

Digital Eye Strain and Repeated Clinical Testing

By

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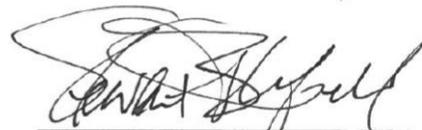
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Abstract

Purpose: The use of digital devices has increased substantially over the past decades across all age groups for educational, career and leisure purposes. Although a high prevalence of Digital Eye Strain (DES) has been well established, especially during the recent pandemic, little is known about the association between repeated clinical testing and DES symptoms. The aim of this study was to determine whether symptoms of DES are associated with repeated measurements of standard clinical near-vision tests.

Method: The study was performed on 30 young, normally-sighted individuals. Each participant completed 3 sessions to test accommodation (monocular facility, push-up amplitude), vergence (near point of convergence (NPC), near heterophoria) and accommodative-vergence interaction (AC/A ratio, binocular accommodative facility). Participants performed a cognitively demanding reading task from a tablet computer positioned at 33cm for 20 minutes. Repeated clinical measurements (3 readings) were taken both before and immediately after the reading task. Additionally, subjects completed a questionnaire regarding ocular and visual symptoms prior to and immediately after the reading period.

Results: While a statistically significant difference between pre- and post-task DES symptom scores was observed ($p < 0.01$), no significant task-induced change in accommodation, vergence and accommodative-vergence measurements were found. Furthermore, there was no significant difference between the three consecutive readings for any of the pre- or post-task clinical parameters.

Conclusion: These results indicate that repeated measurements of standard clinical near-vision tests are not associated with Digital Eye Strain (DES) symptoms. Additionally, no significant difference between the three repeated pre- or post-task measurements was found.

Introduction

Digital Eye Strain

The use of digital devices has increased rapidly in the past decade, and their use for both leisure and vocational use has become ubiquitous. The Vision Council reported in 2016 that nearly 90% of Americans use their devices for at least 2 hours a day, and around 65% of Americans report experiencing digital eye strain (DES).¹ The wide diversity of digital devices nowadays brings with it associated widespread visual and ocular discomfort. Digital Eye Strain, also termed Computer Vision Syndrome (CVS), is a condition of visual and ocular disturbance related to the use of digital screens. Ocular symptoms of DES include tired eyes, tearing, burning sensation, redness, itching and irritation.² Visual discomfort includes difficulty refocusing between viewing distances, headache, eye strain, blurred vision and double vision.³⁻⁵ Chu *et al.* examined DES symptoms after reading identical material from a computer screen or hardcopy and observed that the discomfort following sustained digital screen use was worse than hard copy fixation under similar conditions.⁶ Understanding the physiology underlying DES is important to allow better diagnosis and treatment as well as more efficient task performance while viewing digital screens.

Additionally, the economic impact of DES is extremely high and may lead to substantial financial loss. A study of New York City office workers noted a significant positive correlation between symptom scores and number of hours spent on the computer during the work day, with the most prevalent symptom being tired eyes. Symptoms of tired eyes occurred 'at least half the time' in 40% of subjects followed by 32% reporting dry eye and 31% reporting eye discomfort.⁷ Ocular and visual discomfort contributes to

an increase in the number of errors made during a computer task and require more frequent breaks.³ Additionally, Bohr found that musculoskeletal injuries associated with computer use may account for at least half of all reported work-related injuries in the USA.⁸

The COVID-19 pandemic has led to an increase in home-isolation and social distancing, which caused an uptick in digital device use.^{9,10} As quarantine measures forced people to stay at home, many relied on digital devices for vocational and non-vocational activities. Overall time spent on digital devices since the start of the COVID pandemic was significantly greater than during the pre-quarantine period.¹¹ This increased amount of device use may impact symptoms, task performance and ultimately employment due to reduced visual function and reading efficiency.¹² While the long-term effects of this condition are still unknown and symptoms are usually transient, DES may cause significant and frequent discomfort for digital device users that might result in substantial economic consequences and decreased quality of life.¹³ There is a considerable need to educate the public on effective and ergonomic methods of viewing digital screens to reduce symptoms of eye strain.

Evaluation of Digital Eye Strain

Most evaluations of DES have used subjective questionnaires to determine discomfort while using digital devices. However, objective measures may provide a more accurate indication of ocular and visual symptoms. Additionally, objective measures can allow more precise clinical management when symptoms present in the clinical setting.

