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Impact of Forms of Visual Attenuation on Short-Term Eye Changes Under Controlled Reading Visibility

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Purpose: Animal studies have suggested that visual degradation impacts eye growth due to the attenuation of high spatial frequencies. However, the influence of perceptual visibility remains unclear in humans. The aim of this study was to investigate the impact of visibility on visual attenuation-related eye changes during reading.

Methods: Axial length (AxL) and choroidal thickness (ChT) changes associated with reading tasks were measured in two separate experiments. In the first experiment, the reading task was conducted under different forms of visual attenuation (contrast, resolution, defocus, noise, and crowding). For each form of visual attenuation, the text was set at a sub-threshold level of visibility, evaluated via prior measurement of reading performance, and kept constant via adaptive control of the intensity of the stimulation. Each sub-threshold reading condition was compared with a supra-threshold reading text, serving as control. In the second experiment, the effect of visibility on lens-induced defocus was further examined by comparing the effect of text stimulation with an equivalent dioptric of 5.5 D under sub- and supra-threshold levels of resolution.

Results: Near distance reading with supra-threshold texts caused eye elongation (AxL: +12.942 µm ± 2.147 µm; ChT: −3.192 µm ± 1.158 µm). Additional defocusing failed to exacerbate axial elongation under sub-threshold text visibility (mean difference: −0.135 µm ± 2.783 µm), revealing a clear inhibitory effect of lowering visibility on eye changes. Other forms of visual degradation, including crowding (mean difference: 6.153 µm ± 2.127 µm) and noise (mean difference: 5.02 µm ± 2.812 µm) also showed an inhibitory effect on eye elongation. The significant effect of crowding indicated that post-retinal mechanisms, involving attentional processes related to crowded characters, may play a role in the influence of visibility.

Conclusion: Although the featural composition of visual stimulation can drastically influence eye changes, this study revealed an important mediating role of visibility, previously underscored in chick studies, which warrants further explorations of the impact of post-retinal processes in eye growth.

Keywords: reading, crowding, myopia, axial length, choroidal thickness

Introduction

Myopia is a major health concern,[1] which develops in the early school years and affects the majority of the population of East Asia.[2] While the etiology of myopia remains under debate, it is widely acknowledged that myopia is a vision-dependent process.[3] Several studies have reported an association between reading and myopia,[4–6] suggesting that some reading factors may distinguish readers developing myopia from emmetropic readers.[7] However, the myopiagenic influence of parameters of reading remains extremely challenging to monitor over extended periods due to continuous variations of reading stimulation.[8] Recent research has utilized short-term ocular changes in humans as indicators of myopia,[9] revealing the influence of reading duration,[10] dioptric,[10–12] text polarity,[12–14] and letter size.[14] Several other unknown factors may contribute to myopia in reading. Animal studies have indicated that a large variety of visual

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manipulations, including optical degradation (defocus,[15] astigmatism[16]), non-optical degradation (diffuser,[17] low-pass filtering,[18] and basic scene-dependent properties (reduced contrast[19,20] and spatial frequency[19–21] and temporal frequency[22] attenuation) may modulate eye growth, although many of these parameters remain untested in humans. All these manipulations influence the degree of visibility/saliency of stimulus. This general effect of visual degradation could indicate the potential role of visibility of images in eye growth,[23] pairing with the idea that eye growth is an attempt of the visual system to improve visual images. This has been well illustrated by lens-induced eye growth observed in both animal[9] and human eyes[24–28] as precise compensatory modulation of the eye length with induced optical defocus. However, whilst eye growth can modulate visibility, in non-optical degradations, such as form deprivation,[29] an enhancement of visibility is less probable, raising the question of why the visual system optically adjusts itself to images that cannot be corrected.

One of the difficulties in answering this question, which is probably the reason why visibility per se has received little attention, is that visibility is hard to quantify in animal eyes due to its subjective component. In humans, visibility could play an important role, as it may determine the effort to see under prolonged, constrained human tasks, including reading. Visual effort is also known to influence the ocular[30–33] and neural responses,[34] impacting the balance of the autonomic pathways[35,36] controlling key ocular components, including the choroid, the ciliary muscle, and the sclera,[37] but also possibly being involved in the regulation of dopamine[38,39] and choroidal thickness modulations.[40–42] Prolonged imbalance of these systems during reading may be thus considered.

A role of visibility implies, however, visual analyzers of the myopia response capable of judging the overall quality of the image. For instance, at the neural level, the effort to see through degraded stimuli could serve to estimate the amount of degradation, and the required ocular compensatory response, to be informed via neuronal feedback mechanism to the retina. However, this potential neuronal influence has been strongly contested by animal studies, which showed that lesions of the optic nerve did not prevent emmetropization.[43] Despite this automatic aspect of ocular compensatory responses, a contribution from brain processes is evidenced by effects of the lesion on the quality of emmetropization.[44,45] More importantly, brain processes may gain influence with the involvement of voluntary vision in goal-oriented tasks like reading, which are absent in animals. Thus, animal findings might downplay the contribution of higher-level neural pathways to the visual stimulation in myopia.

Nevertheless, the general effect of degradation may be explained by retinal sensitivity to special properties/feature(s) of degradation, which would not require a complex processing of image quality. Such features, if common to the aforementioned growth-related parameters, could explain differential ocular responses to various forms of degradation. This hypothesis has been propounded in a previous chick study,[18] which demonstrated that the energy in high spatial frequency, rather than contrast slopes, could explain eye growth. This finding carries the important implication that any degradation altering the spectrum of high spatial frequency could impact eye growth, irrespective of visibility. This means reading parameters, including contrast, resolution, defocus, noise, and crowding, may be potential mediators of eye growth, given their respective influence, whether selective or not, on high spatial frequency. Several of these critical reading parameters lack relevance in animal studies and have not been systematically studied or compared in humans. Therefore, it remains unknown whether reading parameters influencing visibility or spatial frequency affect eye growth, and, if so, what is their respective degree of influence.

