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# Blink Rate Measured In Situ Decreases While Reading From Printed Text or Digital Devices, Regardless of Task Duration, Difficulty, or Viewing Distance

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**PURPOSE.** To compare blinking measured in situ during various tasks and examine relationships with ocular surface symptoms. The day-to-day repeatability of the blink rate and interblink interval was assessed.

**METHODS.** Twenty-four students ( $28.6 \pm 6.3$  years; 8 male and 16 female) completed six reading tasks (printed text, laptop, TV, smartphone, smartphone at 50% brightness, smartphone with complex text), and two nonreading tasks (conversation, walking) in a randomized cross-over study. Ocular surface symptoms and clinical signs were assessed. The blink rate and interblink interval were measured using a wearable eye tracking headset. Blink parameters were compared across tasks and time (linear mixed model and post hoc comparisons with Bonferroni correction). Associations between blinking, symptoms, ocular surface, and clinical signs were assessed (Spearman's correlation). The smartphone reading task was completed twice to determine the coefficient of repeatability.

**RESULTS.** The blink rate was lower (mean  $10.7 \pm 9.7$  blinks/min) and the interblink interval longer (mean  $9.6 \pm 8.7$  seconds) during all reading tasks compared with conversation (mean  $32.4 \pm 12.4$  blinks/min;  $1.5 \pm 0.6$  seconds) and walking (mean  $31.3 \pm 15.5$  blinks/min;  $1.9 \pm 1.3$ s) ( $P < 0.001$ ). There were no significant differences in blink parameters between any of the reading tasks or between conversation and walking. Changes in blinking occurred within 1 minute of starting the task. No associations were evident between blink rate or interblink interval and ocular surface symptoms or signs. The coefficient of repeatability was  $\pm 12.4$  blinks/min for blink rate and  $\pm 18.8$  seconds for interblink interval.

**CONCLUSIONS.** Spontaneous blinking can be measured reliably in situ. The blink rate was decreased and the interblink interval increased during reading compared with conversation and walking. Changes in blinking were immediate, sustained, and not associated with ocular surface symptoms or signs.

Keywords: blinking, dry eye, smartphone, ocular surface, reading, repeatability, digital device

Blinking maintains a stable tear film, thereby sustaining ocular surface integrity and visual function.<sup>1</sup> Disruptions to blinking disturb ocular surface homeostasis and may contribute to ocular discomfort and dry eye.<sup>2,3</sup>

Blinking is affected by the type, complexity or difficulty, and cognitive demand of the task undertaken during measurement.<sup>4-8</sup> Differences in viewing distance, factors such as font size, contrast, and device used create different demands on blinking.<sup>5,9</sup> Previous studies have found increased discomfort linked with impaired blinking during smartphone and computer use.<sup>3,9-11</sup> Blinking has been investigated during various tasks, (e.g., conversation, reading, playing computer games, watching a film, listening to music, resting quietly) of various

complexities and on various devices including printed text, desktop and laptop computers, and tablet, and at various viewing distances and gaze positions.<sup>11-18</sup> However, blink assessment remains hampered by the lack of a gold standard method and standardized conditions of measurement.

A wide range of mean blink parameters have been previously reported ranging from 11 to 36 blinks/min during conversation, 4 to 14 blinks/min during reading, and 5 to 26 blinks/min during rest and directed fixed gaze in adults.<sup>19</sup> This wide range can be explained in part by differences in the definitions of spontaneous blinking. Various definitions of a blink include a "25% downward movement of the upper eyelid" from the fully open position,<sup>20</sup> an "obvious downward eyelid movement,"<sup>21</sup> the "upper



eyelid reaching downwards from the top of the pupil,"<sup>22</sup> a "downward movement of the upper eyelid covering 30%–75% of the cornea,"<sup>27</sup> and a "15% decrease in the height of the upper eyelid."<sup>23</sup> Blinking is difficult to assess clinically or in situ outside of the laboratory setting; thus, a method that allows more natural measurement may be helpful in standardizing the definition of spontaneous blinking.