DES may manifest as a single symptom or a vague collection of asthenopia-related complaints.^{14,15} As these symptoms can be caused by multiple underlying factors, approaches should be tailored to managing the patient's complaints.³

Symptoms experienced while using digital devices may be associated with changes in the binocular system, particularly variations in accommodative and convergence responses that form two components of the near triad (with the third being pupillary miosis).¹⁶ However, there are limited objective data indicating how these oculomotor parameters change during digital device use and mixed results have been found.

Accommodative abnormalities such as inaccurate responses and/or infacility have been proposed as a potential cause of DES. It is unclear how smartphones and tablets might disturb the flexibility of the accommodative system. The added cognitive demand might adversely affect accommodation, consequently affecting one's ability to make rapid changes in focus.¹⁷ Wick and Morse reported that the lag of accommodation was approximately 0.33D higher when reading from a digital screen compared with printed material¹⁸ while Collier and Rosenfield reported a stable mean lag of approximately 0.93D during a 30-minute laptop-based task. Further, no difference in the mean static accommodative response was seen between the most and least symptomatic groups.¹⁹ Accommodative facility testing, which requires rapid changes in accommodation, seems particularly pertinent to device use, as switching fixation from the screen to other materials or into the distance occurs frequently during real-life tasks. Indeed, Sheedy *et al.* found that poor accommodative facility was the most common diagnosis (20.3%)

among symptomatic computer users.²⁰ However, Rosenfield *et al.* observed no significant change in accommodative facility before and after a 25-minute reading task.²¹

Accommodation of the eye is not stable and is constantly varying by a small amount of up to 0.50 diopters.²² These small variations in the accommodative response to a stationary near target may give insight into the negative feedback system that guides and maintain the response. Microfluctuations are dominated by a low frequency component (LFC) (< 0.6 Hz) and a high frequency component (HFC) ($1.0 \leq \text{HFC} \leq 2.3$ Hz) to allow for accurate accommodative responses to a stimulus.²³ Iwasaki and Kurimoto found that these microfluctuations (0-1.5 Hz) increased significantly after computer work but not after a paper-based task. However, the study did not differentiate between LFC and HFC.²⁴ Gray *et al.* observed overall no significant variation in either LFC or HFC when performing a 20-minute task with five varying displays, including hard copy and liquid crystal display (LCD).²⁵ The study examined the response of asymptomatic individuals. It is possible that examination of microfluctuations in symptomatic subjects may provide objective information on accommodative accuracy and near visual performance.

The ability of the eye to vary its focus, known as ocular accommodation, is critical in adapting to objects at different distances. The accommodative mechanism is controlled by the autonomic innervation to the ciliary smooth muscle, which is mediated principally by the parasympathetic nervous system and supplemented by the sympathetic nervous system.²⁶ The antagonistic actions of the autonomic functions are analogous to the other structures in the body that show a dual nerve supply. Near accommodation reflects the properties of the parasympathetic response, while relaxation of

accommodation reflects the properties of both a reduced parasympathetic and increased sympathetic response.²⁷ The concept of dual innervation relates to the neural control of accommodation based on the visual demands. Malmstrom *et al.* found that the psychological stress due to near tasks involving high cognitive demand can produce hyperopic shifts in accommodation due to increased sympathetic input to the ciliary muscle.²⁸ Gilmartin further suggested that the accommodative demands required for normal near visual tasks are solely under the parasympathetic system, whereas sustained visual tasks necessitating higher visual demands involve both parasympathetic and sympathetic innervation.²⁹ The hyperopic shift in accommodation during intense periods of mental activity coupled with the maintenance of near focus for long periods of time, such as the case with extended digital device use, could be an explanation for eye fatigue that many users experience. As many people are spending a considerable amount of time performing cognitively demanding tasks on digital devices, ocular accommodative abilities are important in providing appropriate focus to maintain a clear retinal image.