Although chick studies support the existence of influential features in degradation, whether eye growth is entirely unrelated to visibility has not been clarified. This study aimed to examine the role of text visibility with respect to its impact on different forms of visual attenuation and increasing susceptibility to eye growth. To achieve these goals, the short-term effects of varying reading parameters affecting text visibility were tested under controlled levels of reading difficulty, allowing a systematic and quantitative comparison of different forms of visual attenuation. It was hypothesized that the myopiagenic effect of visual reading is contingent on the degree of visibility. The results first indicated that short episodes of near reading lead to eye elongation, characterized by both an increase in AxL and a thinning of ChT. Experiment 1 demonstrated that reduced visibility mitigates AxL elongation, achieved through crowded and noisy text, suggesting a potential anti-myopiagenic effect. Finally, experiment 2 shows that the inhibitory effect of visibility, adjusted via text resolution, varies with an individual susceptibility to defocus. All in all, this suggests a mediation of the impact of near distance reading by text visibility.

Study 1

Methods

Subjects and Criteria

A convenience sample of 13 young Chinese adults (SER: −4.00 D ± 2.82 D, 19–25 years old, 6 females) was recruited. Based on the study from,[11] it was estimated via the statistical software G*Power version 3.1 that 13 participants would be required to detect a significant change in ChT of −5 µm ±6 µm in response to the dioptric blur induced by near reading with 80% power (two-tailed paired *t*-test) and a significance level of 0.05. For this sample size, the expected power to detect a significant change in AL of +7 µm ± 6 µm[25] in response to dioptric blur is 99 % at the same significance level.

All participants met the following inclusion criteria: (1) best-corrected distance visual acuity of logMAR 0.00 or better in both eyes; (2) spherical-equivalent error≥0 diopters (D); and (3) age under 30 years. The exclusion criteria were as follows: (1) astigmatism >1.50 DC; (2) anisometropia ≥1.50 D; (3) abnormal binocular vision or accommodation; (4) any type of eye disease; (5) ocular trauma, or (6) surgery; (7) a history of myopia control intervention; or (8) prescription of medication were excluded.

The experimental procedures were approved by the human ethics committee of The Hong Kong Polytechnic University, and the research was conducted according to the principles expressed in the Declaration of Helsinki. Informed consent was obtained from each participant.

Experimental Design

Apparatus

Subjects were asked to binocularly read texts presented on a linearized, IPS tablet display (SmarterWar, 13.4" diagonal, 3840 × 2160), allowing high pixel density (ie, 332 pixels/inch). Subjects were seated at a working distance of 40 cm using a chin rest for stability so that the screen subtended a visual field of 40 deg x 25 deg. This distance was chosen because it is a typical near reading distance when looking at reading materials.[46,47] A white-on-black (Black: 1 cd/m2; white: 107 cd/m2) text written in Chinese using Yahei Microsoft fonts in photopic light conditions (Room luminance: 23 cd/m2) with reading time of 15 min was presented. The text comprised 310 rows of characters split into 31 rows of characters centred on a white background, which were presented as one document on the display. To ensure the same number of characters appeared on each row, sentence punctuation was removed from the text. To ensure reading speed was only limited by visibility, and not by character complexity or knowledge, simple texts were chosen, derived from the book *Twenty Thousand Leagues Under the Sea* by Jules Verne. Whilst reading, subjects used a hand-held mouse that they pressed to record the completion of each line of the text.

Text Manipulations & Purpose

The study examined the impact of various reading parameters on short-term eye changes by simulating five types of text visual attenuation for each subject. These attenuations included the manipulation of the level of (i) contrast, (ii) resolution, (iii) defocus, (iv) noise, and (v) crowding of the visual text and were performed by adjustment of (i) the pixel size of the characters of text, (ii) the luminance of the characters, (iii) the centre-to-centre distance between characters of the text, (iv) individual's refractive errors using trial lenses and (v) zero-mean Gaussian white noise added to the text, respectively. Normal reading conditions served as the control group and featured text with high contrast and resolution, but without crowding, noise, or defocus. All visual attenuation forms of reading were compared against this baseline. Using a repeated measures design, each subject was exposed to all five types of text visual attenuation, as well as the control condition. The resulting short-term eye changes were measured and analyzed to determine the specific effects of each type of visual attenuation on reading performance and ocular response.

Temporal Structure of the Test

Each subject attended a total of four sessions (total duration: 4–5 hours), each set on a separate day in the morning between 9 AM to 11 AM to minimize diurnal-related choroidal thickness variations. In the first session, the subject underwent a phase of pre-measurement (duration: 1 hour), including non-cycloplegic objective refraction followed by the assessment of reading acuity performance of the subject for each visual form of attenuation of reading. After the threshold reading assessment, subjects were invited to perform six different 15-min reading tasks, with two reading tasks per session each separated by a recovery period of 20 minutes allowing disadaptation. For each 15-minutes reading task, a different visual attenuation condition was simulated, which was randomly selected in order to counterbalance conditions across subjects. For each of the reading sessions, the test commenced with a 10-min washout period during which subjects were asked to navigate inside a large room and engage in varying visual activities to ensure no prior visual adaptation from sustained retinal stimulation. After washout, ocular biometric measurements were performed including AxL measurement (duration test< 10s) with a commercial partial coherence interferometer (IOL master 500, Carl Zeiss Meditec AG) followed by ChT measurement (duration test< 20 s) with swept-source optical coherence tomography (DRI OCT Triton, Topcon) and objective refraction using an open-field autorefractor (Shin-Nippon NVision-K 5001, Rexxam Co.) for both eyes, systematically starting with the right eye first for each measurement. A radial scan pattern (9.0 mm diameter, 1024 A-scans x 12 lines) was used to measure central choroidal thickness from the central subfield of the Early Treatment Diabetic Retinopathy Study (ETDRS) grid, utilizing the SS-OCT device's built-in software. Immediately after measurements, the subjects performed the reading task for a duration of 15 minutes, then repeated the ocular biometric measurements after the 20-min recovery period in the same sequence order. There was a total of three sessions with two conditions per session separated by a recovery period of 20 minutes allowing desadaptation. Each condition was counterbalanced between the subjects to ensure constancy of the intensity of the stimulation across the tests (assessment and reading task), both individual threshold determination and reading test were controlled by custom software developed using the Psychophysics Toolbox Version 3[48,49] in MATLAB (version 2022a), allowing to present the stimulation on the same visual support.