Blink measurements in previous studies have occurred typically in settings not representative of real-life situations, often requiring participants to keep a stationary head position.<sup>19</sup> Fixed head positions during measurement may stimulate participants' awareness and potential changes in blink dynamics.<sup>24</sup> It seems reasonable to assume that blink measurements whereby participants are placed in a fixed head position may be unsuitable for activities involving shifts in gaze and facial orientation,<sup>25</sup> such as during reading, conversation, and walking. Robust blink measurement requires the whole anterior eye to be constantly visible so that the full range of eyelid movements can be observed.<sup>26,27</sup> Head-mounted eye tracking technologies with cameras in close proximity to the eye allow more robust blink monitoring.<sup>25</sup> A higher than 95% blink detection accuracy in relation to pupil detection has previously been demonstrated with head-mounted eye tracking technology that allows free head positioning.<sup>26</sup> It would be reasonable to assume that the measurement of blinking in real time in a head position more reflective of the real-life situation is desirable to improve understanding of blink behavior.

A recent study in children demonstrated that the blinks counted by the Pupil software blink detection algorithm using the wearable eye tracker were in agreement with a manual count.<sup>27</sup> Hence, blinking in situ could be reliably measured using a wearable eye tracking headset, showing a rapid decrease in the blink rate during 1 hour of smartphone gaming, which was linked to ocular discomfort.<sup>27,28</sup> However, it is not clear if this effect was due to the use of smartphones per se or due to the task of reading itself.

The repeatability of recent and commonly used blink measurement methods has not been assessed. Repeated measurements of blink rate have been reported for electrophysiology methods (magnetic search coil technique and electro-oculography),<sup>6,18,29</sup> and for manual counting of blinks from eye video recording<sup>30–32</sup> conducted in a laboratory setting where participants' head position was fixed. However, none of these studies reported standard measures of repeatability.<sup>33</sup>

The current study aimed to compare blink parameters (blink rate, interblink interval) during various reading and nonreading tasks measured in situ using a wearable eye tracking headset and to examine associations with ocular surface symptoms. In addition, the day-to-day repeatability of the blink rate and interblink interval measurement was assessed.

## METHODS

A randomized cross-over study was conducted. Approval was obtained from the University of New South Wales (UNSW) Human Research Ethics Advisory Panel and the tenets of the Declaration of Helsinki were adhered to. Informed consent was obtained from all participants before participation.

## Participants

Students aged 18 to 40 years were recruited from the UNSW Sydney campus. Minimum unaided visual acuity of 0.1 LogMAR at 6 m and 40 cm and binocular vision (accommodation and convergence) normal for age were required for participants to be enrolled in the study including a minimum amplitude of accommodation of 5 diopters (D) (push up to blur with Royal Air Force rule) and a near phoria equal or smaller than 6 prism D (modified Thorton test).<sup>34</sup> Participants were excluded if they wore spectacle or contact lenses, or had a history of ocular conditions including eye allergies, systemic conditions (e.g., Parkinson's disease, diabetes) or medications (e.g., cornea cold thermoreceptor stimulants such as menthol ointment, dopamine antagonist drugs) likely to impact blinking.<sup>35,36</sup> Sample size calculation (SAS 9.4, SAS Institutes, Cary, NC, USA) showed that 24 participants were required to detect a difference in blink rate between various tasks of 5.8 blinks/min,<sup>12,15</sup> with 90% power at an alpha ( $\alpha$ ) level of 0.05/7 (statistical significance corrected for multiple comparison of seven tasks) and to account for a possible 20% attrition. Twenty-four participants were also sufficient to assess the day-to-day repeatability of the blink rate and interblink interval, based on a desired precision of  $\pm 30\%$ , which was expressed as a percentage of within-person SD, with two repeated measurements.<sup>37</sup>