Investigations that have examined changes in the vergence response following digital device use have yielded mixed results. For example, one study reported a receded near point of convergence (NPC) after 20 minutes of both smartphone and computer use³⁰ while another did not find a significant change in this parameter over 5 hours of continuous computer use.³¹ Watten *et al.* reported significant reductions in vergence ranges (positive and negative relative convergence) at the end of the working day,³² while other studies have shown no difference in vergence functions resulting from computer use.^{23,34} Interestingly, a short-term drift towards exophoria at near has been reported after digital use.^{30,35} Collier and Rosenfield measured the associated phoria during a period of

sustained fixation on a digital screen and found that DES was significantly worse in subjects with zero fixation disparity when compared to those with exo associated phoria.¹⁹ This suggests that DES may be reduced by creating an exo associated phoria, which might provide a more comfortable oculomotor posture than precise ocular alignment.

Changes in accommodation-vergence interaction from screen use also show variable results. For example, a significant *increase* in binocular accommodative facility was found after digital device use for 25 minutes.²¹ In contrast, Golebiowski *et al.* observed a significant *reduction* in binocular accommodative facility from 11.3 cycles per minute (cpm) to 7.8 cpm post-task.⁵ The small size of some portable screens may require reduced font sizes, leading to closer viewing distances, which increase the demand on both accommodation and vergence, and their interactions with one another.³ Measurements that assess the interaction can be particularly helpful for individuals where tasks may require changes in target distance.

Repetition of clinical testing

One modification that has been suggested in performing clinical near vision tests is repeated testing, with the assumption that symptomatic individuals will show greater recession with repeated testing compared to normals.³⁶ For example, Davis suggested that a breakdown of the near point of convergence (NPC) in individuals with convergence insufficiency would occur at the fifth to sixth repetition, indicating poor convergence reserve.³⁷ Others have also suggested that repetition of clinical tests may provide valuable

information regarding the visual system.^{38,39} However, there is little supporting literature on the effects of repeated testing and how much change with repetition of clinic tests should be considered significant.

The marked increase in the use of digital devices since the start of the COVID-19 pandemic has resulted in increased stress on the visual systems. Bahkir and Grandee showed that since 2019, the average increase in digital device usage was 4.8 hours per day, with an average total screen time per day of 8.65 hours.⁴⁰ The total number of hours of continuous fixation during device use drastically varies from the amount of fixation time that is required to complete a clinical test, which usually spans only a few seconds. Thus, the visual demand exerted when performing each clinical test only once, which is generally the case in clinical practice, may not induce the visual strain that occurs after hours of device use.

Previous research have not found an association between standard clinical testing and DES. However, this may be because most conventional clinical tests are relatively brief, typically requiring fixation for only a few seconds, and so may not accurately reflect the sustained visual demands associated with viewing screens. The purpose of this study is to compare the findings of near vision tests before and after a sustained reading period to determine whether repeated clinical tests of accommodation, vergence or accommodation-vergence interaction are indeed associated with DES. The study also aims to identify which clinical tests best reflect DES symptoms.

Methods

From June 2020 to July 2021, a total of 30 volunteers from the student body at the SUNY College of Optometry between 22 to 29 years old (mean \pm standard deviation of 24.2 ± 1.81 years) were enrolled in this study. All participants had distance visual acuity of logMAR 0.0 or better in each eye and binocularly. Exclusion criteria included a history of refractive surgery, diagnosis of ocular pathology, strabismus, accommodative or vergence dysfunction. Dysfunction was defined as an amplitude of accommodation less than the minimum required as calculated from Hofstetter's equation ($15 - 0.25 * \text{age}$ in years), monocular accommodative facility less than 5.5 cycles per minute, binocular accommodative facility less than 4 cycles per minute, NPC break point greater than 10cm, near heterophoria greater than 6Δ esophoria or 12Δ exophoria, or a stimulus AC/A ratio less than 2:1. All participants were provided with information regarding the nature of the study and gave written informed consent prior to participation. This research protocol was approved by the Institutional Review Board (IRB) at the SUNY College of Optometry and conducted in accordance with the Declaration of Helsinki.

Subjects were tested on three separate occasions. Accommodation, vergence, or accommodation-vergence interaction was assessed both before and immediately after a sustained 20-minute reading period. Each of the 3 sessions were scheduled at least 24 hours apart, and no more than 21 days was allowed between the 3 sessions. The order of the 3 sessions were counterbalanced using a Latin square design. The order of the 2 standard clinical tests within each session were counterbalanced across subjects. All monocular testing was measured using the right eye. The following tests were performed

for the respective sessions. All tests were illuminated with a local overhead incandescent lamp in addition to the ambient florescent lighting.

