reading speed in individuals with visual impairments. In Study 2, it was shown that a variety of novel assistive technology devices can be used to improve reading speeds at a small print-size in younger and older adults with normal vision/simulated visual impairments, and older adults with actual visual impairments. In young adults with normal vision, there was no impact of device on reading speeds compared to baseline. This is expected given that young adults with normal/corrected-to-normal vision do not have age-related changes in vision, e.g., loss of elasticity in the lens, and can therefore resolve the visual information at baseline even without optimal lighting conditions provided by the devices. Conversely, with simulated reductions in visual acuity/contrast sensitivity, reading speeds were significantly improved from baseline in younger adults when using the LuxIQ and smart bulb. All devices improved reading speeds in older adults with normal/corrected-to-normal vision in both the normal vision and simulated impairment conditions. In the normal vision condition, there were no differences between device effectiveness, illustrating that older adults read faster than baseline with optimal lighting and colour conditions. In the simulated impairment condition, the LuxIQ saw the highest increases in reading speeds compared to baseline. Finally, older adults with visual impairments only saw significant improvements in reading speed from baseline when using the LuxIQ. It's hypothesized the LuxIQ was the most effective device at improving reading speeds across conditions due to its ability to produce the highest level of illumination compared to other devices; indeed, on average participants across conditions chose higher levels of illumination when using the LuxIQ. This study achieves the second objective of this dissertation and provides an evidence base for the use of these novel devices in low vision rehabilitation.

The third objective of this dissertation was to determine how the impact of lighting and colour effects reading speed in younger and older adults with normal/corrected to normal vision and with simulated reductions in visual acuity/contrast sensitivity. In Study 2, it was found that optimal levels of colour and illumination for reading at a small print-size varied across younger and older adults with normal vision and simulated impairments. Specifically, it was found that for younger and older adults in the normal vision condition that illumination did not predict increases in reading speed, however, colour temperature and age did predict reading speed, such that as age increases reading speed decreases and as colour temperature increases reading speed decreases. Conversely, in the simulated impairment condition colour, illumination, and age successfully predicted reading speed, such that as age increased reading speed decreased, as colour temperature decreased reading speed increased, and as illumination increased reading speed increased. This study achieves the third objective of this dissertation and these findings are consistent with the literature and the results of Study 1. Given that the literature, e.g., Henry et al. (2020), suggests older adults with visual impairments read faster at higher colour temperatures it was surprising that in both the normal and simulated impairment conditions younger and older adults read faster at lower colour temperatures. It is possible that participants chose lower colour temperatures based on subjective psychological comfort, which would be consistent with research by Yu and Akita (2019) who found that reading with lower colour temperature lighting facilitated feeling positive, secure, and restful. Physiologically, at higher levels of illumination research has shown that higher wavelengths of light (low colour temperature) are perceived as brighter than lower wavelengths (high colour temperature; Anstis, 2002; Barlow, 1957; Barlow et al., 1957). As the visual systems of this sample are intact, i.e., they do not have central field loss merely simulated reductions in acuity/contrast sensitivity, it is possible that even though a higher colour temperature may increase contrast it may not be perceived as brighter because vision will be cone mediated.

The fourth objective of this dissertation was to determine how the impact of lighting and colour effects reading speed in older adults with low vision. In Study 2, it was found that optimal levels of colour, illumination, and impairment severity predicted reading at a small print-size in older adults with visual impairments. Consistent with the literature, e.g., (Legge et al., 1985; Seiple et al., 2018; Wolffsohn et al., 2012), it was found that increased illumination increased reading speed, increased colour temperature increased reading speed, and increased impairment severity predicted decreased reading speed. This study achieves the fourth objective of this dissertation and this research is consistent with the literature indicating that increased brightness improves reading speed in the visually impaired, e.g., Brunnström et al., 2004; Cornelissen et al., 1995; Legge et al., 1987; Rubin & Legge, 1989; Seiple et al., 2018. These findings are also consistent with the findings of Wolffsohn and colleagues (2012) regarding the impact of colour temperature on reading speed, such that older adults with visual impairments in this sample read faster at higher colour temperatures. There are a few possible explanations for these findings; the first being that older adults with visual impairments in this study were recruited from a low vision rehabilitation centre and therefore likely already had received training to choose optimal lighting conditions that increase brightness and contrast to facilitate reading. If this is the case, then a high brightness at a high colour temperature would produce lighting conditions that maximize both lighting and contrast of the reading material. Another possibility is that given that the majority of the sample had a diagnosis of AMD, characterized by central field loss, is that this sample may be more likely to have rod mediated vision. If this is the case, then older adults with more severe impairments would perceive higher colour temperatures as brighter even at low levels of illumination, which is why then higher colour temperatures would increase reading speed. Finally, consistent with the literature, e.g., Legge et al., 1992; Owsley, 2016; Ramulu et al., 2009, as impairment severity increased, reading speed decreased.