Individual Threshold Assessment (Session 1)

To ensure the text's low visibility, individual reading performances were characterized in a preliminary test (session 1) by measuring reading performance as a function of the text intensity for each of the simulated visual attenuations (as depicted in Figure 1). Reading performance was measured using reading speed, which was defined as the number of Chinese characters read per minute. To determine reading speed, the duration required by subjects to read one line of text was measured for successive lines of a text. The intensity of the text was decreased at each line read by a nominal increment of 1 pixel (~0.7 arcmin) for resolution acuity, −0.50 D for defocus, 1.2 % Weber contrast for contrast, 0.02 in variance for noise (given a normalized image), 0.05 line spacing unit (~1.3 arcmin from center-to center distance) for crowding, thus producing speed-versus-intensity curves for each visual attenuation condition.

During the test, subjects were instructed to read aloud, as fast as possible, without discontinuation in case of reading errors or doubt, and press the left button of the mouse at the end of each line of the text, before reading the next lines. At each button press, the text intensity was updated and the reading speed at the previous intensity calculated. The default setting was a text with character sizes subtending 20.6 arcmin (ie, font size of 32 pixels), 99 % Weber contrast, center-to center distance of 28.4 arcmin (ie, 1.1 line spacing unit). In the visual attenuation conditions, the default setting was kept the same, but the manipulated variable was changed. Each threshold measurement was repeated twice for each simulated condition.

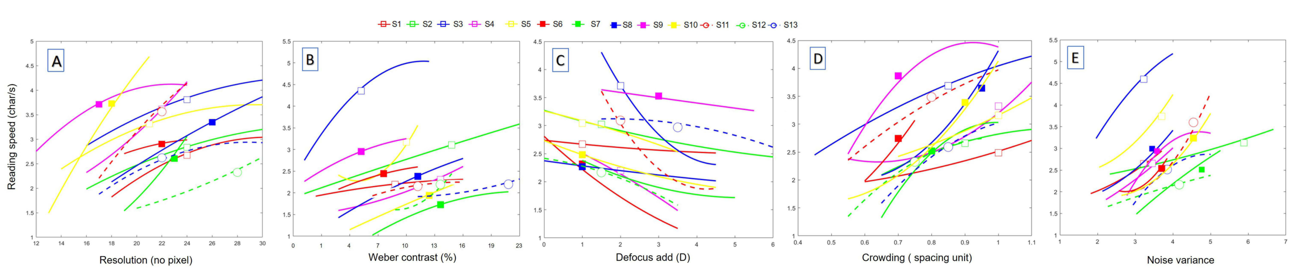

Figure 1 Determination of reading threshold. Fitted reading acuity curves with the calculated reading threshold (symbols in color) for each subject Si under the simulated conditions: (**A**) resolution (**B**) contrast (**C**) defocus (**D**) crowding, and (**E**) noise. Note the large individual intervariability in the reading acuity curve for the five tested visual attenuation conditions, justifying individual threshold adjustment.

The text comprised a set of 31 lines with the same number of characters/words, which were displayed simultaneously on the screen. To prevent subjects from reading the next line during mouse clicks, each line was separated by a dummy line consisting of sequences of the written instruction “do not read”, which informed subjects to read the next lines after clicking. To ensure easy discrimination of the location of new read lines, each line was numbered sequentially. The use of the dummy lines prevented visual crowding, especially for the crowded text.

Case of Defocus

For the assessment of defocus threshold, the measurement of reading speed was separated by a brief pause during which the experimenter changed the level of defocus tested. The procedure had the following structure: Subject was signaled to read a line of text by a beep and click the left button of the mouse at each end of line read, generating a sound signal that alerted the experimenter to increase the level of simulated defocus by addition of trial lenses. After defocus adjustment, the experimenter pressed a button, which activated a sound signal instructing the subject to read the next line.

For each tested condition, data were fitted with a two-order polynomial curve (depicted in Figure 2) using a least square method, after exclusion of the plateau of intermediate character sizes and/or decline in reading speed for very large characters. Individual intensity thresholds were set as the stimulus intensity for which the normalized reading speed of the fitted curve was reduced by 70 % to make reading sub-threshold but achievable over the entire duration of the test. In the control condition, the resolution of the text was at supra-threshold and used 100 % of the normalized reading speed of the fitted resolution curve, using the largest font size for which reading performance remained maximal. These thresholds were estimated based on the fitted reading acuity curves, obtained from two consecutive measurements of reading acuity after removal of outliers. For each tested visibility condition and repeat, a different visual text was used.