1. Accommodation: (i) Monocular accommodative facility for 1 minute using $\pm 2.00\text{D}$ flippers while fixating a 20/30 target on the Game card (Good-Lite “GAME” near visual acuity chart, NO. 926000) at a viewing distance of 40cm. An occluder was used to cover the left eye. Subjects were asked to view a single 20/30 word and ensure that the word was clear prior to the test. A $\pm 2.00\text{D}$ lens was placed in front of the eye and the subject reported each time the word became clear through the lens. At that point, the experimenter flipped to the alternate signed lens. $\pm 2.00\text{D}$ lenses were alternated for 1 minute. (ii) Push-up amplitude in free space using a 20/20 target on the Game card. An occluder was placed in front of the left eye. The subject was asked to hold the card at eye level 40cm away while focusing on a single 20/20 sized word, and slowly move the card towards their right eye until the target just became blurry, as defined by the edges of the target appearing out-of-focus. A millimeter ruler was then used to measure the distance between the card and the front of the subject’s eye. This measurement was then converted to diopters.
2. Vergence: (i) Near point of convergence (NPC) using a pen tip. The subject was asked to focus on a single pen tip that was slowly moved towards the subject. The break point was recorded when the patient either reported diplopia or if one eye was seen to lose fixation. The pen tip was then slowly moved away from the subject. The recovery point was recorded when the

subject either reported that the pin tip was single again (if diplopia was noted previously) or when binocular fixation was regained. Both values were measured from the outer canthus of the eye to the pen tip with a ruler. If the pen tip approached the subject's nose and no break was reported or loss of fixation was seen, NPC was recorded as to the nose (TTN). When this occurred, values of 3cm and 5cm were used for the break and recovery measurements, respectively. (ii) Modified Thorington (MT). A Maddox rod (MR) was placed in the horizontal position in front of the right eye. A calibrated MT card was held at 40cm while a transilluminator light was shone through the central hole in the card. The patient was asked to maintain a clear view of the numbers on the MT card and report the location of the vertical red Maddox streak relative to the white light. If the white light and red line were aligned, the subject had no horizontal heterophoria. If the red line was to the left of the white light, the subject was exophoric. If the red line was to the right of the white light, the subject was esophoric. If heterophoria was indicated, then the subject reported the number on the MT card that the red line appeared to cross. This corresponded to the magnitude of the oculomotor deviation in prism diopters.

3. Accommodation-vergence interaction: (i) Binocular accommodative facility for 1 minute using ± 2.00 flippers as the subject fixated on a 20/30 word on the Game card at a viewing distance of 40cm. A pen tip was placed at 20cm as a suppression check. $\pm 2.00D$ lens was placed in front of the eyes and the subject reported each time the word became clear through the lens. The \pm

2.00D lenses were alternated for 1 minute. Suppression was indicated if the subject reported seeing a single pen tip at any point, and the test was terminated. (ii) AC/A ratio with MT using the phoropter at 40cm. A horizontal MR was positioned in front of the right eye and a calibrated MT card was presented at 40cm. A transilluminator was shone through the central hole in the card. The patient was asked to report the location of the vertical red line relative to the white light and to maintain a clear view of the numbers on the MT card. If the white light and red line were aligned, the patient had no horizontal heterophoria. If the red line was to the left of the white light, the subject was exophoric. If the red line was to the right of the white light, the subject was esophoric. If heterophoria was indicated, then the subject reported the number on the MT card that the red line crosses. The procedure was repeated with $\pm 1.00D$ lenses in front of both eyes in the phoropter. The AC/A ratio was calculated by taking the average of the difference between the measured near heterophorias.

