Effects of color-tinted lenses on visual behavior

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Tim Schilling
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Dekan der Math.-Nat. Fakultät:	Prof. Dr. Thilo Stehle
Dekan der Medizinischen Fakultät:	Prof. Dr. med. Bernd Pichler
Erster Berichterstatter:	Prof. Dr. Siegfried Wahl
Zweiter Berichterstatter:	Prof. Dr. Andreas Bartels
Prüfungskommission:	Prof. Dr. Siegfried Wahl
	Prof. Dr. Andreas Bartels
	PD Dr. Annette Werner
	Prof. Dr. Hanspeter Mallot

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Datum Unterschrift

Statement of contributions

I. TuebingenCSTest – a useful method to assess the contrast sensitivity function

Schilling, T., Ohlendorf, A., Leube, A., & Wahl, S. (2017). TuebingenCSTest – a useful method to assess the contrast sensitivity function. Biomedical optics express, 8(3), 1477–1487.

In this work, I developed the methodology with help of Alexander Leube. Arne Ohlendorf and I interpreted the results. I collected and analyzed the data, wrote the manuscript, and improved it based on feedback from all co-authors. Siegfried Wahl supervised the research and improved the interpretation with his ideas.

II. Color-Tinted Lenses and Contrast Sensitivity

Schilling, T., Ohlendorf, A., Leube, A., & Wahl, S. (2020). Color-Tinted Lenses and Contrast Sensitivity. Manuscript in preparation.

I, Arne Ohlendorf, and Siegfried Wahl designed and interpreted the research. I developed the methodology with the help of Alexander Leube. I collected and analyzed the data and wrote the manuscript. I used input from Arne Ohlendorf and Alexander Leube to improve the manuscript.

III. Color-Tinted Lenses and Lag of Accommodation

Schilling, T., Sipatchin, A., Ohlendorf, A., & Wahl, S. (2020). Color-Tinted lenses and Lag of Accommodation. Manuscript in preparation.

I, Arne Ohlendorf, and Siegfried Wahl designed the research. Alexandra Sipatchin and I collected the data. I analyzed the data and wrote the manuscript. Arne Ohlendorf and I interpreted the results. I used input from Arne Ohlendorf to improve the manuscript.

IV. Looking Through ‘Rose-Tinted’ Glasses: The Influence of Tint on Visual Affective Processing

Schilling, T., Sipatchin, A., Chuang, L., & Wahl, S. (2019). Looking Through “Rose-Tinted” Glasses: The Influence of Tint on Visual Affective Processing. Frontiers in Human Neuroscience, 13, 187.

“All authors were involved in the interpretation and summarizing of the study, and their special contributions were the following: T.S., L.C. and S.W. designed the experiment; T.S. and A.S. conducted the experiment; T.S., L.C. and A.S. analyzed the data; S.W. was the principal investigator. All authors reviewed the manuscript” from the chapter “Author Contributions” in Schilling, Sipatchin et al. (2019).

Furthermore, the work was inspired by Prof. Friederichs’s work concerning color-tinted lenses in visual processing disorders (Friederichs & Wahl, 2017) in Bamberg, where I went for a lab-exchange. I came up with the ideas for custom-designed spectral curves of color-tinted lenses and the conception to investigate the brain activity. The exploration of the emotional component with color-tinted lenses was the idea of Hamed Bahmani. Feedback about the experimental design came from the pupil research group in Tuebingen.

V. Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes

Schilling, T., Ohlendorf, A., Varnas, S. R., & Wahl, S. (2017). Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes. Investigative ophthalmology & visual science, 58(9), 3319–3324.

For this academic work, I collected and analyzed the data. Arne Ohlendorf, Saulius R. Varnas, and I designed and interpreted the experiment. Arne Ohlendorf wrote the manuscript with input from Saulius R. Varnas and myself. Siegfried Wahl supervised the research and improved the interpretation with his ideas.

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Contents

Summary

The ability to perceive light as different colors strongly impacts our daily behavior and is associated with visual performance and emotions. Color perception can be modified with light filters, also called color-tinted lenses, that form spectral patterns. The purpose of this thesis is to describe the effects of color-tinted lenses on visual behavior by assessing visual, opto-physiological, and emotional performance. Visual performance can be exemplarily determined psychophysically by contrast sensitivity tests. When focusing on near distances, opto-physiological performance is reflected in the lag of accommodation, which can be modulated by progressive addition lenses. Emotional performance, as reflected in the arousal level under affective conditions, can be described by a late positive potential in the brain measured by electroencephalography.

This thesis considers three approaches to investigate the effect of custom-designed and existing color-tinted lenses on different measurements of performance in human participants: contrast sensitivity, lag of accommodation, and visceral neurophysiology. First, to accurately evaluate the influence of color-tinted lenses on visual performance, a contrast sensitivity test was developed with higher precision, repeatability, and reliability than existing tests, called the Tuebingen Contrast Sensitivity Test. With this test, it was found that neither existing color-tinted lenses nor high- and band-pass-filter color-tinted lenses significantly improved contrast sensitivity. Second, red-tinted lenses were able to reduce the lag of accommodation. Third, with red-tinted lenses, physiological measurements revealed a higher amplitude of the late positive potential and skin conductance after showing affective pictures, such as a smiling baby, an erotic couple, or a mutilated body.

The color-tinted lenses investigated appear to affect opto-physiological and emotional performance, but not visual performance when compared to clear lenses. In future experiments, a potential common mechanism behind the two effects observed in opto-physiological and emotional performance, namely, better lag of accommodation with red-tinted lenses and higher arousal level under emotional conditions, could be explored. In summary, this thesis shows that color-tinted lenses can change visual behavior.

1. Introduction

Colored glasses are employed with a specific color-tint and different absorption levels for a variety of reasons, such as for protection (Hammond, Johnson, & George, 2014). Color-tinted lenses are called “sunglasses” when such tinted lenses show a higher absorption level. Historically, these color-tinted lenses have been used to protect against sun glare, since 1752 as was announced by James Ayscough (Dain, 2003). First reports go back to the Roman emperor Nero, who held emerald gemstones against the sunlight and supposedly watched gladiator competitions through the gemstones, as reported by Gaius Plinius Secundus Major in *Naturalis Historia*, book 37, chapter 16 (Wenzel, 2017).

Besides the protective aspects of such lenses, color itself changes our perceptual impression. For example, it modulates sensitivity to contrast (Mullen, 1985) at a psychophysical level and at the level of psychophysiology, such as by causing arousal changes (Wilson, 1966). This thesis explores the effects of specific color-tinted lenses on different levels of human visual behavior. More specifically, research has been conducted and published to understand the effects of color better on i) the visual performance of the eye in terms of contrast sensitivity; ii) the opto-physiological performance, described by changing the power of the crystalline lens, which is called accommodation; and iii) the emotional performance characterized by the late positive potential, measured by electroencephalography (EEG). Each method has been carefully selected and optimized for the examination of the effects of color-tinted lenses. This thesis aims to establish a reliable procedure that results in equivalent luminance at the eye for each color-tinted lens, so that a better understanding can be achieved of how color-tint influences contrast sensitivity, accommodation, and emotional arousal.

The structure of this thesis is as follows. The first chapter explains the motivation why this thesis deals with color-tinted lenses. The following subsections present the details of how visual, opto-physiological, and emotional performance is processed. Visual performance is considered as contrast sensitivity, opto-physiological performance as accommodation, and emotional performance as autonomic arousal and cortical brain response. After defining the objectives for this thesis, a review summarizes and reviews what this research discovered with regard to the scientific background and scientific novelty.

1.1 Motivation

Color is an important feature that makes daily life easier by facilitating the distinguishing of objects from the background (Gegenfurtner, 2003; Gegenfurtner & Rieger, 2000). It has been

reported that color and color-tinted lenses can potentially influence human behavior at different levels (Jalil, Yunus, & Said, 2012; Lawrenson, Hull, & Downie, 2017). One inspiration for this work comes from findings on the beneficial effects on migraine of colored light and tinted lenses, measured by different methodologies (Coutts, Cooper, Elwell, & Wilkins, 2012; Huang et al., 2011; Noseda et al., 2016; Wilkins, Patel, Adjamian, & Evans, 2002; Wilkins, Huang, & Cao, 2007).

The subjective brightening effect of color-tinted lenses (Chung & Pease, 1999; Kelly, 1990), appears when wearing yellow- or orange-tinted lenses in gray weather, for example. Besides their use outdoors, color-tinted lenses have already been used in practical applications: for example, with respect to reading impairments and visual stress (Friederichs & Wahl, 2017). Some studies have shown that color-tints improved reading abilities, although with a generally small effect (Griffiths, Taylor, Henderson, & Barrett, 2016). Additionally, one has to be aware that benefits from prescribed tinted lenses are likely to be attributable to the placebo effect (Elliot & Wood, 2017; Evans & Allen, 2018).

First, in the context of the visible light spectrum, a repeatedly reported improvement in contrast sensitivity is based on effects from chromatic aberration (Chou & Cullen, 1985) and the wavelength dependence of straylight in the eye (Van den Berg, Franssen, & Coppens, 2010) when short-wave light has been reduced. Therefore, yellow- or orange-tinted lenses are frequently used as contrast enhancers due to their absorption of blue light. However, there has been only a little objective evidence that tinted lenses can enhance contrast sensitivity (Clark, 1969; Eperjesi, Fowler, & Evans, 2002) when tests were performed under laboratory conditions. Furthermore, only a few studies have found that they improve visual performance under particular conditions, such as intense light or glare (Erickson, Horn, Barney, Pexton, & Baird, 2009; Lee et al., 2002). Such an improvement in visual performance with tinted lenses may be beneficial for athletes (Erickson et al., 2009), whether professionals or amateurs, but it may also improve the quality of life of older individuals who suffer from cataracts (Tupper, Miller, & Miller, 1985). Because of the lack of precise measurement techniques for contrast sensitivity, it was necessary to develop a reliable method for assessing visual performance with color-tinted lenses, see Chapter 7.1 (Schilling, Leube, Ohlendorf, & Wahl, 2020; Schilling, Ohlendorf, Leube, & Wahl, 2017).

Second, another subject of color research is the wavelength dependency of the refractive development of the eye. Since different wavelengths of light are refracted differently in the optical media of the eye, resulting in different focus points and defocus (Marcos, Burns, Moreno-Barriusop, & Navarro, 1999; Marcos, Moreno, & Navarro, 1999), the resulting color of light could also influence eye-length growth (Chakraborty et al., 2018). By the year 2010, 100 million people were suffering from moderate and severe vision impairments or blindness

due to uncorrected refractive errors (Bourne et al., 2013), of which myopia is only one part. The prevalence of myopia, which is one type of refractive error, is expected to increase tremendously in the coming years (Holden et al., 2016). The effects of wavelength on myopia development have already been investigated in animal models for myopia (Rucker, 2013; Smith et al., 2015; Zhao & Huang, 2016). However, a transfer of the findings to possible treatments in humans has not yet been demonstrated. Besides the physical effect of the different wavelengths of light on the focal point, the focal point itself can be changed physiologically by the accommodation ability of the eye, which changes the optical properties of the lens (Rosenfield, Logan, & Edwards, 2009). Opto-physiological performance in terms of accommodation can be described by accommodative response or lag of accommodation. In Chapter 7.2, the influence of color-tint on the accommodative response in myopic participants is reported (Schilling, Sipatchin, Ohlendorf, & Wahl, 2020).

Third, regarding arousal research, color is a relevant influencer on emotional processing. The color red, for example, is associated with excitement (Wexner, 1954) and increased arousal (Ali, 1972). Some studies connect red with positive qualities such as love (Elliot & Niesta, 2008) but also negative qualities such as anger (Fetterman, Robinson, & Meier, 2012) and failure (Gerend & Sias, 2009). However, the transfer of effects from color to color-tinted lenses is patchy. The last study of this thesis reconsiders the saying ‘Seeing the world through rose-colored glasses’, see Schilling, Sipatchin et al. (2019) in Chapter 7.3.

In summary, color-tinted lenses have not yet been investigated in terms of their ability to improve visual and opto-physiological performance, such as lag of accommodation, and emotional performance, like arousal and the brain’s response to emotional pictures. Color-tinted lenses have the potential to improve quality of life not only as a therapeutic agent, such as for myopia and emotional disorders but also in recreational lifestyle applications.

1.2 Assessment of visual performance

Visual performance can be assessed non-invasively by psychophysical test procedures to discover contrast sensitivity.

Gustav Theodor Fechner developed the term psychophysics as early as the late nineteenth century (Fechner, 1860). Stimulus detection tasks are designed with limited response options to force a response choice, such as via button press. While assessing visual performance, detection fails at a certain point due to the limitations of the detection system: attenuation due to optical defects in the refractive system of the eye (Campbell & Green, 1965) or neuronal attenuation due to retinal inhibition of ganglion cells (Enroth-Cugell & Robson, 1966; Schade,

1956). Therefore, plotting correct and incorrect responses against stimulus intensity results in a psychometric function with a turning point where the slope is maximum. “For sinusoidal grating detection, the slope of the psychometric function [correlates] with the threshold” (Jäkel & Wichmann, 2006). The threshold is at a specific physical intensity level, which is associated with a particular visual performance level. The psychometric function usually does not reach 100%, due to lapses in a reasonable psychological observer (Wichmann & Hill, 2001).

Several methods have been developed to assess the psychometric function. The method of constant stimuli measures performance for discrete stimulus intensities (Fechner, 1860). Hence, when repeated many times, the method of constant stimuli is highly accurate but time-intensive and inefficient compared to adaptive methods (Kellogg, 1929; Watson & Fitzhugh, 1990). Adaptive procedures are forms of staircase procedure, two of which are “best parameter estimation by sequential testing” (best PEST) and psi (Kontsevich & Tyler, 1999; Lieberman & Pentland, 1982). Psychophysical methodology also covers other approaches besides the method of constant stimuli, such as the method of limits and the method of adjustment (Gescheider, 1997).

Visual performance can be investigated by various tests, with visual acuity measurements capturing only a subset of the visual performance by describing the cut-off frequency. Contrast sensitivity measurements, however, can provide indications of several abnormalities, such as glaucoma (Arden & Jacobson, 1978) and macular degenerations (Sjöstrand & Frisén, 1977).

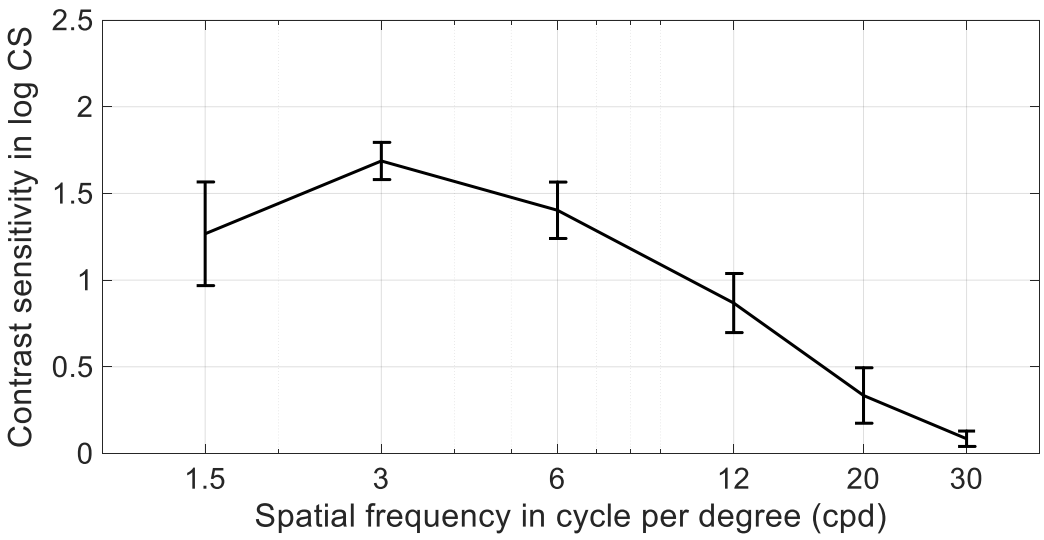

Figure 1: Example of a contrast sensitivity function. Contrast sensitivity for eight participants is plotted against spatial frequency with mean and standard deviation (SD). Contrast thresholds are from the measurement of untrained, naïve participants, measured with the TuebingenCSTest (Schilling, Leube, Ohlendorf, & Wahl, 2018).

In the contrast sensitivity function (CSF), the dependence of contrast sensitivity is plotted against the spatial frequency of the stimulus grating pattern. On the right side of the CSF,

contrast sensitivity for higher spatial frequencies is limited by optical components (Campbell & Green, 1965). On the left side of the CSF, lateral inhibition of receptive fields is considered to decrease contrast sensitivity at lower spatial frequencies (Enroth-Cugell & Robson, 1966; Schade, 1956). To illustrate, a typical inverted U-shaped CSF is plotted in Figure 1. Besides spatial frequency, the luminance of the stimulus also changes the basic level of the CSF (Van Meeteren & Vos, 1972). Thus, lower luminance leads to lower contrast sensitivity.

1.3 Assessment of opto-physiological performance

Opto-physiological performance can be assessed non-invasively by objective measures, with light rays to derive the lag of accommodation, and when light rays refract at a lens, their focal point is dependent on the wavelength of the light ray.

“Lag of accommodation” describes the poor focusing of the crystalline lens, especially when viewing the near distance, which occurs especially in young myopes (Charman, 1999; Gwiazda, Thorn, Bauer, & Held, 1993). Depending on the direction of the gaze and the viewing distance, the crystalline lens can vary opto-physiological performance by changing its shape (Kasthurirangan, Markwell, Atchison, & Pope, 2011). This flexibility of the crystalline lens is called the accommodation process, which was discovered by Young (1801) and von Helmholtz (1867). The mechanism for adapting the power of the crystalline lens to different distances through ciliary muscle activity is called accommodation (Norton, 1873). Ocular accommodation is a neuromuscular process (Rosenfield et al., 2009). Parasympathetic neural commands are transmitted to the ciliary muscle from midbrain areas — such as the Edinger-Westphal nucleus — in order to regulate the accommodative response (Gamlin, 1999; 2002; Gamlin, Zhang, Clendaniel, & Mays, 1994). If the crystalline lens is less able to change its refractive power sufficiently – for example, in presbyopia – near vision can be facilitated with optical solutions, such as progressive addition lenses (PALs), multifocal intraocular lenses (IOLs), or single vision lenses.

The interaction of light with a lens can be described using the refractive index. In addition, for different monochromatic light, a lens has different refractive indices, causing chromatic aberration. This phenomenon is an effect of optical dispersion, which Newton experienced when a prism split white light into rainbow colors (Newton & Sarton, 1930). Chromatic aberration consists of lateral and longitudinal chromatic aberrations. In this thesis, when speaking about chromatic aberration only longitudinal chromatic aberration is considered. Chromatic aberration induces shorter wavelengths, such as 400 nm, to be focused in front of longer wavelengths, such as 600 nm, along the optical axis, see Figure 2.

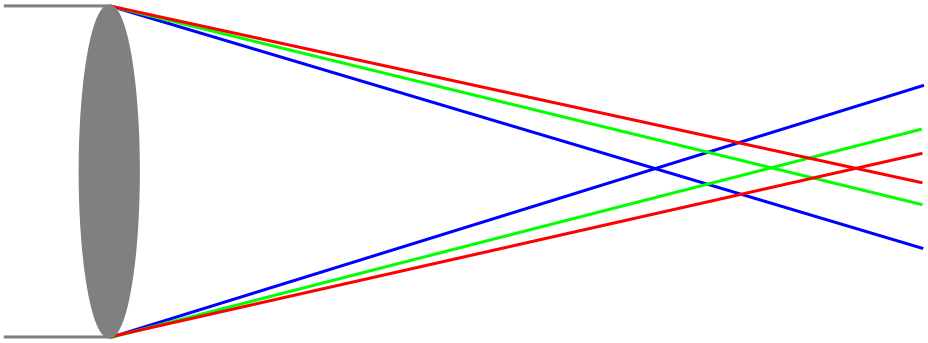

Figure 2: The focal point of short-wavelength light, drawn in blue, converges in front of the medium-wavelength, drawn in green, and the focal point of medium-wavelength light converges in front of the long-wavelength light, drawn in red. The lens and incoming light rays are drawn in gray. This figure is illustrative and does not claim absolute correctness in distances and ratios. Inspired by Figure 9 from Wallman and Winawer (2004).

The focal plane of the eye is usually located between the medium-wavelength (green) focal point and the long-wavelength (red) focal point (Marcos, Burns, et al., 1999). The chromatic difference of the focus is -1.0 D at 450 nm and +0.25 D at 650 nm if the eye's focal plane is at 570 nm (Marcos, Burns, et al., 1999). Hence, the difference of refraction from 550 nm to 450 nm is larger than the difference of refraction from 550 nm to 650 nm. Therefore, in the schematic Figure 2, the distance between the short-wavelength light (blue) and the green focal point is drawn larger than the distance between the red and the green focal point.

1.4 Assessment of emotional performance

In this thesis, "emotional performance" refers to arousal and the brain's response to emotional events. Arousal is a term that can have slightly different meanings, depending on the context in which it is used.

From the perspective of emotional responses, arousal is used to describe physiological reactions to affective events, such as changes in skin conductance and heart rate – also called "visceral responses" (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000). Arousal is also associated with viewing time and interest ratings, and arousal ratings co-vary with skin conductance magnitude when affective pictures are presented (Lang, Greenwald, Bradley, & Hamm, 1993). A valence–arousal model describes two axes along which the stimuli can be

sorted: the first axis is the arousal axis, with high and low arousal; and the second axis is the valence axis, with pleasant, neutral, and unpleasant valence (Russell, 1980).

Cortical changes due to exposure to emotional pictures are visible in the late positive potential, which shows greater elevation the higher the arousing content of the emotional event (Brown, van Steenbergen, Band, de Rover, & Nieuwenhuis, 2012; Cuthbert et al., 2000; Dolcos & Cabeza, 2002; Hajcak, Dunning, & Foti, 2009; Hajcak, MacNamara, & Olvet, 2010; Schupp et al., 2000; Spreckelmeyer, Kutas, Urbach, Altenmüller, & Münte, 2006). The neural result of the stimuli is measurable with sensory physiological devices, such as EEG.

2. Spectral transmission of color-tinted lenses

Color-tinted lenses were designed especially for this thesis to investigate the effects of pure color-tinted lenses via band- and high-pass filters. Each color-tinted lens returns a distinctive spectral transmission, as shown in Figure 3.

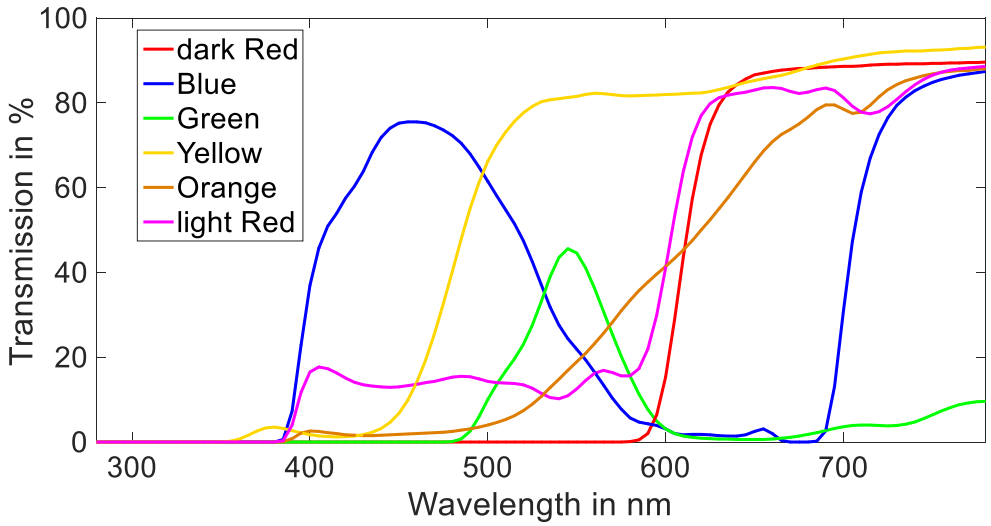

Figure 3: Spectral transmission of color-tinted lenses in percentages. The green- and blue-tinted lenses transmit inverted U-shaped spectral curves with peaks at ca. 550 nm and 460 nm, respectively. The light and the dark red-tinted lenses are high-pass filters with cut-off points at ca. 600 nm and 610 nm. The light red-tinted lens, called "light Red", shows low transmission between 400 nm and 600 nm. The orange-tinted lens transmits slowly, with increasingly more light transmission starting from 500 nm and crossing the red-tinted lens's spectral curve at approximately 600 nm and 610 nm. Own illustration plotted with data from manufacturer sheets, which was reprinted and modified from Figure 2 in Schilling, Sipatchin et al. (2019), distributed under the terms of the Creative Commons Attribution License (CC BY).