The fifth and final objective of this dissertation was to determine how the effects of lighting, colour, and device on reading speed vary as a function of print-size in participants with simulated and actual visual impairments. In study 3, it was found that device effectiveness varied as a function of print-size and conditions; such that in the simulated impairment condition the devices were less effective at improving reading speeds from baseline at large print-sizes (1.2 LogMAR), but as print-size decreased device effectiveness increased. In both younger and older adults with simulated impairments the greatest effect appeared at the smallest print-sizes (≤0.4 LogMAR). In older adults with actual visual impairments, a greater number of devices were effective at improving reading speeds from baseline at larger print-sizes, but their effect diminished as print-size decreased. At the smallest print-sizes, ≤0.4 LogMAR, only the LuxIQ was effective at improving reading speeds in this sample, again this is likely due to the luminance output capabilities of this device. In the simulated impairment condition at a larger print-size, 1.2 LogMAR, neither luminance nor colour significantly predicted reading speeds, however age did, such that as age increased reading speed decreased. As print-size decreased in this sample, 0.8 LogMAR, both luminance and age became significant predictors of reading speed although colour was not, such that as age increased reading speed decreased and as lux increased reading speed increased. It was only at a smaller print-size, 0.4 LogMAR, that age, luminance, and colour, all became significant predictors of reading speeds (see objective 3; chapter 3). In older adults with visual impairments at both a medium and large print-size, 1.2 and 0.8 LogMAR, only impairment severity and luminance were significant predictors of readings speed, whereas colour was not a significant predictor, such that as impairment severity increased reading speed decreased and as luminance increased reading speed increased. Similar to the simulated impairment condition, colour only became a significant predictor of reading speed at a smaller print-size of 0.4 LogMAR (see objective 4; chapter 3). This study achieves the fifth objective of this dissertation and, taken together, these findings provide a clearer picture regarding the impacts of illumination, colour, and device effectiveness at a variety of print-sizes on reading speeds in individuals with simulated and actual visual impairments. Specifically, it appears that increased print-size is key to improving reading speeds across all conditions, however the efficacy of increased brightness and colour varies by print-size, age, and impairment severity. Moreover, the effect of colour appears to be implicated at improving reading speeds at select print-sizes; consistently being effective only at smaller print-sizes. With print-size considered, it appears as though effect of colour becomes diminished, proper illumination is essential, and device effectiveness may vary depending on the brightness output capability of the device.

Contributions to Theory and Research

Study 1 provides new standardized reading speed values, i.e., means and standard deviations, to be used when assessing the reading speeds of older adults (60+ years-old) using the IReST. This is an important contribution to the field of low vision rehabilitation, as it will allow low vision rehabilitation specialists to have a standardized measure of reading speed that does not overestimate the true reading speeds of older adults. Without these new values, baseline measures for comparison would be off by 38 words per minute. Using these new values clinicians can have a better measure for baseline levels of reading before low vision rehabilitation interventions and develop more accurate post-intervention models for improvements in reading speeds. Additionally, having more accurate baseline measures of reading speed using the IReST is important as some research (Brussee et al., 2014, 2015; Kortuem et al., 2020) has found that measures of reading speeds that use continuous paragraphs, as opposed to sentences, provide a more stable measure of reading speed over time.

This research also provides insight into the complex roles of illumination, colour, and print-size have on reading speeds in individuals with and without visual impairments. Previous research has shown that high illumination is important for improving reading speed in individuals with visual impairments and that the effect of illumination varies as a function of print-size (Bowers et al., 2001; Seiple et al., 2018). However, there have been few, if any, studies that have simultaneously investigated the role of illumination, colour, and print-size. This research is consistent with the literature showing that increased illumination and higher colour temperatures increase reading speed in the visually impaired. Importantly, it was found that in the absence of higher levels of illumination, e.g., less than 2000 lux, high colour temperatures can still increase reading speeds in the visually impaired. This is important as many older adults with severe visual impairments report they experience pain and glare at high levels of illumination (Brown et al., 2014; Hatton, 1977; Ko et al., 2014; Ludt, 1997; Stringham & Hammond, 2007); indeed, although not empirically tested, participants in this study incidentally reported they chose lower levels of illumination due to pain and glare. Furthermore, these findings are consistent with both the physiological, e.g., *Purkinje Shift*, and psychological, e.g., prior experience, explanations discussed in the literature review. Analyzing the effects of illumination and colour by systematically varying the print-size has also elucidated a reason as to why the effect of coloured lighting on reading is controversial in the literature: i.e., the effect of colour in this study only became effective as print-size decreased. In many studies researchers examine the data based on criterions such as maximum reading speed at participants critical print-size or logRAD, however, these criteria will be different for each participant. By examining the effect of illumination and colour at a variety of print-sizes systematically, it can be observed how these predictors of reading speed change as a function of print-size across all participants. Based on the findings of this research it appears that large print-size and high illumination are key factors to improving reading speed in the visually impaired, however, as print-size decreases the use of a higher colour temperature light source may be beneficial. As there are many situations where the print-size of reading material cannot be controlled, e.g., print media, the provision of assistive technology devices that can provide illumination at high colour temperatures may be beneficial. Moreover, the provision of assistive technology devices whose lighting and colour settings can be differentially adapted to suit a variety of situational/environmental circumstances would be ideal. For example, take the iPad: the iPad is an effective assistive technology device that can be used in a number of different environments, e.g., grocery store, pharmacy, living room, and its colour/illumination output can be modified to digitally augment the lighting/colour conditions of the environment to facilitate reading.

