Article • Comparison of Accommodative Responses to e-Ink vs. LCD vs. Standard Ink on Hard Copy

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ABSTRACT

Background: Adverse visual symptoms with electronic devices have been reported, but causes have yet to be clearly defined. Previous studies have neither equated stimulus luminance across devices nor studied subjects with verified normal accommodation prior to testing. Pupil size during device use also has not been explored. We compared pupil sizes and accommodative responses to targets of similar size displayed with ink on paper, an e-ink reader, and an LCD device in young, healthy adults with normal accommodation.

Methods: Subjects were 42 healthy adults, aged 22 to 33 years, with near acuity 20/20 (6/6) or better in the tested eye. Normal accommodation was verified with accommodative amplitude and facility (+/-2.00 flippers) tests. The reading text was presented at 40 cm, and text size and device luminance were matched across devices. While the subject read the passage aloud, pupil size was measured. Accommodative responses were obtained twice with near retinoscopy and twice with an open-field autorefractor for each device.

Results: One-way ANOVA for correlated samples and Tukey's HSD test were used to compare mean pupil size and mean accommodative response across devices. The differences in mean pupil size for paper versus e-ink (5.1 ± 0.9 vs. 5.5 ± 0.8, $p<0.01$) and LCD versus e-ink (5.1 ± 0.9 vs 5.5 ± 0.8, $p<0.01$) were significant. By retinoscopy, the difference in mean accommodative response was significant only for e-ink and LCD (1.48 ± 0.76 D vs. 1.78 ± 1.26 D, $p<0.01$). By autorefraction, no significant differences in mean accommodative response were found across device type. Linear regression showed that accommodative response was not predicted by pupil size for any of the devices.

Conclusions: In this group of young adults with normal accommodation, accommodative response was not significantly different for ink on paper, e-ink, or LCD devices of matched luminance. Pupil size did not predict accommodative response for any device.

Keywords: accommodation, electronic device, e-reader, MEM retinoscopy open-field autorefraction

Introduction

Electronic devices used for reading and other near tasks have been associated with adverse visual symptoms, such as tired eyes, eyestrain, and dry eyes.[1-4] Whether these symptoms result from changes in visual responses instigated by properties of the devices themselves or whether work demands and interest in the vast array of digital content available have simply increased the amount of time spent on near tasks is uncertain.

Several studies have attempted to investigate whether digital display use is correlated with clinical evidence of reduced visual function.[2-6] For example, in their study of 76 video display terminal (VDT) users who averaged almost 7 hours per day of computer use, Shrestha et al. found accommodative infacility to be the most common functional problem identified (+/-2.00 D binocular flippers at 40 cm, target size equivalent to N8, diagnostic criterion set at 10 cycles/minute).[2] Given that the test was administered binocularly, whether vergence dysfunction contributed to the reduced test results is unknown. Their subjects, whose mean age was 28.5 ± 5 years, were recruited from a population of patients presenting to a clinic specifically seeking eye and vision care; therefore, the results of the study may not be representative of the responses that would be obtained from a randomly sampled population. With respect to other factors that can contribute to computer vision syndrome, Shrestha et al.[2] acknowledged the roles of ergonomics: furniture used, presence of glare, temperature, humidity, location of VDT, task performed, and undiagnosed or untreated vision problems; however, neither these factors nor the parameters of the VDTs used by their subjects were assessed in the study and are unlikely to have been uniform across their subject population. Finally, whether the accommodative infacility identified in their subjects would lead to similar symptoms with the same duration of near work using hard copy is unknown.

In two well-controlled studies that examined the effects of VDT use on visual functions in new users of VDTs in a single office, Yeow et al. found a slightly greater reduction in near point of accommodation over two years for the VDT users compared to non-VDT users.[5,6] Their study involved repeated testing every three months, used a site where all VDT users worked with the same type of terminal, and controlled for subject age. Additionally, their control group consisted of subjects who worked in the same office environment and did similar work tasks as the experimental group but who did not use a VDT during their workday. The VDT terminals used by the subjects in the study were an older type of technology (phosphor P31, producing greenish characters on a greyish background) than used for most digital displays in this century (LCD, e-ink, etc.), and the VDT users spent at least 50 percent of their workday viewing the terminal. Not reported by the authors is whether the presence of accommodative or vergence dysfunction was an exclusion criterion for participation; additionally, no data were collected while the subjects viewed the VDTs.

While desktop terminals are still widely used today, hand-held digital devices of varying sizes have become ubiquitous in daily work and leisure life. In 2014, Hue et al. compared reading from electronic devices versus hard-copy text and found that reading rate was slower and accommodative lag was larger for the iPod electronic device than for the hard-copy text, whereas visual symptoms were greater for the Kindle electronic device than for the hard-copy text.[7] A direct comparison of the two electronic devices on the same group of subjects was not made. Interestingly, the accommodative assessment, done with an infrared optometer, showed no significant change in response over the 12-minute reading time for any of the conditions tested. The report states that the targets were matched for contrast (80%) and viewed under the same ambient illumination, but no information was given about whether the target luminance values were similar. As with many previous studies on visual function and digital device use, the subjects were not screened for accommodative and vergence disorders or for dry eye prior to enrollment.

Benedetto et al. explored the effects of display technology on objective (number of eye blinks per second) and subjective (Visual Fatigue Scale score) indicators of visual fatigue.[1] Their twelve pre-presbyopic subjects participated in three separate prolonged (70-minute) reading sessions, using a device with a different display technology (LCD vs. e-ink vs. hard copy) at each session. Viewing distance was 60 cm; displays were equated for page size, font size, typeface, and number of words per page; and all sessions took place in a controlled and standardized room. Visual Fatigue Scale score was evaluated before and after the reading sessions, whereas the blink rate was evaluated during the reading sessions. Their results showed a significant increase in the mean of the before- versus after-reading session Visual Fatigue Scale score for the LCD device only. With respect to blink rate, analysis showed a significantly lower mean blink rate while using the LCD device compared to the e-ink and hard-copy devices, but no significant difference in the mean blink rate was found between the e-ink and hard-copy devices. Due to the differences in luminance across the devices, the researchers compared the tonic pupil size during reading with each of the devices. They found that the mean pupil size during reading with the LCD device was significantly smaller than when reading with either of the other two devices. Thus, the effects of the smaller pupil (e.g., increased depth of focus) created by the higher luminance on the LCD compared to the other two devices used in this study could have contributed to the differences found in their subjects. Accommodative responses were not measured, closer reading distances were not evaluated, and their subjects were not screened for accommodative and vergence disorders or for dry eye.