Blue-, red-, green-, and orange-tinted lenses were custom-designed in cooperation with Carl Zeiss Vision Italia SpA, Varese, Italia, whereas the yellow-tinted lens was pre-existing (Carl

Zeiss Vision International GmbH, Aalen, Germany). The methodology is further described in each paper or manuscript.

3. Objectives

The primary objective of this work was to investigate the influence of color-tinted lenses on several research fields, covering the visual, the opto-physiological, and the emotional levels with different methodologies.

Performance indicators such as contrast sensitivity, lag of accommodation, and late positive potential measurements were used for the subsequent investigations. The two papers and two manuscripts that are appended and the attached paper can be matched to these three main topics and are dedicated to these investigations, see Chapters 7.1, 7.2 and 7.4, and 7.3.

In the first section, a novel method for contrast sensitivity assessment was developed to measure precisely visual performance, resulting in a repeatable and reliable contrast sensitivity test, called the TuebingenCSTest (Schilling, Ohlendorf, Leube, et al., 2017). With this psychophysical test, a study was performed to assess the contrast sensitivity with color-tinted lenses, reflecting the visual performance of the eye. Many studies do not consider matching luminance for filter transmission (Eperjesi et al., 2002), and some found a reduction in contrast sensitivity when measured through light filters, such as absorptive tinted lenses (Kanazawa & Uozato, 2013). Such light filters always reduce the total transmittance, and therefore a decrease in visual performance can be expected. Consequently, it was necessary to establish a procedure that adjusted the brightness of the monitor for each color-tinted lens separately. This adjustment results in an equivalent or constant luminance at the eye, separately for each color-tinted lens and in combination with the monitor used. This procedure to ensure constant luminance should become standard for future experiments with color-tinted lenses.

In the second section, the lag of accommodation was assessed under the influence of color-tinted lenses. The purpose of this study was to test whether color-tinted lenses have a similar effect on accommodation as that was shown in monochromatic light (Graef & Schaeffel, 2012; Kröger & Binder, 2000; Seidemann & Schaeffel, 2002) and if the opto-physiological performance can be improved; that is, whether a reduction of the lag of accommodation can be achieved with color-tinted lenses. Band- and high-pass color-tinted lenses were developed to achieve transmissions that did not achieve monochromatic properties but absorbed light from specific wavelength regions. The aim of these absorptions was to reduce the adverse effects of chromatic aberration. The results indicate how color-tinted lenses modulate the lag of accommodation. The proper coordination of lens and ciliary muscle is essential for opto-

physiological performance, which is mainly appreciated when performance decreases in near-distance tasks, such as reading, when presbyopia occurs.

In the third section, the aim was to investigate the effects of color-tinted lenses on emotional performance. In psychological color science, different emotional effects have been studied and attributed to different colors (Jalil et al., 2012). The question was whether these findings could be transferred to the color-tinted lenses that had been developed. The emotional performance was examined not only using late positive potential but also using skin conductance and heart rate measurements. The results can be used to further develop color-tinted lenses for arousal related situations: for example, to enhance the performance of athletes, for recovery, for recreation, or for therapeutic usage. In terms of neuroergonomics, applications of color-tinted lenses are considered for demanding work, such as long-duration driving, or to keep arousal high during tiring work (Schilling, Sipatchin, et al., 2019).

4. Review of results and discussion

This thesis compiles investigations that have been conducted to address the scientific question “What is the influence of color-tinted lenses on visual behavior?”. More specifically: “How do color-tinted lenses improve visual, opto-physiological, and emotional performance?”.

There has already been research into the topics covered by these questions using other color-tinted lenses. Publications reporting these previous studies are considered in more detail in the following sections, see pages 11–14. However, a holistic view of the custom-designed color-tinted lenses, see Figure 3, has been developed in this work, which covers a neuroscientific range from the visual through the opto-physiological to the emotional. Different methods were elaborated and adapted for each performance measurement separately, which provides a broader perspective than would be gained by using a single method. With regard to the visual performance of the eye measured by contrast sensitivity, both increasing and decreasing effects are reported (Eperjesi, 2011; Eperjesi et al., 2002; Renzi-Hammond & Hammond, 2016; Wolffsohn, Cochrane, Khoo, Yoshimitsu, & Wu, 2000). The reasons why there were such different findings are considered later. At the opto-physiological level, which can be assessed by the lag of accommodation, findings on chromatic aberration and accommodation are described (Graef & Schaeffel, 2012; Kröger & Binder, 2000; Seidemann & Schaeffel, 2002). The connection between lag of accommodation and myopia (Charman, 1999; Gwiazda et al., 1993) is used for therapeutic purposes by optical solutions, such as PALs (Gwiazda et al., 2003; Hasebe, Jun, & Varnas, 2014; Leung & Brown, 1999), but its causality is controversial (Aleman & Schaeffel, 2018). Direct insights into myopia development under

the influence of colored light have been investigated in animal studies (Foulds, Barathi, & Luu, 2013; Jiang et al., 2014; Smith et al., 2015), whereby the transfer from animal studies to humans can be questioned. For emotional performance, the findings of color-tinted lenses are related to the ecological valence theory (Palmer & Schloss, 2010), color-in-context theory (Buechner & Maier, 2016), and arousal theory (Wilson, 1966). Several references discussing the effects of different colors on emotions and arousal are highlighted. Next, the findings of this thesis on the three themes are elaborated in more detail, see pages 14–16. After reviewing the limitations of the previous work, this review then focuses on the limitations and perspectives of this thesis, from page 16. One major limitation is the difference between color-tinted lenses and the local color itself, which is described in detail, see also Chapter 7.3 (Schilling, Sipatchin, et al., 2019). Further limitations are identified including the spectrum of the light source, such as the monitor used.

Color-tinted lenses are employed to increase contrast vision under detrimental conditions. This popular statement is debated in the scientific literature. First, Wolffsohn et al. (2000) found an increase in contrast sensitivity using yellow-tinted lenses in combination with white-on-blue gratings but not in combination with white-on-black gratings; they concluded that yellow-tinted lenses might be beneficial under specific conditions, such as when the background is blue, for example, the sky (Renzi-Hammond & Hammond, 2016). Second, under bright sunlight, green and amber contact lenses provided better visual performance, including better contrast sensitivity, than clear lenses (Erickson et al., 2009). Third, under a spectrum similar to sunlight, photochromic tinted lenses exhibited an improvement in heterochromatic contrast sensitivity compared to a clear lens, using a blue background to mimic the light from the sky (Renzi-Hammond & Hammond, 2016). They used a luminance of 2 cd/m² for the target (Renzi-Hammond & Hammond, 2016), which is similar to the study of color-tinted lenses and contrast sensitivity described in this thesis, see Schilling, Leube, et al. (2020) in Chapter 7.1.
Nevertheless, constant luminance at the eye for each tinted lens was not reported in Renzi-Hammond & Hammond's study, whereas it was achieved in the study Schilling, Leube, et al. (2020) in this thesis. Only a few studies with objective evidence suggest improvements of visual performance with tinted lenses, and their effects in helping people with low vision remain controversial (Elliot & Wood, 2017; Eperjesi et al., 2002). Other studies show reverse and non-beneficial effects; they suggest that contrast sensitivity and visual acuity are worsened by using yellow filters, with and without glare (Eperjesi, 2011). Eperjesi explains this deterioration as due to the loss of total light transmission because of the light-absorbing properties of the tinted lenses (Eperjesi, 2011). An increase in brightness is often perceived with yellow-tinted lenses (Wolffsohn et al., 2000). A reasonable explanation for this effect comes from pupil investigations, showing that yellow-tinted lenses dilate the pupil more compared to a matched neutral density filter and thereby render the impression brighter (Chung & Pease, 1999; Kelly,

1990). This impression might not necessarily lead to improved visual performance but it might make lens wearers believe that their yellow-tinted lenses are advantageous for contrast vision. As early as the 1950s, it was reported that shooting performance was not improved when yellow-tinted lenses were worn (Bierman, 1952). Nevertheless, it has been shown that under glare conditions, using a bright light source, yellow-tinted lenses even result in a larger threshold contrast increase, representing a worsening in visual performance, while it has been suggested based on trends that blue- and purple-tinted lenses may improve contrast sensitivity (Lee et al., 2002). Although the idea that yellow-tinted lenses enhance contrast has persisted until today, the improvement may be limited to bright illuminance conditions or to conditions with a blue background (Erickson et al., 2009; Renzi-Hammond & Hammond, 2016; Wolffsohn et al., 2000). Reports about the effects of tinted lenses on visual performance are not limited to short- and medium-wavelength transmitting tinted lenses; for example, some studies report a subjective beneficial effect on visual function in patients suffering from retinitis pigmentosa when using red tints (Severinsky et al., 2016; Van den Berg, 1989).

In general, the theory exists that chromatic aberration is reduced with short-wavelength-filter tinted lenses. This idea is outlined in this sentence: “Filters that diminish transmission of the short wavelength (blue) portion of the visible light spectrum improve retinal image quality by reducing the amount of chromatic aberration (Chou & Cullen, 1985)” (Erickson, 2007); Chou’s & Cullen’s study as cited in Erickson (2007). In contradiction of this theory, others have found that blue light, with a peak at 460 nm, decreases accommodative lags relative to white light with a peak at 560 nm, and red light with a peak at 632 nm, when accommodative errors were corrected by chromatic differences in refraction (Nagra & Wildsoet, 2015). Previous studies have shown that accommodation follows the longitudinal chromatic aberration function in monochromatic light (Graef & Schaeffel, 2012; Kröger & Binder, 2000; Seidemann & Schaeffel, 2002), meaning that participants accommodate more in red than in blue light. It can be shown that the custom-developed color-tinted lenses have a similar effect on accommodation responses (Schilling, Sipatchin, et al., 2020). Moreover, the lag of accommodation can be reduced in a pattern-related visual stress group by using a colored overlay (Allen, Hussain, Usherwood, & Wilkins, 2010). In animal studies, colored light has been shown to have an influence on the development of myopia (Rucker, 2013; Zhao & Huang, 2016). Although consistent findings exist for chicken and guinea pigs with short-wavelength light (Foulds et al., 2013; Long, Chen, & Chu, 2009), in tree shrews and rhesus monkeys long-wavelength treatment induced a hyperopic shift or relative hyperopia (Gawne, Siegwart, Ward, & Norton, 2015; Gawne, Ward, & Norton, 2017; Smith et al., 2015). In humans, myopes show an increased lag of accommodation and their insufficient accommodation is suspected to be associated with the progression of myopia (Charman, 1999; Gwiazda et al., 1993). It is controversial whether the lag of accommodation is a useful predictor for myopia and this is not

even assumed by Aleman and Schaeffel (2018) and Mutti et al. (2006). Additionally, the lag of accommodation rises with decreasing viewing distance and increasing accommodative demand (Charman, 1999; Gwiazda et al., 1993; McBrien & Millodot, 1986; Ramsdale, 1979), which could be confirmed in the appended and attached studies of this thesis, see Schilling, Sipatchin, et al. (2020) in Chapter 7.2 and Schilling, Ohlendorf, Varnas, & Wahl (2017) in Chapter 7.4. The closer the accommodation stimulus is, the larger the lag of accommodation, indicating a weaker opto-physiological performance, which has previously been shown (Gwiazda et al., 1993). Besides the object distance, it was found that the lag of accommodation depends on the design of PALs (Schilling, Ohlendorf, Varnas, et al., 2017). Designs with more negative horizontal mean power gradients were able to reduce the lag of accommodation in myopic participants most efficiently (Schilling, Ohlendorf, Varnas, et al., 2017).

In addition to visual and opto-physiological performance, emotional performance has been investigated in the context of color effects. For example, the categorization of angry faces is facilitated when the background is red (Young, Elliot, Feltman, & Ambady, 2013). Red has appetitive motivational implications (Elliot & Niesta, 2008) and defensive motivational implications (Elliot & Maier, 2007; Fetterman et al., 2012; Gerend & Sias, 2009). Furthermore, the color red is associated with larger skin-conductance responses (Jacobs & Hustmyer, 1974; Wilson, 1966) and higher alpha power in EEG (Ali, 1972). The arousing quality of red follows the ecological valence theory, which gives each color an ecological value (Palmer & Schloss, 2010). Green is therefore associated with positive feelings, such as the experience of being in a natural environment with chlorophyll-containing plants (Akers et al., 2012), and headache-reducing effects (Noseda et al., 2016). An increase of arousal in general could be observed using red-tinted lenses (Schilling, Sipatchin, et al., 2019), which is consistent with previous findings concerning red light and skin conductance responses (Jacobs & Hustmyer, 1974). The study Schilling, Sipatchin, et al. (2019) in Chapter 7.3, was not designed to investigate color-in-context theory (Buechner & Maier, 2016) because grayscale images have been used in combination with color-tinted lenses that color the entire visual field. The context of valence does not appear to be relevant, as the late positive potential was elevated in all valence conditions when using the red-tinted lens (Schilling, Sipatchin, et al., 2019). However, our results agree with Wilson's arousal theory (Wilson, 1966): arousal-enhancing effects of red-tinted lenses could be identified in the study described in this thesis (Schilling, Sipatchin, et al., 2019). However, only a few studies have found alerting effects from blue light versus longer wavelengths (red or green) using monochromatic light exposure (Cajochen et al., 2005; Lockley et al., 2006), while other studies failed to show this effect (Papamichael, Skene, & Revell, 2012). For details, see the review Souman et al. (2017).

Furthermore, it has been shown that arousal modifies contrast sensitivity (Lee, Baek, Lu, & Mather, 2014). This connection could be explained by a shift in attention when arousal is

affected (Shapiro & Johnson, 1987), as attention modifies the detection measured by psychophysical procedures, such as in attention-caused lapses by eye movements (Blackwell, 1952; Itti, Koch, & Braun, 2000). Therefore, this might indicate a connection between visual and emotional performance that has not been thoroughly investigated in this thesis but could form part of future investigations. However, a difference between feedback and no feedback was shown in the TuebingenCSTest with regard to pupil response, which could be an indicator for attention as well as arousal (Schilling, Bahmani, Ohlendorf, & Wahl, 2017). As reported by Bach and Schaefer, feedback for correct and incorrect responses from the observer is recommended, at least for the comfort of the participant (Bach & Schäfer, 2016). However, the TuebingenCSTest does not return a significant improvement in contrast sensitivity with auditory feedback compared to no auditory feedback, although there was a tendency for lower spatial frequencies to be improved, for example, with violet-tinted lenses (Schilling, Bahmani, et al., 2017).

With an accurate stimulus presentation, the TuebingenCSTest showed high repeatability and excellent reliability that makes it suitable for the assessment of color-tinted lenses. High precision was achieved by incorporating an adaptive staircase method with a high resolution of contrast levels using 16-bit gray-level resolution and the magnification of the spectacle lens. The time-efficiency of the TuebingenCSTest is another advantage when using high computational power. Even gaze-contingency could be integrated, although this feature was not incorporated for standard investigations because participants were instructed to fixate sufficiently. In the publication of the TuebingenCSTest, an attempt was made to demonstrate that a 16-bit gray-level resolution should be preferred over lower gray-levels, and especially over 8-bit gray-level resolution, which is most often used currently (Schilling, Ohlendorf, Leube, et al., 2017). The higher gray-level resolution makes it possible to determine low spatial frequencies much more precisely. In addition to its use with color-tinted lenses, the test has already been used in further studies, for example in Schilling, Ohlendorf, & Wahl (2019). This paragraph refers to the first-author publication Schilling, Ohlendorf, Leube, et al. (2017), which is part of this thesis and appended in Chapter 7.1.

In addition to the TuebingenCSTest's precision in stimulus presentation (Schilling, Ohlendorf, Leube, et al., 2017), the requirement for constant luminance was successfully fulfilled for the first study of 'color-tinted lenses and contrast sensitivity' under two luminance conditions: first, low photopic luminance with 3 cd/m², and second, photopic luminance with 50 cd/m² (Schilling, Leube, et al., 2020). Contrast sensitivity compared to clear lenses did not improve nor was it reduced with any color-tinted lens when tested with classical statistics. However, the red-tinted lens showed an elevation in contrast sensitivity compared to the blue-tinted lens, which was dependent on the spatial frequency for the custom-developed color-tinted lenses. At 3 cycles per degree (cpd), the blue- and green-tinted lenses worsened the contrast sensitivity compared

to the red-tinted lenses. The causes for this effect could originate from chromatic aberration because short-wavelength light is refracted differently than long-wavelength light, as described in Chapter 1.3. This study revealed that blue- and the red-tinted lenses are able to influence visual performance, when compared with each other. However, most color-tinted lenses did not affect visual performance in terms of contrast sensitivity, particularly not when compared to the clear lens condition. Since the custom-developed color-tinted lenses indicated the potential to separate the contrast sensitivity, these color-tinted lenses were tested for their opto-physiological performance as well. This paragraph refers to the manuscript Schilling, Leube, et al. (2020), which is part of this thesis and appended in Chapter 7.1.

The second study with color-tinted lenses and lag of accommodation was performed in myopic participants who had to accommodate to near distances. Color-tinted lenses with longer wavelength transmission appeared to reduce the lag of accommodation in myopic participants. In contrast, blue-tinted lenses, which transmit shorter wavelengths, increased the lag of accommodation. In conclusion, the lag of accommodation was increased with blue- and decreased with red- and orange-tinted lenses, indicating, presumably, an effect of chromatic aberration. The accommodative response, directly reflecting the opto-physiological performance, was thus inversely affected. This paragraph refers to the manuscript Schilling, Sipatchin, et al. (2020), which is part of this thesis and appended in Chapter 7.2.

The third study with color-tinted lenses used emotion-inducing images to examine how visual affective processing is influenced by visceral and cortical responses. Visceral response was evaluated on the autonomic level by skin conductance and heart rate; on the cortical level, event-related potentials were examined by EEG. It has been shown that the band- and high-pass filter color-tinted lenses were able to modulate the cortical response to emotional events (Schilling, Sipatchin, et al., 2019). On the cortical level, red-tinted lenses were shown to increase the late positive potential compared to yellow-tinted and none-tinted lenses. In general, color-tinted lenses shifted the late positive potential reaction to pleasant conditions higher than to unpleasant conditions. On the autonomic level, discrete arousal response was increased only to unpleasant images. This increase indicates regulation on the cortical level by color-tinted lenses. This regulatory effect of color-tinted lenses appears to enhance pleasant and reduce unpleasant visual processing on the cortical level. Additionally, red-tinted lenses increased the tonic skin conductance response compared to none-tinted lenses. This supports the theory that the color red itself, tested in this study by using red-tinted lenses, is arousing, independent of valence condition (Wilson, 1966). Hence, red-tinted lenses can be used to maintain an elevated general arousal level under viewing conditions such as tiring work or watching pictures. In conclusion, the regulation of responses to negative events is modulated on the cortical level by color-tinted lenses. This paragraph refers to the publication Schilling, Sipatchin, et al. (2019), which is part of this thesis and appended in Chapter 7.3.

In summary, color-tinted lenses are able to modulate visual, opto-physiological, and emotional performance to some extent. A substantial effect can be found in the reduction of the lag of accommodation with red-tinted lenses. In addition, red-tinted lenses elevated and modulated the cortical response to affective pictures.

At this point, it is necessary to note the difference between color-tinted lenses and color, which is essential for proper research into tinted lenses. There can be a difference between local color and global color. In natural images, each object is colored separately with regard to their color quality and their location (Nascimento, Amano, & Foster, 2016). This coloration of objects creates chromatic contrast in the visual scene. Under color-tinted lens conditions, the entire scene is globally and homogenously colored by the lens, as is mentioned in the study Schilling, Sipatchin, et al. (2019), which is contained in this thesis. With very dark-tinted lenses, this can lead to a total reduction of chromatic contrast. Of course, natural scenes exist where one color is predominant: for example, a completely green meadow or an image captured close to an object, such as a red rose. This is also called priming with predominant colors (Rajae-Joordens & Hanique, 2012). Such dominance of a color in an image does not necessarily mean the dominance of a delimited wavelength region since mixed colors can be composed of more than one wavelength - for example, purple or magenta is referred to as a non-spectral color (Gilbert & Haeberli, 2008; Silva & Topa, 2001). However, even if such natural images with a predominant wavelength consist of limited contributions from other wavelengths, color-tinted lenses are able to filter absolutely and distinctly, such as with the red-tinted lens, see Figure 3. By looking through a color-tinted lens, the visual impression can be compared to watching a black-and-white film or looking at a sepia picture, as the tinting of silent movies with one color was popular at the beginning of the twentieth century (Case, 1987; Read, 2009). Furthermore, filters of the light spectrum and color-tints can be found not only in color-tinted lenses but also in many daily life circumstances: night-shift filters in smartphone applications, colored overlays, the windshields of cars, tints of windows, and cloudy weather conditions (Ishii, Otani, Takashima, & Xue, 2013; Nagare, Plitnick, & Figueiro, 2019; Tällberg, Jelle, Loonen, Gao, & Hamdy, 2019; Uccula, Enna, & Mulatti, 2014; Walsh & Pearce, 2010).

There is evidence to suggest that color-tinted lenses reduce visual stress by decreasing low-frequency components of accommodation, which were greater with no lens; however, this is without color specificity (Simmers, Gray, & Wilkins, 2001). Furthermore, some studies suggest that the selection of the color of a tinted lens should be individual in order to achieve optimal results, such as for visual stress (Friederichs & Wahl, 2017; Suttle, Barbur, & Conway, 2017). In the studies contained in this thesis, such individual effects were not considered, which limits the potential effects of this individual component.

Another limitation in visual experiments regarding color is the characteristic spectrum of the monitor used. The ViewPixx Monitor (VPixx Technologies Inc., Saint-Bruno, Canada) has the

advantage that the peak level of each RGB-channel can be controlled individually, and the overall luminance can be set to a specific value. Nevertheless, the spectrum of the ViewPixx Monitor contains gaps and cannot be called continuous. Therefore, the orange-tinted lenses were not used in combination with this monitor, as the orange-tinted lens modulates the light in the gap in the ViewPixx Monitor's spectrum between the green and red peak. There remains a need in color science for a monitor with a homogenous spectrum, especially for research with light filters such as color-tinted lenses. If technically possible, future monitors should deliver a homogenous spectrum to conduct experiments under similar spectral conditions to those found outdoors.

