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Myopes experience greater contrast adaptation during reading

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Abstract

In this study, we investigated whether reading influences contrast adaptation differently in young adult emmetropic and myopic participants at the spatial frequencies created by text rows and character strokes. Pre-adaptation contrast sensitivity was measured for test gratings with spatial frequencies of $1cdeg^{-1}$ and $4cdeg^{-1}$, presented horizontally and vertically. Participants then adapted to reading text corresponding to the horizontal “row frequency” of text ($1cdeg^{-1}$), and vertical “stroke frequency” of the characters ($4cdeg^{-1}$) for 180s. Following this, post-adaptation contrast sensitivity was measured. Twenty young adults (10 myopes, 10 emmetropes) optimally corrected for the viewing distance participated. There was a significant reduction in logCS post-text adaptation (relative to pre-adaptation logCS) at the row frequency ($1cdeg^{-1}$ horizontal) but not at the stroke frequency ($4cdeg^{-1}$ vertical). logCS changes due to adaptation at $1cdeg^{-1}$ horizontal were significant in both emmetropes and myopes. Comparing the two refractive groups, myopic participants showed significantly greater adaptation compared to emmetropic participants. Reading text on a screen induces contrast adaptation in young adult observers. Myopic participants were found to exhibit greater contrast adaptation than emmetropes at the spatial frequency corresponding to the text row frequency. No contrast adaptation was observed at the text stroke frequency in either participant group. The greater contrast adaptation experienced by myopes after reading warrants further investigation to better understand the relationship between near work and myopia development.

Keywords
Myopia
Contrast Adaptation
Near work
Spatial Frequency

INTRODUCTION

Myopia's threat to vision throughout the world is growing (Wong, Ferreira, Hughes, Carter & Mitchell, 2014). Its prevalence has doubled in the United States and Europe over the last 50 years (Dolgin, 2015) and it has reached epidemic levels in South East Asia (Sood & Sood, 2014). An association between near work and myopia was first proposed in the 17th Century by Johannes Kepler who observed that, "*those who do near work in their youth become more myopic,*" (Mutti & Zadnik, 2009). Near work is frequently cited as being myopigenic (Saw Wu, Seet, Wong, Yap, Chia, Stone & Lee, 2001; Mutti, Mitchell, Moeschberger, Jones & Zadnik, 2002; Saw, Chua, Hong, Wu, Chan, Chia, Stone & Tan 2002) and epidemiological studies have found a significant correlation between myopia rate and increasingly competitive and rigorous education systems that involve prolonged periods spent reading (see Morgan & Rose, 2005, for a review).

Reading text may lead to contrast adaptation (Greenhouse, Bailey, Howarth & Berman, 1992; Chen, Brown & Schmid, 2006). Contrast adaptation is a change in contrast sensitivity at specific spatial frequencies that occurs in response to prior exposure to a similar spatial frequency distribution contained in an adaptor target that has been viewed over a prolonged period (Blakemore & Campbell, 1969; Blakemore, Nachmias & Sutton, 1970; Blakemore, Muncey & Ridley, 1973). Adaptation is thought to occur to maintain contrast constancy, *viz*., limiting the perception of stimulus blur and facilitating responses to changes in stimulus contrast (Georgeson & Sullivan, 1975; Greenlee & Heitger, 1988). Contrast adaptation can be orientation specific (Blakemore & Campbell, 1969; Blakemore & Nachmias, 1971), and corresponds to the spatial frequency content of the adapting stimulus (Pantle & Sekuler, 1968; Blakemore, Muncey & Ridley, 1971).

Reading text entails the prolonged viewing of a high-contrast stimulus class that contains a repetitive pattern in which a restricted range of spatial frequencies and orientations are found (Wallman & Winawer, 2004). The repetitive patterns in printed text yield a spatial frequency distribution that is quite unlike that found in natural images: natural images possess a 1/*f* amplitude spectrum, with diminishing power at higher frequencies (Field, 1987; Tolhurst, Tadmor & Chao, 1992; Webster & Mollon, 1997); conversely, the amplitude spectrum of text is narrow (Solomon & Pelli, 1994) and is purported to contain peaks that correspond to the row frequency and character stroke frequency (Majaj, Pelli, Kurshan & Palomares, 2002). Hence, it is reasonable to surmise that reading text will produce contrast adaptation that alters subsequent spatial frequency sensitivity, relative to a more naturalistic visual diet.

The role of retinal image quality in driving ocular growth in the development of myopia has been demonstrated in animals, leading to increased interest in the factors that affect retinal image quality in humans (Smith & Hung, 1999; Wallman & Winawer, 2004). Animal models have shown that sharp, high fidelity stimuli comprising a variety of spatial frequencies (Bartmann & Schaeffel, 1994) presented at supra-threshold contrast (Schmid, Brinkworth, Wallace & Hess, 2006) are critical for normal ocular development. A degraded retinal image, as a consequence of contrast adaptation (which will contain sub-threshold contrast), may therefore lead to perceptual blur, and ultimately ocular elongation and therefore myopia.

The effects of adaptation on blur perception have previously been shown in myopes and emmetropes using visual acuity measurements (Pesudovs & Brennan, 1993; Mon-Williams, Tresilian, Strang, Kochar & Wann, 1998; Rosenfield & Abraham-Cohen, 1999; George & Rosenfield, 2004 and blur sensitivity (Cufflin, Mankowska & Mallen, 2007; Wang, Ciuffreda & Vasudevan, 2006). Vera-Diaz, Gwiazda, Thorn & Held (2004) increased near accommodation responses in myopes but not emmetropes after three minutes of blur exposure. Adaptation to natural scenes viewed through defocus blur has been shown to increase supra-threshold contrast sensitivity at 3.22cdeg^{-1} (Ohlendorf & Schaeffel, 2009), between 3-4cdeg^{-1} (Venkataraman, Winter, Unsbo & Lundström, 2015) and at 8cdeg^{-1} and 12cdeg^{-1} (Rajeev & Metha, 2010)$^{.}$ However, extant studies that have investigated the effect of blur adaptation on contrast sensitivity have not examined the influence of refractive group.