15-Minutes Reading Simulation (Sessions 2-4)

To test the impact of text visibility and form of visual attenuation on the short-term eye responses, eye changes were recorded before and after reading manipulated text having the same visibility. The degree of visibility was equalized by adjusting the 15-min visual text separately for each subject and conditions to the individual’s threshold of visibility (see section threshold determination). To ensure consistency of reading stimulation and performance (i.e, with respect to the pre-test), the reading texts were presented under the same display settings (ie, luminance viewing distance, etc.) with similar level of cognitive complexity of the text, and only a slight variation in the structure. Similar to the text used for

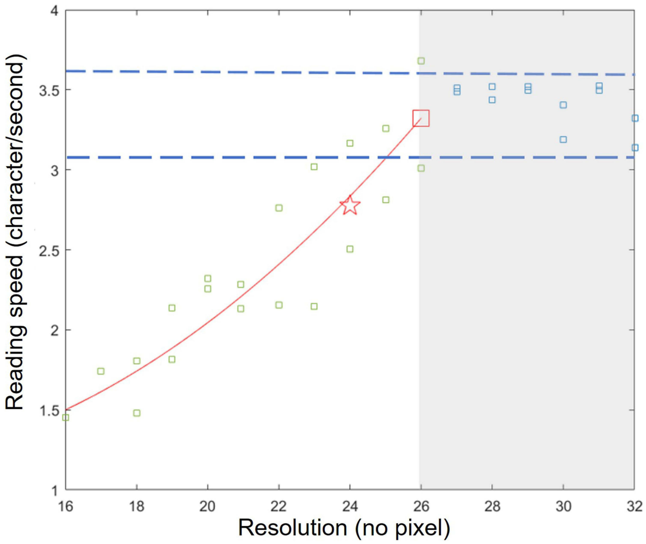

Figure 2 Speed-versus-resolution curve. Illustration showing the estimation of the visibility threshold and suprathreshold of the visually attenuated and control conditions based on the fitted acuity reading curve. The subthreshold intensity level, indicated by the red star, is set at (the discrete threshold value closest to) 70 % of the normalized reading speed of the fitted curve for each condition. The 100 % of the normalized reading speed of the fitted resolution curve, indicated by the red square, was used to set resolution in the conditions with fixed font size (i.e, control, contrast, defocus, noise, and crowding conditions). The blue dotted lines delineate the regions where reading speed was maximal.

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the threshold assessment, the 15-min reading task was implemented using a text made of a total of 10 pages of text. Each page comprised 31 lines of equal length (ie, having the same number of characters) presented simultaneously on the display and centered on a white background. Subjects were instructed to read each line of text of the presented page and press the left mouse button immediately after reading the last character of each line for speed recording. Immediately after the subject read the last character of the page, the next page of text appeared on the screen, until completion of 15 minutes of reading.

Adaptive Adjustment

To ensure a stable level of visibility/difficulty with the time spent reading and avoid potential failure to continuously read at visual sub-threshold, the text intensity was adaptively adjusted based on the subject's real-time reading performance. The adaptive algorithm measured reading speed in consecutive segments of 20 read characters (depicted in Figure 3). It calculated an average speed from two segments. The slope of the reading speed change was estimated by fitting a least-squares linear curve to each of four consecutive average reading speeds (ie, every 80 = 20×4 characters read). Whenever the modulation in reading speed fit (ie, |max reading speed – min reading speed|) was larger than 0.3 s, the algorithm adjusted the text visibility. Specifically, it increased visibility when speed decreased and decreased visibility when speed increased. This approach aimed to help the subject maintain a constant reading speed throughout the test.

Statistical Analysis

Model 1: All statistical analyses were carried out using IBM SPSS Statistics Version 21 (Armonk, NY, USA). To test the effect of reading on short-term eye responses, linear mixed model analyses with restricted maximum likelihood estimation were performed to account for individual differences and accommodate missing data due to poor measurements and outlier exclusion.

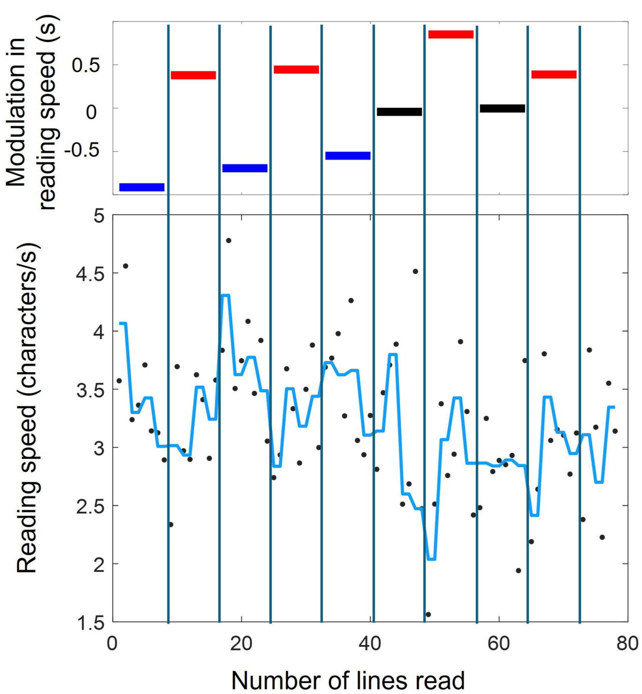

Figure 3 Stabilization of reading difficulty. Reading speed calculated for each line of text throughout the 15-min reading task, with its real time analysis and correction, for a representative subject. In each time section, the slope of the reading speed was evaluated (see top panel). When the absolute modulation in reading speed was greater than 0.3s (blue and red lines), the stimulus intensity was adjusted in the next time section, but remained unchanged otherwise (black lines). Black dots show the reading speed measured at each line and the blue curve the average reading speed.

An initial linear mixed model analysis of AxL (or ChT) was performed to test the effect of reading time (ie pre/post) and conditions, assuming an unstructured variance structure. Reading time, reading conditions, and their interaction were set as fixed factors, and subjects as random effects using the identity covariance structure.