Nevertheless, there have been setups developed to simulate sunlight conditions without a monitor (Hammond, Renzi, Sachak, & Brint, 2010). Therefore, an intelligent solution to avoid these gaps in the monitor spectrum can be found for indirect lighting by a specific light source. The Solux light source (Tailored Lighting Inc., Rochester, NY, USA), which was used in the accommodation study, see Schilling, Sipatchin, et al. (2020) in Chapter 7.2, delivers a homogenous spectrum similar to the sun's spectrum. Another approach to investigate the discontinuous light spectrum uses LED (light-emitting diode) technology (Cajochen et al., 2019). For precise presentation, especially regarding time latency, a LED monitor such as the ViewPixx is optimized for temporal characteristics and performs better than other monitors suitable for vision research (Ghodrati, Morris, & Price, 2015). Precision in time was necessary for the EEG study, see Schilling, Sipatchin, et al. (2019) in Chapter 7.3.
Further limitations of the color-tinted lenses appear with their total absorption and their darkening consequences. A solution is to decrease the absolute absorbance level by elevating transmission levels from zero to 10% or 20%: for example, compare 'dark Red' and 'light Red' in Figure 3. The color-tinted lenses used, see Figure 3, are not monochromatic filters because their transmission is much broader than the transmissions from monochromatic band-pass-filters, which are for example ±2 nm broad (Leube, Kostial, Ochakovski, Ohlendorf, & Wahl, 2018). Nevertheless, the effect of chromatic aberration should appear also in the difference between red- and blue-tinted lenses because their transmission curves barely overlap, see Figure 3.

In addition to the conducted studies during the thesis, there remain untouched areas of color-tinted research. Although the contrast sensitivity experiments using color-tinted lenses reported in the literature deliver ambiguous findings (Eperjesi et al., 2002), opto-physiological performance results were found in line with the chromatic aberration theory (Graef & Schaeffel, 2012; Kröger & Binder, 2000; Schilling, Sipatchin, et al., 2020; Seidemann & Schaeffel, 2002). One question arising from this thesis is why red-tinted lenses showed a better contrast sensitivity, mainly at 3 cpd, compared to blue-tinted lenses (Schilling, Leube, et al., 2020).

Additionally, the study of the lag of accommodation measurements showed that red-tinted lenses improved the opto-physiological performance of the eye (Schilling, Sipatchin, et al., 2020). It has been shown previously that the accommodative response is optimal at around 3 cpd (Mathews & Kruger, 1994; Owens, 1980). A smaller lag of accommodation with red-tinted lenses and a better contrast sensitivity seem to fit plausibly together. In addition to investigations of color-tinted lenses, the developed TuebingenCSTest can serve as a tool for measuring visual performance in general – in clinical diagnostics, for example. The TuebingenCSTest also supports applications such as slope estimations (Schilling et al., 2018) and pupil evaluations (Schilling, Bahmani, et al., 2017).

In addition to chromatic aberration, melanopsin could also play a role, as the blue-tinted lens primarily transmits blue light, which stimulates the intrinsic photosensitive retinal ganglion cells (ipRGCs) containing melanopsin, and ipRGCs are involved in the regulation of circadian rhythms (Berson, Dunn, & Takao, 2002). It has been shown that blue-wavelength components of light can affect the synchronization of circadian rhythms (Berson, 2003; Mottram, Middleton, Williams, & Arendt, 2011; Munch et al., 2006), cognitive brain function (Vandewalle, Maquet, & Dijk, 2009), and melatonin suppression (Cajochen et al., 2011). Therefore, the so-called “night shift” application found on modern devices reduces short-wavelength components to avoid circadian rhythm changes. However, it is questionable if changing the color spectrum changes melatonin suppression when using the “night shift” function (Nagare et al., 2019). Nevertheless, it is plausible to consider the effects of red- and blue-tinted lenses on circadian physiology for several reasons. First, blue-tinted lenses revealed the highest change in melatonin suppression compared to “night shift” conditions, when referred to an orange-tinted lens as a baseline (Nagare et al., 2019). Second, amber-tinted lenses or short-wavelength blocking filters may improve sleep quality and sleep duration and increase melatonin levels when worn prior to sleep (Barrau, Elbaz, Poletto, & Léger, 2019; Barrau, Swital, Poletto, Villette, & Burgos, 2017; Kimberly & James R, 2009; Ostrin, Abbott, & Queener, 2017). However, each color-tinted lens has a unique fingerprint in the spectral transmission, and thus it cannot be guaranteed that the custom-designed color-tinted lenses, see Figure 3, will have identical effects to those reported with similar transmissions, although a similarity in the spectra makes a transfer of results appear possible.

Regarding the assessment of arousal and emotional performance using color-tinted lenses, a common mechanism regulated by melanopsin could be considered for opto-physiological and emotional performance because red-tinted lenses, as opposed to blue-tinted lenses, showed the main effect in both performances, see Schilling, Sipatchin, et al. (2020) in Chapter 7.2 and Schilling, Sipatchin, et al. (2019) in Chapter 7.3. Potential applications, such as for athletes, could be assessed by physical performance tests with and without red-tinted lenses. Although only a small effect was found for green-tinted lenses (Schilling, Sipatchin, et al., 2019), they

should be considered for migraine therapy; not only our results but also former experiments suggest a potential therapeutic effect with green light (Noseda et al., 2016) and thus with green-tinted lenses. Continued studies with the custom-developed color-tinted lenses will show what further potential the lenses show under other conditions. Understanding the underlying mechanism of how color-tinted lenses work would be an important foundation for precise application of color-tinted lenses.

In this overview, several effects of color, colored light, and color-tinted lenses are shown and also how color-tinted lenses are limited. The new findings of this thesis regarding human visual behavior can contribute to a broader understanding of how color-tinted lenses influence visual, opto-physiological, and emotional performance. The fascination for immersion in a color tone through color-tinted lenses has engaged observers in the past and will hopefully not lose its appeal in the future.

5. References

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6. List of papers and manuscripts appended

I. TuebingenCSTest – a useful method to assess the contrast sensitivity function

Schilling, T., Ohlendorf, A., Leube, A., & Wahl, S. (2017). TuebingenCSTest – a useful method to assess the contrast sensitivity function. Biomedical optics express, 8(3), 1477–1487.

Status: Published.

II. Color-Tinted Lenses and Contrast Sensitivity

Schilling, T., Ohlendorf, A., Leube, A., & Wahl, S. (2020). Color-Tinted Lenses and Contrast Sensitivity. Manuscript in preparation.

Status: Not published.

III. Color-Tinted Lenses and Lag of Accommodation

Schilling, T., Sipatchin, A., Ohlendorf, A., & Wahl, S. (2020). Color-Tinted Lenses and Lag of Accommodation. Manuscript in preparation.

Status: Not published.

IV. Looking Through "Rose-Tinted" Glasses: The Influence of Tint on Visual Affective Processing

Schilling, T., Sipatchin, A., Chuang, L., & Wahl, S. (2019). Looking Through "Rose-Tinted" Glasses: The Influence of Tint on Visual Affective Processing. Frontiers in Human Neuroscience, 13, 187.

Status: Published.

V. Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes

Schilling, T., Ohlendorf, A., Varnas, S. R., & Wahl, S. (2017). Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes. Investigative ophthalmology & visual science, 58(9), 3319–3324.

Status: Published. Attached.

7. Appended papers and manuscripts

7.1 First section

I. TuebingenCSTest – a useful method to assess the contrast sensitivity function

Visual performance can be assessed psychophysically by contrast sensitivity tests. A contrast sensitivity test was developed to measure precisely visual performance, resulting in a repeatable and reliable contrast sensitivity test, called TuebingenCSTest.

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TuebingenCSTest – a useful method to assess the contrast sensitivity function

TIM SCHILLING,[1,*] ARNE OHLENDORF,[1,2] ALEXANDER LEUBE,[1] AND SIEGFRIED WAHL[1,2]

[1]*Institute for Ophthalmic Research, Eberhard Karls University Tuebingen, Elfriede-Aulhorn-Straße 7, 72076 Tuebingen, Germany*
[2]*Carl Zeiss Vision International GmbH, Turnstrasse 27, 73430 Aalen, Germany*
[*]*tim-tobias.schilling@uni-tuebingen.de*

Abstract: Since contrast sensitivity (CS) relies on the accuracy of stimulus presentation, the reliability of the psychophysical procedure and observer's attention, the measurement of the CS-function is critical and therefore, a useful threshold contrast measurement was developed. The Tuebingen Contrast Sensitivity Test (TueCST) includes an adaptive staircase procedure and a 16-bit gray-level resolution. In order to validate the CS measurements with the TueCST, measurements were compared with existing tests by inter-test repeatability, test-retest reliability and time. The novel design enables an accurate presentation of the spatial frequency and higher precision, inter-test repeatability and test-retest reliability compared to other existing tests.

OCIS codes: (330.0330) Vision, color, and visual optics; (330.1800) Vision - contrast sensitivity.

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1. Introduction

Contrast vision is fundamental for visual perception. The human visual system is more sensitive to local luminance contrast than absolute luminance [1]. Contrast is defined as relative difference between two color or luminance values e.g. between dark and bright. Objects with a large difference in luminance or color are better distinguishable from each other displaying a high contrast. The relative difference in luminance is usually expressed by the difference between maximum and minimum values divided by the sum of them, which Michelson called visibility [2]. Today the so called Michelson contrast is used to define the contrast of periodic pattern such as sine wave gratings including the so-called 'Gabor Patches', sinusoidal luminance patterns named after D. Gabor [3]. The contrast sensitivity (CS) is the reciprocal of the minimum contrast required for detection [4], and this contrast is called threshold contrast. Contrast sensitivity plotted against the spatial frequency of the Gabor Patch reveals the contrast sensitivity function (CSF) of the eye.

Reliable contrast sensitivity measurements are essential to describe precisely the visual function. The resultant CSF reveals the visual performance at different spatial frequencies including visual acuity, which corresponds to the cutoff-frequency on the high frequency end of the CSF [5].

Clinically, contrast sensitivity becomes relevant for several eye diseases such as cataract [6–8], glaucoma [9, 10], amblyopia [11, 12], multiple sclerosis [13–15], macular degenerations [16, 17], and diabetic retinopathy [18, 19]. The knowledge of the smallest perceivable contrast is also essential in order to verify the success of ocular surgeries e.g. laser-assisted in situ keratomileusis or intraocular lens implantation [20], by characterizing the entire visual function of the patient, using the CSF.

To measure contrast sensitivity, computer-based stimulus presentations nowadays replace paper-based charts like the traditional Pelli-Robson chart [21]. Therefore, display technologies such as cathode ray tube (CRT), liquid crystal display (LCD) or organic light emitting diode (OLED) need to be set up properly to present contrast pattern accurately. Although several methods have been developed in order to assess the contrast sensitivity function, little attention has been paid to a method which combines a precise stimulus presentation, a time-efficient psychophysical method and an accurate presentation of the spatial frequency resulting in repeatable and reliable results. In a view of time efficiency, the method of constant stimulus suffers from long measurement duration because of large trial numbers. Although methods of constant stimuli are probably highly accurate, they are less time-efficient than adaptive staircase procedures. Adaptive procedures use an algorithm to select the next stimulus intensity automatically which makes them time-efficient, by calculating and reducing the uncertainty [22].

The aim of the current research was to develop a new contrast sensitivity test that includes a time-efficient four-alternative forced choice (4AFC) staircase method together with a high resolution of the contrast levels while incorporating the magnification of currently worn prescriptions leading to repeatable and reliable contrast sensitivity measurements.

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2. Methods

2.1 Development of the TuebingenCSTest

2.1.1 The Ψ method – a Bayesian adaptive staircase procedure

A Bayesian adaptive method that is called Ψ (psi) method was used for the acquisition of the threshold contrast of the psychometric function [23]. The Ψ method was implemented into the Palamedes Toolbox [24], which can be controlled by the software MATLAB (Matlab R2010b, MathWorks Inc., Natick, USA) running on Mac OSX, version 10.9.5, using 4AFC. For this experiment, the slope of the psychometric function was fixed and set to 2.74 with a lapse rate of 4%, as suggested used by Hou [25]. To be time efficient, 50 trials were used to determine the threshold contrast of the participants' eye. The Ψ method considered the range of possible stimuli for each trial and calculated the probability and the uncertainty of correct and incorrect response [22]. To select the next stimulus, the expected uncertainty for all discrete stimuli was calculated and the stimulus intensity with the lowest calculated uncertainty was automatically selected in order to maximize the expected information [22]. A typical course of 50 trials is shown in Fig. 1, which ends in the estimated threshold contrast.

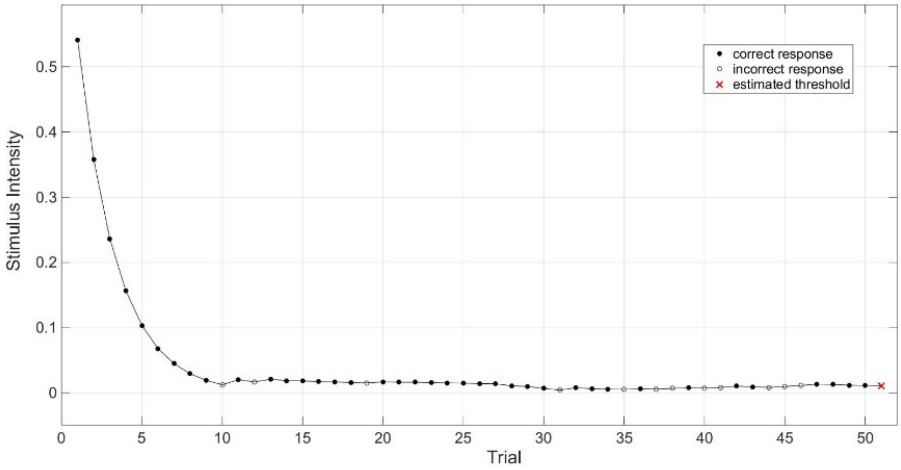

Fig. 1. The Ψ (psi) method estimates the threshold contrast (red x) after 50 trials. Closed circles indicate correct responses and open circles an incorrect response. Stimulus intensity is defined in Michelson contrast.

2.1.2 The 16-bit gray-level resolution

A LCD-Display (ViewPixx 3D, VPixx Technologies, Saint-Bruno, Canada) with a mean luminance of 40 cd/m^2 and a pixel resolution of 1920 x 1080 was used for the presentation of the stimuli (Gabor Patch gratings), with a gray-level resolution of 16 bits (2^{16} levels). Since Lu and Dosher recommended a gray-level resolution of at least 12.4 bits [26], the current gray-level resolution of the used setup is high enough to assess high sensitivities to contrast. This keeps true even if the gray-level resolution is reduced by ca. 1 bits by gamma correction and by ca. 3 bits by the need for at least eight steps to draw a sine wave, ending up about 12 bits which corresponds to a stimulus presentation with contrast as low as 0.025% (3.61 log CS). Gamma correction and luminance was checked with a luminance meter (Konica Minolta LS-110, Konica Minolta, Inc., Tokyo, Japan).

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2.1.3 The incorporation of lens magnification

Positive and negative lenses were used to correct ametropic eyes, but these lenses usually change the retinal image size. The total magnification (N_G) depends on the thickness (d) and the refractive index (n) of the lens, the distance between eye and lens (e), distance between corneal vertex and the first principal point of the eye (e'), and the front surface power of the lens (D) and the back vertex power (S') in Eq. (1) [27].

$$N_G = \frac{1}{(1-\frac{d}{n}D)} \cdot \frac{1}{(1-(e+e')S')} \tag{1}$$

with d = 0.0005 m for negative lenses and d = 0.001 m for positive lenses; e = 0.012 m, e' = 0.001348 m and n = 1.52. The magnification of the lens was corrected by changing the size and the spatial frequency of the stimulus, so that both were rearranged. Without this correction of magnification each participant would have been presented slightly different spatial frequencies.

2.2 Validation of the TuebingenCSTest

Contrast sensitivity was measured by the four following tests: Functional Acuity Contrast Test (F.A.C.T.), Freiburg Acuity and Contrast Test (FrACT), quick CSF (qCSF) and the newly developed Tuebingen Contrast Sensitivity Test (TuebingenCSTest). The FrACT Version 3.9.3 was used with auditory feedback 'with info' setting and 8-bit gray-level resolution [28, 29], F.A.C.T. (Stereo optical co., inc., Chicago, IL, USA, developed by Ginsburg et al. [30]) was used as described in the manufacturer's recommended testing procedure. The qCSF method was originally developed for 2AFC grating orientation identification task [31], while we used 4AFC with 50 trials for the qCSF. The TuebingenCSTest was used with 4AFC grating orientation identification task which means that one stimulus was presented per trial and four keyboard response choices were available. The incorporation of magnification of the lens was done in the new TuebingenCSTest and qCSF.

As mentioned before, Gabor patches (TuebingenCSTest, qCSF) and circular grating patches (FrACT, F.A.C.T.) were used as stimuli and presented by a Mac OSX, version 10.9.5 using the Psychophysics Toolbox Version 3.0.9 [32–34]. The possible orientations of both stimuli were depending on the test that was used – either 3AFC (orientation: 90°, 75° and 105°) for F.A.C.T. or 4AFC (orientation: 0°, 90°, 45° and 135°) for FrACT, qCSF and TuebingenCSTest. Since the visual angle of the stimuli is fixed to 1.7° in the F.A.C.T., the visual angle of the stimuli, used for the other test, was adapted to the same size. In case of the TuebingenCSTest, the FrACT and the qCSF, the stimuli were presented with a presentation time of 300 milliseconds (ms), while in the F.A.C.T. the stimuli are presented the whole time. The qCSF and TuebingenCSTest used technical 16-bit gray-level resolution whereas the FrACT can use only 8-bit.

To provide feedback to the participants, a tone was implemented into the TuebingenCSTest that played a high tone after correct responses and a deep tone after wrong responses, similar to the feedback 'with info' in FrACT. Additionally, the participants performed a short training with high contrast stimuli including each spatial frequency before the TuebingenCSTest begun to measure contrast sensitivity. In FrACT, the internal feedback was switched on. No feedback was provided in the qCSF whereas a neutral tone was played when a stimulus was presented.

Twelve participants were enrolled in the validation study of the TuebingenCSTest. The average age was 27 ± 3 years and habitual refractive errors (mean spherical refractive error: –2.06 ± 4.10 D) were corrected to normal vision using trial lenses. The study followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of

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the medical faculty of the University of Tuebingen. Informed Consent was obtained from all participants after the content and possible consequences of the study had been explained. The participants were placed in 6.1 m (20 feet) in front of the LCD-Display in a darkened room using a chin rest. Threshold contrast measurements were done monocular (right eye) for spatial frequencies of 1.5, 3, 6, 12 and 18 cycle per degree (cpd), while the order of spatial frequencies was randomized. The contrast sensitivity was measured for each spatial frequency separately. The whole block of the contrast sensitivity measurements was measured two times, separately for each test (FrACT, F.A.C.T., qCSF, TuebingenCSTest), with randomized order of the tests.

Statistics were performed with a statistics software (IBM SPSS Statistics 22, IBM Deutschland GmbH, Ehningen, Germany), using a Friedman test and two-way mixed intraclass correlation coefficient with absolute agreement. For post-hoc analysis a Dunn-Bonferroni test was used. Bland-Altman analysis were analyzed using a spreadsheet software (Microsoft Office Excel 2016, Microsoft, Redmond, USA) [35].

Inter-test repeatability was assessed using the Bland-Altman analysis and the test-retest reliability was evaluated via intraclass correlation coefficient (ICC) [36, 37]. Bland-Altman analysis included the coefficient of repeatability (COR) which is the 1.96 times the standard deviation of the difference between the test and the retest scores [35], which are contrast sensitivity measurements within one participant in the analysis.

3. Results

In order to verify the measurement of the CSF with the newly developed TuebingenCSTest (TueCST), we compared the obtained contrast sensitivity measures with three established contrast sensitivity tests (FrACT, F.A.C.T. and qCSF). Repeatability and reliability of contrast measurements for every contrast sensitivity test due to repeated measurements was investigated. Table 1 contains mean and standard deviation (SD) for test and retest contrast sensitivity in log CS of twelve participants.

Table 1. Mean and standard deviation (SD) for the FrACT, F.A.C.T., TueCST and qCSF using repeated contrast sensitivity measurements in log CS

Contrast Sensitivity (log CS)	Spatial Frequency (cpd)									
	1.5		3		6		12		18	
	Test	Retest	Test	Retest	Test	Retest	Test	Retest	Test	Retest
FrACT	1.93 (0.18)	1.91 (0.13)	1.96 (0.14)	1.88 (0.16)	1.78 (0.29)	1.74 (0.29)	1.36 (0.24)	1.31 (0.25)	1.02 (0.25)	0.94 (0.35)
F.A.C.T.	1.89 (0.11)	1.93 (0.10)	2.16 (0.07)	2.17 (0.07)	2.13 (0.18)	2.16 (0.13)	1.81 (0.27)	1.90 (0.21)	1.26 (0.24)	1.40 (0.35)
TueCST	1.85 (0.15)	1.84 (0.18)	1.91 (0.15)	1.96 (0.14)	1.74 (0.20)	1.77 (0.22)	1.29 (0.24)	1.31 (0.26)	0.93 (0.31)	0.95 (0.26)
qCSF	1.67 (0.27)	1.58 (0.24)	1.88 (0.22)	1.76 (0.30)	1.71 (0.24)	1.68 (0.22)	1.16 (0.42)	1.19 (0.25)	0.73 (0.49)	0.74 (0.30)

3.1 Accordance of different contrast sensitivity tests

From each contrast sensitivity test, the CSFs were plotted along the measured contrast sensitivities at five spatial frequencies, and are presented in Fig. 2. A typical form of a CSF curve with a shape of an inverted 'U' was measured with all of the four tests. The CSF of F.A.C.T. showed its maximum at 6 cpd, FrACT at 3 and 6 cpd, qCSF and the TuebingenCSTest at 3 cpd. The shapes of the inter-individual mean CSFs were similar among the FrACT and the TuebingenCSTest. The standard deviation (SD) of the two repeated measurements varied with spatial frequency and reached smallest at 3 cpd within F.A.C.T., FrACT or TuebingenCSTest. In contradiction when the qCSF assessed the CSF, the smallest SD was obtained at 6cpd within qCSF.

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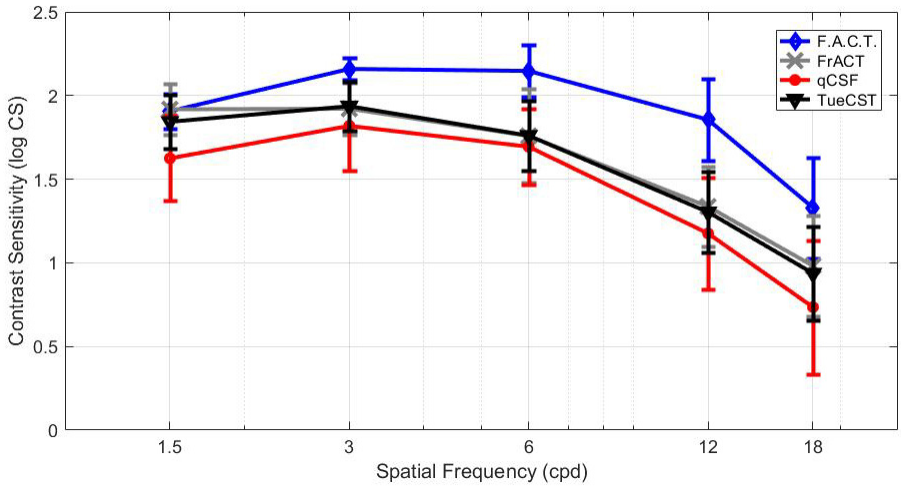

Fig. 2. Mean and standard deviation (SD) of contrast sensitivity measurements in log CS for TueCST, FrACT and qCSF for a luminance of L = 40 cd/m^2, and for F.A.C.T for L = 85 cd/m^2.

Kolmogorow-Smirnow test revealed that the measured contrast sensitivity data of FrACT, TuebingenCSTest and qCSF were normally distributed, but not those of F.A.C.T. ($p<0.05$). Statistical analysis of the contrast sensitivities demonstrated a significant difference among the four methods (χ^2 (3) = 165.43, $p < 0.001$, n = 120, Friedman Test). The post-hoc analysis found a significant difference between qCSF and the TuebingenCSTest ($p < 0.001$), between qCSF and FrACT ($p < 0.001$), between qCSF and F.A.C.T. ($p < 0.001$), between FrACT and F.A.C.T. ($p < 0.001$) and between F.A.C.T. and TuebingenCSTest ($p < 0.001$). But the post-hoc test showed no significant difference between FrACT and TuebingenCSTest ($p = 0.92$).