Chronic blur adaptation due to uncorrected refractive error could alter sensitivity to retinal image defocus. Whilst imposed optical defocus may simulate the visual experience of an uncorrected myope, this does not explain the role of near work as a myopigenic stimulus prior to myopia onset. Therefore, investigating contrast adaptation for in-focus text targets (as corrected myopes would perceive them), rather than targets viewed through optical defocus, may be more informative in understanding the role of near work in myopia development.

Adaptation following prolonged viewing of text on a computer screen has been investigated previously by Lunn & Banks (1986), Greenhouse *et al.,* (1992) and Magnussen, Dyrnes, Greenlee, Nordby & Watten (1992). Although not specifically concerned with the influence of contrast adaptation and myopia, their findings are noteworthy in that they all found the greatest magnitude of contrast adaptation at the fundamental spatial frequencies of the text targets.

More recently, adaptation to printed text was explored in myopic and emmetropic children (Yeo, Atchison, Lai & Schmid, 2012). Less contrast adaptation was noted following text viewing when compared to 2-D sinusoidal stimuli in all participants, and a greater magnitude of adaptation was elicited in myopic children across all frequencies (Yeo et al., 2012). However, adaptation effects were relatively small, and were not shown to be specific to the row or text stroke frequency. While consistent with contrast adaptation during reading, the lack of specificity, a hallmark of adaptation, leaves open the possibility that other processes could have been involved.

In this study, we investigated contrast adaptation following 180s of reading on-screen text in myopic and emmetropic adult participants. We measured contrast sensitivity to spatial frequencies corresponding to the horizontal text rows (text row frequency) and vertically to the character strokes (text stroke frequency), to ascertain whether reading altered sensitivity specifically to these spatial frequencies. In addition, contrast sensitivity was measured for the same spatial frequencies but at orthogonal orientations. These served as control stimuli, enabling us to establish whether measured effects corresponded specifically to the combined peak spatial frequencies and orientations present in our adapter stimulus. The contrast sensitivity measurement protocol that followed the adaptation period was interspersed with 30s intervals of additional reading to “top-up” adaptation. Our hypothesis was that reading would induce contrast adaptation that would result in a degraded retinal image. It has been shown that a degraded retinal image may contribute to myopia development in both animal studies (Sivak, Barrie & Weerheim, 1989; Bartmann and Schaeffel, 1994) and in humans (Robb, 1977; Schaeffel, 2006).

METHOD

Participants

Twenty young adult participants took part, aged 19 to 34 years (mean age 24.35 ± 4.57), 10 of whom were classified as myopic (spherical equivalent refraction, sphere + ½ cylinder [SER]) (SER > -0.75D; mean ± SD: -2.78 ± 1.40D) and 10 emmetropic (SER +0.50 to -0.25D; 0.03D ± 0.14D), summarized in Table 1. Refractive error was determined by subjective assessment of maximum plus consistent with best visual acuity to the nearest 0.12D.

Inclusion criteria were: best-corrected acuity ≤ 0.00 logMAR in each eye; monocular Pelli-Robson Chart log contrast sensitivity ≥ 1.65; SER between -5.00DS and +0.50DS; astigmatism ≤0.75DC, anisometropia ≤ 1.00D, an absence of ocular pathology and suitability for contact lens wear. All participants were fully corrected for their spherical equivalent distance correction with Biotrue ONEday soft contact lenses (Bausch & Lomb, fitting parameters: base curve 8.6mm; total diameter 14.2mm; Dk/t 42 @ center for -3.00 and water content 78%). All tasks were performed binocularly.

	Emmetropes	**Myopes**
Mean age (y) ± SD	23.7 ± 5.19	25 ± 4.03

Gender (male:female)	7:3	4:6
Mean SER ± SD (D)	0.01 ± 0.14	-2.78 ± 1.40

Table 1: mean age, gender and mean spherical equivalent refractive error (SER) for emmetropic and myopic participants.

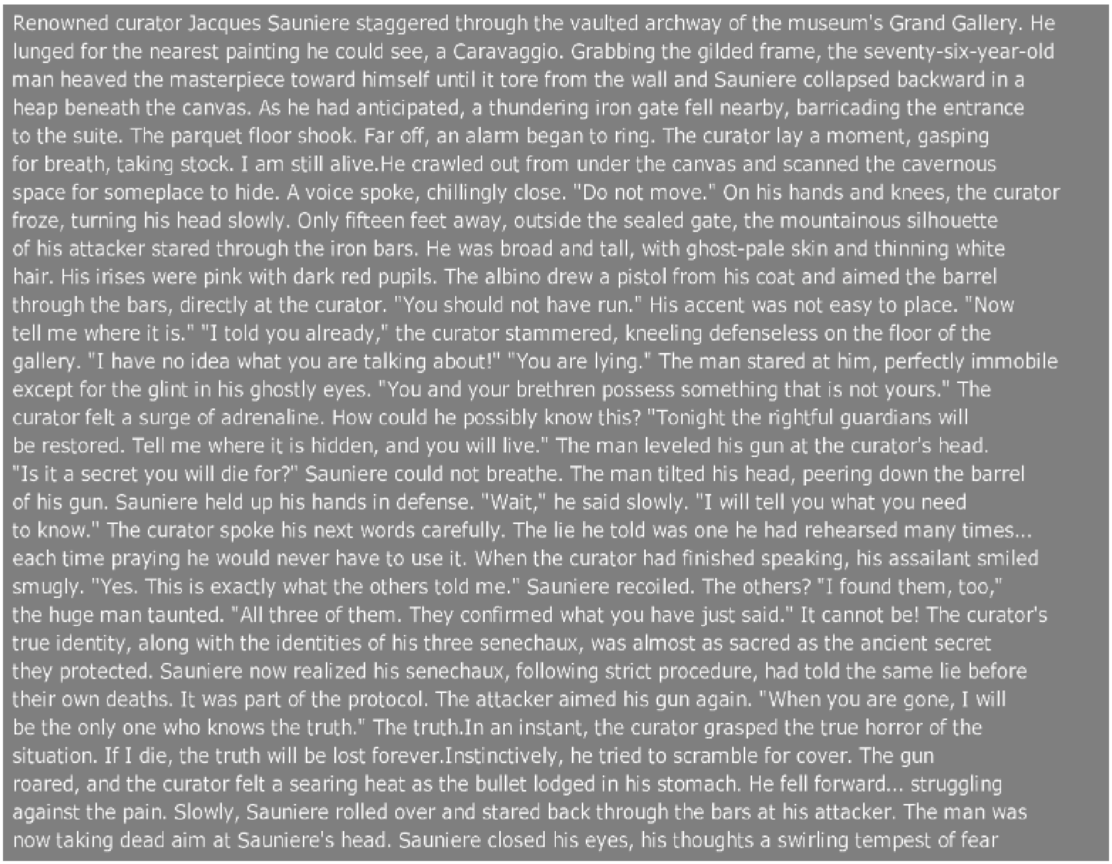
Informed written consent was obtained from all participants following an explanation of the experiment. Procedures were approved by the University ethics panel, and followed the tenets of the Declaration of Helsinki. Data were collected from all participants in one session.