Another study compared results of a symptom survey and measures of adopted reading distance while subjects read for an hour using either a back-lit LED device (experimental group) or hard copy (control group). The experimental group manifested significantly greater scores for eyestrain and irritation than did the control group.[8] Since the mean adopted reading distance between the two groups did not differ, this factor could not explain the difference in eye strain and irritation between the two groups. Again, the subjects, while having normal near vision, were not screened for accommodative and vergence disorders, nor was a cross-over design used to determine whether similar results would occur if the groups switched reading devices. Additionally, no information was given relative to the equivalence of the luminance or the contrast of the targets for the two devices.

Table 1. Subject Inclusion Criteria

20/20 or better visual acuity at near (40 cm) in the tested eye
No strabismus, amblyopia, ocular disease affecting crystalline lens anatomy or function, or other ocular disease in the tested eye
No current or recent (within 30 days of testing) use of medications known to affect accommodation or otherwise cause blurred vision
Not over-minused with habitual correction to avoid confounding of the accommodative response data (see text for details)
Normal accommodation: verified with measurement of monocular accommodative facility (+2.00/-2.00D lens flipper test, at least 11 cpm in test eye) and amplitude of accommodation (push-up to blur value at least 15 – 0.25(age in years) diopters) in the test eye

The present study was initiated specifically to evaluate the accommodative response and pupil size to targets created with different display technologies in young, healthy adults. To the extent possible, given the devices and the technology available to us for the study, we equated the stimuli across the devices for size and luminance and controlled for accommodative disorders by screening subjects for accommodative dysfunction prior to enrollment.

Methods

Subjects

After receiving study approval from the Institutional Review Board at the Southern College of Optometry and obtaining the participants' informed consent, 42 adults between the ages of 22 and 33 years, inclusive, who met the inclusion criteria outlined in Table 1 were recruited for this study. In order to ensure that subjects were not overminused with the correction to be used during the study, subjects were seated 6 meters from a high-contrast Snellen chart displayed on an LCD monitor. Monocular distance acuity was assessed in each eye with the subject's current spectacle or contact lens prescription. If the monocular introduction of +0.50 D sph in front of the test eye did not degrade visual acuity by