Finally, this research provides an empirical basis for the use of novel assistive technology devices, specifically the iPad, LuxIQ, and smart bulb, in low vision rehabilitation. The findings of Study 2 indicate that the LuxIQ was consistently the most effective device at improving reading speeds in individuals with normal vision, simulated impairments, and actual visual impairments at a variety of print-sizes. It is hypothesized that the effectiveness of this device hinges on its capacity for high luminance output. A limitation of the LuxIQ is that it can only be used for print media and has a small viewing window. Conversely, the smart bulb was not found to be an effective device at any print-size in older adults with visual impairments, while it did improve reading speeds in the normal vision and simulated impairment conditions. There are a number of reasons why the smart bulb may have been less effective: (1) the intensity of the luminance output was less than both the LuxIQ and the iPad; (2) the smart bulb was installed in an adjustable lamp, therefore participants could manipulate the distance from the reading material in the vertical and horizontal dimensions which could reduce the level of illumination; and (3) while the lamp shade directed the light towards the reading material, the light was not diffused equally, therefore there may have been regions of the text that were less illuminated than others. Given the utility of the device in the normal vision condition, it is possible that it may be a useful tool for older adults with visual impairments given the above limitations are addressed, and future inquiry is warranted. The iPad, however, may be the most promising device for use in low vision rehabilitation, given its proven effectiveness (Morrice et al., 2017; Wittich et al., 2018) and its versatility. The iPad can be used with both digital and print media: digital media can be viewed online or purchased through apps, whereas the camera on the device can be used as a spot magnifier or even as a CCTV given the purchase of an additional stand. Manipulating the lighting/colour output through the display accommodations will then in effect allow for an augmented reality when using the camera application for reading, magnification, etc. There are also a number of other accessibility services for use by individuals with low vision not assessed here, e.g., voice over, contrast manipulation, reversed polarity, text magnification, and applications that can be purchased/downloaded to facilitate use of the iPad for individuals with low vision. All three devices merit further investigation for their use in low vision rehabilitation services, however, it is clear that in the present research the LuxIQ and the iPad are the most effective devices for improving reading speeds in the visually impaired at a variety of print-sizes.

In summary, the studies presented in this dissertation provide significant contributions to theory, research, and the field of low vision rehabilitation and stand to make meaningful impacts on the lives of those with low vision. Study 1 will allow for researchers and clinicians to better assess the reading skills of individuals with visual impairments and deepens our understanding of the effects of aging on reading. Study 2 clarifies the roles of illumination, colour, age, and impairment severity on reading and empirically validates the usefulness of three novel assistive technology devices to improve reading speed in individuals with and without visual impairments. Finally, Study 3 provides a deeper understanding of how the effects of colour and illumination vary as a function of print-size, and therefore when specific devices and interventions might be most useful, e.g., coloured lighting at small print-sizes. The provision of these devices and interventions are essential for individuals with low vision given their effectiveness at improving reading speed and ability, as well as the profound downstream psycho-social effects these interventions can have on a person's quality of life.

Limitations and Future Directions

Although the studies presented in this dissertation make significant contributions to the field, they are not without limitation. Originally, the IReST had been intended to be used as the reading material across all conditions, however, older adults in the simulated and actual impairment conditions were unable to read the texts. This necessitated the use of different texts to be used in the simulated and actual impairment conditions: the MNRead. The IReST is a measure of reading speed that assesses continuous reading, whereas the MNRead assesses reading speed based on short sentences at print-sizes that decrease logarithmically in size. Therefore, it is conceivable that the reading processes engaged in the normal vision and simulated impairment conditions are different (Altpeter et al., 2015; Brussee et al., 2015; Kortuem et al., 2020). Indeed, when the average reading speed values at 0.4 LogMAR (10-point Times New Roman) are compared to the standardized values for older adults obtained in Study