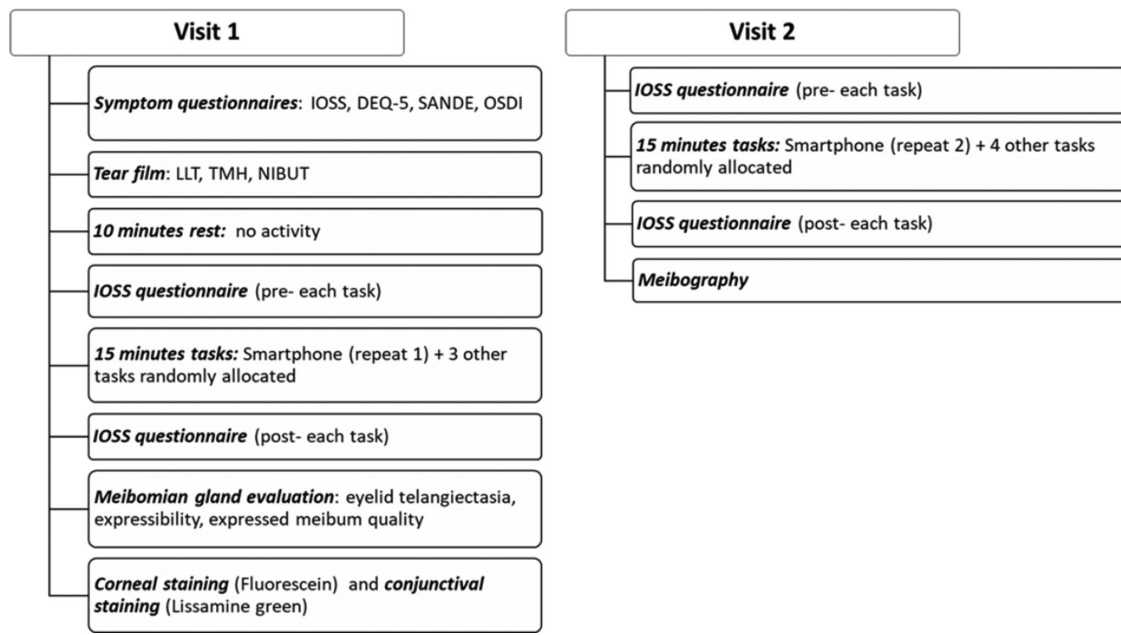
## Procedures

All participants attended two visits (Fig. 1) during which they completed a questionnaire on demographics and daily hours of digital device use, and eight tasks as described elsewhere in this article. Ocular surface symptoms and the ocular surface clinical indices were assessed and in situ blinking was measured. In line with the coronavirus disease 2019 safety protocol and guidelines that came into effect in Sydney, Australia, part way through the study, some of the participants wore a surgical mask that covered from nose to chin for all assessments during both study visits (Figs. 2C, 2D).