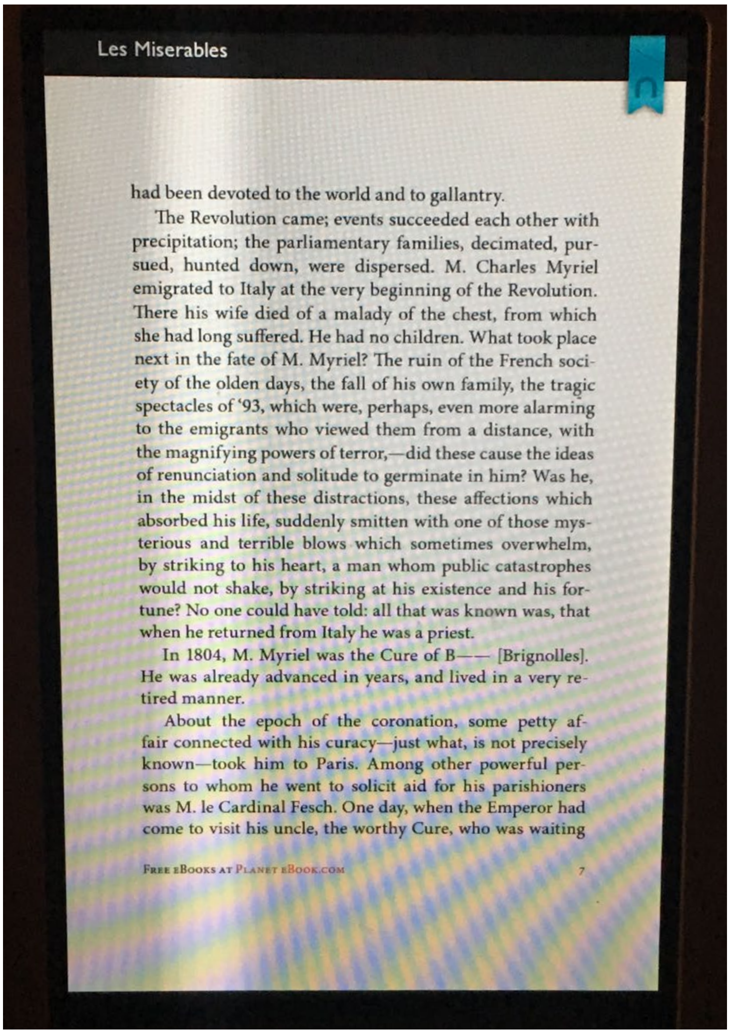

Figure 1. *Nook Tablet e-reader, 7" screen, LCD*

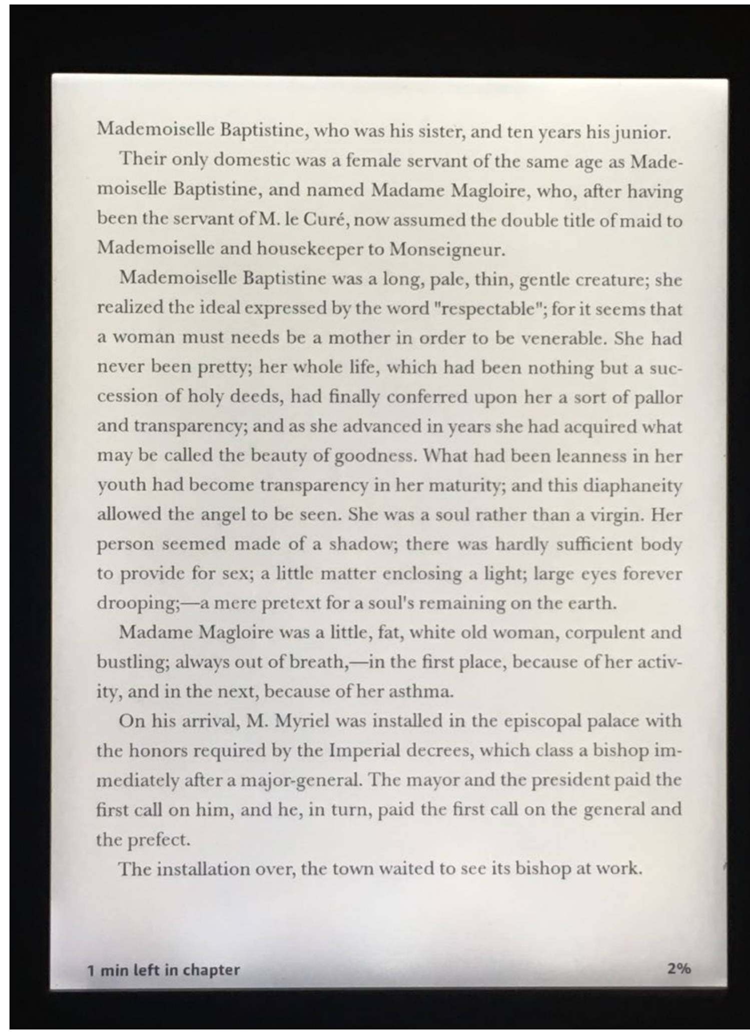

Figure 2. *Kindle Paperwhite e-reader, 6" screen, e-ink*

at least 1 letter, the subject was considered overminused and was not included in the study. If the subject could tolerate +0.25 D over-refraction without a loss of any letters of acuity at distance, s/he was included in the study, and the +0.25 D over-correction was compensated by adjusting the accommodative demand for that subject from 2.50 D (test distance) to 2.75 D determining the accommodative response.

Apparatus

Static accommodative responses were obtained via two methods.

1. Modified MEM (Monocular Estimate Method) retinoscopy:
   With the current spectacle or contact lens correction in place, the subject monocularly fixated the reading device in the plane of the retinoscope positioned 40 cm from the subject, at a viewing angle of approximately 90 degrees. This was a modification from the typical procedure for MEM, where the patient keeps both eyes open. The examiner observed the retinoscopic reflex and, in order to measure the dioptric distance between the device location and reflex neutrality, briefly introduced a +0.25 D or -0.25 D spherical trial lens (depending on whether the initially observed reflex motion was with or against) in front of one of the subject's eyes while the subject read aloud from the reading device. If a neutral reflex was not immediately observed, the trial lens was removed, the reflex with no lens was observed again, and the lens power was incremented by 0.25 D in the appropriate direction and briefly introduced to observe its effect on the reflex. The lens

power that first produced a neutral reflex when briefly introduced was identified, and the dioptric difference between the test distance and the lens required for reflex neutralization was recorded as the accommodative response.

2. Autorefraction at distance and near with an open-field autorefractor (Grand Seiko, 5100K):
   Distance autorefraction with the subject's current spectacle or contact lens correction in place was measured while the subject viewed a line of 20/20 (6/6) letters displayed on an LCD monitor at a distance of 6 m. Autorefraction was repeated while the subject read aloud from the reading device presented at a distance of 40 cm using the near-point rod attached to the autorefractor, creating a viewing angle of approximately 90 degrees. The dioptric difference between the spherical component of the distance and near refractions was recorded as the accommodative response.

Stimuli

Accommodative responses were recorded while subjects read from each of three different devices:

1. Nook Tablet e-reader (backlit LCD 7-inch screen, Figure 1)
2. Kindle Paperwhite e-reader (e-ink, 6-inch screen, Figure 2)
3. Paper (black print on white background, 4.5-inch width, 5.5-inch height)
   The reading passage, from *Les Misérables* (English), was the same for all devices. Text size (approximately 0.75 M), font type, and device luminance (90-100 cd/m^2) were matched across devices prior to each data collection session, and, when necessary, an additional lamp was used to increase the luminance in order to ensure approximately equivalent luminance among all devices. All reading devices were viewed under standard room lighting (fluorescent, approximately 270 lux) during both measurement methods. Contrast, although not measured, was set to the highest value on each device and was well above threshold for all three stimuli.

Experimental Design and Procedures

Subjects were asked to avoid reading and other near tasks for at least 15 minutes prior to the data collection session. After verifying eligibility and obtaining informed consent, a web-based random number generator was used to determine the test eye and to determine the order of devices for each subject. The non-tested eye was occluded with a black patch, and each subject wore his/her habitual vision correction during testing. The subject first underwent two measurements of accommodative response by modified MEM retinoscopy on all three devices, then underwent two measurements of accommodative response by autorefraction on all three devices. Since all data were collected by a single examiner, the modified MEM was done first to avoid influence of knowledge of the accommodative response by autorefraction on the modified MEM measurement. Since Hue et al. found no significant change in accommodative response during continuous reading for 12 minutes with any of the devices that they tested, we elected to have subjects read from the devices just long enough to record the accommodative responses.

Pupil size was measured with a millimeter ruler: the examiner matched, by gross observation, the subject's pupil size to the half moon on the ruler closest in size while the subject read the passage from each of the devices. Pupil measurements were taken after the accommodative response measurements and recorded to the nearest 0.5 mm.