Apparatus

All stimuli were presented on a 19’’ Sony Trinitron GDM-F520 CRT that was calibrated for luminance and chromaticity at the start of each session using a ColorCal colorimeter (made for Cambridge Research Systems by Minolta, Japan). Mean luminance was 50 cd/m^2. The display was 38.2 × 28.5cm, and was placed at distance 52cm from participants (who were positioned in a forehead and chin rest), and therefore subtended 36.3° × 28.7° of visual angle. At a spatial resolution of 1280 × 961, this produced 85 DPI horizontally and vertically. Test gratings (see *Stimuli*) were generated using a ViSaGe visual stimulus generator, with 14-bit color and luminance control (Cambridge Research Systems Ltd, Rochester, UK). The room illumination was measured with a CEM DT1308 light meter (MeterShack, Ruby Electronics, San Jose, USA) for each participant. The average room luminance was 111cd/m^2 (range 109-115cd/m^2). The psychophysical paradigm and CRT calibration routines were implemented with MATLAB (The Mathworks Inc., Natick MA) using the PsychToolbox extensions (Kleiner, Brainard, Pelli, Ingling, Murray & Broussard, 2007; Brainard, 1997; Pelli. 1997), which could test contrast sensitivity and display the adaptor target. Functions from the CRS Toolbox (Cambridge Research Systems Ltd, Rochester, UK) were used for stimulus rendering.

Stimuli

A high-contrast text stimulus was created using an English text excerpt from the novel “The Da Vinci Code” (Transworld Publishers, London, UK), such that the maximum pixel intensity was 255 and the minimum was 127 in the range 0..255 (i.e., 8-bit grayscale). Thirty lines of text were visible on the screen at any time, with line spacing equal to the height of uppercase letters, and text was formatted as continuous prose without paragraph breaks, and filled the entire screen. The Verdana font was used as, in a study that compared a range of serif and sans serif fonts, it was found to elicit the fastest reading time and was deemed the most legible (Bernard, Lida, Riley, Hackler & Janzen, 2002). Rather than specifying text parameters in points, text size, height, kerning and line spacing were reverse engineered to generate the desired row frequency (1cdeg^{-1}) and stroke frequency (4cdeg^{-1}) whilst maintaining a naturalistic appearance for reading. A sample of the text adaptor is shown in Figure 1.



Renowned curator Jacques Sauniere staggered through the vaulted archway of the museum's Grand Gallery. He lunged for the nearest painting he could see, a Caravaggio. Grabbing the gilded frame, the seventy-six-year-old man heaved the masterpiece toward himself until it tore from the wall and Sauniere collapsed backward in a heap beneath the canvas. As he had anticipated, a thundering iron gate fell nearby, barricading the entrance to the suite. The parquet floor shook. Far off, an alarm began to ring. The curator lay a moment, gasping for breath, taking stock. I am still alive.He crawled out from under the canvas and scanned the cavernous space for someplace to hide. A voice spoke, chillingly close. "Do not move." On his hands and knees, the curator froze, turning his head slowly. Only fifteen feet away, outside the sealed gate, the mountainous silhouette of his attacker stared through the iron bars. He was broad and tall, with ghost-pale skin and thinning white hair. His irises were pink with dark red pupils. The albino drew a pistol from his coat and aimed the barrel through the bars, directly at the curator. "You should not have run." His accent was not easy to place. "Now tell me where it is." "I told you already," the curator stammered, kneeling defenseless on the floor of the gallery. "I have no idea what you are talking about!" "You are lying." The man stared at him, perfectly immobile except for the glint in his ghostly eyes. "You and your brethren possess something that is not yours." The curator felt a surge of adrenaline. How could he possibly know this? "Tonight the rightful guardians will be restored. Tell me where it is hidden, and you will live." The man leveled his gun at the curator's head. "Is it a secret you will die for?" Sauniere could not breathe. The man tilted his head, peering down the barrel of his gun. Sauniere held up his hands in defense. "Wait," he said slowly. "I will tell you what you need to know." The curator spoke his next words carefully. The lie he told was one he had rehearsed many times... each time praying he would never have to use it. When the curator had finished speaking, his assailant smiled smugly. "Yes. This is exactly what the others told me." Sauniere recoiled. The others? "I found them, too," the huge man taunted. "All three of them. They confirmed what you have just said." It cannot be! The curator's true identity, along with the identities of his three senechaux, was almost as sacred as the ancient secret they protected. Sauniere now realized his senechaux, following strict procedure, had told the same lie before their own deaths. It was part of the protocol. The attacker aimed his gun again. "When you are gone, I will be the only one who knows the truth." The truth.In an instant, the curator grasped the true horror of the situation. If I die, the truth will be lost forever.Instinctively, he tried to scramble for cover. The gun roared, and the curator felt a searing heat as the bullet lodged in his stomach. He fell forward... struggling against the pain. Slowly, Sauniere rolled over and stared back through the bars at his attacker. The man was now taking dead aim at Sauniere's head. Sauniere closed his eyes, his thoughts a swirling tempest of fear

Figure 1: A sample of the high-contrast text adaptor stimulus.