3.2 Inter-test repeatability – coefficient of repeatability

Table 2 contains mean and standard deviation (SD) and the Bland-Altman coefficients of repeatability (COR) for test and retest contrast sensitivity in log CS. High inter-test repeatability is indicated by a lower COR. Compared to already established test for the measurement of the CS, the CORs were lowest at 1.5, 6, 12 and 18 cpd for the new TuebingenCSTest, when compared to FrACT, F.A.C.T. and qCSF. Only repeated measurements at the spatial frequency of 3 cpd showed a slightly lower COR for F.A.C.T. compared to the TuebingenCSTest (COR 0.15 log CS vs. COR 0.18 log CS). The highest agreement between two measurements of contrast sensitivity using the TuebingenCSTest was at 6 cpd with a COR of 0.15 log CS.

Table 2. Coefficient of repeatability (COR) for the FrACT, F.A.C.T., TueCST and qCSF using repeated contrast sensitivity measurements in log CS

COR (log CS)	Spatial Frequency (cpd)				
	1.5	**3**	**6**	**12**	**18**
FrACT	0.23	0.20	0.26	0.33	0.48
F.A.C.T.	0.22	0.15	0.39	0.29	0.47
TueCST	0.17	0.18	0.15	0.23	0.38
qCSF	0.64	0.55	0.40	0.66	0.81

Although the COR values of F.A.C.T. were robust at 1.5, 3 and 12 cpd, the F.A.C.T. had a COR of 0.39 log CS at 6 cpd, while the TuebingenCSTest and the FrACT showed a better repeatability. The FrACT test demonstrated a marginal better average COR value with 0.30 log CS compared to F.A.C.T. with COR 0.31 log CS, but the repeatability for qCSF turned out in a poor agreement with COR of 0.61 log CS. On average the TuebingenCSTest revealed

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a COR of 0.22 log CS indicating that the developed test showed a higher repeatability when compared to FrACT, F.A.C.T. and qCSF.

3.3 Test-retest reliability - intraclass correlation coefficient

Table 3 contains intraclass correlation (ICC) for the test and retest of the contrast sensitivity in log CS. The ICC were highest for the TuebingenCSTest compared to FrACT, F.A.C.T. and qCSF. According to Cicchetti ICC between 0.75 and 1.00 are interpreted as excellent, between 0.60 and 0.74 as good, between 0.40 and 0.59 as fair and smaller than 0.4 as poor [38]. An ICC of 0.31 for qCSF at 1.5 cpd and an ICC of 0.33 for F.A.C.T. at 6 cpd indicated almost poor reliability, nevertheless on average the qCSF and F.A.C.T. demonstrated a good reliability with ICC of 0.61 and 0.63, respectively. The FrACT and the TuebingenCSTest came up with excellent reliability at all tested spatial frequencies. However, the developed TuebingenCSTest revealed always higher ICCs with a range between 0.88 and 0.96 ICC, representing the best reliability among all four contrast sensitivity tests.

Table 3. The Intra-class correlation (ICC) for the FrACT, F.A.C.T., TueCST and qCSF using repeated contrast sensitivity measurements

	Spatial Frequency (cpd)				
	1.5	**3**	**6**	**12**	**18**
FrACT	0.83	0.82	0.94	0.86	0.81
F.A.C.T.	0.60	0.59	0.33	0.87	0.76
TueCST	0.93	0.88	0.96	0.94	0.88
qCSF	0.31	0.58	0.77	0.70	0.67

3.4 Time duration

The TuebingenCSTest was performed with a mean duration (± SD) of 10.17 ± 1.52 minutes, while qCSF took 2.17 ± 0.87 minutes, FrACT 9.08 ± 1.35 minutes and F.A.C.T. 5.17 ± 1.37 minutes. Since all these tests need some time to instruct the participant, an average instruction time of 1-2 minutes can be estimated, depending on the age of the participant as well as whether the participant is naïve to these kinds of measurements or not. This instruction has to be conducted before the measurements start and has to be added to the actual measurement time.

4. Discussion

The newly developed contrast sensitivity test was designed to be able to work with a sufficiently high gray-level resolution, using an effective staircase procedure and accurate presentation of the spatial frequency by incorporating the magnification of spectacle lenses. Good agreement with the FrACT confirmed that the new TuebingenCSTest is measuring contrast sensitivity at the correct range of log CS values. Although the coefficients of repeatability (COR) were lowest at 3 cpd for F.A.C.T., the CORs were lowest in the TuebingenCSTest separately at 1.5, 6, 12 and 18 cpd indicating the TuebingenCSTest to have a better repeatability compared to the FrACT, the F.A.C.T. and the qCSF for measuring contrast sensitivity. Conformingly, the intraclass correlation coefficients (ICC) were highest for TuebingenCSTest when compared to FrACT, F.A.C.T. and qCSF.

One reason why F.A.C.T. showed significant higher contrast sensitivities compared to FrACT, qCSF and TuebingenCSTest is simply explained by the fact that the contrast sensitivities are higher with higher luminance because F.A.C.T. used 85 cd/m^2, but whereas the other tests used the ViewPixx monitor that had a luminance of 40 cd/m^2. Compared to the F.A.C.T and FrACT test, the TuebingenCSTest and qCSF used Gabor patches with Gaussian edge while the other two tests used circular grating patches with abrupt edges. Due to the Gaussian filtering of the edge, a Gabor Patch also contains low spatial frequencies compared to a circular grating. But since abrupt edges have a sharper transition from stimulus to

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background, this 'edge sharpening' can induce contrast enhancement in images for example [39], and hence a Gaussian edge is preferred for the test of the threshold contrast and was therefore applied in the qCSF and the TuebingenCSTest. The influence on the perception of the edge itself of the stimuli can be assumed as small, because a Gaussian edge of 0.1° was used, whereas the stimulus size was 1.7°. Furthermore, the F.A.C.T. did not present the stimuli with 300 ms and also all nine contrast levels were presented at the same time as long the participant wanted to look at them. In addition, due to the fact that the F.A.C.T. uses a 3-AFC, the probability for the participant to reach one step above their threshold (also called guess rate) is 33%, while the probability to score two steps above the threshold is 11% [40]. By using a 4AFC in the other tests, the guess rate to measure higher thresholds is 25% for one step and 6.25% for two steps. Although the F.A.C.T. holds all these advantages, its repeatability and its reliability was worse than the TuebingenCSTest for all spatial frequencies, excluding the COR at 3 cpd. The ICC of the FrACT ended up better when compared to the F.A.C.T. for almost all spatial frequencies, whereas the repeatability was similar. Due to the total number of only 50 trials, the main advantage of the qCSF is the very short duration of the measurement, but the test suffers from a low repeatability, reliability and came up with significant poorer contrast sensitives than FrACT and the TuebingenCSTest. The repeatability of the qCSF could be probably increased by increasing the number of trials, as shown by Dorr [41].

It is well known that the test of the CS has advantages especially in the detection and monitoring of ocular pathologies. Because such a test takes commonly long, especially in older and untrained participants or patients, most practitioners avoid the test of the CS. Possible solutions to reduce the time needed for this CS measurement, especially while using the TuebingenCSTest, are: On the one hand, a faster computer with more random-access memory (RAM) can be used, while on the other hand, it is also possible to reduce the number of presentation of the used stimuli. The experiments were conducted on a computer with limited random-access memory (RAM), which prolongs the inter stimulus interval leading to a longer duration of the measurement. With more RAM memory, we were able to achieve a time duration of 55 ± 11 seconds (mean ± SD) per spatial frequency. With initial instruction, the whole test would take at least 6 minutes, which would roughly halve the current duration of ca. 10 minutes of the TuebingenCSTest. While the use of a fast personal computer only requires an investment of money, the use of fewer trials has some disadvantages that need to be additionally addressed. Most likely, the repeatability and as well as the reliability will be affected in case fewer trials are used.

The measurement with the TuebingenCSTest is more time-efficient if the slope is fixed, since in that case, the threshold contrast can be assessed within only 50 trials. Hou and colleagues showed that the slope is constant within individuals, but varies among individuals [42]. To estimate both, the slope and the threshold, the Ψ (psi) method needs more than 250 trials for a 2AFC [23]. Our 4AFC procedure might need less trials than for 2AFC to determine the slope, but still probably more than 50 trials. For future experiments, the slope can be estimated with the TuebingenCSTest to use individual slopes for each participant in order to increase the accuracy of the threshold contrast determination.

The Ψ method of Kontsevich and Tyler was indicated as the best method for getting both thresholds and slopes [23, 43]. Relevant for the TuebingenCSTest, pro and contra arguments for and against the Ψ method are listed in Table 4.

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Table 4. The Ψ (psi) method: arguments pro and contra

Pro	Contra
Ψ adapts fast near to coarse threshold and then slowly and precisely to the threshold [23], like other adaptive procedures, see Fig. 1.	Lapses and biases (e.g. serial dependencies [44]) affect adaptive procedures regarding the accuracy of threshold estimation.
Threshold and slope of the psychometric function can be determined within the same measurement [23].	Lapses can have an impact rather on adaptive procedures than method of constant stimuli for example.
Adaptive procedures are more time-efficient than the method of constant stimulus, in which the stimulus presentation is repeated at exactly the same intensity level multiple times.	Lapses can occur for example due to pressing button wrongly [45], or not fixating on the stimulus by eye blinks or involuntary saccades.
	To estimate the threshold and especially the slope, the Ψ algorithm needs a lot of computational power, especially RAM memory, for calculating the uncertainty [45].
	Calculations in real-time can unintentionally prolong the inter stimulus interval leading to longer duration of the measurement [45].

One disadvantage of adaptive procedures like the Ψ method is the fact that errors in the first trials affect the further procedure [23, 25]. This can occur because observers make for example lapses such as occasional finger errors which are considered as stimulus-independent [46]. Obviously, also eye blinks or involuntary saccades would lead to less fixations on the stimulus that would lead to errors in the measurement of the contrast sensitivity. Therefore, to partly overcome such attentional-caused lapses by eye movements, a gaze contingent presentation of the used stimulus can be implemented in the TuebingenCSTest. Another disadvantage are biases, such as serial dependencies e.g. that right-handed observers may be biased to press the right button on the response keyboard [47].

Since perceptual learning can change the slope [48], a threshold measurement should be done in trained observers. Because the participants in the current study were naïve observers, we used the following method to overcome this effect: a short training with feedback was presented in the TuebingenCSTest and a constant slope was assumed. Feedback was provided for every trial to reduce the chance for biases and lapses. As described for visual acuity measurements using the FrACT, systematic feedback does not affect reproducibility and also offers advantages such as greater comfort [49].

To accurately present stimuli for a contrast sensitivity measurement, a sufficiently high gray-level resolution as well as an accurate presentation of the spatial frequency are needed. The sufficiently high gray-level resolution was achieved by using the ViewPixx monitor with a 16-bit gray-level resolution. The advantage of using 16-bit gray-level resolution is the fact that the Gabor Patch can be presented smoothly, which means that the sine wave consists of additional but smaller steps. Since the human eye is able to perceive contrasts up to 0.15% (2.82 log CS) [50–52], the second advantage of a 16-bit gray-level resolution is the fact that the minimum amplitude of the sine wave stimuli (the lowest contrast level) can be smaller compared to the 8-bit gray-level resolution. In the current experiment, the FrACT was presented with a gray-level resolution of 8 bits. Due to the loss by gamma correction and by a smooth oscillating presentation of the Gabor Patch, this would lead to a 4-bit gray-resolution that corresponds to a minimal presentable contrast of 6.25% (1.20 log CS). In case the contrast levels are defined, the staircase procedure would continue in order to approach further threshold contrasts lower than 1.20 log CS. In this case, an 8-bit resolution would not present a Gabor Patch with smooth oscillating sine waves. Thus, the Gabor Patch would rather convert to square wave stimulus. These steps of the square wave can appear as sharp edges in the gray-level dimensions and it was shown that this ‘edge sharpening’ can induce contrast enhancement in images for example [39]. Such gray-level edges would become more

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obvious for Gabor Patches with lower spatial frequencies, because they cover more pixels in-between one cycle which can be filled with more gray-levels than in Gabor Patches with higher spatial frequencies. Furthermore, these gray-level edge sharpening will increase detectability: This increased sensitivity to edges can be explained by the antagonistic receptive fields of retinal ganglion cells and their lateral inhibitory connections which seemingly enhances contrast perception [53]. At 1.5 cpd, the FrACT showed a higher contrast sensitivity compared to the TuebingenCSTest (1.94 vs. 1.84 log CS). This difference was not significant, but could be explained by contrast enhancement through sharpening of edges in the 8-bit gray-level resolution.

As Blackwell described in his criteria called 'sensory-determinacy', methods that lead to lower threshold are preferred [54], since higher thresholds may indicate that the used method would lead to more unwanted extrasensory influences on the observer [47]. But the FrACT with an 8-bit gray-level resolution should be not preferred, although thresholds were lower than in the TuebingenCSTest because the observers were predisposed to lower threshold values due to increased gray-level edges.

Also an accurate presentation of the spatial frequency was achieved by incorporating the magnification of spectacle lenses. Other authors like Radhakrishnan corrected for spectacle magnification by altering the test distance [55]. For the new TuebingenCSTest, the correction for magnification was accomplished before recording the response. Therefore, with the TuebingenCSTest, measured contrast sensitivity for a certain spatial frequency may afford a better comparison over participants with different prescriptions.

Furthermore, another advantage of the TuebingenCSTest and the FrACT is that it can be used for detecting notches in the CSF, which are selective spatial frequency losses due to optical defocus [56]. Tests such as qCSF tend to overlook these notches because they estimate the CSF with a given function that is not able to reflect selective spatial frequency losses.

5. Conclusion

We have successfully implemented the time-efficient Ψ method to measure the contrast sensitivity of the human eye with a sufficiently high gray-level resolution that allows a smooth oscillating Gabor Patch presentation. Correcting the presented spatial frequencies and the stimulus size to overcome the magnification of worn spectacle lenses helps to gain comparable threshold contrasts for participants with different habitual refractive errors. The new presented method, called TuebingenCSTest, can be set up customized and shows high precision, repeatability and reliability over a wide range spatial frequencies regarding contrast sensitivity measurements.

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II. Color-Tinted Lenses and Contrast Sensitivity

The influence of color-tinted lenses on the visual performance was measured with the TuebingenCSTest to examine if existing color-tinted lenses or high- and band-pass filter color-tinted lenses show an improvement in contrast sensitivity.

Color-Tinted Lenses and Contrast Sensitivity

Tim Schilling[1]*, Alexander Leube[1,2], Arne Ohlendorf[1,2] & Siegfried Wahl[1,2]

[1]Institute for Ophthalmic Research, Eberhard Karls University Tuebingen, Tuebingen, Germany

[2]Carl Zeiss Vision International GmbH, Aalen, Germany

*Corresponding author: tim-tobias.schilling@uni-tuebingen.de

Yellow-tinted lenses are often sold as contrast enhancers, although little objective evidence of a benefit in contrast sensitivity exists. Some studies have demonstrated a reduction in contrast sensitivity, whereas a few others have found the opposite. Therefore, the TuebingenCSTest, which is able to achieve reliable and repeatable measurements, was further developed as a precise tool to assess contrast sensitivity under equi-luminant conditions. Contrast sensitivity was determined for clear and fashion-related tinted lenses (none, chillout green, sweet violet, spicy red, happy yellow and space blue) from 0.5 to 12 cycles per degree (cpd) in 15 participants, as well as for clear (none), high-pass (yellow, red) and band-pass color-tinted (blue, green) lenses from 0.5 to 6 cpd in eight participants. No improvement in contrast sensitivity with any tinted lens was found relative to the none-tinted lens condition in both groups. At a middle spatial frequency of 3 cpd, red-tinted lenses displayed a significantly better contrast sensitivity than blue-tinted and green-tinted lenses. Furthermore, contrast sensitivity was not altered with fashion-tinted, high- or band-pass color-tinted lenses – meaning that contrast sensitivity was not reduced, but also not increased.

Keywords: contrast sensitivity, lens, color-tint

1. Introduction

The visual performance of the eye can be assessed by contrast sensitivity. In comparison to visual acuity, the advantage of contrast sensitivity is that it covers the complete spatial performance of an eye. Fine pattern gratings, consisting of higher spatial frequencies, and gratings with broad stripes, consisting of lower spatial frequencies, display lower contrast sensitivity than the medium spatial frequencies in-between. On the high spatial frequency end, the optics of the eye, such as aberrations and diffraction, limits the visual performance; on the low spatial frequency edge, receptive limitations, such as cortical and size of the receptive fields in the retina, have been discussed [1]. Given this variation in spatial dimensions, contrast sensitivity should be assessed over several specific spatial frequencies. If contrast sensitivity is plotted over spatial frequencies, the revealed curve is called the contrast sensitivity function (CSF). Apart from spatial frequency, the luminance of a stimulus changes the level of the entire CSF [2]. This effect must be considered when contrast sensitivity is assessed through color-tinted lenses because tinted lenses act as light filters and always reduce the total transmittance and hence the luminance.

Tinted lenses are also called filters or colored glasses because they absorb a specific part of the visual spectrum. Each filter displays a characteristic transmission spectrum of the remaining light, resulting in certain tints such as red or green. Contrast enhancement is strongly associated with color-tinted

lenses and has been described in several studies [3-5], which have investigated a variety of different tinted lenses. However, a review by Eperjesi et al. [4] presents little objective evidence that color-tinted lenses improve the visual performance of the eye. Therefore, a reliable contrast sensitivity measurement and control over the luminance are important. The methodological aim of this study is to achieve a constant luminance, independent of the contribution of the filter and the light source. In this study, the contrast sensitivity of fashion-related tinted lenses, with soft modulation of the transmission spectrum, is investigated first. Since a slight modulation of the spectra could lead to different effects in contrast sensitivity than stronger modulations of the spectrum, high- or band-pass color-tinted lenses are used in a second experiment. The purpose of the experiments is to examine if any of the color-tinted lenses exhibit an increase or decrease in contrast sensitivity.

2. Methods

Objective refraction of the eye using a wavefront aberrometer (ZEISS i.profiler Plus, Carl Zeiss Vision GmbH, Aalen, Germany) and a subjective refinement of the correction of a habitual refractive error was done prior to the main measurements. Two separate groups of participants consisted of 15 and eight participants, respectively. Moreover, the study was approved by the Institutional Review Board of the medical faculty of the University of Tuebingen, following the tenets of the Declaration of Helsinki. Therefore, informed consent was obtained, and possible consequences of the study were explained.

The main experiment was conducted with the TuebingenCSTest with similar adjustments, see settings in Schilling et al. [6]. The stimuli consisted of 1.7° Gabor patches that were shown consecutively for 300 ms. Using a chin rest, participants were placed 80 cm in front of the monitor in a darkened room. Monocular measurements were performed at 0.5, 1, 1.5, 2.1, 3, 4.2, 6, 8.5 and 12 cycles per degree (cpd) in the first group and at 0.5, 1.5, 3 and 6 cpd in the second group. Fifty trials were used to assess each spatial frequency, and acoustic feedback was provided for correct or incorrect responses. The measurement distance was corrected with a +1.25 diopter trial lens.

The fashion-related tinted lenses were produced by Carl Zeiss Vision GmbH (Aalen, Germany), and they included the colors “chillout green,” “sweet violet,” “spicy red,” “happy yellow” and “space blue”, see Fig. 1 (top) for details of their transmission. Furthermore, the high- and band-pass color-tinted lenses were manufactured by Carl Zeiss Vision Italia SpA (Varese, Italia) and included a blue, a red and a green tint, see Fig. 1 (bottom) for details of their transmission. Additionally, a yellow filter with cut-off, quickly increasing transmission, at 480 nm was used (Carl Zeiss Vision GmbH, Aalen, Germany). The LCD-Display (ViewPixx 3D, VPixx Technologies, Saint-Bruno, Canada) was used with a pixel resolution of 1920 x 1080, a 16-bit grayscale resolution, incorporation of the lens magnification [6] and 50 cd/m² for the “fashion-related tinted lenses” group and 2.5 cd/m² for the “high- or band-pass color-tinted lenses” group. Moreover, the luminance was controlled with a luminance meter (Konica Minolta LS-110, Konica Minolta, Inc., Tokyo, Japan).

The software JASP (0.11.1, JASP Team, 2019, Amsterdam, Netherlands) was used for the statistical analysis. The mean of the logCS was tested with a repeated ANOVA, with a p-value < 0.05 indicating significance, and a pairwise Bonferroni corrected post-hoc test. In addition, Bayesian inference statistics was conducted to test the presence of a difference. The Bayes factors were sorted to the degrees of evidence by Kass and Raftery (Kass & Raftery, 1995); that is, $BF_{10} = 1–3$ was interpreted as weak evidence, $BF_{10} = 3–20$ was interpreted as positive evidence, $BF_{10} = 20–150$ was interpreted as strong evidence, and $BF_{10} > 150$ was interpreted as very strong evidence.

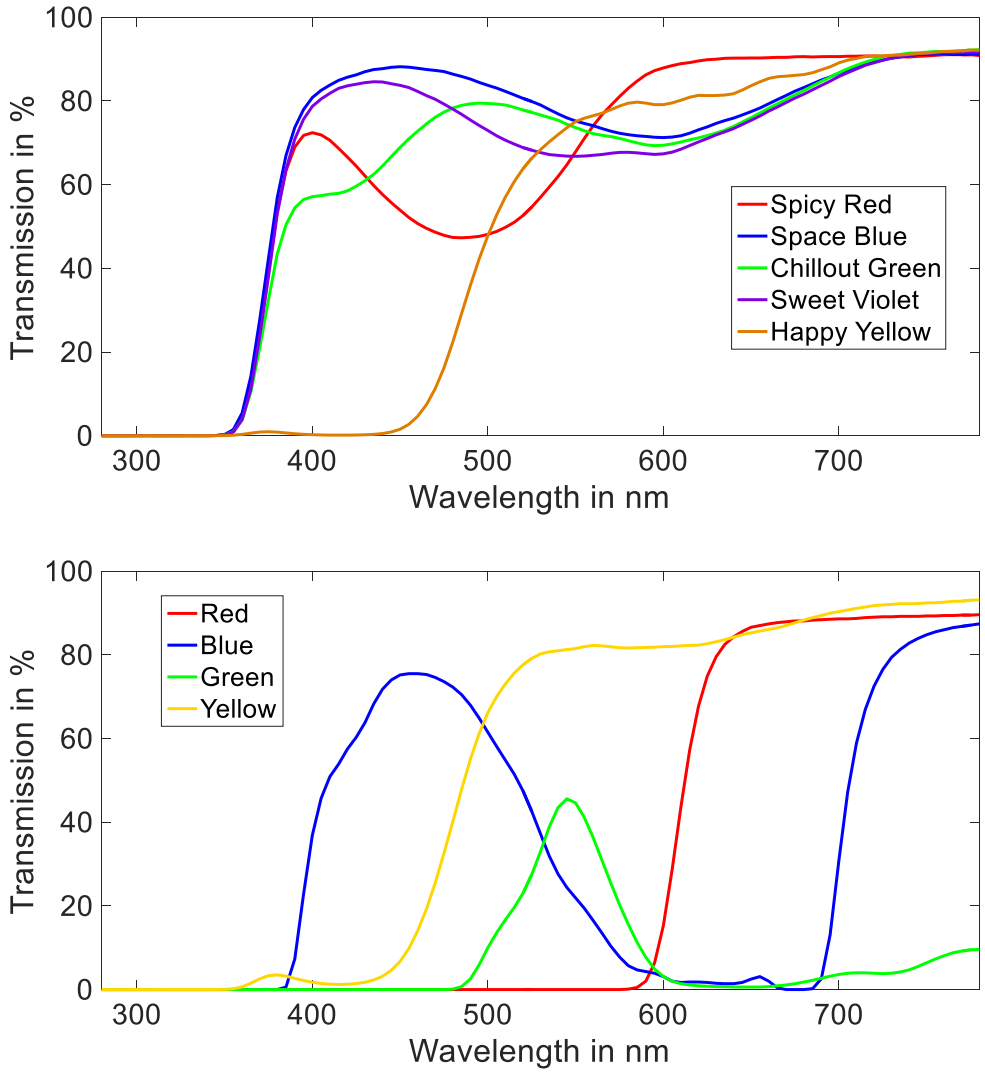

Figure 1: Spectral transmission of fashion-related tinted lenses (top) and high- (yellow and red) and band-pass (blue and green) color-tinted lenses (bottom) in percentage. Own illustration plotted with data from manufacturer sheets, which was reprinted and modified from Fig. 2 in Schilling et al. [7], distributed under the terms of the Creative Commons Attribution License (CC BY).