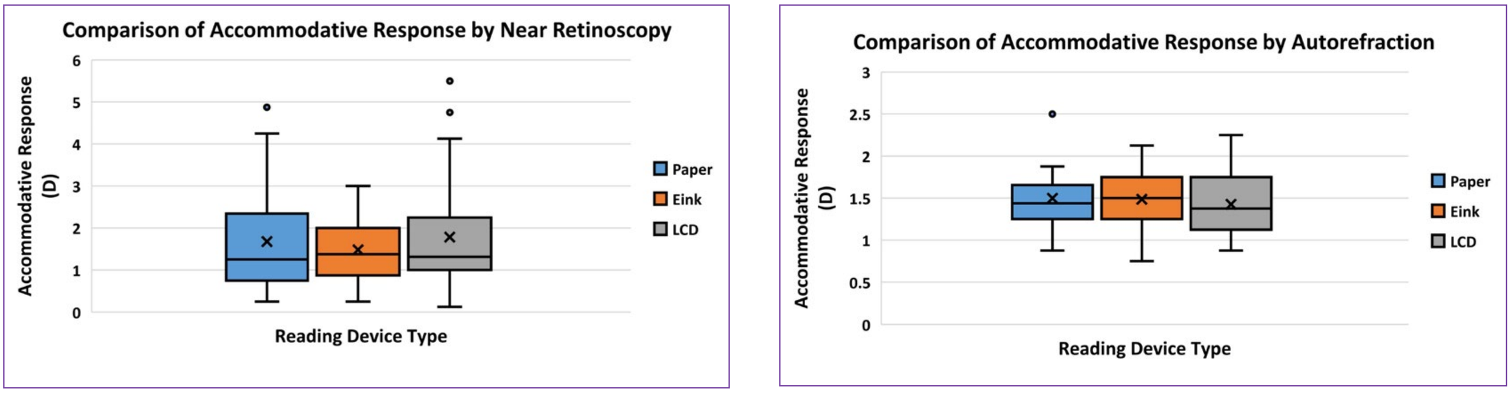

Figure 3. *Comparison of accommodative response by (a) MEM retinoscopy and (b) open-field autorefraction for the three reading devices. The median accommodative response is indicated by the horizontal line within each box, and the mean response is indicated by the X. See text for details.*

Table 2. Statistical Analysis of Mean Pupil Size and Mean Accommodative Response

Reading Device	Mean Pupil Size (mm)	Accom. Resp. D (Ret)	Accom. Resp. D (Auto)
Paper	5.1 ± 0.9	1.7 ± 1.2	1.5 ± 0.4
E-Ink Reader	5.5 ± 0.8*	1.5 ± 0.8**	1.5 ± 0.3
LCD Reader	5.1 ± 0.9	1.8 ± 1.3	1.4 ± 0.4

Results

One-way ANOVA for correlated samples and Tukey's HSD test for posthoc analysis (Table 2) were used to compare mean pupil size and mean accommodative response across devices. Figure 3 shows the range of measurements for each device, with the median and mean indicated within each boxplot. Figure 3a displays the results obtained with the modified MEM technique, and Figure 3b shows the results obtained with the autorefraction technique. The mean pupil size measured while subjects read from the e-ink device was significantly larger than the mean pupil size measured when subjects read from either of the other two devices ($p<0.01$). Mean accommodative response measured by modified MEM retinoscopy was significantly smaller for the e-ink device than for the LCD device (1.5 ± 0.8 D vs. 1.8 ± 1.3 D, $p<0.01$), but no difference in mean accommodative response was found between the e-ink device and paper or between paper and the LCD device. Mean accommodative response measured by autorefraction was not significantly different across any of the devices.