The spatial frequency created by text rows in our stimulus was calculated as follows. Where screen height h = 28.5cm, and the distance to the screen from the observer d = 52cm, the angle of elevation from the observer, measured in degrees, was given by $\tan^{-1}(h \div d) = 28.72°$. Since our stimulus comprised 30 rows of text, spanning the entire vertical extent of the screen, the angle subtended by a single cycle of text (which was defined as a row of text and the following inter-text row of blank space) was $28.72 \div 30 = 0.96$ cdeg^{-1} (i.e., $\approx 1\text{cdeg}^{-1}$).

The stroke frequency was calculated using the method described in Majaj et al. (2002), in which it is suggested that the stroke frequency created by letters is a suitable representation of the centre spatial frequency of text in the horizontally meridian. To account for the unjustified right edge of text, a straight edge was used to divide the screen in half vertically. A horizontal line was drawn through a row of text at half the height of a lower case letter and the number of vertical strokes crossing this line were counted and repeated for first 30 rows of text. Average stroke frequency was calculated by dividing the average number of strokes across all rows by half the horizontal screen size in degrees to give a stroke frequency of 3.96 ± 0.47 (mean ± SD) strokes per degree. Once a page of text had been read, participants pressed a button on a response keypad to advance to a new page of text, with similar stroke frequency characteristics, to help maintain interest and concentration (see *Procedure*).

Contrast sensitivity was measured for 1cdeg^{-1} and 4cdeg^{-1} using Gabor test gratings orientated at both 90° (vertical) and 0° (horizontal), and subtended 2.35° visual angle at the screen distance of 52cm.

Procedure

A QUEST two-alternative forced choice (2AFC) procedure was used, wherein participants were requested to a push a button to indicate whether a grating appeared to the left or right of a central fixation target. Stimuli were presented for 300ms, using a raised cosine temporal envelope. The termination criterion was set at a confidence interval of 95% and a white circle (size 0.2°) was displayed at the screen centre as a fixation target. The contrast sensitivity test protocol was explained to participants, who were then given the opportunity to practice until confident with their comprehension of the procedure. Pre-adaptation contrast sensitivity measurements were recorded for Gabor test gratings of 1cdeg^{-1} and 4cdeg^{-1} at both 90° and 0° orientations. One staircase for each stimulus orientation/frequency setting was run, with trials for each of these four conditions interleaved randomly, terminating at convergence.

The 1cdeg^{-1} horizontal grating matched the “row frequency,” of the text whilst the 4cdeg^{-1} matched its vertical “stroke frequency,” (Majaj et al., 2002). The orthogonally orientated (1cdeg^{-1} vertical and 4cdeg^{-1} horizontal) Gabors acted as corresponding controls for the two frequencies derived from the text stimuli. Three pre-adaptation measurements of contrast sensitivity were obtained at each spatial frequency and orientation, the average of which was taken as the pre-adaptation contrast sensitivity. Following the three pre-adaptation contrast sensitivity measurements, participants read the text continuously for 180s, after which post-adaptation contrast sensitivity measurement was automatically started.

The post-adaptation measurements used a “top-up” procedure whereby after 15s (five trials) of testing contrast sensitivity, the text adaptor was automatically displayed for 30s of reading, after which contrast sensitivity testing recommenced for another 15s followed by 30s text top-up until the staircase was completed for each of the four test conditions. Gabor patches for contrast sensitivity measurement were displayed on the same screen as the text adaptor, thereby negating the need for any re-fixation or head movement. An audible beep denoted the commencement of the contrast sensitivity measurement. This seamless alternation between text adaptor and contrast sensitivity measurement facilitated rapid, smooth switching between the two tasks, thereby minimizing any loss of adaptation during the transition and avoiding the need to accommodate at different distances.

Analysis

Contrast thresholds were recorded as the common logarithm of the reciprocal of the threshold contrast, i.e. log contrast sensitivity (logCS). Our dependent variables, pre-adaptation logCS, post-adaptation logCS, and changes in logCS pre-post adaptation, were entered into a mixed model ANOVA, with refractive group as the between participants factor (two levels: myopia and emmetropia) and contrast sensitivity (two levels: pre- and post-adaptation) as the within participants factor. Planned contrasts (paired t-tests) were used to compare pre- and post-adaptation logCS.

RESULTS

Contrast sensitivity measurements were found to be reliable: the coefficient of variation (COV) was calculated for the pre-adaptation logCS values for each subject, and for each spatial frequency, to determine the repeatability of the measurements. The standard deviation of each participant's 3 pre-adaptation logCS measurements was divided by the mean of the 3 logCS values to give the COV. The mean COV for all participants and spatial frequencies was 3.57% (when COV is expressed as a percentage it is the relative standard deviation) (range: 0.52-12.85%), well within the acceptable range defined by Lesmes, Lu, Baek & Albright, (2010).

Figure 2 shows mean pre-adaptation and post-text adaptation logCS when measured with both horizontal and vertical test gratings at 1cdeg^{-1} and 4cdeg^{-1} for all participants (left), emmetropic participants (center) and myopic participants (right). A mixed between-within participants ANOVA was conducted to compare logCS before and after reading (i.e., adaptation) in myopic and emmetropic participants. For 1cdeg^{-1} horizontal, there was a significant adaptation effect [Wilks' Lambda = 0.33; $F_{(1,19)} = 36.61$, $p<0.01$, $h_p^2 = 0.67$], with both refractive error groups showing reduced logCS after reading (Table 2).