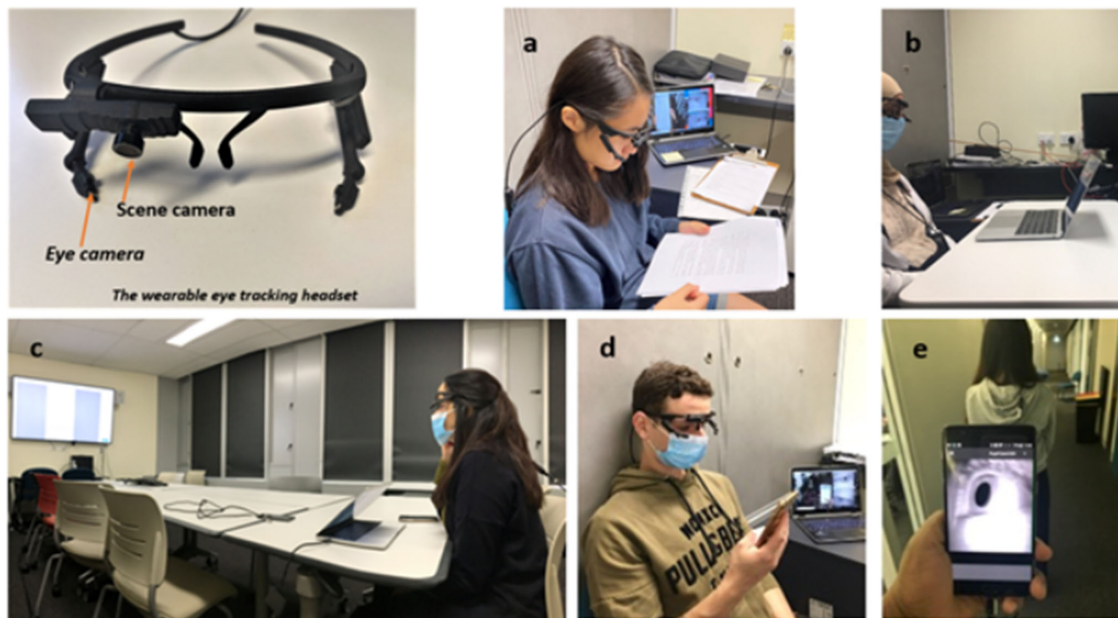
## Tasks

The tasks comprised six reading tasks (printed text, laptop, smart TV at 6 m, smartphone, smartphone at 50% brightness, smartphone with more complex text), and two nonreading tasks (conversation, walking indoors). Text complexity throughout this article refers to the difficulty of reading text comprehension according to the Flesch–Kincaid grade level scale.<sup>39</sup> All tasks were 15 minutes in duration. Tasks were completed in random order, other than the smartphone task, which was completed first at each visit (repeated twice) (Fig. 1). Data for the repeat 1 of the smartphone task was used for all analyses, except for repeatability, where both repeats were used.

A reading level of the fifth to seventh grade was selected for the reading tasks.<sup>38,39</sup> A text at a reading level of a university graduate was selected for the complex smartphone reading task.<sup>39,40</sup> For all reading tasks, the default text font size was 16 pixels (equivalence of 12 points), black Times New Roman. However, the viewing distances, screen, or display size and the varying digital device pixel may affect the actual angular extent and therefore alter the font sizes.<sup>41,42</sup> The printed text reading task was printed one-sided in



**FIGURE 1.** Flowchart of study visits and order of clinical assessments. Note: Visit 2 was conducted 2 days after visit 1. Smartphone task was completed twice before other tasks at each visit for assessment of repeatability. Other tasks randomly allocated include six reading tasks (printed text, laptop, smart TV at 6 m, smartphone, smartphone at 50% brightness, smartphone more complex text), and two non-reading tasks (conversation, walking indoors). DEQ-5, Dry Eye Questionnaire 5; LLT, lipid layer thickness; NIBUT, noninvasive tear break-up time; OSDI, Ocular Surface Disease Index; TMH, tear meniscus height; SANDE, Symptoms Assessment in Dry Eye.



**FIGURE 2.** Study set-up showing the wearable eye tracking headset (Pupil Labs GmbH) with two inbuilt high-speed adjustable eye cameras and a scene camera for real time monitoring from participants' vantage point. The headset was worn by study participants during various tasks including reading from (a) printed text, (b) laptop, (c) smart TV at 6 m, (d) smartphone, and (e) walking indoors and conversation (not shown). The wearable eye tracking headset was connected to a laptop for task monitoring and data acquisition for all tasks other than walking indoors, where an android phone was used for the same purpose, while the examiner followed behind the participant holding the android phone to monitor recording (Fig. 2e). Participants' consents were obtained for use of these images.

A4 format. Conversation was elicited using age-appropriate great conversation starters.<sup>43</sup> The walking indoors task was conducted in a level corridor of a temperature-controlled university building.