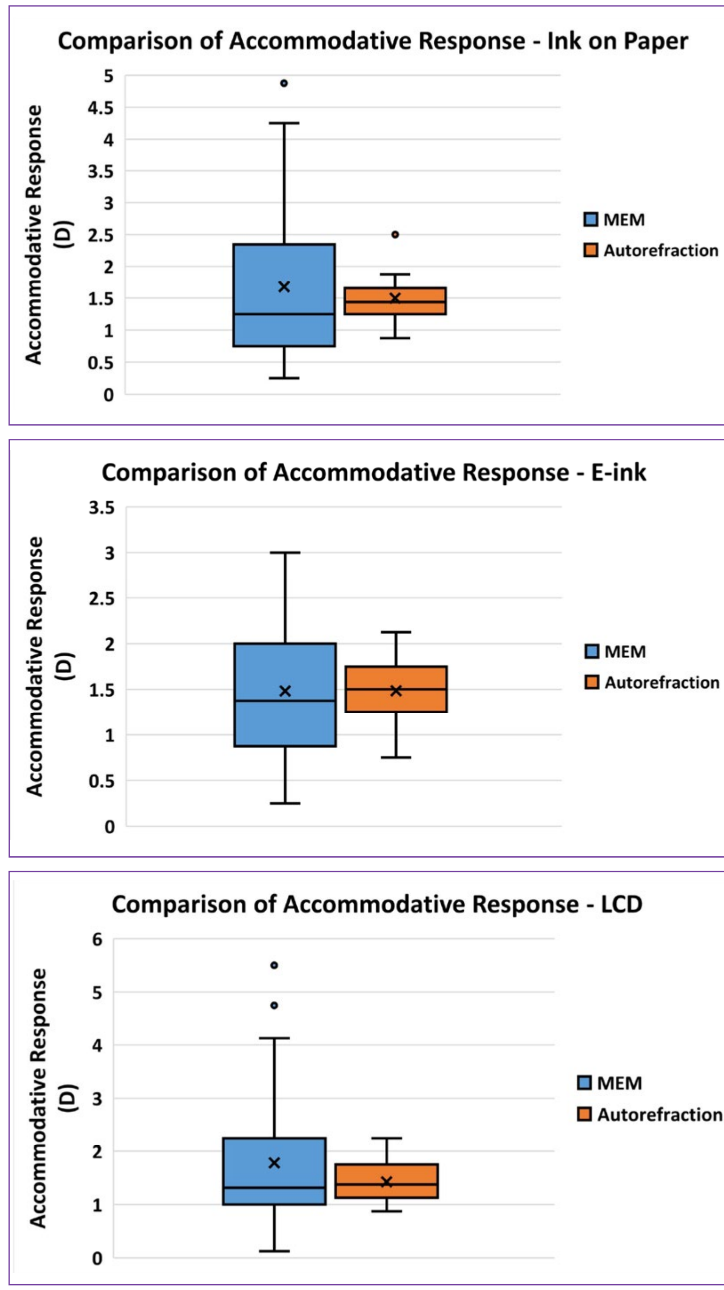

Figure 4. *Comparison of accommodative response between MEM retinoscopy and open-field autorefraction is shown separately for each reading device: (a) ink on paper, (b) e-ink, and (c) LCD backlit screen. The median accommodative response is indicated by the horizontal line within each box, and the mean response is indicated by the X.*

Two-tailed t-test for correlated samples was used to compare the accommodative response obtained with modified MEM retinoscopy to that obtained with autorefraction for each device. No difference in mean accommodative response was found when reading from the ink on paper, from the e-ink device, or from the LCD device (p>0.05, Figure 4a-c). Inspection of the boxplots for all three devices shows a greater variability in the measurements by modified MEM retinoscopy than by autorefraction.

In order to evaluate the agreement between the two methods of accommodative response measurement, Bland-Altman analysis was applied to the data.[9,10] Figure 5a-c shows comparisons of the measurements taken with the two techniques across the three devices. The solid black line on each plot indicates the mean of the differences between the modified MEM and autorefraction measurements. The sign of the mean difference indicates the direction of the bias, with a positive mean difference indicating that a larger accommodative response was measured with the modified MEM technique. The dashed horizontal lines in the plots indicate two standard deviations from the mean difference. The mean differences in accommodative response were 0.18 D for the ink-on-paper device (Figure 5a), -0.003 D for the e-ink device (Figure 5b), and 0.36 D for the LCD device (Figure 5c). For all three devices, most of the differences between the two measurements fell within two standard deviations of their respective means. Visual inspection of all three plots, however, shows that autorefraction tended to measure a larger accommodative response than modified MEM for lower averaged accommodation values, whereas modified MEM tended to measure a larger accommodative response for higher averaged accommodation values. Additionally, the two-standard-deviation range-of-measurement differences between the techniques was quite large for all three devices (4.6 D for ink on paper, 2.8 D for the e-ink device, and 4.7 D for the LCD device). Because the distribution of the differences between the measurements for the two methods was not normal for any of the reading devices, limits of agreement determined with the Bland-Altman analyses may have limited accuracy, although Bland and Altman state that a non-normality of the difference distribution may not be a serious violation.[10]

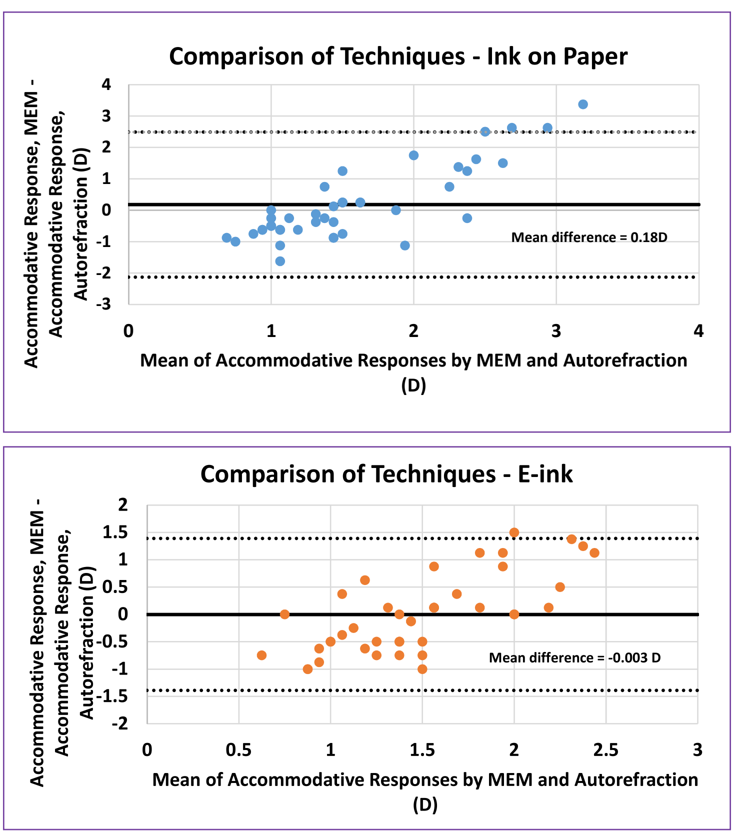

Figure 5. *Bland-Altman analysis shows the agreement between MEM retinoscopy and open-field autorefraction separately for each reading device: (a) ink on paper, (b) e-ink, and (c) LCD backlit screen. The mean difference is indicated by the solid black horizontal line; the 95% limits of agreement region is flanked by the two black dashed lines.*

Figure 6 (modified MEM) and Figure 7 (autorefraction) show the relationship between pupil size and accommodative response for the (a) paper stimulus, (b) e-ink stimulus, and (c) LCD stimulus. Simple linear regression indicated that accommodative response was not predicted by pupil size for any of the devices (p>0.05 for all conditions).