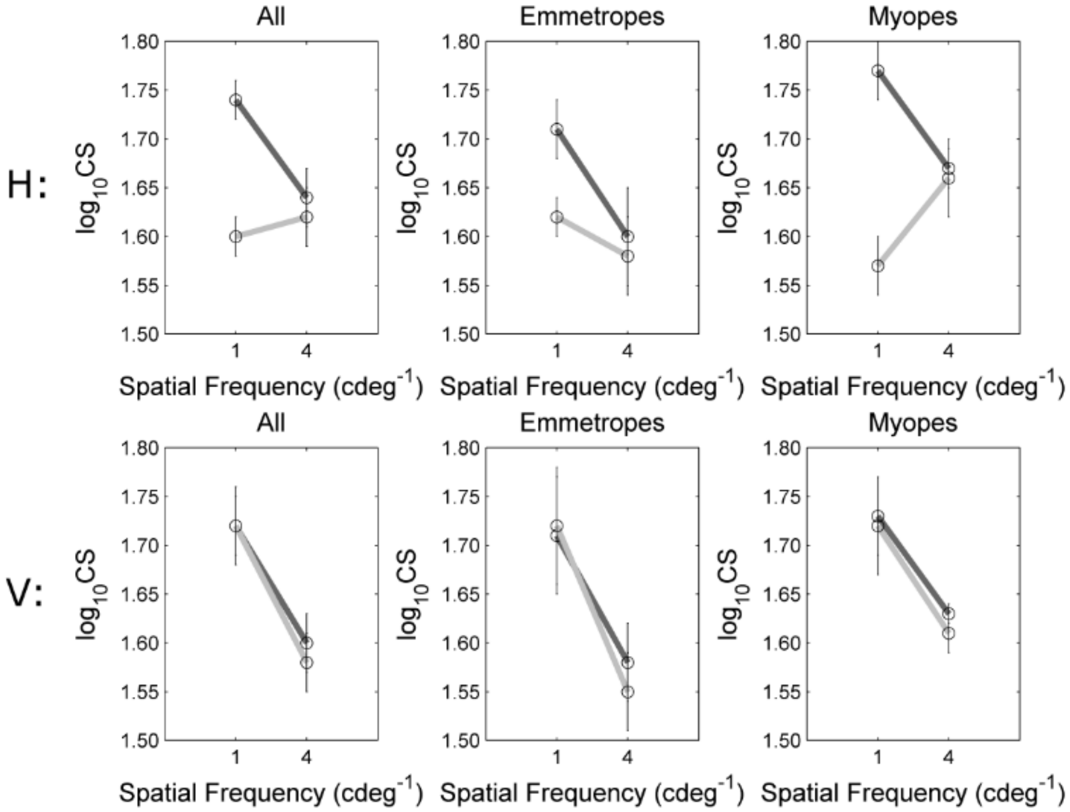


Figure 2: Mean pre-adaptation (dark line) and post-adaptation (light line) logCS for horizontal (H: upper row) and vertical (V: lower row) test gratings for all participants (left), emmetropes (center) and myopes (right). Error bars show ± 1 SEM.

Contrast adaptation was defined as the magnitude of change in logCS pre-post text adaptation (Figure 3 and Table 3).

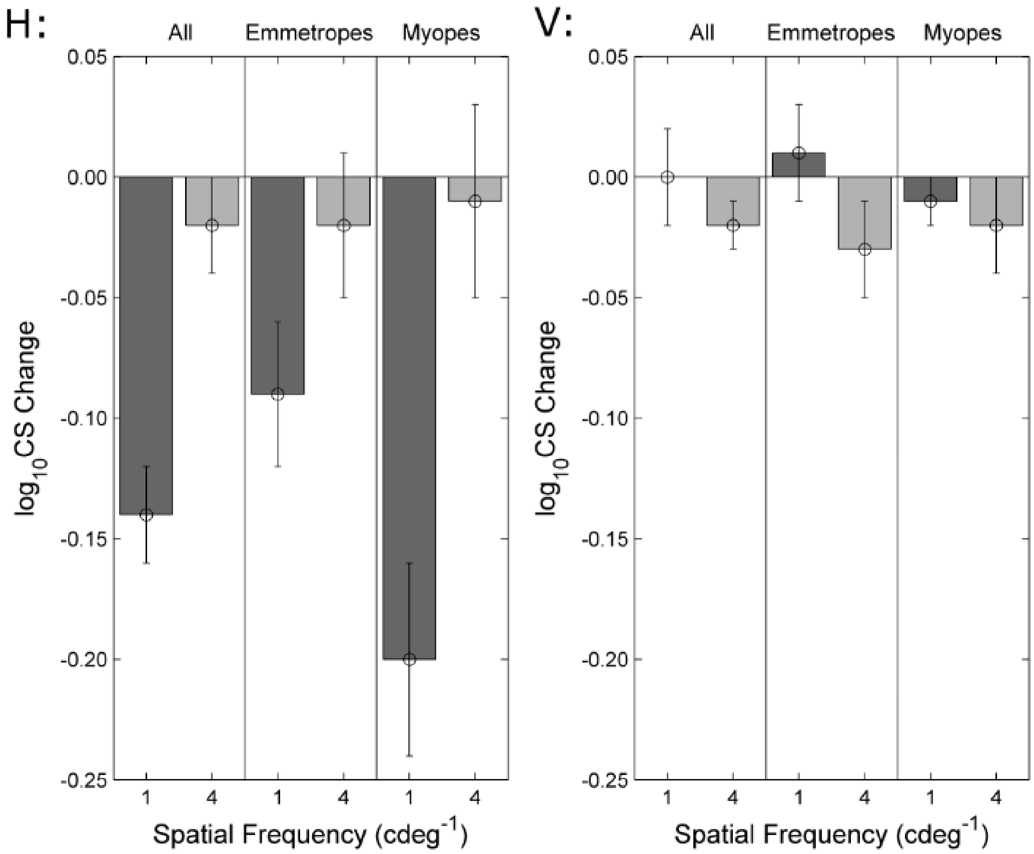


Figure 3: logCS change (contrast adaptation) after text adaptation for horizontal (H) and vertical (V) test gratings for all participants, emmetropes and myopes. Error bars show ± 1 SEM.