Model 2: To examine and quantify the influence of the eye position and dominance, a second linear model was used with AxL changes (post AxL - pre AxL) (or ChT changes) set as the dependent variable, which allowed simplification of the first model and achieving convergence. Eye position (or eye dominance), reading conditions, and their interaction were set as fixed factors, and individual subjects as random effects, assuming an unstructured variance structure. Main effects and interactions were tested using least significant differences for post hoc tests.

To examine the association between eye changes, accommodative changes, and refractive errors, Pearson correlations between eye changes, accommodative changes, and refractive errors were performed for each condition individually, as well as across all conditions combined.

For each tested condition, individual outlier data (>5%) were identified as data for which the ocular measures deviated from the median of the group for the tested condition by more than ±2.5 median absolute deviation.[50] All data are reported as mean and standard errors.

Results

Visibility Equalization

Individual intensity thresholds (depicted in Figure 1) showed substantial variation across subjects for resolution (14.5 arcmin ± 0.5 arcmin [18 arcmin, 11 arcmin]), contrast (Weber contrast: 12.056 % ± 1.20% [5.47%, 21.86%]), defocus (1.6923 D ± 0.2232 D [1 D, 3.5 D]), noise (Variance: 0.2715 ± 0.0173 [0.17,0.31]) and crowding (line spacing: 0.8731 ± 0.0303 [0.7,1]), highlighting the importance of adjusting the level of visibility individually for equating the degree of visibility.

Effect of Near Reading Exposure

For AxL, a significant main effect of reading time (AICc = −1335.155, F (1,24.257) = 141.756, p < 0.001) was found (depicted in Figure 4), showing a general myopiagenic effect of near reading (Pre: 25.32 mm ± .21mm, p<0.0001, Post:

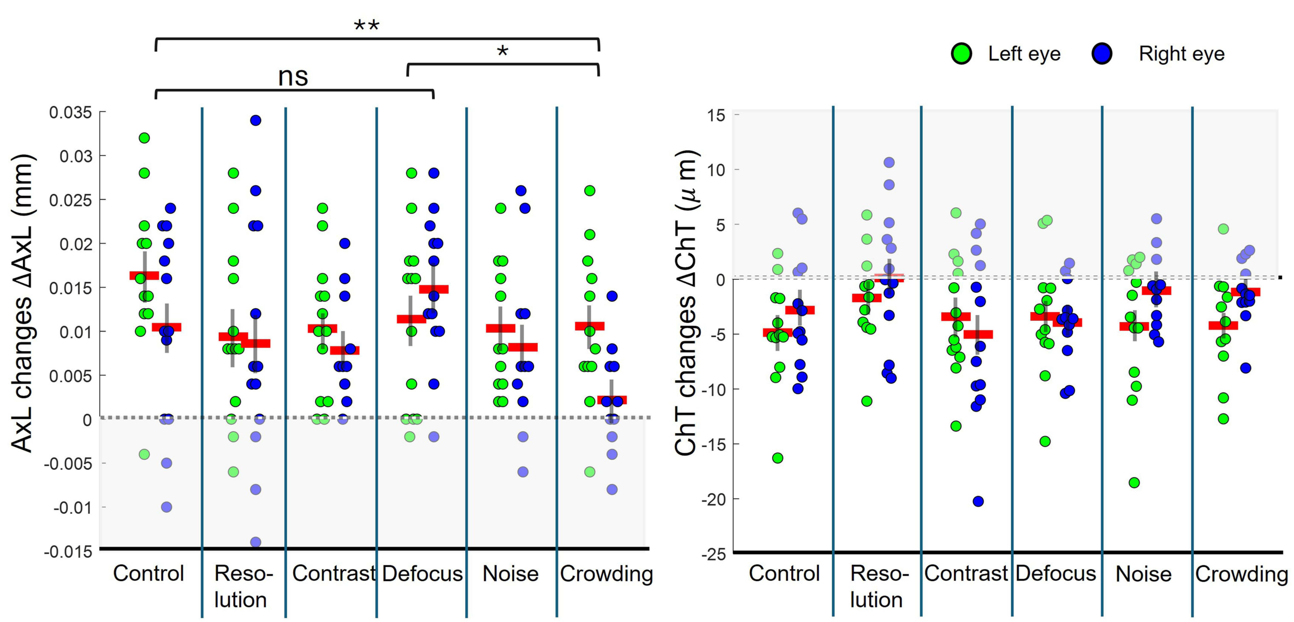

Figure 4 Effect of text visibility. AxL and ChT changes obtained for each sub-threshold visual condition, as well as the supra-threshold visual threshold (control) for left and right eyes. Red bars and filled dots correspond to mean and individual data after outlier exclusion. A systematic increase in AxL is found, accompanied by a thinning of ChT, on average and in the two eyes. The gray area highlights data corresponding to a hyperopic shift of the eye. The symbols **, *, ns represents p-values ≤ 0.01, < 0.05, and > 0.1 respectively.

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25.33 mm ±.21 mm, p<0.001; mean difference: 0.01 mm ± 0.001 mm, p<0.001). There was no main effect of reading conditions (F (5,19.184) = 0.588, p = 0.709), but a small, but significant effect on reading time by reading condition interaction (F (5,15.456) = 3.34, p = 0.031). The control (β = −6.91 µm, t = −2.637, p = 0.026) and defocus (β = −6.23 µm, t = −2.817, p = 0.009) groups showed a significantly faster rate of change as compared to the crowding group, but not the resolution (β = −2.15 µm t=−.843, p = 0.407), contrast (β = −2.15 µm, t =−.821, p = 0.431), or noise groups (β = −9.14 µm, t= −0.303, p = 0.766): ie, the control and defocus group exhibited a dominant effect on AxL changes, as compared to the other groups. While ChT (secondary measure) confirmed a significant main effect of reading time (AICc = 1973.527, F (1,23.868) = 37.5, p < 0.001), no significant main effect of condition nor reading time by reading condition interaction (F (5,22.274) = 2.003, p = 0.117 was observed.