3. Results

The assessment of fashion-related and both high- and band-pass color-tinted lenses revealed no significant change in the measured contrast sensitivity for fashion-related tint, see Fig. 2 above. The ANOVA provided a non-significant effect of the factor tint on fashion-related tinted lenses ($p = 0.29$). In addition, a significant main effect of the factor tint was revealed on high- and band-pass color-tinted lenses ($p < 0.05$) and the interaction between spatial frequency and tint ($p < 0.001$), see Fig. 2 below. Relative to no filter condition, none of the selected tinted lenses could provide an improvement in contrast sensitivity. Regarding factor tint, a pairwise Bonferroni-corrected post-hoc comparison delivered a significant difference between blue- and red-tinted lenses ($p < 0.01$). Moreover, concerning the interaction between spatial frequency and tint, a pairwise Bonferroni-corrected post-hoc comparison delivered significant improvement – in particular, 3 cpd of red-tinted lens compared to both blue-tinted lenses ($p < 0.001$) and green-tinted lenses ($p < 0.001$), but not to none- and yellow-

tinted lenses (p = 0.19; p = 0.22). An uncorrected Bayesian analysis also revealed positive evidence of space blue showing a lower contrast sensitivity than the none (BF_{10} = 17.3), happy yellow (BF_{10} = 8.1) and spicy red (BF_{10} = 5.7) color tint groups.

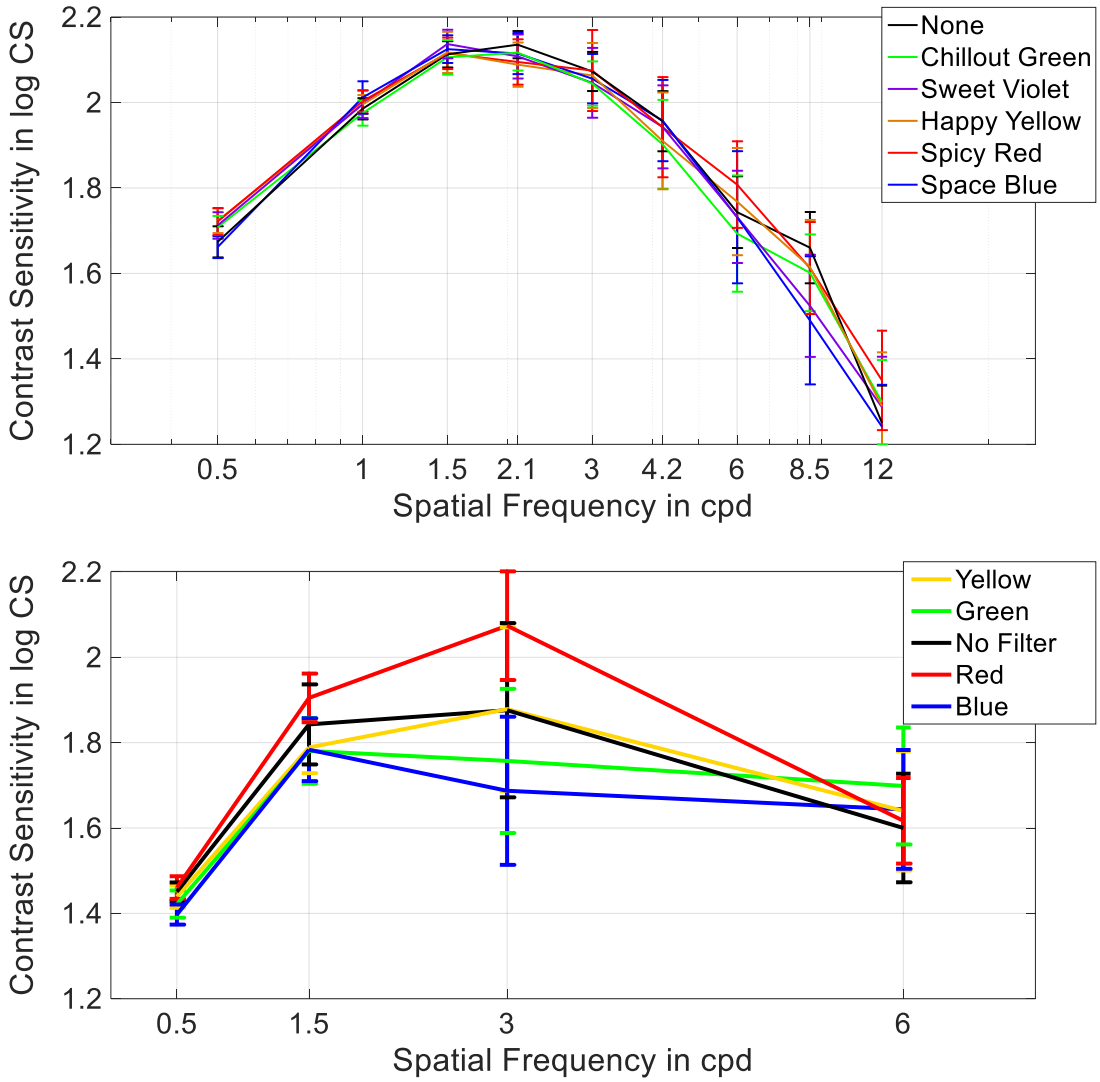

Figure 2: Contrast sensitivity function for fashion-related tinted lenses (top) and for high- and band-pass color-tinted lenses (bottom). Mean and standard errors of contrast sensitivity in log CS are plotted.

The ANOVAs returned a significant effect of the factor spatial frequency on both the "fashion-related tinted lenses" group ($p < 0.001$) and the "high- or band-pass color-tinted lenses" group ($p < 0.01$). Therefore, the CSF of both groups followed the typical inverted U-shape. Furthermore, contrast sensitivities for high- or band-pass color-tinted lenses were lower than for fashion-related tinted lenses because the total luminance was 50 cd/m² for the latter group and 3 cd/m² for the former group.

4. Conclusion

The TuebingenCSTest was additionally equipped with a procedure to ensure constant luminance behind the filter and before the light enters the eye. Therefore, it was possible to measure comparable contrast sensitivities for light filters, which absorb the spectrum differently. The results revealed that

tinted lenses have no consequence for the visual performance of the eye compared to the condition when no filter was worn. Accordingly, no detrimental or beneficial effects of tinted lenses were observed regarding contrast sensitivity.

Following the chromatic aberration, long-wavelength-transmitting color-tinted lenses provided a slightly better contrast sensitivity when compared to short-wavelength-transmitting tinted lenses. This difference was most prominent in the middle spatial frequency of 3 cpd between red- and blue-tinted lenses. The edges of the CSF are presumably affected by other factors, such as receptive and optical limitation, rather than chromatic aberrations; therefore, it was assumed that this effect did not occur at the measured edges of the CSF. Furthermore, an improvement in contrast sensitivity with yellow-tinted lenses could not be found in this study, although other research, for example Wolffsohn et al. [3], has found an effect. It should be considered that while some colored-tinted lenses, for example yellow, might give the impression of amplified brightness [8], this does not necessarily mean that contrast sensitivity is enhanced. A better explanation for this subjective visual impression is that yellow filters lead to a larger pupil size under equi-luminant conditions [8, 9].

One application-specific limitation of this study is that it was conducted under low luminance, but still under photopic conditions, and it cannot be ruled out that contrast sensitivity will improve under intense light, as has been demonstrated, for example, under glare conditions [10, 11]. Finally, although the luminance for high- or band-pass color-tinted lens was much lower than for fashion-related color-tinted lenses, contrast sensitivity for red-tinted lenses reached a similar level at 3 cpd. In conclusion, fashion-related and high- or band-pass color-tinted lenses were not able to modify the CSF substantially.

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7.2 Second section

III. Color-Tinted Lenses and Lag of Accommodation

Opto-physiological performance can be quantified by lag of accommodation. The lag of accommodation was assessed under the influence of color-tinted lenses to identify if color-tinted lenses show the same effects as monochromatic light and if the opto-physiological performance can be improved.

Color-Tinted Lenses and Lag of Accommodation

Tim Schilling[1]*, Alexandra Sipatchin[1], Arne Ohlendorf[1,2] & Siegfried Wahl[1,2]

[1]Institute for Ophthalmic Research, Eberhard Karls University Tuebingen, Tuebingen, Germany

[2]Carl Zeiss Vision International GmbH, Aalen, Germany

*Corresponding author: tim-tobias.schilling@uni-tuebingen.de

The opto-physiological performance in regard to the accommodative response of the eye describes a focusing error of the eye, depending on the state of the accommodative response. Myopia progression is associated with this type of insufficient accommodation. In this work, the accommodative response was investigated in 10 distance-corrected myopic participants when looking through clear and color-tinted lenses (none, blue, green, orange, red). The difference in the accommodation response between clear and color-tinted lens conditions was explored for three near-viewing distances (25, 33, and 40 cm). The lag of accommodation – a reduced accommodative response – was significantly different between red- and none-, between red- and blue-, between orange- and blue- as well as between blue- and none-tinted lens conditions. In conclusion, an enhanced accommodative response and a reduced lag of accommodation were observed in cases where color-tinted lenses were worn that transmitted long-wavelength visible light. This result is in accordance with previous studies, reporting that the accommodative response increased with longer wavelengths of light. It could thus be shown that color-tinted lenses have an influence on the accommodative response.

Keywords: myopia, lag of accommodation, lens, color-tint

1. Introduction

Ocular accommodation is the eye's ability to adjust the optical power of a crystalline lens to objects at different distances using neurophysiological mediated ciliary muscle activity so that the images are focused at the retina [1, 2]. Accommodative response describes the opto-physiological performance of an eye, where improper accommodation causes images to appear blurred. Young myopes have been found to show a reduced response of their accommodative system, which has been linked to both the onset and progression of myopia [3-6]. This reduced accommodative response is called lag of accommodation, where the focus is farther away than the stimulus and increases with viewing distance [6-10]. The lag of accommodation is an error of accommodation and can also be used as a measure for the opto-physiological performance of an eye.

Chromatic aberration is an optical error caused by the fact that the refractive index of optical media increases with decreasing wavelengths. Therefore, a monochromatic filter that transmits only blue light in front of an eye should have a similar effect as a plus lens, as the result is a myopic defocus, where the focus point is closer to the lens than with a minus lens. In contrast to a blue-tinted lens, a monochromatic filter that transmits only red light should behave in the same way as a minus lens because of increased hyperopic defocus. Previous studies have demonstrated that accommodation follows the longitudinal chromatic aberration function under monochromatic light conditions [7, 11,

12], thus leading to the conclusion that the accommodative response increases for a long-wavelength light (such as red), when compared to a short-wavelength light (blue). The purpose of this study is to investigate whether the accommodative response of the eye, reflecting the opto-physiological performance, changes when color-tinted lenses with varying transmittance are worn. Since high- and band-pass color-tinted lenses display a distinct transmission spectrum with a clear reduction of certain wavelength regions in visible light, red-, green-, blue- and orange-tinted lenses are used for this study. The following hypothesis is thus tested: shorter and longer wavelength-transmitting color-tinted lenses exhibit a difference in accommodative response and thus in the lag of accommodation.

2. Methods

Ten participants were examined after their informed consent was obtained and possible consequences of the study had been explained, following the tenets of the Declaration of Helsinki. Furthermore, the study was approved by the Institutional Review Board of the Medical Faculty of the University of Tuebingen. Prior to the main measurements, an objective refraction (i.profiler Plus) and subjective refraction were assessed.

The color-tinted lenses included a blue-, a red-, a green- and an orange-tinted lens, see Fig. 1. To avoid possible artifacts due to the light source, the Solux Lamp 4700K (Tailored Lighting Inc., Rochester, NY, USA) was used to obtain a homogenous spectrum similar to the spectrum of the sun [13].

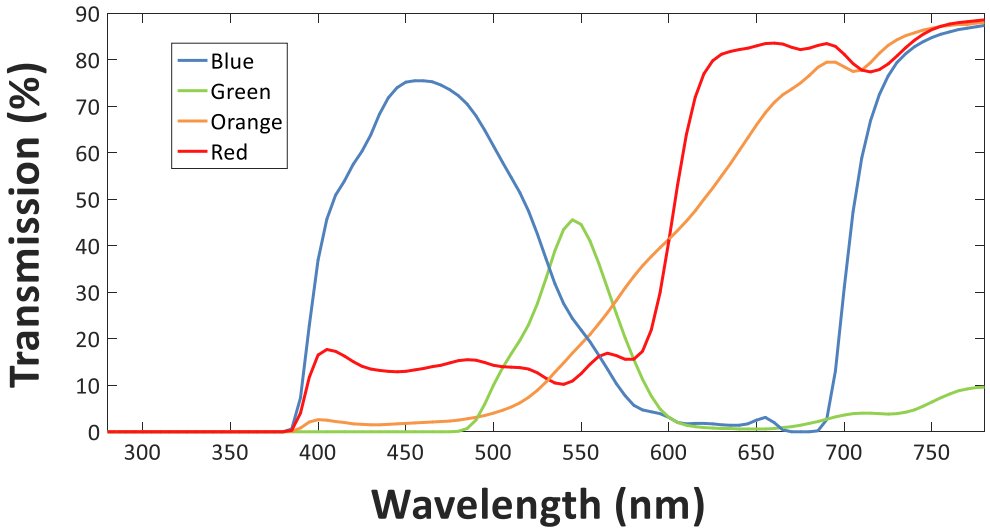

Figure 1: Spectral transmission of color-tinted lenses in percentage. The blue- and green-tinted lenses transmit the spectral curve of an inverted U-shape with peaks at ca. 460 nm and 550 nm, respectively. The red-tinted lens is a high-pass filter with a cut-off at 610 nm and a low transmission between 400 and 600 nm. The orange-tinted lens transmits more light slowly and increasingly, starting from 500 nm and crossing the red-tinted lens' spectral curve at 600 nm. Own illustration plotted with data from manufacturer sheets, which was reprinted and modified from Fig. 2 in Schilling et al. [14], distributed under the terms of the Creative Commons Attribution License (CC BY).

The main examination included measurement of the refractive error of the non-dominant eye, covered with an infrared-transparent filter (Kodak IR 87C, Kodak Corp., Rochester, NY, USA), using the Grand Seiko WAM-5500 autorefractor (Grand Seiko Co., Ltd., Fukuyama Hiroshima, Japan) and following the procedure described by Schilling et al. [15]. The distances (25, 33, 40, and 400 cm) and

the color-tinted lenses were tested in a randomized order, and the spherical equivalent refractive errors were measured five times. Moreover, the lag of accommodation was calculated by subtracting the accommodative response from the accommodative demand; for details, see Atchison and Varnas [16].

Statistical analysis was conducted using the software JASP (0.11.1, JASP Team, 2019, Amsterdam, Netherlands). The mean of the lag of accommodation was tested with a repeated ANOVA, with p-value < 0.05 for significant differences, followed by a pairwise Bonferroni corrected Post-hoc analysis.

3. Results

The ANOVA returned a significant main effect for the factor color-tint ($F(5,45) = 5.0$, $p < 0.001$), while the lag of accommodation reached the highest mean values when participants wore blue-tinted lenses. In the post-hoc test, the lag of accommodation of blue-tinted lenses was significantly higher than the lag of accommodation of red- ($p < 0.001$), orange- ($p < 0.01$), and none-tinted ($p < 0.05$) lenses. Furthermore, the post-hoc test revealed a significantly smaller lag of accommodation for red- than for none-tinted lenses ($p < 0.05$), see Fig. 2.

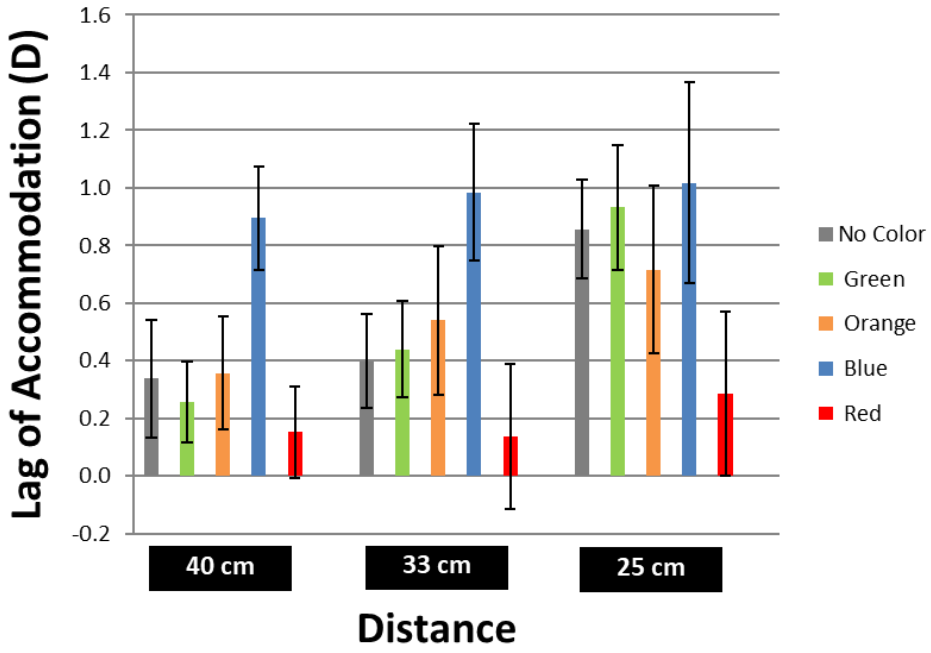

Figure 2: Lag of accommodation for color-tinted lenses at various distances. The calculated mean and standard errors are plotted for all viewing distances (40, 33, and 25 cm) and separately for all tints (none, green, orange, blue and red).

In accordance with a previous study [15], the lag of accommodation changed significantly with the viewing distance ($F(2,18) = 7.6$, $p < 0.01$). Post-hoc tests returned a significant difference for the lag of accommodation between 40 cm and 25 cm ($p < 0.01$) as well as between 33 cm and 25 cm ($p < 0.01$), but not for the comparison of 40 versus 33 cm. The increasing lag of accommodation for the three different viewing distances is illustrated in Fig. 2. The interaction between the color-tint factor and viewing distance was not significant ($F(10,90) = 1.4$, $p = 0.21$).

4. Conclusion

The results of this study suggest that color-tinted lenses have an effect on the accommodative response. More specifically, the results indicate that color-tinted lenses with a longer wavelength transmission aid the accommodative response in young myopic participants, reflected in the changes in the lag of accommodation. The hypothesis has been confirmed that a difference exists in the lag of accommodation and in the accommodative response between shorter and longer wavelength-transmitting color-tinted lenses. These findings are in line with previous results that accommodative response increases with longer wavelengths in the visible spectrum [12].

The lag of accommodation is described as an accommodation error, where the eye observes a near target, but the accommodation does not reach the near point and is shifted between the far point and the near point [17]. With an object closer to the eye, the image blurs because defocus increases, which was assumed to be due to lag of accommodation [3]. More defocus as a result of a higher lag of accommodation has been suggested to result in faster progression of myopia in chicken [18]. However, no clear result was obtained regarding whether lag of accommodation precedes myopia or develops parallel to myopia, and it seems to be more likely that lag of accommodation is not a useful predictor for myopia onset [19, 20]. Assuming that lag of accommodation has an effect on ocular growth and myopia development, several studies have attempted to reduce lag of accommodation with optical solutions, for example with progressive addition lenses (PALs): some studies have demonstrated that the use of PALs could reduce myopia [21-26], at least in the first year of use. Furthermore, specific near-zone-designed PALs have been shown to reduce the lag of accommodation in myopes [15]. A limitation of this study was that the chromatic aberration was not included in the calculation of the accommodative demand. This systematic error would affect all lag of accommodation calculations, depending on the wavelength but not the accommodative response. Since the subjective refraction was not conducted for each single color-tinted lens, a correction could not be performed and therefore could not be included in the lag of accommodation calculations.
In monochromatic light, the accommodative response has been shown to follow the chromatic aberration [11], which means that accommodative response increases with visible light of higher wavelengths. However, others have found that accommodative response increases when using wavelengths lower than 430 nm [7, 27]. This reverse effect could not be observed with blue-tinted lenses, with peak at 460 nm in this study, likely because the blue-tinted lens transmits light of wavelengths both lower than 430 nm and higher than 550 nm. Related to higher wavelengths, this study indicates that the lag of accommodation is lower with red-tinted lenses. A potential connection between myopia inhibition and red light has been demonstrated before by Smith and colleagues, whereas exposure to long-wavelength lighting could reduce myopia progression in monkeys [28]. However, in different animal models, myopia inhibition has been shown by blue light and not by red light, for example, in chicken [29] or guinea pigs [30]. Furthermore, choroidal thickness, which might be involved in eye growth regulation, has recently been found to be relatively increased after 1h of blue light stimulation in humans, compared to red light [31]. Therefore, the increased accommodative response with red-tinted lenses might not be sufficient to have a positive effect on eye growth.

In conclusion, these contradictory findings from animal and human studies and the missing proof of causality between lag of accommodation and myopia do not allow for a clear and unambiguous transfer of color-tinted lenses to myopia development. Nevertheless, a retardation of lag of accommodation with red-tinted lenses has been overserved, and it could be confirmed that color-tinted lenses follow the chromatic aberration.

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7.3 Third section

IV. Looking Through ‘Rose-Tinted’ Glasses: The Influence of Tint on Visual Affective Processing

Emotional performance can be described by a late positive potential in the brain, measured by EEG. The effects of color-tinted lenses on emotional performance were investigated to explore neuroergonomic applications for color-tinted lenses.

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Looking Through "Rose-Tinted" Glasses: The Influence of Tint on Visual Affective Processing

Tim Schilling[1,2]*, *Alexandra Sipatchin*[1,2], *Lewis Chuang*[2,3] and *Siegfried Wahl*[1,4]

[1]Institute for Ophthalmic Research, Eberhard Karls University Tuebingen, Tuebingen, Germany, [2]Department of Perception, Cognition and Action, Max Planck Institute for Biological Cybernetics, Tuebingen, Germany, [3]Department of Human-Centered Ubiquitous Media, Institute for Informatics, Ludwig-Maximilians-University Munich, Munich, Germany, [4]Carl Zeiss Vision International GmbH, Aalen, Germany

The use of color-tinted lenses can introduce profound effects into how we process visual information at the early to late stages. Besides mediating harsh lighting conditions, some evidence suggests that color-tinted lenses can influence how humans respond to emotional events. In this study, we systematically evaluated how color-tinted lenses modified our participants' psychophysiological responses to emotion-inducing images. The participants passively viewed pleasant, neutral or unpleasant images from the International-Affective-Picture-System (IAPS), while wearing none, blue, red, yellow or green tinted-lenses that were controlled for luminance. Established neuroergonomic indices of arousal were measured on the autonomic level, namely Skin-Conductance-Response (SCR) and Heart-Rate-Variability (HRV), and on the cortical level, with electroencephalography (EEG) event-related potentials (ERPs). Phasic SCR responses were significantly enhanced for unpleasant images and both pleasant and unpleasant images induced significantly larger ERP amplitudes of the Late-Positive-Potential (LPP), with pleasant images having the greatest impact. Interestingly, a significant main effect was found for tint. Similar to viewing pleasant images, red-tinted lenses induced the largest LPPs. Taken together, these findings suggest that the autonomic response to affective images is modulated at the cortical level of processing, congruent with the use of red-tinted lenses.