Paired *t*-tests showed a statistically significant reduction in logCS post text adaptation at the text row frequency (1cdeg^{1} horizontal) [$t_{(19)} = 5.38$; $p < 0.01$] but only a marginal effect at text stroke frequency (4cdeg^{-1} vertical) $t_{(19)} = 1.83$; $p = 0.08$. When split by refractive error group, the reduction in logCS at 1cdeg^{-1} horizontal was significant for both emmetropes [$t_{(9)} = 2.66$; $p = 0.03$] and myopes [$t_{(9)} = 5.76$; $p < 0.01$]. Myopic participants showed significantly greater adaptation compared to emmetropic participants (0.20 ± 0.04 log units *vs*. 0.09 ± 0.03 log units); independent samples *t*-test [$t_{(18)} = 2.47$; $p = 0.02$ (two-tailed)].

1cdeg^{-1} horizontal	**Pre**	**Post**
All participants	1.74 ± 0.02	1.60 ± 0.02
Emmetropes	1.71 ± 0.03	1.62 ± 0.02
Myopes	1.77 ± 0.03	1.57 ± 0.03

Table 2: logCS values pre and post text adaptation for 1cdeg^{-1} horizontal ± 1 SEM (log unit).

For all participants, there was no significant change in logCS pre-post text adaptation at the orthogonal control spatial frequencies of 1cdeg^{-1} vertical [paired t-test $t_{(19)}$ = 0.24; p = 0.98], or 4cdeg^{-1} horizontal [paired t-test $t_{(19)}$ = 0.46; p = 0.65]. Furthermore, there was no significant difference in the magnitude of contrast adaptation between the refractive groups at 1cdeg^{-1} vertical [independent samples t-test $t_{18)}$ = 1.07; p = 0.30 (two-tailed)] or at 4cdeg^{-1} horizontal [independent samples t-test $t_{18)}$ = -0.10; p = 0.92 (two-tailed)].

	Test Grating			
	Horizontal		Vertical	
Mean contrast adaptation ± SEM (log unit)	1cdeg^{-1}	4cdeg^{-1}	1cdeg^{-1}	4cdeg^{-1}
All participants	-0.14 ± 0.02*	-0.02 ± 0.02	0.00 ± 0.02	-0.02 ± 0.01
Emmetropes	-0.09 ± 0.03*	-0.02 ± 0.03	0.01 ± 0.02	-0.03 ± 0.02
Myopes	-0.20 ± 0.04*	-0.01 ± 0.04	-0.01 ± 0.03	-0.02 ± 0.02

Table 3: log contrast adaptation (post-adaptation logCS – pre-adaptation logCS) values for all participants, emmetropes and myopes for each test grating. *denotes contrast adaptation significant at $p \leq 0.05$.

DISCUSSION

Consistent with earlier studies (Magnussen et al., 1992; Greenhouse et al., 1992 and Lunn & Banks, 1986), we found that reading text displayed on a computer screen produces significant contrast adaptation. Additionally, our results show that myopes exhibit significantly greater contrast adaptation than emmetropes. This is in agreement with Yeo et al. (2012), in which significant contrast adaptation was found in children after reading a page of printed text. Moreover, our results show adaptation effects at the text row frequency (1cdeg^{-1} horizontal), but not at the text stroke frequency (4cdeg^{-1} vertical), with no contrast adaptation for the orthogonal control frequencies.

Contrast adaptation at 1cdeg^{-1} was greater for myopic participants (0.20 log units) than emmetropic participants (0.09 log units). Yeo et al. (2012) were the first to demonstrate greater contrast adaptation in myopes than emmetropes after reading printed text. Their emmetropic participants showed significant contrast adaptation at 2.7cdeg^{-1}, which was not one of the dominant spatial frequencies present in their text target. Furthermore, amongst their myopic participants, the text row and stroke frequencies did not show the greatest magnitude of adaptation of the five spatial frequencies tested. The observed pattern of reduced sensitivity at all tested frequencies and the greatest sensitivity depression at spatial frequencies unrelated to text leave open the possibility that some processes besides adaptation may have contributed to reported group differences. Direct comparison between this study and our own is complicated by the use of different participant groups (children *vs.* adults) and stimuli.

In the present study, we have shown contrast adaptation specific to the frequency and orientation of text rows for both participant groups, and that adaptation was significantly greater in myopic participants. This result shows that there is a difference in adaptation susceptibility between the two refractive error groups. Furthermore, the specificity of adaptation as demonstrated by a significant change in logCS at 1cdeg^{-1} using a horizontally oriented Gabor, coupled with no effect at the control frequency of 1cdeg-1 using a vertically orientated Gabor, highlights the role of the text row frequency in inducing contrast adaptation during reading.

We found a greater magnitude of contrast adaptation than Yeo et al., (2012), which may be due to a more robust experimental paradigm that incorporates a top-up procedure, and the use of a single display screen for adaptation and contrast sensitivity testing (eliminating differences attributable to accommodative lag), but could also potentially be a consequence of our binocular adaptation and contrast sensitivity measurements, compared with their binocular adaptation and monocular contrast sensitivity measurements.

Majaj et al., (2002) suggested that the stroke frequency of letters is a viable predictor of their central spatial frequency along the horizontal meridian. Having failed to induce contrast adaptation at the stroke frequency of 4cdeg^{-1}, we applied a Fast Fourier Transform (FFT) to an image containing the text adaptor to test this assumption.

Figure 4 (A-C) illustrate how our text stimulus was processed to obtain an FFT that represents vertical power (created by horizontal text rows), by taking vertical samples through the image that through each of the 30 text lines (A-B, shown as an average pixel intensity profile in C, wherein red shows the average of the 30 vertical samples, and blue all vertical columns through the image). Figure 4 (D) shows the FFT, with peak power observed at 30 whether using the 30 vertical columns (red), or all columns (blue). This equates to 30 cycles across the entire image, wherein one cycle is a row of text and the subsequent inter-text blank row. Peak power vertically, created by horizontal rows of text, was therefore the FFT max pixels ÷ vertical visual angle (30 ÷ 28.7) = 1.07cdeg^{-1}, as expected.