Eye Changes

For AxL, the analyses of eye changes confirmed the significant effect of reading conditions on eye changes (AICc = 1039.216, F (5,21.937) = 3.633, p < 0.015), showing a predominant axial elongation in the following order: defocus (estimated mean: 13.08 µm ± 2.15 µm), control (estimated mean: 12.94 µm ± 2.15 µm), contrast (estimated mean: 9.205 µm ± 1.644 µm), resolution (estimated mean: 9.0 µm ± 2.48 µm), noise (estimated mean: 7.922 µm ±1.919 µm), crowding (estimated mean: 6.80 µm ± 1.87 µm). In spite of, there were no significant differences between control and defocus (mean difference = −0.135 µm ±2.78 µm, p > 0.1). However, in line with fixed effects describing AxL, significant differences between crowding, yielding the lowest axial elongation, versus control conditions (mean difference = −6.15 µm ± 2.13 µm, p = 0.008) and defocus conditions (mean difference =−6.29 µm ±2.32 µm, p = 0.014) was found. Furthermore, marginal differences were observed between noise and both control (mean difference =−5.02 µm ±2.81µm, p = 0.087) and defocus conditions (mean difference =−5.16 µm ±2.87 µm, p = 0.086).

Significant effect of eye position (F (1,10.811) = 7.609, p = 0.19), with a larger change for the left eyes (11.33 µm ± 1.26 µm), as compared to the right (8.32 µm ± 1.26 µm), but no effect of eye dominance (F (1,12.573) = .209, p = 0.655). No interaction between reading condition and eye position (F (5,21.993) = 1.635, p = 0.192), nor eye dominance (F (5,21.170) = 1.627, p = 0.196), on eye changes was found.

For ChT, the model shows a non-significant effect of reading conditions on ChT changes (F (5,20,234) = 1.185, p = 0.351), which could be indicative of an attenuation of the effect of reading conditions due to the late ChT measurement. The effect of eye position was also only marginal (F (1,9.851) = 3.265, p = 0.101) and no interaction between reading condition and eye position (F (5,20.231) = 0.558, p = 0.731), nor eye dominance (F (1,13.84) = 0.067, p = 0.8) on eye changes was found.

Association Accommodation and Eye Changes

AxL (RE: r(78) = 0.306, p = 0.006, LE: r(78) = 0.228, p = 0.045) and ChT (RE: r(78) = −0.009, p = 0.935, LE: r(78) = −0.213, p = 0.062) changes showed slight positive and negative associations with the degree of myopia, respectively, but this only reached significance for AxL. However, no association was found between the observed eye changes and accommodative changes for AL (RE: r(78) = 0.038, p = 0.739, LE: r(78) = 0.069, p = 0.548) and ChT (RE: r(78) = 0.027, p = 0.813, LE: r(77) = 0.167, p = 0.146).

Results

Both AxL and ChT showed a consistent myopiagenic effect for the near reading task, with systematic axial elongation and choroidal thinning for both eyes on average across visual conditions.

The control and defocus conditions exhibited the strongest myopiagenic effect. The myopiagenic effect of the control is attributable to the 2.00 D dioptric stimulation caused by the near viewing distance settings. Apart from the defocus condition, this myopiagenic effect was reduced under the low visibility conditions, especially for crowding and noise, which indicate a potential countering effect of visibility on myopia. This explanation is further supported by the surprising absence of difference between the control and defocus conditions, given previous observations of a proportional increase in axial elongation with defocus when visibility is not adjusted.[51–53]

This finding suggested that the level and type of visual attenuation did not significantly influence the short-term eye responses. Indeed, a lack of difference between the control and the defocus conditions was unexpected since defocus is known to increase myopiagenic eye changes.[51–53] It was reasoned that the limited difference between defocus and control conditions on eye changes could have been because of the small level of defocus added in the defocus condition (1.57 D ± 0.23 D) or, alternatively, due to a neutralizing effect on lens-induced eye changes of lowering visibility. To test this hypothesis, a second experiment was conducted comparing the effect of lens-induced eye changes under low and normal visibility of reading.

Study 2

Methods

Subjects and Criteria

This phase of the study tested the hypothesis that the myopiagenic effect of hyperopic defocus is reduced when reading is sub-threshold. To test the effect of text visibility on defocus-induced eye changes, the influence of defocus on eye changes was measured under stabilized sub-threshold acuity resolution and supra-threshold acuity resolution in 15 subjects (SER: −3.84 D ± 2.48 D, 19–25 years old, 7 females). The same subject eligibility criteria as in experiment 1 were applied. During all the tests, subjects looked through a −3.00 D spherical power added onto their refractive correction. It resulted in a total dioptric error of about −5.50 D, given the viewing distance of 40 cm. Using the same experimental protocol as in study 1, sub-threshold acuity resolution and supra-threshold acuity resolution were first assessed in a preliminary session, and set to the 70% and 100% of the normalized reading speed, respectively. After determination of threshold, each subject performed the 15-min reading task for both sub-threshold and supra-threshold conditions, with conditions counterbalanced across subjects.

Analysis

A linear mixed model analysis of AxL (or ChT) was performed to test the effect of reading time and conditions, assuming an unstructured variance structure. Reading time, reading conditions, and their interaction were set as fixed factors, and subjects as random effects using the identity covariance structure. To further examine whether the effect of resolution depended on the susceptibility of eye changes to defocus, Pearson correlations between the effect of resolution, estimated as the difference in eye changes between the supra-threshold and sub-threshold conditions (ie AxLsupra - AxLsub), and eye changes were performed.