Keywords: electroencephalography (EEG), physiological response, color-tinted lenses, red, emotion

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Gianluca Borghini,
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Giulia Cartocci,
Sapienza University of Rome, Italy
Roman Mouček,
University of West Bohemia, Czechia
Petr Jezek,
University of West Bohemia, Czechia

***Correspondence:**
Tim Schilling
tim-tobias.schilling@uni-tuebingen.de

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INTRODUCTION

It is claimed that soldiers of the US Civil War were prescribed glasses with colored lenses with the intention to treat disorders such as depression (Henry, 2016). Supposedly this practice gave rise to the phrase "To see the world through rose colored glasses," which refers to individuals who hold a positive outlook on life. Regardless of the veracity of this apocryphal tale, color is an important ubiquitous feature of the visual world that the brain is highly selective for. It allows us to readily recognize objects (Gegenfurtner and Rieger, 2000), facilitates visual memory (Wichmann et al., 2002) and can be used to segment objects from the background (Gegenfurtner, 2003). Color can also exert a strong influence on physiology.

Blue light has an essential function in chronobiology as a pacemaker of the circadian rhythm (Berson et al., 2002). It mediates the circadian rhythm through intrinsically photosensitive retinal ganglion cells containing the photopigment melanopsin, which is most sensitive to approximately 480 nm (Berson et al., 2002). Green light has been found to exacerbate migraine headache less than white, blue, amber or red lights (Noseda et al., 2016). Red coloration is associated with male dominance and testosterone in animals (Andersson et al., 2002; Pryke et al., 2002; Setchell and Jean Wickings, 2005) and it may reflect dominance in humans as well (Hill and Barton, 2005). For example, human anger correlates with reddening of the skin due to increased blood flow (Darwin and Prodger, 1998; Drummond and Quah, 2001). It has been proposed, that color associations and preferences developed on the basis of emotions evoked by colored objects (Ou et al., 2004a,b). The ability to detect red colored objects such as ripe fruits and berries against green leaves was evolutionarily important. It has been claimed that the color vision system adapted its color preferences, especially in female (Hurlbert and Ling, 2007). The hypothesis that colors have ecological value is summarized in the Ecological Valence Theory (Palmer and Schloss, 2010).

Colors can also strongly influence emotional processing. According to the circumplex model, emotions can be classified into two categories: affective valence (pleasure-displeasure axis) and arousal (arousal-sleepiness axis; Russell, 1980); these categories showed a clear relation to physiological responses (Lang et al., 1993; Mauss and Robinson, 2009). The color red is connected with excitement (Wexner, 1954) and can increase arousal i.e., greater electroencephalography (EEG) alpha wave recovery (Ali, 1972) and Galvanic-Skin-Response (GSR; Wilson, 1966; Jacobs and Hustmyer, 1974; Lee and Westland, 2015). Besides physiological arousal, red is also linked to emotions on a color association level. It has positive appetitive implications like attraction (Elliot and Niesta, 2008). On the opposite, as a negative valence color, red is linked to danger, failure (Gerend and Sias, 2009), anger and aggression (Elliot and Maier, 2007; Fetterman et al., 2012). For example, a red background makes it easier to categorize angry faces (Young et al., 2013). This influence on psychological functioning, emotional and cognitive decision-making is known as the red effect (Gilston and Privitera, 2016). Green, as the opponent color to red, is often connected to a positive meaning (Elliot et al., 2007; Gnambs et al., 2010) e.g., green promotes creativity (Lichtenfeld et al., 2012) and is associated with safety (Pravossoudovitch et al., 2014). In addition, green hue is said to have a calming, stress-reducing effect (Jalil et al., 2012). Going out to the natural environment with plants containing chlorophyll is associated with green as well (Akers et al., 2012). Yellow hue is often used for warning signs in combination with black. In nature, this warning sign of yellow-black contrast appears on bees for instance (Rowe and Halpin, 2013).

Color can be seen naturally or it can be modified on a spectral illumination level. The modification of visual light occurs already in the atmosphere for sun light and generally when absorbed or reflected from any object. The light, which is reflected or emitted by the object, appears as the object color. Almost every object is emitting or reflecting a certain wavelength pattern, called spectrum. Filters can modify these spectra through wavelength-specific reflection, absorption and transmission. Neutral density or gray filters reduce the spectra equally over all wavelengths, whereas tinted lenses selectively absorb the wavelengths except for those related to the tint. For instance, a red-tinted lens transmits light higher than ca. 600 nm and absorbs light below. Tinted lenses are also called filters or colored glasses. A common filter is the yellow cut-off filter, which is a high pass filter, strongly absorbing light of wavelengths lower than the cut-off wavelength (ca. 480–500 nm) and transmitting light of higher wavelengths than this cut-off wavelength. From a cognitive point of view, yellow-tinted lenses have been shown to modulate the level of attention: reading speed (Hollingsworth et al., 2015) and response time (Lacherez et al., 2013) were improved by yellow tints. From a physiological point of view, yellow-tinted lenses increase the pupils size (Kelly, 1990; Chung and Pease, 1999) and prevent short wavelength light from reaching the eye, protecting (Downie, 2017; Lawrenson et al., 2017) the eye from light damage similarly like the UV-blocking function (International Commission on Non-Ionizing Radiation Protection, 2004). It is important to keep in mind that color and colored light modulated by tinted lenses are not necessarily the same. For example, a color appears often strong when there is a color contrast, whereas colored filters alter the spectrum that is transmitted to the eye and color contrast is then usually diminished. The strongest difference between color and colored light appears when colored light is filtered completely to a monochromatic narrow wavelength bandwidth by tinted lenses. Under this condition, no color contrast will be presented on the retina. Limitations of previous studies have been the unequal luminance levels for different color conditions. In this study, we carefully calibrated the luminance resulting in equal luminance for each tinted lens condition.

It has already been reported that there are abundant studies on the colors red and blue and that other colors are underrepresented (Jalil et al., 2012). Despite such extensive research into color, so far no investigations are known to the authors on the effect of tinted lenses on visual affective processing. Transferring the results from psychological color science to optically tinted lenses, one could expect that tinted lenses influence how humans respond to emotional events. The purpose of this study was to investigate such a potential influence of color-tinted lenses on visual affective processing at both the autonomic level, meaning heart-rate-variability (HRV) and skin-conductance-response (SCR) measures, as well as the cortical level, meaning EEG measures. In particular, it is predicted that images with emotional content will give rise to larger responses at both levels. If color-tint has an influence, it ought to moderate these responses, especially at the cortical level. As a sustained positive component of the event-related potential (ERP) waveform in the EEG, the LPP indicates a selective processing of emotional stimuli and activation of motivational systems in the brain (Cuthbert et al., 2000); it is a well-established finding, that emotional arousing pictures

induce a more positive LPP than neutral pictures (Cuthbert et al., 2000; Schupp et al., 2000; Hajcak et al., 2009, 2010; Brown et al., 2012). The focus was on the LPP component for two reasons: color is related to emotional processing (Jalil et al., 2012), and, the LPP component reflects emotional arousal level (Cuthbert et al., 2000; Schupp et al., 2000; Dolcos and Cabeza, 2002; Spreckelmeyer et al., 2006). Among the plenty of studies on emotions and LPPs, previous work has shown that a non-meditating control group had higher LPP compared to meditators while viewing unpleasant International-Affective-Picture-System (IAPS) stimuli (Sobolewski et al., 2011). Regarding emotional regulation, the LPP is reduced when emotions are strategically suppressed (Moser et al., 2006; Foti and Hajcak, 2008). Additionally, LPP reflects automatic attention to emotional visual stimuli (Hajcak et al., 2009). A review about the relation of affective picture processing and ERP components reveals that attention is linked to early components (<300 ms) and memory encoding is associated with later components (>300 ms; Olofsson et al., 2008); besides LPP, also other ERP components as the P300 are related to emotional stimuli (Hajcak et al., 2010). The LPP was selected to be investigated, because of its often-described connection to arousal, motivation and attention, when affective pictures are presented, in the literature.

Autonomic responses were evaluated in terms of HRV and SCR responses. It has been shown that the heart rate co-varies with affective valence, whereas SCR was increased with arousal (Cuthbert et al., 2000). These previous findings are validated here, namely that phasic SCR was significantly larger for unpleasant images compared to neutral images.

MATERIALS AND METHODS

Three different physiological responses were assessed: EEG, HRV and SCR.

Participants

Thirty-one participants were enrolled in this study, which contained 12 male and 19 female participants. The average age was 25.9 ± 3.5 years and the objective refractive errors were corrected to normal vision using trial lenses (mean spherical refractive error: OD −2.80 ± 2.37 D, OS −2.55 ± 2.28 D) measured with an open field autorefractor (Grand Seiko WAM-5500, Grand Seiko Co., Ltd., Fukuyama Hiroshima, Japan). The study followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of the Medical Faculty of the University of Tuebingen. Informed consent was obtained from all participants after the content and possible consequences of the study had been explained.

Stimuli and Experimental Procedure

For this study, stimuli from the IAPS were used with normalized ratings for valence and arousal level to experience emotional events (Lang et al., 2008). According to Russell's valence-arousal model (Russell, 1980), stimuli are usually separated into non-emotional (neutral) stimuli with low arousal and emotional (pleasant, unpleasant) stimuli with high arousal (e.g., Keil et al., 2002). Stimuli consisted of 96 pictures from the IAPS (Lang et al., 2008), with 32 pleasant[1] (adventure, erotic, sport, babies; mean pleasure = 7.0; mean arousal: 5.5), 32 neutral[2] (people; mean pleasure = 4.9; mean arousal = 3.6), and 32 unpleasant[3] (mutilated bodies, guns, sad; mean pleasure = 2.4; mean arousal = 5.9) pictures. The experimental design was adapted from Bradley et al. (2008), as detailed next, to avoid disturbances from unbalanced self-reported arousal and visual complexity of the images. This study involved five different tint-filtering conditions. Each filter condition was tested in 16 blocks of trials, with each block containing two neutral, two unpleasant and two pleasant images in random order. One block thus contained six trials, resulting in 96 trials per tint. Each trial consisted of 500 ms fixation period, 3 s stimulus presentation and 6 s inter-trial-interval, as illustrated in **Figure 1**. The tint order was also randomized to avoid LPP potentiation for the repeated images for each tint presentation (Codispoti et al., 2007). Pictures were presented using the Psychophysics Toolbox Version 3.0.11 (Kleiner et al., 2007) under MATLAB (Matlab R2013B, 64 bit, MathWorks Inc., Natick, MA, USA) running on a PC with Windows 7 Enterprise, 64 bit operating system. Participants passively viewed the images presented on a ViewPixx 3D LCD-Display (ViewPixx 3D, VPixx Technologies Inc., Saint-Bruno, QC, Canada) with 16 bit grayscale resolution at a distance of 1 m. The images subtended a visual angle of 16° horizontally and 12° vertically. The mean luminosity across all grayscale images was computed and the contrast of each single image was adjusted so that the sum of luminance values across all pixels resulted in the mean luminosity value. Interestingly, if the color information of emotional pictures is removed, this had no effect on affective modulation in LPP (Codispoti et al., 2012). Therefore, a difference is not expected when using grayscale instead of colored images. Thus, this study controlled for color information within the images themselves—all pictures were presented in grayscale. If color information was available, effects from local color contrasts could not be excluded, which might vary from image to image. Participants wore artificially tinted lenses that colored the entire grayscale picture homogenously and did not selectively filter image contents locally. Although the majority of human visual experience is not in grayscale, but rather naturally or artificially lit, gray-scaling has the advantage of investigating the effect of color-tinted lenses only rather than effects of local color differences.

Color-Tinted Lenses

The tinted lenses included a blue-tinted lens (Carl Zeiss Vision Italia SpA, Varese, Italia), a red-tinted lens (Carl Zeiss Vision Italia SpA, Varese, Italia), a green-tinted lens (Carl Zeiss Vision Italia SpA, Varese, Italia) and a yellow-tinted

[1]Pleasant IAPS picture No.: 2208, 2250, 2260, 2501, 2560, 2650, 4611, 4617, 4640, 4653, 4659, 4666, 4687, 4694, 5621, 8041, 8080, 8090, 8116, 8120, 8161, 8180, 8200, 8280, 8300, 8320, 8330, 8370, 8380, 8400, 8420 and 8465

[2]Neutral IAPS picture No.: 2020, 2190, 2200, 2210, 2214, 2215, 2220, 2221, 2235, 2240, 2270, 2272, 2278, 2383, 2393, 2410, 2441, 2491, 2493, 2514, 2579, 2745.1, 2749, 2752, 2810, 2850, 2870, 2890, 3210, 5455, 7550 and 9210

[3]Unpleasant IAPS picture No.: 2120, 2205, 2520, 2590, 2691, 2730, 2750, 2800, 3015, 3030, 3053, 3100, 3170, 3180, 3181, 3400, 3500, 3530, 3550, 6210, 6211, 6212, 6821, 6834, 6838, 9041, 9250, 9254, 9341, 9405, 9800 and 9921

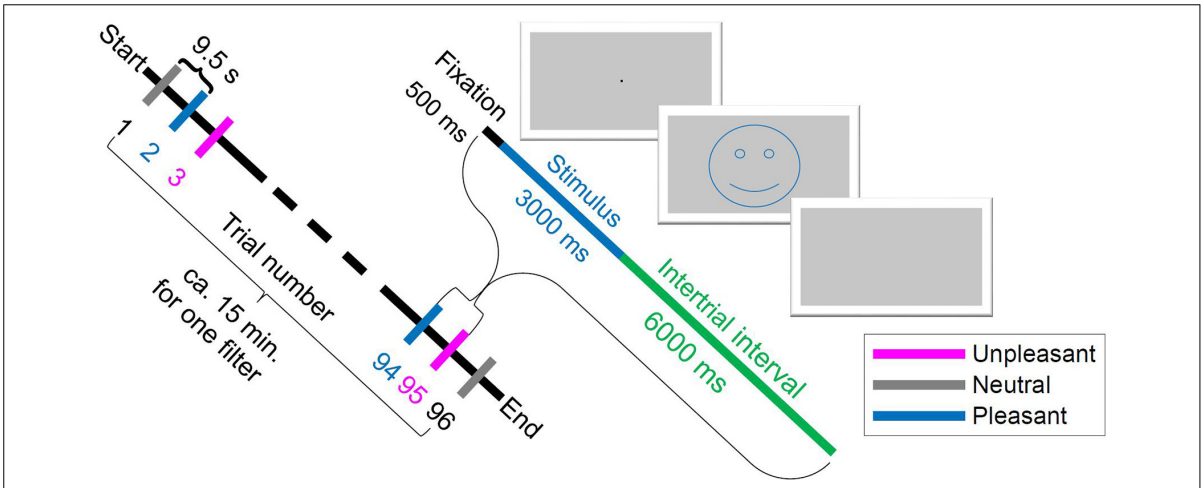

FIGURE 1 | Scheme of experiment procedure: one trial began with 500 ms fixation, then 3 s stimulus image presentation and an inter-trial interval of 6 s. The smiley just illustrates the valence and was not shown in the experiment. The order of trial numbers from Start to End is an example of a randomized order.

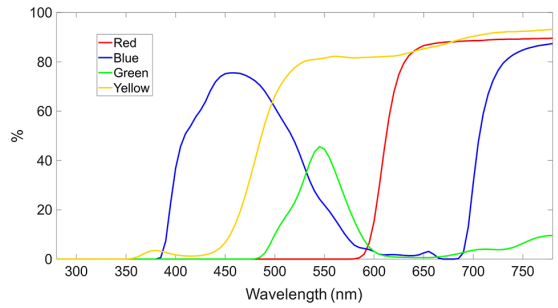

FIGURE 2 | Spectral transmission of color-tinted lenses in percentage. The yellow- and red-tinted lens are high-pass filter with cut-off at ca. 480 nm and 610 nm, respectively. The blue- and green-tinted lens transmits the spectral curve of an inverted U-shape with peak at ca. 460 nm and 550 nm, respectively.

lens (Carl Zeiss Vision International GmbH, Aalen, Germany). Transmission spectra are plotted in **Figure 2**. In the none-tinted lens condition, the participants wore only the trial lenses to be corrected to normal vision.

The luminance of the ViewPixx monitor was adjusted for each tinted lens, by a spectrometer (SpecWin Pro spectrometer, Instruments Systems GmbH, Munich, Germany) to 2.40 ± 0.07 cd/m^2. For comparison with other studies, CIE color coordinates were measured as: no filter/none (x = 0.25, y = 0.25, z = 0.50), blue (x = 0.13, y = 0.19, z = 0.68), yellow (x = 0.34, y = 0.42, z = 0.24), green (x = 0.17, y = 0.74, z = 0.08) and red (x = 0.60, y = 0.29, z = 0.12) tinted lens.

Preference

Participants were asked to evaluate their preference for each tinted lens just before the experimental tint condition started (main experiment). For each lens, they selected one out of three options: like (preferred), dislike (not preferred) or neutral. This approach was not suitable for statistical analysis; therefore, absolute values in percentage were described.

Heart Rate Variability

HRV was measured using a photoelectric pulse sensor (g.PULSEsensor, g.tec medical engineering GmbH, Schiedlberg, Austria). The sensor was positioned at the tip of the index finger and monitored analog pulse wave signal changes in the reflected blood vessels' light (0.01–60 Hz). HRV was analyzed by calculating the frequency-domain measure low-filter/high-filter (LF/HF) ratio with the HRVAS analysis tool (Ramshur, 2010).

Galvanic Skin Response

Skin conductance, also called electro-dermal activity was measured using a GSR sensor (g.GSRsensor, g.tec medical engineering GmbH, Schiedlberg, Austria). Two small electrodes were fixed on the third and the fourth finger through a wrapping band. The data was decomposed into its phasic and tonic component using the Ledalab toolbox (Benedek and Kaernbach, 2010). First, it was downsampled to 20 Hz and then processed by the Continuous Decomposition Analysis. For SCR, the integral of the phasic activity over the response window (ISCR) was taken in a time window of 1–9 s after stimulus onset (Benedek and Kaernbach, 2010). While this phasic driver is linked to the event related SCR responses, the tonic activity characterizes the basic SCR level. To correct for skewed data distribution, SCR data was log10-transformed (Boucsein, 2012) resulting in normalization.

Electroencephalography

EEG has become popular to address emotional processing in the human brain (Brown et al., 2012). In relation to EEG, the

focus was on a particular component, the late positive potential (LPP), a slow change with a positive shift which can begin around 200–300 ms (Cuthbert et al., 2000; Schupp et al., 2000) or later around 500 ms (Dolcos and Cabeza, 2002; Spreckelmeyer et al., 2006). To record the EEG, 61 active electrodes (ActiCHamp, Brain Products GmbH, Gilching, Germany) were used based on the International 10/20 system held on the scalp with an elastic cap. The contact to the skin was ensured by gelling the electrodes to ensure low impedance (<20 kOhm). There was no gelling afterward. Four electrodes were used to record the Electrooculogram (EOG): the electrodes were positioned at the outer canthi of the left and right eye, and above and below the left eye. The central electrodes were placed vertically in a line with the nose from the forehead to the neck in the following order according to the 10/20 system: pre-frontal (Fp), anterior-frontal (AF), frontal (F), frontal-central (FC), central (C), central-parietal (CP), parietal (P), parietal-occipital (PO) and occipital (O). The reference electrode was fixed to the FCz and the ground electrode was placed at AFz. To localize the position in space individually, cap-tracking was performed using the CapTrak system Version 1.0 (Brain Products GmbH, Gilching, Germany) for 61 channels. The EOGs' positions were set to default values. A differential amplifier system amplified the signal, which was then transferred to a data recording computer to record and store the EEG-data. Event triggers were sent from the display computer to the data recording computer *via* an analog/serial port to ensure synchrony of display and recorded data.

BrainVision Recorder Professional (V. 1.20.0701, Brain Products GmbH, Gilching, Germany) recorded the EEG-data with a sampling rate of 1,000 Hz, a sampling Interval of 1,000 μS, a low cut-off of 10 s (0.016 Hz), a high cut-off at 1,000 Hz, a resolution of 0.1 μV for EEG and 0.5 μV for EOG, Pulse and GSR. Although the signals of GSR and pulse sensor were differently amplified compared to EEG, all signals (Puls, GSR and EEG) were recorded in synchronization with the BrainVision Recorder. In offline processing, the data was downsampled to 250 Hz and high-pass filtered at 0.1 Hz with a basic finite impulse response (FIR) filter. Line noise was removed using the Matlab "CleanLine" function from Tim Mullen. After cleaning the data, offline re-referencing to the common average reference was performed. Artifact Subspace Reconstruction was used to correct EEG data, followed by an Adaptive Mixture Independent Component Analysis (AMICA) and a single equivalent current dipoles estimation for removing the biological artifacts. Data were then back-projected to the sensor space.

The ERP signal was processed by 200 ms pre-stimulus reference period and 3 s after picture onset. These 3 s are exactly the stimulus presentation duration. The reference was computed over all EEG electrodes, see common average reference. The late positive potential (LPP) between 500 ms and 1,500 ms was transmitted to statistical analysis. Processing and analysis of the ERP signal were performed with MATLAB and the open source MATLAB toolboxes EEGLAB Version 14.0.0b (Delorme and Makeig, 2004) and ERPLAB Version 6.1.3 (Lopez-Calderon and Luck, 2014).

Central electrodes were analyzed such as Fpz, AFz (mean of AF3 and AF4), Fz, FCz (mean of FC1 and FC2), Cz, CPz, Pz, PO and Oz. Channels Cz and FCz were chosen for detailed evaluation because both channels showed significant main effects for factor tint along the central line, see **Table 1**. In addition, the enhanced LPP for emotional stimuli relative to neutral shows its maximum in the centroparietal topography (Liu et al., 2012). To avoid movement related artifacts in EEG, pulse and GSR, the participants were instructed to refrain from moving during the recording session lasting for about 15 min.

Statistics

Statistical analysis was conducted using the software JASP (0.8.4, JASP Team (2018), Amsterdam, Netherlands). For analysis of the data acquired, the basic parameter for comparison is the mean. The mean was tested with a repeated analysis of variance (ANOVA). A p-value < 0.05 was deemed statistically significant. Thus, the five different tinted lenses were compared for statistical significance.

The mean values of the responses to each picture were calculated. These mean values of the LPP (500–1,500 ms) were extracted from the EEG data, these mean values of ISCR and tonic SCR were extracted from the GSR data and the mean LF/HF ratio was extracted from the HRV data. To determine the effect of factor tint and factor valence, the data was entered in a two-way ANOVA. *Post hoc* analysis was performed pairwise with Bonferroni correction for multiple comparisons.

RESULTS

Preference

The liking for the green-tinted lens revealed with 74.2% the highest, followed by blue- with 51.6%, then red- with 48.4% and finally yellow-tinted lenses with 29.0%. Dislikes were most for red- with 35.5%, then yellow- with 25.8%, blue- with 3.2% and green-tinted lenses with zero percentage. Blue- and yellow-tinted lenses were equally rated as neutral with 45.2%, green- with 25.8% and red-tinted lenses with 16.1%.

Heart Rate

In the HRV, the LF/HF ratio showed no significant effect for factor tint ($p = 0.63$) or factor valence ($p = 0.66$). Interestingly, the interaction between tint and valence became significant ($p < 0.05$) in this repeated ANOVA.

Skin Conductance

The ANOVA of the phasic activity revealed a significant main effect for valence ($p < 0.05$), but not for tint ($p = 0.78$) or interaction ($p = 0.60$). Pairwise *post hoc* testing with Bonferroni correction showed that ISCR was significantly larger for unpleasant pictures compared to neutral pictures ($p < 0.05$), but not between pleasant and neutral pictures ($p = 0.17$) and not between pleasant and unpleasant ($p = 0.69$).