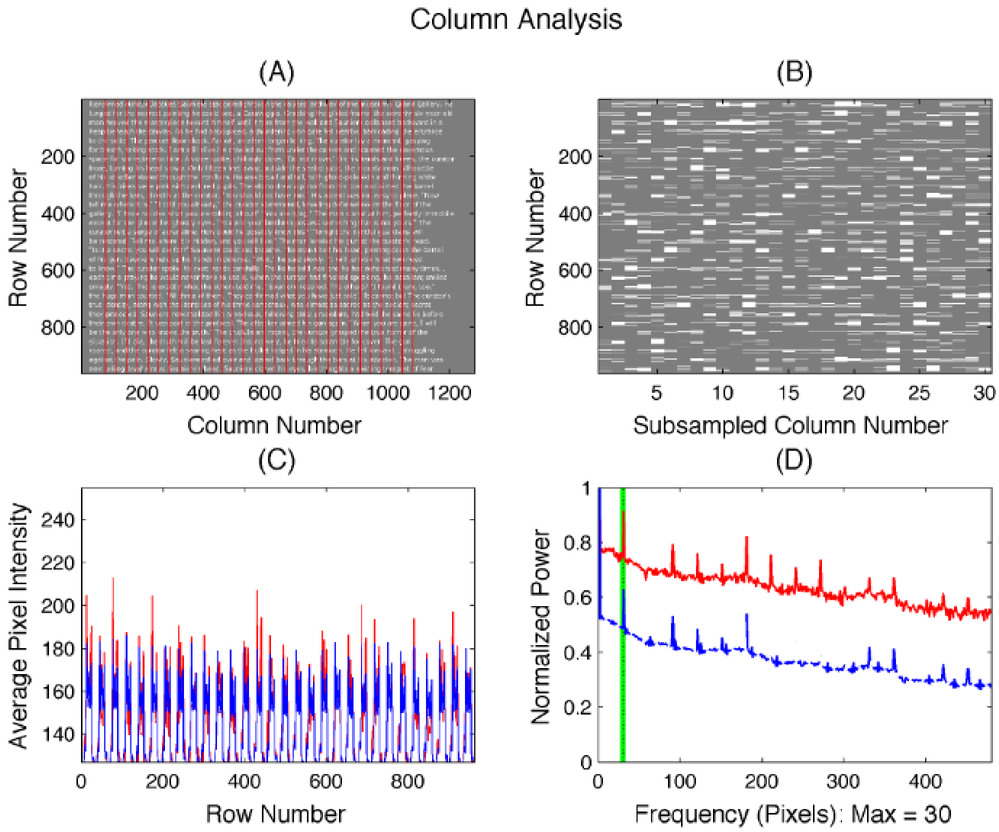


Figure 4: Analysis of text stimulus vertical power (A) Acquisition of stimulus subsample (30 columns, red lines); (B) Stimulus subsample; (C) Average pixel intensity profile following column averaging (blue: all columns, red: 30 column samples); (D) Average of 1-D FFTs (blue: all columns, red: 30 column samples). Green vertical line shows peak power.

Figure 5 shows the same analysis applied in the horizontal meridian, as created by the character strokes, and reveals a rather less distinct peak in power than the vertical meridian (above), indicating that power is distributed over a relatively wide range of horizontal frequencies. The 30 subsamples taken were aligned precisely with the centre of each row of text, and therefore captured character strokes in a manner similar to the stroke counting technique used in earlier work. The apparent lack of distinct peak(s), c.f. vertical FFT, is most likely a result of spatial uncertainty: characters start in different positions horizontally and the character strokes are not always vertical (e.g. Q, S, W). This creates a wider band peak in the FFT, causing the distribution of power across a larger number of frequencies, and reduces the overall power at each specific frequency in this band. Variation in letter shape would also distribute the power across different orientations, in comparison to the more uniform alternating rows of text and inter-row spaces, which are always in the same position and create a saw-tooth average intensity profile (Figure 4c). It is also apparent that, if all rows are used rather than just 30 rows aligned with the centre of each line of characters, the FFT is considerably less organized. We therefore hypothesize that there may have been insufficient power at $4cdeg^{-1}$ to induce contrast adaptation. Peak power in the horizontal FFT was found to be 192 ÷ 36.3 = $5.29cdeg^{-1}$, which is somewhat higher than the $4cdeg^{-1}$ suggested by the stroke counting technique (see *Stimuli*), drawing into question the efficacy of that approach.