Discussion

The main finding in this study is that in young, healthy adults with normal accommo-

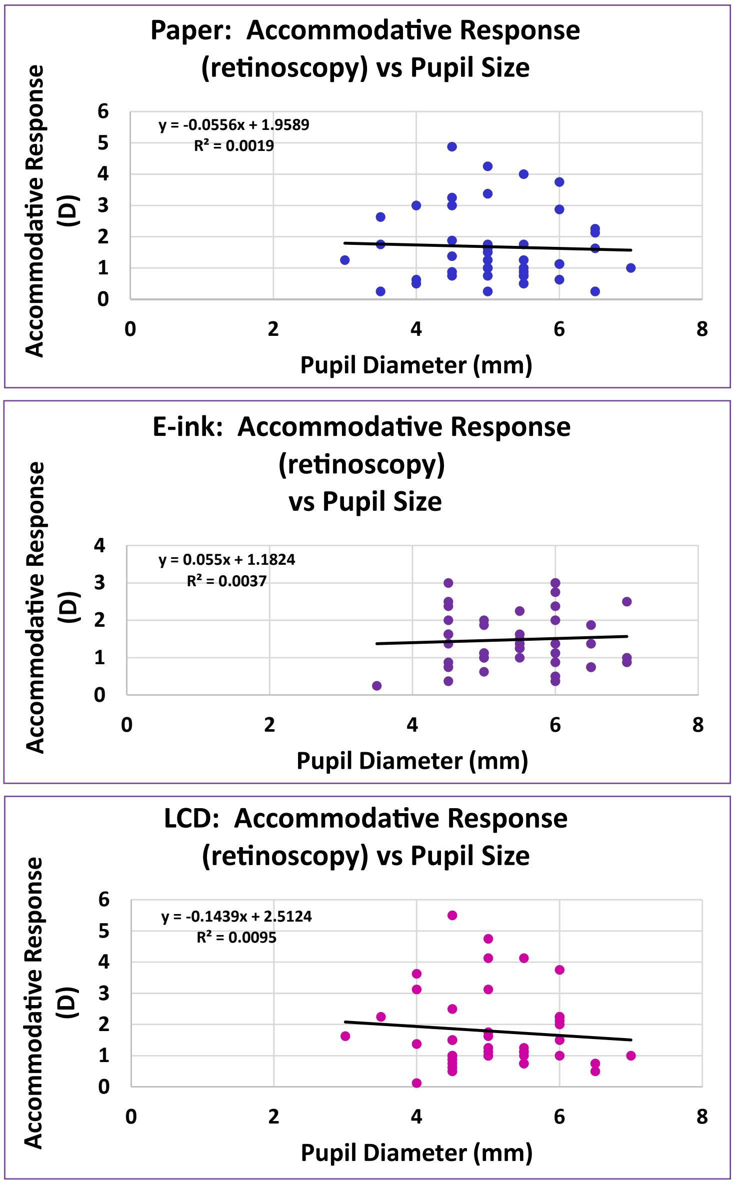

Figure 6. *Simple linear regression of accommodative response measured by MEM retinoscopy and pupil diameter was performed separately for each reading device: (a) ink on paper, (b) e-ink, and (c) LCD backlit screen. The R2 values, displayed on each plot, indicate that no corelation between pupil size and accommodative response was found for any of the three devices.*

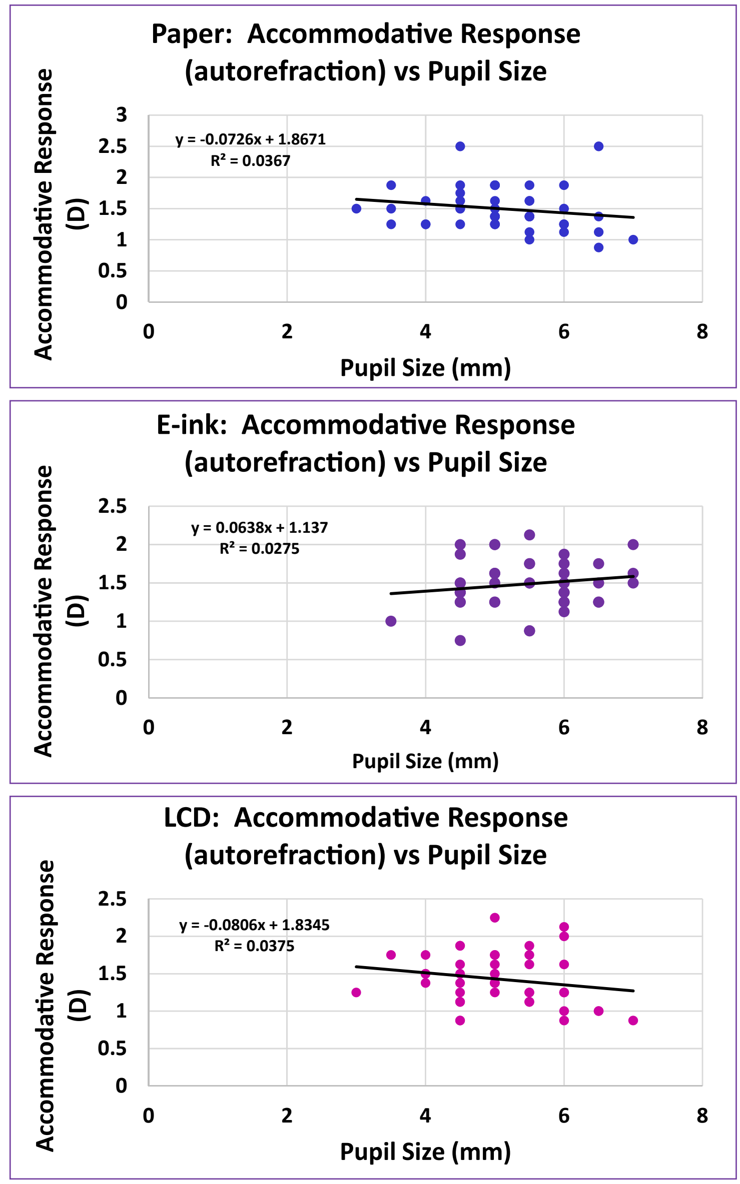

Figure 7. *Simple linear regression of accommodative response measured by open-field autorefraction and pupil diameter was performed separately for each reading device: (a) ink on paper, (b) e-ink, and (c) LCD backlit screen. The R2 values, displayed on each plot, indicate that no correlation between pupil size and accommodative response was found for any of the three devices.*

dative measures on two clinical tests, the accommodative responses to targets displayed with ink on paper, with e-ink on a digital device, and with an LCD backlit screen on a digital device were similar when the devices were equated for luminance and text size and were presented at high contrast. Although a statistically significant difference in accommodative response manifested for the e-ink display compared to the other two displays with modified MEM retinoscopy (0.2-0.3 D), the difference is of questionable clinical significance, particularly since no differences in the mean accommodative responses were found across devices with the autorefraction technique.