The ANOVA of the tonic activity returned a main effect for tint ($p < 0.01$), but not for valence ($p = 0.56$) or interaction ($p = 0.34$). A pairwise Bonferroni-corrected *post hoc*

comparison revealed a significant elevation of only red-tinted lenses compared to none ($p < 0.01$).

Late Positive Potential

The grand average of the ERP revealed a component, which differentiated for the factors of valence and tint. For tint, the grand averaged ERP is illustrated in **Figure 3** and for valence in **Figure 4**. This component was similar to the LPP. The LPP amplitude resembled a plateau in **Figure 3** and was larger when participants wore red- or green- than none-tinted lenses. In contrast, a similar increase was not visible in blue- or yellow-tinted lens conditions, see **Figure 3**. Separately, there appeared to be a difference between pleasant and neutral valence pictures in the LPP component, see **Figure 4**. Interestingly, only in Cz the LPP was elevated for unpleasant conditions compared to neutral condition, see **Figure 4** left, but not in FCz, see **Figure 4** right.

An ANOVA of the mean voltage potential of Cz returned significant main effects for valence ($F_{(2,60)} = 13.7$, $p < 0.001$) and tint ($F_{(4,120)} = 3.4$, $p < 0.05$), but not their interaction ($F_{(8,240)} = 0.71$, $p = 0.68$) see **Table 2**. For FCz, which was calculated by the mean of FC1 and FC2, the ANOVA of the mean voltage potential again revealed a significant effect for valence ($p < 0.001$) and tint ($p < 0.05$), but not their interaction ($p = 0.31$) see **Table 2**.

For further central electrodes, the main effect for tint was significant in FCz and Cz. The electrodes Fpz, AFz (mean of AF3 and AF4), Fz, Pz and POz showed no significant effect for tint, whereas CPz and Oz showed a trend with $p = 0.10$, see **Table 1**. Furthermore, no significant interaction effect was found between tint and valence.

Valence

Pairwise Bonferroni-corrected *post hoc* testing for valence revealed that pleasant ($p < 0.001$) and unpleasant ($p < 0.05$) pictures elicited larger LPPs compared to neutral pictures in Cz. For FCz, the LPP difference between neutral and pleasant was significant ($p < 0.001$). For Cz and FCz, pleasant pictures elicited significant larger LPPs compared to unpleasant pictures ($p < 0.05$; $p < 0.001$). For Cz, LPP of unpleasant pictures were significantly larger than neutral ($p < 0.05$), but not in FCz ($p = 1.00$). This reduction of LPP to unpleasant relative to pleasant pictures appears in an overlapping ERP response to unpleasant and neutral pictures in FCz, see **Figure 4** right.

Tinted Lens

Regarding single tinted lenses, the *post hoc* Bonferroni-corrected pairwise comparison revealed a significant difference between red-tinted lens and no filter condition ($p < 0.001$) as well as between red- and yellow-tinted lens ($p < 0.05$) in terms of LPP. Equivalent statistical results for FCz are listed in **Table 3**. In addition, in Cz the difference in LPP between green- and none-tinted lens was found to be significant ($p < 0.05$), see **Table 3**.

All three valence conditions with red-tinted lenses showed the highest LPP mean values (**Figures 5A,B**), whereas green-tinted lens reached a similar level in the pleasant condition compared to red.

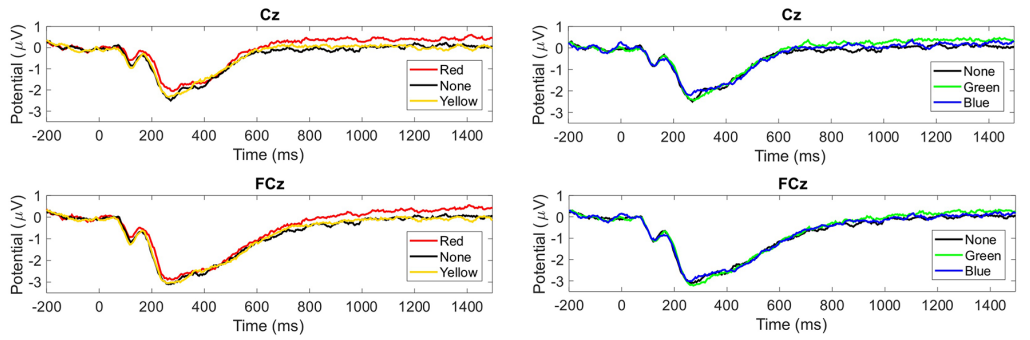

FIGURE 3 | Group mean event-related potentials (ERPs) evoked by tint condition. Upper graphs from Cz and lower graphs from FCz. Left: red-, none- and yellow-tinted lens. Right: none-, green- and blue-tinted lens. Time in milliseconds from picture onset is plotted.

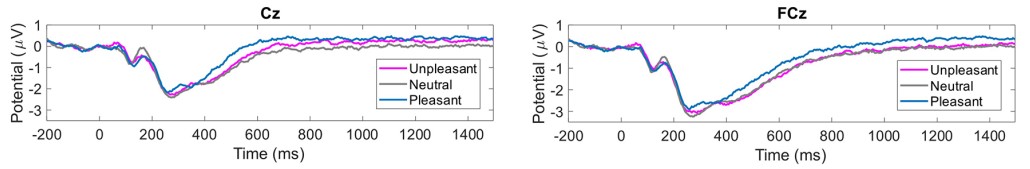

FIGURE 4 | Grand average of the ERPs for each valence condition. Left: Cz. Right: FCz. Time in milliseconds from picture onset is plotted.

TABLE 1 | Analysis of variance (ANOVA) of Late-Positive-Potential (LPP) (500–1,500 ms) for central electrodes.

	Valence				Tint			Interaction		
	df	*F*	*p*	ω^2	*F*	*p*	ω^2	*F*	*p*	ω^2
Fpz	4	8.12	<0.001	0.18	0.74	0.57	0.00	0.84	0.57	0.00
AFz	4	10.78	<0.001	0.24	0.72	0.57	0.00	1.30	0.25	0.01
Fz	4	13.08	<0.001	0.30	1.17	0.33	0.01	1.58	0.13	0.02
FCz	4	13.71	<0.001	0.29	2.80	0.03	0.06	1.18	0.31	0.01
Cz	4	13.69	<0.001	0.29	3.37	0.01	0.07	0.71	0.68	0.00
CPz	4	6.29	0.01	0.14	1.96	0.10	0.03	0.57	0.81	0.00
Pz	4	5.77	0.01	0.13	0.88	0.47	0.00	0.83	0.57	0.00
POz	4	9.21	<0.001	0.21	0.32	0.86	0.00	1.21	0.29	0.01
Oz	4	15.67	<0.001	0.32	1.97	0.10	0.03	1.26	0.27	0.01

TABLE 2 | ANOVA of LPP (500–1,500 ms) in detail.

	Cz					FCz				
	df	Mean Square	*F*	*p*	ω^2	*df*	Mean Square	*F*	*p*	ω^2
Tint	4	2.98	3.37	0.01	0.07	4	1.64	2.80	0.03	0.06
Valence	2	6.15	13.69	<0.001	0.29	2	6.27	13.71	<0.001	0.29
Tint * Valence	8	0.29	0.71	0.68	0.00	8	0.37	1.18	0.31	0.01

DISCUSSION

In this study, the effect of color-tinted lenses was investigated on a brain's and autonomic response to emotional events. Increased autonomic arousal was found to unpleasant pictures and enhanced cortical reaction to pleasant pictures as well as to red-tinted lenses. This suggests that unintentional responses to unpleasant events are modulated at the cortical level; this regulation can be achieved by tinted lenses. Since LPP changed mainly to pleasant and surprisingly not to unpleasant events, we expected a positive influence of tinted lenses on affective processing. Nevertheless, we found no interaction between tint and valence. This means that the effect of color-tinted lenses on LPP can be independent of affective processing. However, several key questions remain:

(1) Which factors besides tinted lenses could also differentiate the reactions to pleasant and unpleasant events? How do GSR and HRV contribute under the influence of tinted lenses?

Participants reacted to emotional pictures with an increased LPP, especially to pleasant pictures in EEG and an elevated ISCR to unpleasant pictures. This agrees only partly with previous findings that emotionality is encoded in higher LPP and skin conductance (e.g., Lang et al., 1993; Cuthbert et al., 2000). We found that this autonomic connection to affective processing occurs also under the influence of tinted lenses in the presence of unpleasant pictures. However, pleasant pictures shifted the LPP even higher than unpleasant images with all tinted lens conditions, which was not reflected in the ISCR. We assume that tinted lenses in general lead to a more positive level by enhancing pleasant and reducing unpleasant impressions on the cortical level. An alternative explanation might be that this enhancement of pleasant pictures is an effect of the differentiation that pleasant pictures involve other brain areas than unpleasant pictures (Liu et al., 2012), leading to an earlier positive shift of pleasant compared to unpleasant pictures (Cuthbert et al., 2000). This earlier positive shift of pleasant pictures is also observed, see **Figure 4**. Nevertheless, this earlier onset of pleasant pictures does not necessarily lead to an increased LPP amplitude. In the literature, contradictory results are reported. Most previous studies did not find an amplitude difference in LPP between pleasant and unpleasant pictures (see review Schupp et al., 2000; Olofsson et al., 2008), however some did (e.g., Cuthbert et al., 2000; Carretié et al., 2006). Additional physiological measurements from heart rate revealed no further insights. Although others found that HRV can reflect human emotion (Kop et al., 2011), but with IAPS pictures only with strong emotional stimuli (Choi et al., 2017), we found no effect of emotional pictures on HRV for tint and valence separately, but for their interaction.

TABLE 3 | Pairwise *post hoc* comparisons with Bonferroni-Correction for Tint.

		Cz	FCz
		p_{bonf}	p_{bonf}
None	Blue	1.000	1.000
	Red	<0.001	0.005
	Yellow	1.000	1.000
	Green	0.049	0.561
Red	Yellow	0.026	0.026
	Green	1.000	0.789
	Blue	0.166	0.197
Blue	Green	1.000	1.000
	Yellow	1.000	1.000
Green	Yellow	1.000	1.000

(2) Can the effect of red tinted lenses be explained by the arousal theory or the color-in-context theory?

It could be shown for the first time that red-tinted lenses elevated cortical components such as LPP, specifically in central

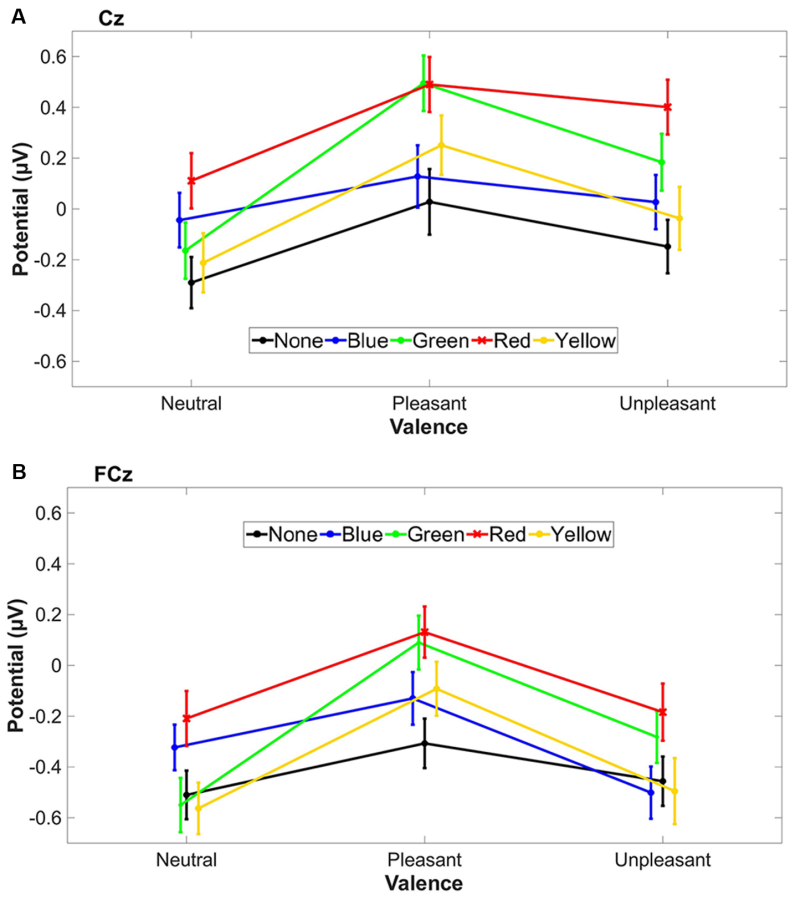

FIGURE 5 | The standard error of the mean (SEM) and the mean LPP amplitude (500–1,500 ms) of tinted lens conditions are plotted for each stimulus valence condition for Cz **(A)** and FCz **(B)**. Valence conditions are connected with a line for better visualization.

and fronto-central brain regions, and autonomic levels such as tonic SCR during emotional and neutral picture presentation. This enhancement by red-tinted lenses might come from visual attention, which is captured and sustained by emotionally arousing pictures (Hajcak and Olvet, 2008). Whereas, the P300 indicates a phasic increase in attention to task-relevant stimuli, the LPP seems to follow the sustained increase in attention toward intrinsically motivating events (Hajcak et al., 2010). The red tint condition showed a higher LPP, even for neutral stimuli. This general increased LPP for red might, therefore, indicate a stronger emotional response of the perceived stimuli which is independent of the valence because we found no interaction between valence and tint. The findings from color psychology studies support a red enhancing effect (Goldstein, 1942; Wexner, 1954). Two theories try to explain the red enhancing effect: first the arousal theory of color (Wilson, 1966) and the color-in-context theory (Buechner and Maier, 2016). The arousal theory is based on Wilson's hypothesis that wavelength vs. arousal shows a U-shaped behavior, that is, colors composed of extremer wavelengths are more arousing (Wilson, 1966). The color-in-context theory claims that the context, in which the color is perceived, affects the emotional response (Elliot and Maier, 2012). Regarding the color-in-context theory, it could be expected that colored lenses should influence only emotional picture presentation and not neutral pictures. For the red-tinted lens condition, the context of valence does not seem to matter, because the LPP was elevated in all three valence conditions. This effect contradicts the color-in-context theory. The color red gets an attentional function, when embedded in non-red context, highlighting the relevance and importance (Buechner et al., 2014) e.g., in red primed angry and happy human facial expressions. This coloration effect of red is not applicable when tinted lenses are worn because a tinted lens colors the entire scenery and not only a single object. This difference between isolated and global coloration might explain the discrepancy of our results to the color-in-context theory. Our findings are in line with the theory that red by itself is arousing. On cortical and autonomic level, the effect of red-tinted lenses can be

independent of the three different valence conditions, because we found no interaction on both levels between tint and valence. Furthermore, the agreement to the arousal theory is supported by the evaluated preferences: only 16.1% of the participants rated red as neutral, but the majority of 83.9% assessed red as "not neutral" (48.4% likes + 35.5% dislikes). Participants may have already recognized that their arousal changed with red-tinted lenses immediately and they rated this change as "not neutral"—already prior to the main experiment and before the perception of emotional events. The high color preferences for green, blue and red are in line with the Ecological Valence Theory (Palmer and Schloss, 2010).

(3) What explains the LPP increase with red-tinted lenses besides psychological explanations?

There might be also an evolutionary explanation. Many animals such as birds show an increased activity during twilight i.e., during dawn and dusk (Palmgren, 1949). During this transitional phase of twilight, environmental stimuli change drastically and quickly i.e., the intensity of illuminance and its associated spectral colors (Stahlbaum et al., 1986). Usually during sunset or sunrise, longer reddish wavelengths are more present than during the daylight, mainly due to amplified Rayleigh scattering because light has to travel much farther through the atmosphere. At times of twilight, sensory areas of the brain are reduced, which facilitates visual detection performance (Cordani et al., 2018). It was shown that the LPP reflects a global inhibition in the visual cortex when emotional stimuli are processed (Brown et al., 2012). Taking these two findings hypothetically together and projecting to our findings, the red-tinted lens may trigger a system activating arousal, which could be involved in the regulation of the twilight activity. To prove this speculative idea and to support more insights, studies with tinted lenses and circadian activity are necessary in the future.

(4) Is there a chance that cortical effects of tinted lenses have nothing to do with hue?

It was shown before that red colored stimuli amplified the skin conductance responses compared to blue stimuli, as well as saturated compared to desaturated stimuli (Rajae-Joordens and Hanique, 2012). The authors suggest that the effect of red light derives from the perceived saturation difference among different colored light. While the luminance was controlled in our experiment, the saturation was not. It might be that the saturation of red-tinted lenses was elevated. Future experiments can address the saturation in tinted lenses. With colored light, it was shown that saturation and brightness of colors have an increasing effect on SCR, also the hue has affected the arousal, and most of all with red (Wilms and Oberfeld, 2018).

Furthermore, the results cannot be generalized to all age groups because we investigated a relatively narrow age group around ca. 26 years. A problem with older participants is that their lens gets yellow in parallel with cataract, which would add an additional color on top to the investigation. This means that transmittance of the crystalline lens decreases with age (Weale, 1988). Therefore, only a young population was included in this investigation. Besides tinted lens, a potential effect of red on arousal and cortical response must also be considered when visible light is filtered software-wise, specifically when the light source changes its spectrum. This happens in the so called "night shift" applications of modern devices like smartphones, tablets or monitors. Such applications reduce the short wavelength components to avoid circadian rhythm shifts. However, it could not be proven that changing color spectrum alone is changing the melanopsin suppression using the "night shift" function (Nagare et al., 2019). In addition to circadian rhythm, the implication of such activated "night shift" filters for emotional arousal and cortical enhancement may be important when watching photos and movies at night or studying at night. Our investigated LPP component, which is starting from 500 ms, belongs to later components (>300 ms) associated with memory encoding (Olofsson et al., 2008). A tinted lens that changes the LPP may, therefore, aid memory encoding. Therefore, further application of red-tinted lenses could be enhancing effects to memory as it has been shown that arousal is able to enhance long-term memory (Singh and Churchill, 1987). Green-tinted lenses increased LPP as well, but mainly in pleasant picture condition, which would strengthen the previously reported idea that green is associated with positive mood (Akers et al., 2012). Additionally, participants evaluated the green-tinted lens with the most likes (74.2%). However, the effect of green-tinted lenses can be also interpreted as independent since there was no significant interaction between tint and valence. If not independent, such a positive implication of green-tinted lens would be aligned with the headache reducing the effect of green light (Noseda et al., 2016). In future studies, it might be worth to investigate if green-tinted lenses have a similar headache reduction like green light. Interestingly, in all tinted lens conditions, the autonomic level changed to unpleasant pictures, whereas the cortical level mainly changed to pleasant pictures. A similar trend occurred for the red-tinted lens independent of the valence. Red-tinted lenses increased physiological basic arousal as well as cortical level. On a physiological level, red-tinted lenses are rather arousing independent of the emotional condition. Possible applications of a red-tinted lens could be to keep arousal level high e.g., during tiring or demanding work or watching pictures.

In summary, the findings indicate that the autonomic response to affective images is modulated at the cortical level of processing. Interesting, the use of red-tinted lenses has a similar influence, in that it also elevates LPP potentials. Thus, it is possible that the presence of red tints could increase the perceived valence of images. It should be noted that the current study does not reveal a significant interaction between the two factors in the LPP and ISCR. Hence, it is premature to believe that red tints moderate valence differentially. Nonetheless, the current results converge with known behavioral findings and subjective reports. Furthermore, we are confident that the results did not arise from low-level differences across color tints, such as contrast and luminance, which could have affected the visibility or spatial content of the images. Having isolated the influence of color tints to red, subsequent work could further investigate if these two factors might interact if the physical properties of red tints and subjective norms of valence intensity

are parametrically manipulated. This would lend more statistical power to determine if the color red can directly moderate affective processing or if it introduces an independent influence on affective processing.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of Institutional Review Board of the Medical Faculty of the University of Tuebingen with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Institutional Review Board of the Medical Faculty of the University of Tuebingen.

AUTHOR CONTRIBUTIONS

All authors were involved in the interpretation and summarizing of the study, and their special contributions were the following: TS, LC and SW designed the experiment; TS and AS conducted the experiment; TS, LC and AS analyzed the data; SW was the principal investigator. All authors reviewed the manuscript.

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Conflict of Interest Statement: TS and AS are scientists at the University Tuebingen. LC is a scientist at the Max Planck Institute for Biological Cybernetics Tuebingen and at the Institute for Informatics Ludwig-Maximilians-University Munich. SW is employed by Carl Zeiss Vision International GmbH and is a scientist at the University Tuebingen. TS is employed by Dopavision GmbH.

7.4 Attachment

V. Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes

Specific near-zone PALs were designed. The PAL designs were adapted for juvenile use in myopes. As a proof of concept experiment, the lag of accommodation was measured under the influence of PALs to determine the opto-physiological performance.

Peripheral Design of Progressive Addition Lenses and the Lag of Accommodation in Myopes

Tim Schilling,[1] Arne Ohlendorf,[1,2] Saulius R. Varnas,[3] and Siegfried Wahl[1,2]

[1]Institute for Ophthalmic Research, Eberhard Karls University Tuebingen, Tuebingen, Germany
[2]Carl Zeiss Vision International GmbH, Aalen, Germany
[3]Carl Zeiss Vision Australia Holdings Limited, Lonsdale, South Australia, Australia

Correspondence: Arne Ohlendorf, Institute for Ophthalmic Research, Eberhard Karls University Tuebingen, Elfriede-Aulhorn Strasse 7, 72076 Tuebingen, Germany; arne.ohlendorf@medizin.uni-tuebingen.de.

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Purpose. Insufficient accommodative response is assumed to result in myopia progression. We have investigated if the accommodative lag in myopes is different between a single vision lens (SVL) and the progressive addition lens PAL 2, clinically trialled for its ability to reduce progression of myopia, and if there exist differences in accommodative lag between PAL 2 and other PALs with the same addition power (+1.50 D).

Methods. The influence of spherical SVL and four different designs of PALs that differ in the near zone width (PAL 1) or that have different signs and magnitude of horizontal gradients of mean power adjacent to their near vision zones (PAL 3 and PAL 4) on the accommodative response was investigated for different near viewing distances (40, 33, and 25 cm) in 31 subjects, aged 18 to 25 years.

Results. The SVL correction resulted in insufficient accommodative response for the near object viewing distances tested. PAL 2 did significantly reduce accommodative lag for all near object distances tested. The PAL design with a more negative horizontal mean power gradient (PAL 4) provided a lower lag of accommodation when compared with PAL 2 at the shortest object distance of 25 cm ($P = 0.03$) and was able to reduce the lag of accommodation to a level below the depth of focus for the higher near working distances tested.

Conclusions. Designs of PAL with more negative horizontal mean power gradients are the most effective in lowering the lag of accommodation in myopes. This could make them good test candidates for myopia control applications.

Keywords: myopia, refractive error, lag of accommodation, lens

With its increasing prevalence, myopia is one of the major refractive errors that can affect eye health. Especially in East Asian countries, reports find prevalences reaching and exceeding 80% to 90%.[1]

It was observed that myopic children show an insufficient accommodation (lag of accommodation [LA]), which would result in a reduced power of the eye during reading.[2] Further research also found that the amount of the LA depends on the reading distance, the device used to measure accommodation, the time of the onset of myopia (early onset [EOM] or late onset [LOM]), and many more (for review, see Ref. 3). Since it is known from animal research that a hyperopic defocus (when the image is behind the retina) leads to the development of myopia,[4] the LA might be a risk factor for the development and/or progression of myopia.[5–7] On the other hand, there are studies that do not support this theory for the onset[8] or progression of myopia.[9–11] There are also investigations that have found the LA to be present in emmetropes but not in myopes[12] or that argued that the LA does not necessarily reflect a reliable loss of image quality on the retina due to the failure to include the effects of higher order aberrations or an increased depth of focus due to pupil constriction during accommodation.[13]

Assuming that the LA does play a role in stimulating excessive elongation of the eyeball resulting in progressing myopia, it is of interest to find the means of reducing the LA in myopes. It has been known that accommodative responses (ARs) can be elicited by stimuli imaged not just on the fovea but also on the peripheral retina (for review see Ref. 14). This opens up a possibility of modulating ARs with aspherized lens designs that change the peripheral focal properties of the visual field. It has already been shown to be possible with bifocal contact lenses[15] and contact lenses with varying amounts of spherical aberration[16] worn by young myopic subjects. Recently this topic was also investigated with multifocal contact lenses.[17] In this study, we are investigating the feasibility of this approach with progressive spectacle lenses, which offer the possibility of aspherizing the area adjacent to the near vision zone without affecting the wearer's distance vision quality.