At the initial evaluation, baseline measurements of monocular and binocular VA, monocular push-up amplitude, monocular and binocular accommodative facility, NPC, MT and AC/A ratio were taken to establish eligibility. During each session, the two relevant clinical tests were performed 3 times before the reading task. Subjects were then asked to read aloud a sequence of randomized words on an iPad mini tablet computer (Model number MD529LL/A, Apple, Inc., Cupertino, CA) at a viewing distance of 33cm for a continuous 20-minute period. The screen measured 20.3cm x 13.5cm. The text was

single-spaced, black-on-white, Times New Roman 12-point font. Participants were allowed to scroll through the text as needed using a single finger. A chin rest was used to ensure the participants maintained the 33cm viewing distance for the 20-minute reading period. Immediately after the reading task, the 2 clinical tests (i.e., either the accommodation, vergence or accommodation-vergence interaction tests) were repeated in the same order three separate times. Before and immediately after the reading task, subjects completed a symptom questionnaire (shown overleaf) regarding visual and ocular symptoms experienced over the past 30 minutes. Each symptom was rated on a scale from 0 (none) to 10 (very severe). The total symptom score was calculated to provide a score between 0 to 100.

Subject name.....

Condition.....

Pre-task SURVEY

Please indicate if you have experienced any of the following symptoms within the **past 30 minutes**. If no, please circle zero for each question. If yes, then please rate the intensity of the symptom on a scale from 1 (very mild) to 10 (very severe), with 5 being a moderate response.

Blurred vision when viewing text up close	0 1 2 3 4 5 6 7 8 9 10
Blurred vision when looking into the distance after reading	0 1 2 3 4 5 6 7 8 9 10
Difficulty or slowness in refocusing my eyes from one distance to another.	0 1 2 3 4 5 6 7 8 9 10
Irritated or burning eyes	0 1 2 3 4 5 6 7 8 9 10
Dry eyes	0 1 2 3 4 5 6 7 8 9 10
Eyestrain	0 1 2 3 4 5 6 7 8 9 10
Headache	0 1 2 3 4 5 6 7 8 9 10
Tired eyes	0 1 2 3 4 5 6 7 8 9 10
Sensitivity to bright lights	0 1 2 3 4 5 6 7 8 9 10
Discomfort in your eyes.	0 1 2 3 4 5 6 7 8 9 10

Post-task SURVEY

During the task you just completed, did you experience any of the following? If no, please circle zero for each question. If yes, then please rate the intensity of the symptom on a scale from 1 (very mild) to 10 (very severe), with 5 being a moderate response.

Blurred vision when viewing text up close	0 1 2 3 4 5 6 7 8 9 10
Blurred vision when looking into the distance after reading	0 1 2 3 4 5 6 7 8 9 10
Difficulty or slowness in refocusing my eyes from one distance to another.	0 1 2 3 4 5 6 7 8 9 10
Irritated or burning eyes	0 1 2 3 4 5 6 7 8 9 10
Dry eyes	0 1 2 3 4 5 6 7 8 9 10
Eyestrain	0 1 2 3 4 5 6 7 8 9 10
Headache	0 1 2 3 4 5 6 7 8 9 10
Tired eyes	0 1 2 3 4 5 6 7 8 9 10
Sensitivity to bright lights	0 1 2 3 4 5 6 7 8 9 10
Discomfort in your eyes.	0 1 2 3 4 5 6 7 8 9 10

Results

Thirty subjects (22 females, 8 males) participated in the study, all of whom were drawn from the student body at the SUNY College of Optometry. Their mean age was 24.2 years (range = 22 to 29 years; sd =1.81). All had distance and near visual acuity of logMAR 0.0 or better in each eye and binocularly, with no strabismus or manifest ocular disease (based on their self-reported history). All subjects provided written consent following a full explanation of the experimental procedures prior to their participation. The experimental protocol was conducted in accordance with the Declaration of Helsinki, and was approved by the Institutional Review Board at the SUNY College of Optometry.

The mean (\pm SD) pre-task total symptom scores for the accommodation, vergence and accommodation-vergence trials were 7.83 (8.89), 6.17 (6.65) and 8.23 (8.78), respectively. One-factor analysis of variance indicated no significant difference between these values ($F = 0.54$; $df=2,89$; $p = 0.58$).

The average pre- and post-task values for each accommodation, vergence and accommodation-vergence clinical test are shown in Table 1. No significant changes were observed between the pre- and post-task findings for any of the clinical tests.

Table 1a. Mean pre- and post-task accommodation findings. Figures in parentheses indicate 1 standard deviation (SD). D = diopters. cpm = cycles per minute.