1, there were significant differences in reading speeds between the two measures. However, there were no significant differences between reading speeds when using these two measures in Study 2 because participants were asked reading comprehension questions after reading each IReST. Our previous research, Morrice et al. 2020, found that asking participants reading comprehension questions when using the IReST resulted on average in a decrease in reading speed of 25 words per minute, which is consistent with the literature, e.g., Carver (1992). In doing so, this resulted in non-statistically significant differences in mean reading speeds at 0.4 LogMAR when using the MNRead compared to the IReST. This incidental finding warrants further investigation as it suggests that the MNRead may better account for reading for comprehension, whereas the IReST may better account for reading for speed. This limitation also uncovers a flaw with the IReST, given that the IReST are developed to assess the prolonged reading speed and ability of individuals with low vision, it is concerning that none of the visually impaired participants were able to successfully read the texts.

Another limitation of this research is that the three devices compared in these studies are not equivalent on a number of dimensions; (1) the lighting output capabilities of the devices differs greatly, i.e., the LuxIQ has a higher luminance output capabilities than the iPad and smart bulb; (2) the iPad and smart bulb are able to produce a wider range of coloured lighting compared to the LuxIQ; (3) the type of reading material was different across devices, i.e., when reading using the LuxIQ and smart bulb participants read print media, whereas when using the iPad they read digital media. Given the LuxIQ has a higher luminance output capability compared to the iPad and smart bulb, it is then not surprising that it was the most effective device across studies at improving reading speed. While the LuxIQ can produce higher lux values than the iPad and smart bulb, its ability to produce different coloured lighting is limited to green and red coloured lighting and colour temperature along the kelvin scale. Conversely the iPad and smart bulb can produce a much wider range of the colour gamut, e.g., reds, greens, blues, yellows, purples, white. While the data in these studies were analyzed based on the Kelvin colour temperature scale so as to keep the findings consistent with the literature and make the results available to a wider audience of both researchers and clinicians the data is available as CIE colour coordinates. Given that CIE colour coordinates may better account for chromaticity compared to the Kelvin scale, in the future secondary analyses on this data may find further differences in reading speed based on CIE colour space versus Kelvin. Additionally, when reading using the iPad the visual information was presented digitally, using additive light that was presented uniformly across the devices screen, comparatively when reading using the LuxIQ and smart bulb light is subtractive and not necessarily uniform. If differences in reading speed could be accounted for based on the digital versus print media limitation, it is more likely that the difference would be caused by then non-uniform representation of light than by the difference between additive versus subtractive light. This is because although there are differences in the way light is produced when additive versus subtractive, there is theoretically no difference in how the light is processed once the photons of light are absorbed by the photoreceptors. Finally, it ought to be noted that there were significant differences between the ages of the older adult samples; such that older adults with normal/simulated low vision were significantly younger than older adults with actual visual impairments. It is conceivable that part of the variability in device effectiveness at improving reading speeds in older adults with visual impairments observed in studies 2 and 3 may also be account for by age-related effects, e.g., cognitive deficits, physiological differences. Future studies ought to examine whether differences would be observed using age-matched samples.

Based on these limitations, further areas of inquiry grounded in these findings, and additional data collected but not analyzed in this dissertation there a number of future directions for this research. Further research ought to investigate whether reading speeds of older adults are different on the IReST in other languages. Given the importance placed by those seeking low vision rehabilitation on improving reading speed and ability, standardized reading comprehension questions ought to be developed for use with the IReST. This will allow clinicians and researchers to monitor not only patient/participants information processing, but their knowledge acquisition as well. As the IReST and MNRead appeared comparable when a reading comprehension question was used with the IReST, researchers ought to investigate whether these findings would be consistent in a larger sample. If they are truly comparable when a reading comprehension question is added, it will allow these tools to become complementary in their use in low vision rehabilitation. Future research is also warranted on the assistive technology devices used in these studies, as while it appears the devices are valid at improving reading speed they may not be reliable. Data was collected in these studies to allow for the investigation of device reliability in the future, i.e., device settings were reset between use and participants had to re-select their optimal lighting and colour conditions. Given there is already research investigating the reliability of the LuxIQ (Wittich et al. 2018), it can be determined if these findings are replicable when using a different LuxIQ of the same model. Another line of inquiry is to investigate how optimal lighting, colour, print-size, and contrast impact reading, given the literature suggesting that reversing the contrast polarity can help improve the reading speeds of individuals with and without visual impairments. As the MNRead was not used in the normal vision condition, it would also be interesting to determine how optimal lighting and colour vary as a function of print-size in individuals with normal vision or normal age-related visual decline. Finally, as the MNRead was used in the simulated and actual impairment conditions, it would be beneficial to know how optimal lighting and colour conditions impact the MNRead reading parameters. More specifically, how does optimal lighting and colour conditions impact a participant maximum reading speed, critical print-size, reading acuity, and accessibility index.

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