In addition to comparing accommodative response across reading devices, the data were analyzed for differences in accommodative response measurements based on technique (retinoscopy vs. autorefraction). Although most of the differences in values between the two measurement techniques across all devices fell within the 95% limits-of-agreement range established with Bland-Altman analysis, the range is too wide to be clinically useful. In other words, the modified MEM retinoscopy and open-field autorefraction techniques for measuring accommodative response did not produce values similar enough on a consistent basis to exchange one technique for the other. The examiner for this study had approximately two years of experience with retinoscopy, which may in part explain the differences in the measurements found with the two techniques. An examiner with more near-point retinoscopy experience may have found a narrower 95% limits-of-agreement range and a smaller variation in the data. For the main purpose of this study, however, no significant difference in accommodative response was found across devices when using either technique.

Poor agreement between near-point retinoscopy and open-field autorefraction for measuring accommodative responses was found by more experienced examiners in the Correction of Myopia Evaluation Trial 2 (COMET 2).[11] Their monocular retinoscopy measurements were taken with binocular viewing of a near-point card in a moderately illuminated environment, whereas their autorefraction measurements were taken with one eye occluded while the test eye viewed a self-illuminated target in a dark environment. These within-study differences in technique may have contributed to the poor agreement between results obtained with the two methods. It is for this reason that the MEM technique was modified to having the fellow eye occluded. In our study, the same target was used for both modified MEM retinoscopy and autorefraction; however, a rather wide 95% limits-of-agreement range was found, possibly in part due to the limited clinical experience of the examiner (two years at the time of data collection). More than one examiner collected data in the COMET 2 study, which also could have contributed to the differences found. In our study, one examiner collected the data, which may explain the comparatively smaller difference in mean accommodative response across methods (0.3-0.4 D vs. 0.4-0.5 D). Alternatively, the difference in mean accommodative response found between the two studies may be related to the difference in subject samples: adults versus children. Again, however, the Bland-Altman analyses of the data in both studies indicate that near retinoscopy and open-field autorefraction measures of accommodative response are not interchangeable.

Other studies have found better agreement between near retinoscopy and open-field autorefraction for the assessment of accommodative responses.[12,13] McClelland et al. used a study sample with a wider age range (6 to 43 years) than was used in our study (22 to 33 years) and wider than that used in the COMET 2 study (9 to 11 years). With MEM retinoscopy, an examiner can verify stability of the accommodative response before recording the measurement, whereas the stability of the response cannot be verified before the autorefraction measurement is recorded (although newer designs for autorefractors than used in this study can take repeated measurements over time). The adults of older age in the McClelland study likely had less variability in the accommodative response during an individual measurement, which may have contributed to the smaller difference they found between techniques. Rosenfield et al., using young-adult subjects (22 to 30 years), also found a smaller difference between near retinoscopy (Nott) and autorefraction measures of accommodative response; however, their 95% limits of agreement between the two techniques also suggest that substituting one technique for the other may not be advisable unless the margin of error for clinical decision-making is greater than 0.65 D (their standard deviation).[13] Finally, Goss et al. in 2005 published a comparison of two dynamic retinoscopy techniques (MEM and Nott), with accommodative responses determined by autorefraction in young adults (20 to 35 years of age).[14] The mean difference in accommodative response measured by both techniques compared to that measured by autorefraction (spherical equivalent) was 0.51 D (greater for autorefraction in both comparisons). However, they noted that when the means of the retinoscopy measurements were compared to the sphere power only of the autorefraction measurements, the mean difference in accommodative response between the retinoscopy and non-retinoscopy techniques was considerably smaller (0.04 D for both MEM and Nott when compared to autorefraction). For our study, we used the spherical component of the autorefraction to determine the accommodative response. Had we used the spherical equivalent of the autorefraction, the difference between the two techniques would have been larger. Other differences between the Goss study and the present study include: 1) the autorefractors were from different manufacturers for the two studies, 2) the Goss study simultaneously acquired autorefraction (ten readings) and Nott retinoscopy data, whereas the present study sequentially obtained autorefraction (two readings) and modified MEM data, and 3) the Goss study used a 20/20 line of print during accommodative response measurements, whereas this study used print of approximately 0.75M (about 20/30 to 20/40). Although we could have used smaller print for this study, we chose the 0.75M font size to match the printed font of the paper copy book from which the hard-copy stimulus was made (i.e., a commonly used stimulus size during daily reading). Whether lighting and/or pupil size differences existed between the studies cannot be ascertained based on the published information.

Interestingly, our study generally found no statistically significant difference in mean accommodative response between the two measurement techniques, whereas the mean of the measure was smaller by near retinoscopy compared to autorefraction in several of the studies mentioned above. We used the same passage for all measurements and asked the subjects to read while the measurements were taken. In the COMET 2 study, different near targets were used for retinoscopy and autorefraction, and the instructions to the subject were also different (read the card during retinoscopy; keep the print clear during autorefraction). Kruger showed that increased cognitive demand is associated with smaller lags of accommodation,[15] and indeed, the studies mentioned above found significantly smaller lags for near retinoscopy compared to autorefraction.