	Push-up amplitude (D)	Monocular accommodative facility (cpm)
Pre-task	8.58 (0.33)	14.1 (0.89)
Post-task	8.32 (0.39)	14.2 (0.87)
P-value	0.46	0.92

Table 1b. Mean pre- and post-task vergence findings. Figures in parentheses indicate 1 standard deviation (SD). A negative heterophoria value indicated exophoria. cm = centimeters. Δ = prism diopters.

	NPC Break (cm)	NPC Recovery (cm)	Near heterophoria (Δ)
Pre-task	5.71 (0.46)	8.28 (0.44)	-2.96 (0.72)
Post-task	6.62 (0.47)	9.05 (0.52)	-2.57 (0.92)
P-value	0.21	0.35	0.74

Table 1c. Mean pre- and post-task accommodative-vergence interaction findings. Figures in parentheses indicate 1 standard deviation (SD). Δ/D = prism diopters per diopter. cpm = cycles per minute.

	AC/A (Δ/D)	Binocular facility (cpm)
Pre-task	2.14 (0.57)	10.76 (0.85)
Post-task	2.31 (0.58)	11.08 (0.98)
P-value	0.52	0.71

Table 2 and Figure 1 indicate the mean total symptom scores before and immediately after the three sessions. The difference in mean pre- and post-task symptom scores were statistically significant for all 3 conditions ($p < 0.01$). Two-factor analysis of variance compared the effects of time (i.e., pre- versus post-task) and conditions (i.e., accommodation versus vergence versus accommodative-vergence interaction). The analysis demonstrated that the effects of time ($F = 44.91$; $F_{crit} = 3.90$ $p < 0.01$) were statistically significant. The effects of conditions ($F = 0.38$; $F_{crit} = 3.05$; $p = 0.69$), and the

interaction of time with conditions ($F = 0.35$; $F_{crit} = 3.05$; $p = 0.70$) were not statistically significant.

Three pre-and post-task readings were recorded for each parameter. To assess the degree of variation amongst the three measurements, the standard deviation of the measurements was calculated, and these are shown in Table 3. These findings indicated that the greatest variation across the three readings was seen for the near point of convergence (NPC) and near heterophoria (Modified Thorington) techniques. A one-factor analysis of variance examining the pre- and post-task values of these parameters revealed no significant difference between the three consecutive readings for each test. This is shown in Table 4.

Table 2. Mean pre- and post-task symptom scores for the three trials. Figures in parentheses indicate 1 standard deviation (SD).

Trial	Accommodation	Vergence	Accommodation-Vergence
Pre-task	7.83 (8.89)	6.17 (6.65)	8.23 (8.78)
Post-task	17.57 (14.96)	19.4 (15.21)	20.47 (13.13)
P-value	< 0.01	< 0.01	< 0.01

Figure 1. Change in pre- and post-task symptom scores for accommodation, vergence, and accommodative-vergence conditions. The lower and upper boundary of each box represents the first (25th percentile) and third (75th percentile) quartile, respectively. The line within each box represents the median, also known as the second (50th percentile) quartile. The “x” depicts the mean value. The upper and lower limit of the whisker illustrates the maximum and minimum value, respectively.