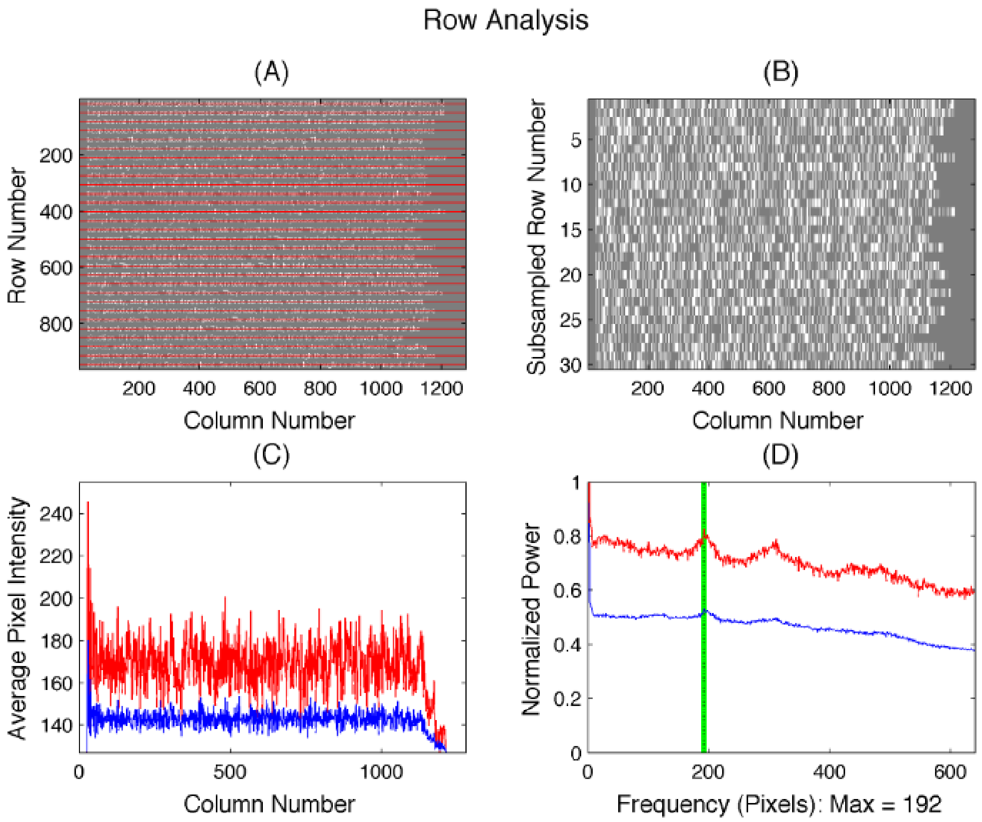


Figure 5: Analysis of text stimulus horizontal power. (A) Acquisition of stimulus subsample 30 rows; (B) Stimulus subsample; (C) Average pixel intensity profile following row averaging (blue: all rows, red: 30 row samples); (D) Average of 1-D FFTs (blue: all rows, red: 30 row samples). Green vertical line shows peak power.

Contrast adaptation has been postulated as an error signal for emmetropization as a consequence of altered sensitivity in the visual system with defocused stimuli (Diether, Wallman and Schaeffel, 1997; Diether and Schaeffel, 1997; Diether and Schaeffel, 1999). In Deither, Gekeler and Schaeffel (2001) it was suggested that contrast adaptation is a retinal error signal for ocular growth and myopia development by correlating contrast adaptation in chicks with myopia onset induced by form deprivation (using frosted occluders and negative lenses), along with low-pass filtered video clips. Furthermore, recovery from contrast adaptation correlated with the retraction of myopia in the chicks. Animal studies propose that intermediate spatial frequencies may influence the emmetropization process (Schaeffel, Weiss & Seidel, 1999; Schmid & Wildsoet, 1997). Schmid & Wildsoet (1997) proposed that a lack of mid-spatial frequencies in text might be responsible for stimulating myopia. Our Fourier analysis of the text also showed a distinct lack of mid-spatial frequency (we detected a mid spatial frequency of 5.29cdeg^{-1}, which correlated with the letter stroke frequency but contained very little power). In future experiments, spatial frequencies to be measured pre- and post-adaptation could more reliably be derived from Fourier analysis of adaptor targets, rather than using stroke counting.

Animal models have shown reduced firing of cortical neurons during contrast adaptation (Movshon & Lennie, 1979; Albrecht, Farrar & Hamilton, 1984). Futhermore, Yeo et al., (2012) proposed that a concurrent reduction in the neural response gain may result in the perception of a defocussed retinal image, similar to the effect of translucent diffusers which degraded retinal image quality and promoted myopia development in animals (Sivak et al., 1989; Bartmann and Schaeffel, 1994). In humans, even very minor changes in retinal image quality have been related to myopia development (Robb, 1977). Mon Williams et al. (1998) reported that a change in contrast sensitivity of 0.1 log unit is clinically significant, given that the contrast sensitivity function is normally stable (Woods, Bradley & Atchison, 1996). Smith & Hung (2000) showed that the degree of image degradation required to induce deprivation myopia in monkeys was relatively low; specifically, a 0.1 logCS reduction at low spatial frequencies, up to an average of 0.75 log unit reduction at higher spatial frequencies. Our results show a similar reduction in logCS at 1cdeg^{-1} horizontal in all our participants, but more importantly our myopic participants showed significantly greater adaptation than emmetropes.

Previous studies have postulated that contrast adaptation may be induced by accommodative inaccuracies resulting from re-fixation between adaptor and test targets presented at different distances (Yeo et al. 2012). This is of particular significance, given that re-fixation could induce accommodative lag and myopes have been reported to exhibit greater lags than emmetropes (Yeo, Kang & Tang, 2006; Abbott, Schmid & Strang, 1998; Gwiazda, Thorn, Bauer & Held (1993); McBrien & Millodot, 1986). Our study has the advantage that all adaptor and measurement targets were displayed on the same screen, and so we can therefore discount accommodative lag and potential near-work induced transient myopia (NITM) resulting from re-fixation as contributing factors in observed contrast adaptation.

Furthermore, our experimental setup facilitated the presentation of top-up images. Indeed, a pilot study measured contrast sensitivity before and after a period of 30 minutes reading without topping up, but failed to show contrast adaptation at either the text stroke or row frequencies. Ohlendorf & Schaeffel (2009) reported that after 10 minutes adaptation, contrast adaptation was maintained for two minutes and reached baseline after five minutes. It is well established that recovery time increases with inspection time (Rose & Evans, 1983; Magnussen & Greenlee, 1985; Georgeson & Georgeson, 1987) however, in our pilot, contrast sensitivity measurement took approximately six minutes. Given Ohlendorf & Schaeffel’s (2009) explanation of a 5:1 inspection to measurement time ratio, this should have been sufficient to measure a contrast adaptation effect, yet no effect was found. Having utilized a top-up procedure in the present study, we highlight the necessity of topping up adaptation.

To summarize, reading text on a CRT induced contrast adaptation at the text row height spatial frequency in young adults. Myopic participants incurred >2× the adaptation of emmetropes. Failure to induce contrast adaptation at the text stroke frequency implies that, despite having been used in earlier work, this may not be an appropriate surrogate for the stroke spatial frequency, evidenced by the lack of a pronounced narrow-band correlate in the FFT power spectrum and mismatch between FFT analysis and stroke counting results, or that stroke frequency simply carries insufficient or insufficiently concentrated power to educe adaptation effects. The greater contrast experienced by myopes at the text row frequency after reading warrants further investigation to better understand the relationship between near work and myopia development.

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