Progressive addition spectacle lenses (PAL) have been investigated in order to assess their influence on the progression of myopia. Most studies using progressive addition lens (PAL) spectacles[10,18–22] found a reduction in myopia progression due to the treatment with PALs of around 30% in the first year when compared to wearers of single vision lenses, with the effect often waning or saturating in the following years. One study[23] did not find any statistically significant effect of a +1.50 D addition PAL on the progression of myopia even in the first year, while another testing the same lens a few years later[24] recorded a 21% retardation of myopia progression (adjusted for confounding variables) after 2 years with no

evidence of effect saturation after 12 months. In earlier days, standard progressive lenses with long corridor lengths developed for presbyopes have been used.[18,19] Later on, new PAL designs adapted for juvenile use with shorter corridors, making it easier for children to access the addition power, have been developed and tested.[21–24] Hasebe et al.[22] investigated the influence of the addition power and the positive aspherization of the distance zone of the PAL on their efficacy to provide retardation of myopia progression. The positive aspherization of the distance zone did not retard myopia and a minimum of +1.50 D addition was required to get an initial efficacy of 30% in the first year.

The purpose of the study was to establish the influence of the design of a PAL on the reduction of the LA by using different widths of the near zone and varying the horizontal power gradients in the immediate vicinity of the near zone of a lens. Assuming the accommodative stimulus is spatially averaged in some way, the expectation was to have greater ARs when the periphery has negative power gradients and lesser responses when those gradients are positive, as the more negative is the power in the periphery, the more stimulus for accommodation one would expect.[16]

Methods

Subjects

Thirty-one participants aged 18 to 25 years with a mean spherical equivalent refractive error of the dominant eye of −2.8 ± 1.5 D (range, −5.6 to −0.8 D) participated in the study. Inclusion criteria for participation were as follows: central refractive errors ≥ −6 D sphere, ≥ −1.5 D of cylinder, and best-corrected visual acuity of 0.0 logMAR or better. Subjects with known ocular diseases were not allowed to participate. Permission was obtained from the Ethics Commission of the Medical Faculty of the University of Tuebingen. The research followed the tenets of the Declaration of Helsinki and, in addition, informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study.

Measurement of Refractive Errors

Objective as well as subjective refraction was measured prior to the course of the study. Autorefraction was measured for a pupil diameter of 3 mm using a wavefront aberrometer (i.profiler Plus, Carl Zeiss Vision GmbH, Aalen, Germany). Subjective refraction was measured under natural pupil conditions, using a Subjective Refraction Unit (SRU; Carl Zeiss Vision GmbH).

After the subjective measurement of the sphero-cylindrical refractive errors, the dominant eye of each participant was determined using the pinhole test.[25] We fitted the progressive lenses into a custom developed frame, where the height and the pupillary distance were adjustable (Engelhardt Eyewear Pty Ltd., Richmond, SA, Australia).

Correction of Refractive Errors and Lens Design

The trial included a single vision spherical lens (SVL) and 4 PAL designs. One of the PAL designs was used as a benchmark with a known myopia control efficacy. This was a +1.50 D addition positively aspherized (PA) PAL trialed for 2 years on the Asian 6- to 12-year-old myopes, having a corridor of 14 mm in length measured from the fitting cross (FC) to the near reference point (NRP).[21] The ability of this lens to reduce the LA was not known prior to the study. This lens was called PAL 2 in the trial and was used as a benchmark against which the ability of other lenses to reduce the LA was judged. It has a progressive surface on the front of the lens and a prescription surface on the back side. The first of the new designs tested, labelled PAL 1, was derived from PAL 2 and also had the +1.50 D addition. The positive aspherization of the distance zone of PAL 2 was removed. Then its corridor length was shortened and the distance–near zone size balance transformed. The aim of the design modifications was to provide a much wider zone for clear distance vision and a higher and narrower near zone. The corridor length was changed to 12 mm, and the new zone size balance adjustment was achieved by rotating the distance zone boundaries down by 24° with the corresponding rotation in the inward direction for the near zone boundaries. The design was implemented on the back surface of the lens configured to provide both the prescription and addition power, with the front surface being spherical.

The second new design, labelled PAL 3, has a +1.50 D addition with a 13-mm corridor length, and a moderately wide distance and near zones. Its unique feature is the design of the periphery, which has a reversed sign (positive) horizontal mean power gradient adjacent to the near zone compared to the conventional PALs (see the optical mean addition power contour plots of PAL 3 in Figs. 1, 2). The design has a relatively high astigmatism in the periphery due to this unusual power distribution. This design was implemented with a progressive back surface and a spherical front surface.

The third new test design, labelled PAL 4, has a 13-mm corridor length with a wide distance zone and a relatively narrow near zone surrounded by areas having the mean optical power close to the power of the distance zone. Consequently, the design has relatively large negative horizontal gradients of mean power around the near zone. It also has relatively large values of peripheral astigmatism in some peripheral areas due to the presence of high power gradients. The progressive surface providing the optical power progression was implemented on the back side of the lens.

All lenses were ordered and produced at Carl Zeiss Vision to correct the sphero-cylindrical errors of the dominant eye for each subject. The contour plots of ray-traced optical astigmatism and optical mean addition power distributions for all PAL designs used in this study are displayed in Figure 1.

To visualize the optical power distribution in the object space provided by the PALs when looking through the near zone of the lens at the target stimulus, we have computed static eye ray traces for each of the tested PALs at three target object distances used during the experiments. The ray tracing has been done for a wearer having a distance prescription of −2.50 D looking through the NRP of each of the PALs at the center of the target stimulus. It has been assumed that the wearer's eye is responding to the accommodative stimulus perfectly with the mean power error being zero at the fixation point marked by the intersection of gray lines. The contour plots of the mean power error distribution on the reference plane in the object space for each of the 4 PALs and three near target distances tested are shown in Figure 2. Under each of the contour plots, the mean horizontal gradient of ray-traced mean power calculated over the nasal (to the right hand side from the center) extent of 92 mm from the center of the target stimulus is printed in units of D/m in object space.

Accommodation Measurement Protocol

While the subjects were wearing a customized spectacle lens correction with one of the five different lenses, the refractive error of the nondominant eye covered with an infrared-transparent filter (Kodak IR 87C, Kodak Corp., Rochester, NY, USA) was measured using the Grand Seiko WAM-5500 autorefractor (Grand Seiko Co., Ltd., Fukuyama Hiroshima,

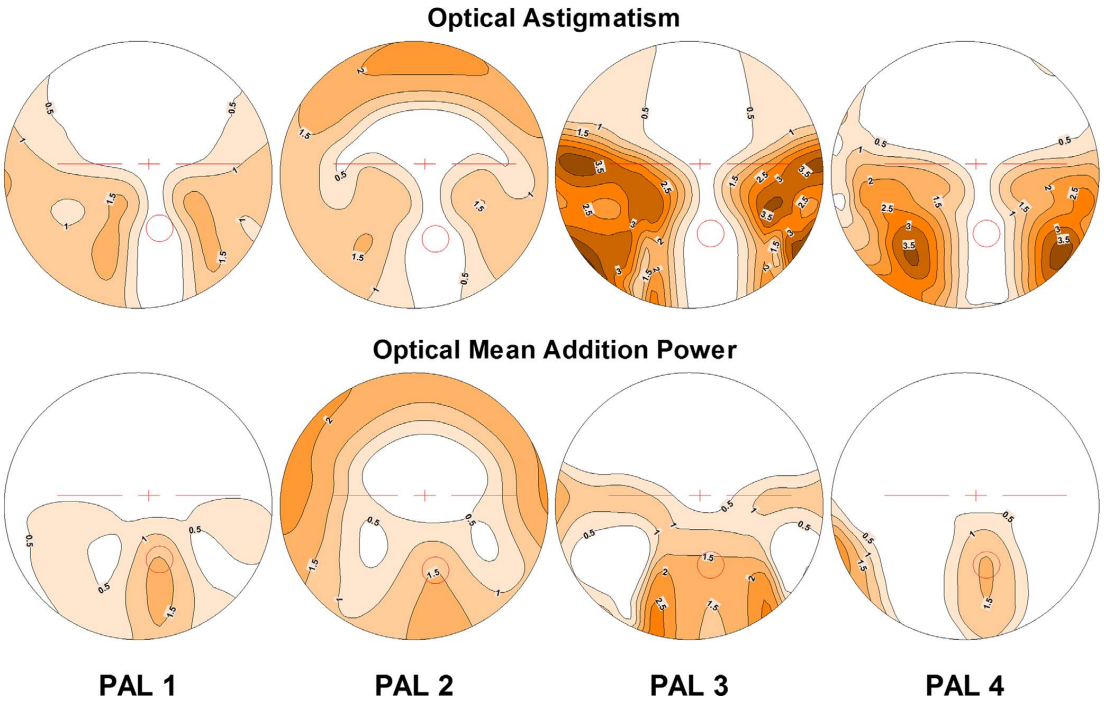

FIGURE 1. The ray traced optical astigmatism and optical mean addition power distributions for the four PAL designs tested. The contours are displayed over the circular zone of 50 mm diameter in the lens front surface scan coordinates.

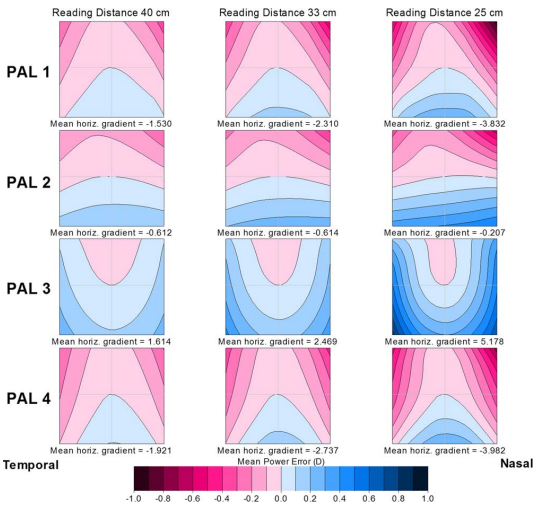

FIGURE 2. The contour plots of the mean power error distribution on the reference plane in the object space for each of the four PALs and three near target distances tested. The ray tracing has been carried out on the perfectly accommodating static eye gazing at the center of the target stimulus marked by the intersection of the *gray lines*. The extent of the object field is 185 mm horizontally and 170 mm vertically.

Japan). The filter was also fitted into the test frame. Refractive errors were measured for distances of 25 cm (4 D dioptric object distance), 33 cm (3 D dioptric object distance), and 40 cm (2.5 D dioptric object distance), as well as for distance vision (400 cm). For each combination of spectacle lens and distance, five individual readings of sphere, cylinder, and axis were obtained. The sequence of testing (# spectacle lens and distance) was randomized between the subjects. During near vision, the subjects were asked to look at an acuity chart and to fixate the lowest line of optotypes. Prior to the measurement and while accommodation for the different distances was measured, the examiner controlled subjectively the alignment of the near point of the spectacle lens and the subject's eye in order to ensure that the subjects looked through the NRP. This inspection was done by checking if the NRP of the spectacle lens was in one line with the eye of the subject and that the acuity chart was on the same height as the NRP and the eye, for every target distance. All far distance measurements of the spherical error were corrected by 0.25 D since the measurements were done at 400 cm distance. The individual readings were transformed into the power vector components of refraction (M, J0, and J45)[26] and averaged.

Calculation of the LA

The different object distances were defined relative to the corneal plane, while the setup of the autorefractor was configured to calculate the measured refractions with the lens 12 mm in front of the corneal plane (equal to the vertex distance [VD]). The following formulae were used to calculate the AR, accommodative demand (AD), and LA at the corneal plane[28]:

TABLE. AR, LA and the Standard Error of the Mean of the LA for All Tested Lenses (SVL, PAL 1, PAL 2, PAL 3, PAL 4) and for the Three Object Distances From the Eye

	Object Distance, 40 cm			Object Distance, 33 cm			Object Distance, 25 cm		
	AR	LA	SEM	AR	LA	SEM	AR	LA	SEM
SVL	1.75	0.60	0.08	2.20	0.64	0.08	2.81	0.94	0.10
PAL 1	0.85	0.15	0.10	1.20	0.32	0.10	2.02	0.43	0.11
PAL 2	0.85	0.15	0.09	1.19	0.32	0.09	1.92	0.53	0.10
PAL 3	0.72	0.27	0.08	1.05	0.47	0.07	1.71	0.74	0.10
PAL 4	0.91	0.09	0.10	1.27	0.25	0.10	2.07	0.39	0.12

$$\mathrm{AR} = \frac{\mathrm{GS(SV)} + 0.25}{1 - \mathrm{VD}[\mathrm{GS(SV)} + 0.25]} - \frac{\mathrm{GS(PAL\text{-}Near)}}{1 - \mathrm{VD} \cdot \mathrm{GS(PAL\text{-}Near)}} \quad (1)$$

$$\mathrm{AD} = \frac{\mathrm{Rx}}{1 - \mathrm{VD} \cdot \mathrm{Rx}} - \frac{1 + (\mathrm{DT} + \mathrm{VD})(\mathrm{Rx} + \mathrm{ADD})}{\mathrm{DT} - \mathrm{VD}(\mathrm{DT} + \mathrm{VD})(\mathrm{Rx} + \mathrm{ADD})} \quad (2)$$

$$\mathrm{LA} = \mathrm{AD} - \mathrm{AR} \quad (3)$$

The following formulae from Atchison and Varnas[27] were used: formula 8b = formula 1, AR; formula 5d = formula 2, AD. For AR (Equation 1), GS(SV) is the Grand Seiko measured sphere equivalent refraction of the occluded nondominant eye when the dominant eye is wearing a SVL equal to the distance Rx and viewing a target at a distance of 400 cm. GS(PAL-Near) is the measured Grand Seiko sphere equivalent refraction of the nondominant eye when the other eye is looking through the NRP of a PAL viewing a target at one of the closer object distances. In formula (2), Rx is the sphere equivalent of the subjective refraction for distance objects, DT is the object distance from the cornea (with a negative sign). ADD is the addition power of the lens—it is zero for the SVL and +1.50 D for each of the PALs. In case the LA is calculated for the SVL, GS(PAL-Near) in Equation 1 is replaced by "GS(SV-Near)"—the Grand Seiko measured sphere equivalent refraction of the nondominant eye when the dominant eye is wearing SVL and viewing a near target. Using this formula for the LA, the lags come out positive and the accommodative leads are negative.

Statistics

Two main hypotheses were formulated before the trial: (1) Narrower near zones lead to lower lags of accommodation, and (2) the high negative horizontal power gradients adjacent to the near zone will provide the maximum reduction of accommodative lag.

Statistical analyses were performed in R (The R Foundation for Statistical Computing). Exploratory data analysis had revealed significant deviations from the normal distribution, as well as the presence of outliers in a range of data sets. Since each subject has been measured with five different lenses at four target object distances, these data sets cannot be regarded as independent. Violation of data independence makes the use of ANOVA analysis inappropriate. Therefore, we applied a robust or nonparametric hypothesis testing method for paired data. A 1-tailed Mann-Whitney U test with an appropriately formulated alternative hypothesis was employed.

RESULTS

Baseline AR With Single Vision Correction and Progressive Addition Lenses

Subjects were wearing SVL or PALs correcting their sphero-cylindrical refractive error of the dominant eye, which was fixating on three different near viewing targets at distances of 40, 33, and 25 cm, while the consensual AR was measured in the nondominant eye occluded by the infrared-transparent filter. The LA in the spectacle plane was calculated using formulae 1 to 3, and the Table shows the ARs, LAs, and standard errors of the LA.

Statistical analysis using the Mann-Whitney U test revealed significant differences for the LA between 25 and 40 cm ($P < 0.001$), as well as between 25 and 33 cm ($P < 0.001$), but not for the comparison of 40 versus 33 cm ($P = 0.06$), in case the SVL were used.

The Lag of Accommodation for the Benchmark PAL and Comparison to SVL

In order to test if the benchmark PAL (PAL 2) reduces the LA during near work when compared to the SVL, a statistical analysis was run to compare the LA. The null hypothesis was that the mean LA for each of the near object distances tested with PAL 2 was the same as that with the SVL. When making these analyses, it was ensured that the alternative hypothesis matched the assumptions. In this case, the alternative hypothesis was that the SVL showed a greater LA than the PAL 2. To test this, a "greater-than" alternative hypothesis [i.e., LA(SVL) > LA(PAL 2)] was needed instead of a "two-sided" alternative hypothesis. Using the Mann-Whitney U test, it was found that SVL causes greater LA than PAL 2 at all object distances ($P < 0.001$ in all cases).

Testing the Hypotheses

In order to test the hypotheses, the lags of accommodation with the different PALs were tested against the defined benchmark. The Mann-Whitney U test with properly formulated one-sided alternative hypothesis for each of the comparisons was used to test the statistical significance of the differences between the lags. The alternate hypotheses in comparisons between the PALs followed the rationale of the formulated primary and secondary hypotheses: the PALs with narrower near zones are expected to give smaller lags of accommodation and PALs with lesser positive gradients or more negative gradients are expected to ensure smaller lags of accommodation.

Statistical analysis revealed the following: PAL 1 did not have less LA than PAL 2 for any object distance at the 5% confidence level but has shown a trend for the 25-cm object distance ($P = 0.07$). PAL 3 had a higher LA than PAL 2 for all object distances ($P < 0.05$). PAL 4 had a lower LA than PAL 2 for the 25-cm object distance ($P = 0.03$), but the effect lost significance for larger object distances ($P = 0.08$ and $P = 0.17$ for the 33-cm and 40-cm object distances, respectively). For details, see Figure 3.

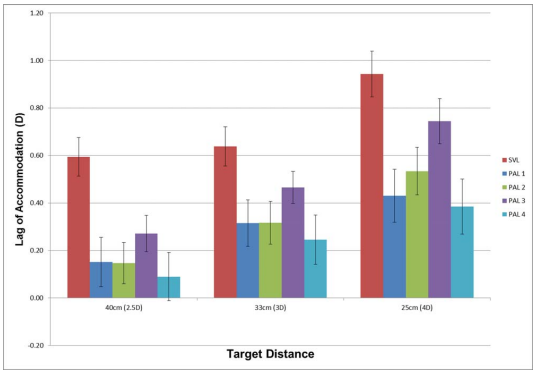

FIGURE 3. Mean LA for the spherical equivalent refractive error, separated for the three target distances, for the five lenses (SVL and PALs). SVL, *red*; PAL 1, *blue*; PAL 2, *green*; PAL 3, *violet*; PAL 4, *turquoise*. *Error bars*: ±1 SEM.

DISCUSSION

The current study investigated the efficiency of a progressive addition lens design on the reduction of the LA, a known risk factor for the development as well as progression of myopia. The results suggest that negative horizontal mean power gradients adjacent to the near vision zone of a PAL enhance a reduction in the LA due to addition power in a young myopic study group.

Baseline LA Using Single Vision Spectacle Lenses

Using SVLs to correct the individual sphero-cylindrical refractive errors, the LA (mean ± SD) increased with an increasing AD (2.5 D: 0.6 D ± 0.5 D; 3.0 D: 0.6 D ± 0.5 D; 4.0 D: 0.9 D ± 0.5 D). Variable amounts of the LA have been found among different studies. Mean lags of accommodation in myopic children and young adults, corrected for their distance vision, for the 33-cm target object distance include 0.6 D,[28] 1 D,[29] 1 D to 1.3 D,[30] and up to 1.5 D.[31] Our mean value at this distance with the SVL of 0.6 D is on the low side of the range but matches Tarrant,[28] which is the only study among those listed above that was measuring young adults.

LA With SVL Distance and Near Correction

Berntsen et al.[9] investigated the influence of the type of correction (SVL or SVL with 2.0 D add power) on the LA in 83 myopic children that had high lags of accommodation for a 4-D Badal stimulus (mean age ± SD: 9.9 ± 1.3 years). The correction of myopia with SVL resulted in a LA of 1.7 ± 0.4 D, while the SVL with +2.00 D add power reduced the lag by 0.5 ± 0.3 D. Measuring the LA with SVL in 29 Chinese myopic children,[29] a reduction of the LA with a 1.5-D add on the SVL to 0.7 (SD: ±0.5 D) was found, while the lag with the SVL was 1.0 D (SD: ±0.7 D). Investigating the influence of 2.0 D add power on the accuracy of accommodation in myopic and emmetropic children, Sreenivasan et al.[32] observed that the +2.0 D addition lenses eliminated the lags of accommodation in myopic children during natural viewing conditions.

Benchmark PAL and SVL

PAL 2 has been used already in a clinical trial to investigate its efficacy in reducing progression of myopia in children.[21] There was a statistically significant ($P = 0.02$) retardation of myopia progression (0.27 ± 0.11 D, equivalent to a reduction ratio of 20%) during the 24-month period of the trial (0.24 D of which has occurred in the first 12 months) for the positively aspherized PAL with the 1.5 D of add power, when compared with a SVL control group.[21] The reduction of myopia progression using the PA-PAL and 1.50 D add power was within the range of reported retardations of myopia from earlier trials that used standard PALs. Standard single vision spherical lenses lead to higher lags of accommodation than the benchmark lens, indicating that the progressive addition lens is effective in the reduction of the LA.

Test of the Two Hypotheses

The ray tracing of test designs for the static eye viewing near targets at the studied range of object distances has revealed that the current study did not succeed in separating the test lens designs into pairs that differ in the width of the near zone only. Lens design PAL 1 has not only a narrower near zone than PAL 2 but also has higher negative horizontal mean power gradients than PAL 2, especially for the 25-cm object distance. Since PAL 1 did not show a statistically significantly different LA from PAL 2 at any object distance, despite some differences in power gradients on top of the near zone width differences, it is most likely that hypothesis #1 is incorrect—narrower near zones in PALs are unlikely to lead to lower LA.

Our results suggest that accommodation responses, when looking at near objects through the center of the near zone of PALs, depend not just on the addition power of the lens but also on the distribution of the peripheral power in the lower viewing zone of the lens, and that the designs with the more negative horizontal mean power gradient lead to a lower LA, especially compared to those with the positive horizontal mean power gradient (the LA with PAL 4 was significantly [$P < 0.005$] smaller for all three object distances when compared to PAL 3). The conventional progressive lens (PAL 2) reduced the LA by approximately 40% to 75% when compared to the SVL, depending on the object distance. PAL 4 appears to further reduce the LA 30% more than conventional PAL.

LA and Depth of Focus

When selecting the optimal PAL design for the retardation of myopia progression, one can hypothesize that the LA should be reduced below the depth of focus, which has been reported to be approximately ±0.3 D.[33] In the set of PALs in the current study, this is satisfied by PAL 4 for the near distances down to 33 cm, but none of the tested PALs was able to do this for the closest object distance tested (25 cm) that some children may also use, especially when working with small electronic devices like hand-held video game devices.

CONCLUSIONS

The current study suggests that accommodation responses using PALs are dependent on the addition power and on the distribution of the peripheral power in the lower viewing zone of the lens. Whether this may have an impact on the rate of myopia retardation needs to be tested in a clinical trial. Measuring the children's ARs when viewing near targets through the lower viewing zone of those lenses would also test the longer term adaptation of the accommodation system to addition power and will hopefully shed some light on the saturation of efficacy of PALs in the reduction of the progression of myopia.

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