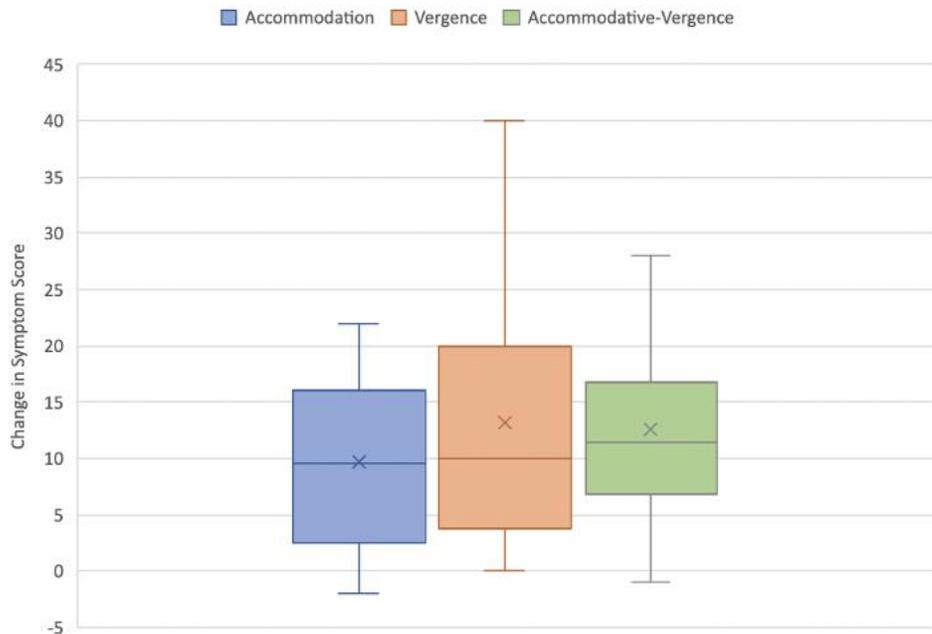


Table 3: Standard deviation of the three consecutive readings.

	Push up Pre-Task (D)	Push up Post-Task (D)	Monocular facility Pre-Task (cpm)	Monocular facility Post-Task (cpm)
SD of the 3 consecutive measurements	0.27	0.30	0.37	0.37

	NPC Break Pre-Task (cm)	NPC Break Post-Task (cm)	NPC Recovery Pre-Task (cm)	NPC Recovery Post-Task (cm)	Near heterophoria Pre-Task (Δ)	Near heterophoria Post-Task (Δ)
SD of the 3 consecutive measurements	0.34	0.39	0.45	0.46	0.49	0.90

	AC/A Pre-Task (Δ /D)	AC/A Post-Task (Δ /D)	Binocular facility Pre-Task (cpm)	Binocular facility Post-Task (cpm)
SD of the 3 consecutive measurements	0.35	0.51	0.26	0.37

Table 4. One-factor analysis of variance for the three consecutive measurements of NPC and near heterophoria. No significant difference was found across the three readings.

Parameter	F	Degrees of Freedom	p-value
NPC Break (Pre-Task)	0.04	2, 89	0.96
NPC Break (Post-Task)	0.005	2, 89	0.99
Near heterophoria (Pre-Task)	0.27	2, 89	0.77
Near heterophoria (Post-Task)	0.14	2, 89	0.87

Discussion

The results of the present investigation showed no significant change in near clinical vision tests following a sustained reading task that produced a significant increase in DES symptoms. Additionally, no significant difference was found across the three consecutive measurements for each clinical test. Therefore, these findings do not support the concept that post-task evaluation with near clinical tests of accommodation, vergence, or accommodation-vergence interaction, or repetition of these tests, can be used as a measurement of DES.

The relevance of components of accommodation in relation to DES has been disputed in the literature. The vast majority of studies (including the present investigation) of accommodative changes following electronic device use have been conducted on young, adult subjects as opposed to older, presbyopic individuals. However, those with presbyopia may encounter additional visual stress, especially when uncorrected, due to the age-related loss of accommodation that is generally necessary to maintain a clear retinal image at near. Some studies have demonstrated an increased lag of accommodation when viewing electronic devices compared to hard copy.^{41,42} Conversely, others found no change in accommodation during electronic device use.^{19,43} One possible explanation for the variability in accommodative findings with digital device use may be that a lag or lead of accommodation may go unnoticed due to the physiological depth of focus. As long as the accommodative error is smaller than the depth-of-focus, then it is unlikely to be perceived by the observer. The different methods of quantifying accommodation utilized in the studies present varying sensitivity to accommodative changes. It has also been suggested that reduced accommodative facility,

i.e., the ability to make rapid and accurate changes in accommodation, may lead to vision-related symptoms of DES.⁴⁴ However, Rosenfield *et al.* observed no relationship observed between symptoms and either monocular or binocular accommodative facility.²¹ The findings of the present study are consistent with the latter investigation, namely that clinical accommodative facility tests do not have an association with symptoms of DES.

Gall and Wick demonstrated that in those individuals with symptoms of binocular vision abnormalities but normal distance and near heterophoria, vergence facility was significantly reduced compared with those who were asymptomatic.⁴⁵ Additionally, Christenson and Winkelstein showed that vergence facility was significantly improved in athletes compared to nonathletes.⁴⁶ These studies indicate that increased visual performance and lower symptom scores are associated with higher levels of vergence facility. The present study found that vergence findings yielded the largest changes following a reading task. However, a significant difference in clinical vergence parameters was not recorded here. The present investigation did not include vergence facility, and it is possible that this test may provide a possible indicator of vergence changes following sustained device use.