Results

Strong, significant correlations between the effect of resolution and the amount of eye changes were found (depicted in Figure 5), especially in the right eye. Significant positive correlations between the effect of resolution and supra-threshold-related changes were observed for both AxL (RE: $r(15) = 0.884$, $p < 0.001$, LE: $r(15) = .362$, $p > 0.1$) and ChT (RE: $r(14) = 0.510$, $p < 0.063$, LE: $r(14) = .855$, $p > 0.001$), indicating that subthreshold resolution tended to decrease lens-induced myopic shifts in subjects with high susceptibility to defocused suprathreshold stimulation. In contrast, significant negative correlations between the effect of resolution and subthreshold-related changes were observed for both AxL (RE: $r(15) = −0.722$, $p < 0.002$, LE: $r(15) =−.507$, $p = 0.054$) and ChT (RE: $r(14) = −0.705$, $p = 0.005$, LE: $r(15)=−.510$, $p = 0.52$), indicating an opposite increase in eye changes in subjects with high susceptibility to defocused sub-threshold stimulation.

In contrast, only a slightly smaller axial elongation was observed for the sub-threshold resolution conditions (RE: 14 µm ± .2 µm; LE: 16 µm ± .2 µm), as compared to the supra-threshold resolution conditions (RE: 17 µm ± .2; LE: 18 µm ± .2) with no main effect of reading conditions (AL: AICc = −350.742, $F(1,27.739) = 1.802$, $p = 0.190$; ChT: AICc = 283.171, $F(1,26.982) = 1.033$, $p = 0.318$), eye position (AL: $F(1,14.282) = 0.361$, $p = 0.557$; ChT: $F(1,27.092) = 0.056$, $p = 0.815$), and their interaction (AL: $F(1,27.739) = 0.249$, $p = 0.622$; ChT: $F(1,26.982) = 0.573$, $p = 0.456$) for AxL and ChT, highlighting the subject dependence of the effect of resolution on lens-induced defocus.

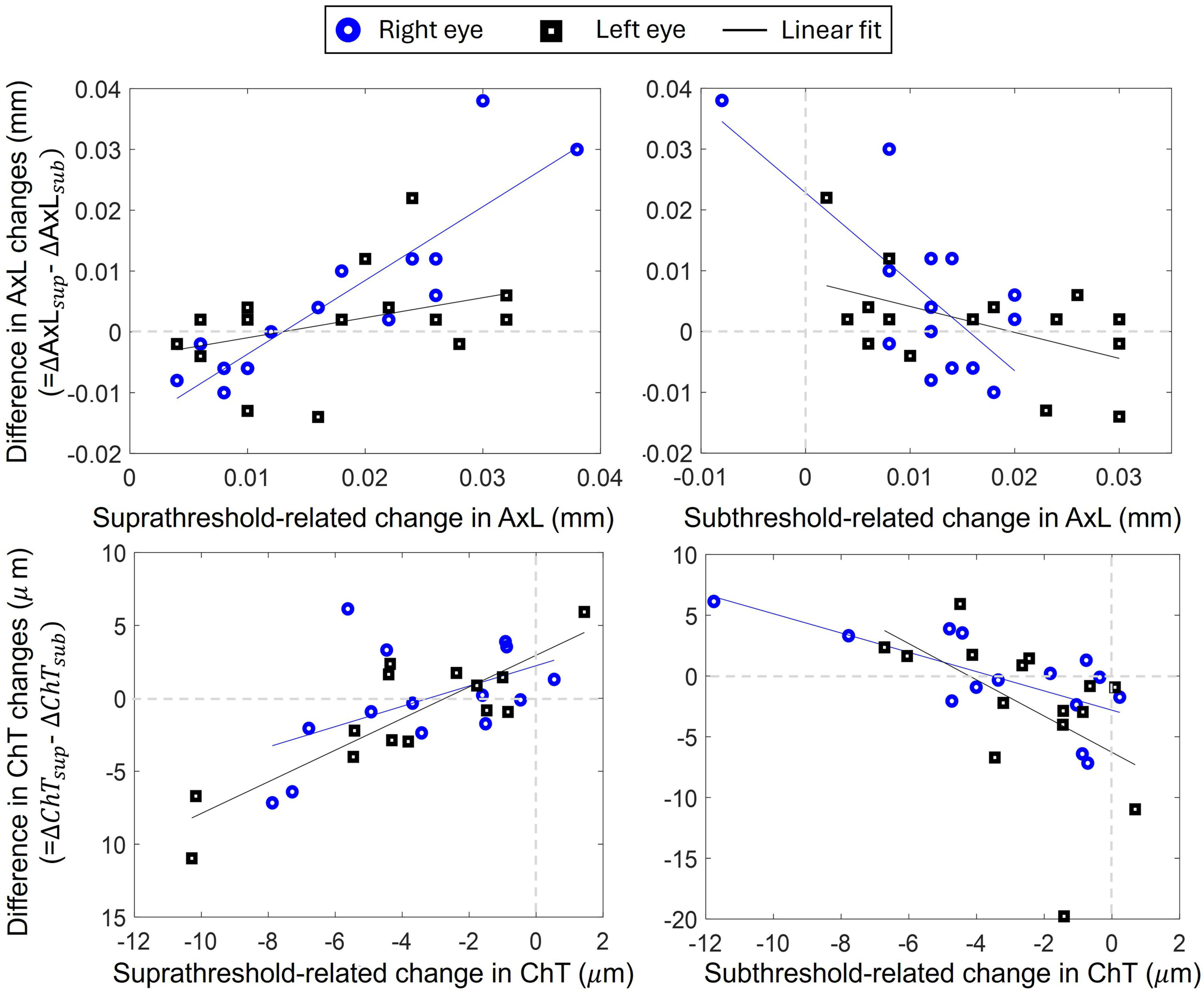

Figure 5 Influence of resolution on susceptibility to defocus of eye changes. Decrease in resolution resulted in reduced lens-induced myopic shifts (ie, axial elongation and choroidal thinning) for subjects exhibiting larger suprathreshold-related myopic changes, and, inversely, for those ones with sub-threshold-related myopic changes.