Few studies have investigated the relationship between accommodative response and digital display characteristics. Benedetto et al. used the outcome measures of critical flicker fusion, eye blinks, and Visual Fatigue Survey score to assess visual responses to different types of digital displays.[1] Maducdoc et al. used outcome measures of reading distance, posture, and score on a survey of eyestrain to compare reading with an electronic device to reading ink on paper.[8] Kretzschmar et al. used concurrent EEG and eye-tracking to assess visual performance while reading from a paper page, an e-reader, and a tablet computer.[16]

Of studies that used digital devices when measuring accommodative response, often only one type of digital device was tested, and luminance was either not measured or not controlled. Harb et al. used an autorefractor to measure accommodative responses during sustained reading but only used a computer monitor as a reading device in their study.[17] Although Sorkin et al. found no difference in accommodative response assessed with near retinoscopy between ink on paper and an older type of digital device (PRIO Computer Vision Tester, by PRIO Cooperation, Dallas, TX – designed specifically to mimic a computer monitor), the luminance of the digital device reduced significantly over the course of device use, which may have made the conditions for the two reading devices not comparable.[18]

Kolker et al. also found no difference in accommodative response as measured with near retinoscopy between the PRIO device and ink on paper, but only a 55 cm viewing distance was tested, and no luminance measures were reported.[19] Accommodative responses at longer viewing distances (as would be adopted for desktop monitor use) may not represent results that would be obtained with the closer viewing distances typically adopted with reading from books or e-readers.

The second finding of this study is that pupil size was approximately 0.4 mm larger when the subjects read from the e-ink device compared to the pupil sizes when reading from the other devices. The luminance of the devices was checked prior to data collection from each subject, and the examiner noted that the e-ink device consistently was at the lower end of the luminance range (about 90-93 cd/m^2). Based on Troland's equation for retinal illuminance (T = LA), the 5.5 mm pupil size would result in about a 10 percent increase in retinal illumination compared to a pupil size of 5.1 mm; thus, if the e-ink luminance was approximately 92 cd/m^2, the retinal illumination with a 5.5 mm pupil would be similar to that achieved with a 5.1 mm pupil when viewing a surface of luminance near 100 cd/m^2. Whether the larger pupil with the e-ink device occurred due to the slightly lower luminance of the e-ink display compared to the other two displays is plausible, but uncertain. The method of pupil size determination allowed for measurement only in 0.5 mm increments; therefore, a difference of less than the measurement increment may not be repeatable.

We did not assess symptoms in this study for four reasons. First, the conditions of the data collection were not representative of the conditions under which the devices are typically used. Unless the electronic device is in a fixed position, such as a desktop monitor, observers can place the device at any distance and angle that is comfortable in a particular environment. We have rarely encountered users positioning the devices for prolonged reading similar to the position used in this study. Although modified open-field autorefractors have been used to measure peripheral refractive error along the horizontal meridian,[20] the subjects' eyelids and the housing of the autorefractor imposed barriers to autorefraction while viewing the devices in a more natural downward reading position. To make the retinoscopy measurement conditions comparable to those of autorefraction, we used a similar reading angle for retinoscopy as for autorefraction. Whether our results would be similar to results obtained by measuring the accommodative response with the eyes positioned slightly downward is unknown.

The second reason for not assessing near symptoms in this study was that the likelihood of finding asymptomatic subjects in the sample used, which was one of convenience, was small. Our subjects were graduate students who routinely spend eight or more hours doing intensive reading and other close work. The first author's past experience with samples from this population has yielded average near work symptom survey results that suggest that the population itself from which the samples were drawn is symptomatic at near.[21,22]

The final two reasons for not administering a symptom survey are also related to the conditions for data collection in the study. This study did not require subjects to read for a prolonged period, reducing the likelihood that symptoms would have evolved during data collection. This study also did not assess dry eye, a condition that can have symptoms similar to those experienced by patients with near vision dysfunction.[23]

Despite the reasons for not including a symptom survey in this study, mean symptom survey results likely would not have been different for the accommodative response results on the three devices by either method, since the mean accommodative responses (i.e., mean accommodative lags of about 0.75-1.00 diopters) were quite similar for all conditions tested (Table 2). However, whether symptom survey score would have correlated with the magnitude and direction of the accommodative response in these subjects is unknown.

We also did not assess our subjects for dry eye signs or symptoms either before or after study participation, nor was dry eye an exclusion criterion for participation. Several studies have shown increases in dry eye symptoms and dry eye signs with digital display use.[24-27] Additionally, recent work suggests a relationship between accommodative instability and dry eye.[28] Because of the short duration of the reading task in this study, we were not likely to see a significant change in measures of dry eye pre- and post-data collection. Although differences in mean accommodative response were not found across devices in this study, a difference in a quantitative measure of tear film stability across devices may have occurred, but this was likely only if subjects had been asked to read for an extended time. Given that the same subjects were used for measurements from all three reading devices, any effect of pre-existing dry eye on their accommodative responses would have been similar across devices, and again, the length of time of data collection was not likely to have exacerbated any pre-existing dry eye condition.

Conclusion

The short-term accommodative response of young, healthy adults with good vision and normal clinical measures of accommodation is not significantly different while reading from different types of devices used to display reading material, as long as the devices are equated for luminance and contrast, are presented at the same viewing distance, and the instructions for viewing are the same for each device during the measurements. Whether accommodative responses with prolonged reading and whether individuals who have accommodative dysfunction would show similar accommodative responses across these devices under constant stimulus conditions remains to be explored. Given that most people use electronic devices in uncontrolled conditions, ways to measure accommodative response in habitual conditions chosen by or incurred upon individual patients would allow for personalized care/recommendations. Some people may have more robust accommodative systems that function well in a variety of conditions, whereas others may have accommodative systems more prone to variable performance as conditions change. Also of interest would be to explore whether people tend to make the same types of changes in their reading habits (e.g., posture, reading distance) when conditions change. For patients who have visual symptoms when using digital devices and for whom a thorough ocular and visual function assessment fails to identify abnormalities, a discussion about adjustments in device parameters (e.g., contrast, luminance, font style, and size) and environmental conditions (e.g., reading distance, environmental illumination, glare reduction, etc.) may help to alleviate symptoms.

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