Wee *et al.* reported that the NPC was significantly reduced, and symptoms of DES were significantly increased after viewing the same 3-D displays for 30 minutes.⁴⁷ Though the NPC findings in the current study indicated receded findings after the 20-minute reading task, the observed changes were not significant. One explanation of why Wee *et al.* observed significant changes in NPC while the current study's findings were not significant may have been the longer task duration (30 minutes compared to the 20-minute task adopted here). Another difference might be the increased vergence demand

of the sustained 3-D display compared to the 1-dimensional display adopted in this study, which presumably placed less stress on the visual system.

A reduction in either blink rate or completeness of blinks are thought to be possible causes of DES. Patel *et al.* found a five-fold reduction in mean blink rate from 18.4 blinks/minute to 3.6 blinks/minute prior to and during digital device use, respectively.⁴⁸ A relationship was also demonstrated between the stability of the pre-corneal tear film and the interval between blinks. Portello *et al.* showed that blink characteristics were correlated with symptoms of digital eye strain, with an increase in symptom scores as the blink rate decreased and blinks became less complete.⁴⁹ Additionally, Jansen *et al.* examined blink parameters and tear film stability with and without contact lens wear.⁵⁰ The study demonstrated that during tasks requiring high levels of concentration without contact lens wear, the interblink interval increased (blink rate decreased) and many blinks were incomplete. Tear film instability increased with contact lens wear and further affected the blink rate and interblink interval, which was associated with increased symptoms of ocular irritation. In the present study, a significant increase in DES symptoms were found after the sustained reading task, but no correlation was found with the clinical near vision procedures tested. It is possible that one factor causing the increase in DES symptoms may be the change in the rate and completeness of blinks. Subjects who wore contact lenses may have noted increased symptoms due to the effects of the contact lenses inducing ocular discomfort during the reading task. It should also be noted that subjects wore the same correction, and in the case of contact lens wearers the same habitual lenses, for all trials. However, blink parameters were not examined in the current study.

Limitations of the present study include the need for self-reporting of ocular conditions as an exclusion criterion. Subjects may not have been fully aware of their ocular health or binocular status prior to enrolling in the study. Although a screening was performed before the first session to ensure that the clinical procedures to be performed had findings within the normal range, we did not perform a comprehensive eye examination to rule out all possible exclusion criteria. Additionally, the three trials were performed at different times of the day, which may have impacted clinical testing and symptom scores due to possible increased symptoms of fatigue towards the end of the day. Given that there was no significant difference between the three pre-task symptom scores, this would suggest that the initial levels of fatigue were similar for each trial.

As mentioned in the introduction, Davis suggested that a breakdown of NPC would occur at the fifth to sixth repetition for those with poor convergence reserve.³⁷ In the current study, repetition of each test was only performed three times, which may not have been sufficient to observe fatigue for clinically significant changes. Additional repetition of clinical tests beyond the three cycles may be required to note differences in measurements. However, this may not be viable clinically due to the prolonged time required (especially if multiple tests need to be repeated five or more times). Finally, subjects were required to wear their full corrective prescription for the distance and maintain consistency in their method of correction throughout the three trials. It is well established that contact lens wear can induce symptoms of discomfort and dryness, especially at the end of the lens wearing day.^{49,51} Since these symptoms resemble the discomfort experienced in DES, it is likely that contact lens wearers may report greater symptom change compared to those who wore spectacles. However, only five of the 30

subjects were contact lens wearers, and so this subgroup was too small for separate analysis.

Future research may examine differences in the form of the refractive correction, such as the effects of wearing contact lenses compared with spectacles, or post-refractive surgery patients. Other objective measures to consider may include vergence facility and assessment of the accommodative response. Similar clinical parameters to those adopted in the present investigation might be used with tasks having greater visual demand or longer duration. DES is an emerging public health issue related to the increased usage of digital technology. As the general population continues to move towards even greater use of electronic devices, it is likely that visual demands will continue to rise. This may pose substantial lifestyle difficulties for many individuals who suffer from DES. Objective measures to quantify the severity of DES is vital to allow proper evaluation of the condition, not only for clinical diagnosis and interventions but also for early detection and possible preventive modalities.

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