Discussion

The effect of resolution was subject-dependent. For both AxL and ChT, the same trend was observed: resolution decrease appears to be anti-myopiagenic and myopiagenic, respectively, in subjects prone to larger myopic eye changes under supra-threshold and sub-threshold conditions. It may thus be that the degree of visibility, set by resolution, matters in the development of eye changes in response to defocus. Thus, on average, resolution had a negligible effect on the impact of defocus, highlighting that both low and high resolution could lead to myopic shifts depending on an individual's sensitivity. The results appear to support a mediating effect of visibility on lens induced-myopia, although it may be argued that such mediation is not caused by visibility itself but alterations of the spatial frequency content of the defocused text associated with the manipulation of resolution. Assuming eye elongation effectively relies on the contrast in the high spatial frequency of the image,[18] it would be expected under this claim that purely-frequency-dependent eye elongation should occur rather for the sub-threshold condition (having higher resolution). However, Study 1 showed opposing observations in studies 1 and 2, with diminished eye elongation in the sub-threshold defocus condition compared with the control and supra-threshold defocus conditions, respectively.

General Discussion

Effect of Reading Distance

This is the first study to test the impact of various manipulations of reading visibility on short-term eye changes in the human eye. The findings extend previous studies showing an effect of simulated defocus[24,51–54] by revealing a systematic eye elongation (ie, axial elongation and choroidal thinning) caused by near reading distance. This finding indicates that even the small amount of defocusing introduced by typical screen distance (in this study, equivalent to 2D for experiment 1) could result in a transient myopiagenic effect, which corroborates with the association found between reading distance and amount of reading with myopia.

Differential Effect of Attenuation Forms

In study 1, visual forms of attenuation modulated this effect with stronger eye elongation for defocus, control, resolution, contrast, noise, and crowding, in descending order of strength. Considering the myopiagenic influence of reduced energy in the high spatial frequencies of the image,[18] it was expected that, if visibility did not influence eye changes, defocus and contrast conditions by lowering the contrast in the high spatial frequency would have caused eye elongation, in contrast with the resolution condition, enhancing energy in the high spatial frequency of the image. Interestingly, however, the results revealed no significant difference between control versus defocus, contrast, and resolution, suggesting a potential inhibitory effect of the degree of visibility of the stimulus on eye elongation. Study 2 indicated that such an inhibitory effect of visibility, when controlled via modulation of resolution, was not systematic, but depended on the individual susceptibility to lens-defocus, which could be caused by the mediation of spatial frequency with resolution. Surprisingly, only crowding and noise showed marked eye shortening as compared with the defocus and control conditions. The effect of crowding on eye changes is unexpected as most animal studies did not investigate its influence, because of the low relevance of crowded features in animal eyes. The effect of crowding is unlikely due to an alteration of the high spatial frequency of the image, since crowding tends to affect the global structure of the image more, while conserving (to some extent) local spatial frequencies of individual characters.[55,] It is thus possible that crowding could cause its inhibiting myopic effect on post-retinal processes related to the attentional effort required to individuate crowded characters - an idea that would support the influence of post-neural processing on eye changes. The second, weaker, inhibitory effect came from the zero-mean Gaussian white noise condition. This was unanticipated because it was expected that the degrading effect of noise would exacerbate eye elongation. However, the introduction of noise in the text led to a concomitant darkening of the image background, modulating the contrast polarity of the text. The effect of the noise confirmed the inhibitory effect of polarity[13,14] and suggests that the modulation of the polarity of the noisy text prevailed upon the myopiagenic effect of degradation. Overall, these results suggest that sub-threshold visibility inhibits myopic stimulation, rather than antimyopic stimulation. A possible explanation for this finding is that the lower visibility during reading increased mental effort. In this respect, it was shown that increased cognitive/mental efforts increased sympathetic activity, causing diminished accommodative response.[56] Given the link between eye change and accommodative response, such a decrease in accommodation could explain eye shortening observed under low visibility. However, this hypothesis was not confirmed by the results of the current study, which failed to reveal such a correlation. This failure may be explained by some limitations of this study. First, the impossibility of simultaneous eye measurements may have allowed partial recovery from induced eye changes, dissipating the simulated effect observed for ChT, refraction, and left eye measurement, despite special precautions taken to minimize the time between reading simulation and measurements. Although our observation confirmed a general agreement between AxL and ChT changes,[57–62] the delay could clarify the absence of correlation between AxL changes and accommodative responses, as well as some of the differences observed between AxL versus ChT, and right versus left eyes. Nevertheless, it is important to note that the different responses to visibility properties of AxL, ChT, and accommodative responses cannot be entirely precluded, and the temporal coupling between short-term eye changes and accommodation changes in myopia remains to be determined. Secondly, the subjects in the study included students with varying degrees of refractive errors. As suggested by the observed correlation between refractive errors and eye changes, possible refractive-related differences in the effect of the forms of attenuation could exist between subjects. A third limitation of this study is the very short time spent reading, which might have limited the myopiagenic effect of the task. Although short-term eye changes are known to occur in matters of minutes, the temporal interplay between myopiagenic cues and visibility remains to be determined. Investigations of the effect of longer duration of reading under low visibility are necessary to provide further insight into whether, and how, the perceptual quality of the image affects long-term eye growth with reading.

Conclusion

In conclusion, a novel technique was developed to control the visibility of the stimulation under visual forms of attenuation. This study revealed a systematic myopiagenic effect of near reading, modulable by the visibility of the stimulation under myopiagenic forms of attenuation. Understanding how visibility conditions the myopiagenicity of visual cues may help build new strategies to prevent myopia, involving neural processing.

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Disclosure

The authors report no conflict of interest in this work.

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