The same smartphone (iPhone 8 Plus, 5.5-inch, 1920 × 1080 pixels at 401 ppi, 2017) was used for all smartphone reading tasks. A MacBook Pro (13.3-inch, 2560 × 1600 pixels at 227 ppi built-in display, 2019) was used for the laptop task,



and a smart TV (NEC, Model: V754Q, 75-inch, 3840 × 2160 pixels at 59 ppi) for reading at 6 m (Fig. 2). Participants were instructed to hold the smartphone at their habitual reading distance, to use one finger to scroll to the next page or the side arrow button on the laptop keyboard to scroll to the next page during reading, and to not alter the screen brightness or font size. The smartphone was set at maximum screen brightness of measured luminance 380 cd/m<sup>2</sup> (Konica Minolta CS-100A) for two tasks and decrease to half during reading from the smartphone at 50% brightness task (measured luminance 121 cd/m<sup>2</sup>). The laptop screen and smart TV were also set at maximum screen brightness, with a measured luminance of 316 cd/m<sup>2</sup> and 316 cd/m<sup>2</sup>, respectively. The measured luminance for the printed text reading was 77 cd/m<sup>2</sup>.

### Ocular Surface Symptoms and Ocular Surface Clinical Assessments

Baseline ocular surface symptoms were assessed using the Instant Ocular Symptoms Survey (IOSS),<sup>44</sup> Dry Eye Questionnaire 5,<sup>45</sup> Symptoms Assessment in Dry Eye,<sup>46</sup> and Ocular Surface Disease Index<sup>47</sup> questionnaires, self-completed by participants. The IOSS questionnaire (printed text) was completed by participants between (before and after) the tasks. The IOSS was found to be an effective tool for instant symptom measurement, with good diagnostic ability and was developed to measure instantaneous symptoms, that is, at the time of administration (compared with the other questionnaires which record symptoms experienced over the preceding weeks), and as such is appropriate to administer for repeated comfort assessment.<sup>44</sup>

The following baseline tear film clinical assessments were conducted before blink measurements: tear film lipid layer thickness (LipiView interferometer; Tear Science, Morrisville, NC, USA), tear meniscus height, and noninvasive tear breakup time (Oculus Keratograph 5; Oculus, Arlington, WA, USA). The index of the lipid layer thickness based on the mean interferometry color units was recorded.<sup>48</sup> The tear meniscus height was assessed in the regions vertically below the pupil center, and directly under the nasal and temporal corneal limbal edges (determined using the integrated ruler) to account for variability in the tear meniscus height along the length of the lower meniscus, and the average of the three measurements was recorded.<sup>49</sup> The automated detection of the first tear break-up was recorded for the noninvasive tear break-up time.<sup>50</sup> Measurement of the tear breakup time with the noninvasive tear break-up time technique was considered preferable,<sup>51,52</sup> because it is automated compared with other subjective methods, such as a videokeratoscope or Tearscope, with which measurements have been found to vary between sessions and observers.<sup>52,53</sup>

Ocular surface clinical assessments were performed on the right eye only, in the same temperature-controlled examination room, in ascending order of invasiveness.<sup>52</sup> General ocular surface health, corneal staining (fluorescein) and conjunctival staining (Lissamine green strips, Green-Glo) (Oxford grading scale),<sup>54,55</sup> telangiectasia,<sup>56</sup> meibomian gland expressibility, and meibography imaging of the upper eyelid (Oculus Keratograph 5) was scored in relation to loss of meibomian glands using the meiboscore (meiboscore: degree 0 = no gland loss, 1 ≤25% gland area of loss, 2 = 26%–50% gland area loss, 3 = 51%–75% gland area loss, 4 ≥75% gland area loss)<sup>57</sup> and the pattern of meibomian

gland morphological changes were assessed<sup>57–59</sup> after all tasks were completed, as shown in Figure 1.

### In Situ Blink Measurement

Blink assessment was conducted after tear film assessment, after 10 minutes of rest. In situ assessment of blink parameters was conducted during each task using a binocular wearable eye tracking headset (Pupil Labs Core GmbH, Berlin, Germany)<sup>60</sup> (Fig. 2). Data were analyzed using the mean values for each minute as well mean values over 12 or 15 minutes of recording.

The wearable eye tracking headset recorded participants' eyes using the two inbuilt adjustable eye cameras with a resolution of 192 × 192 pixels at 120 Hz (Fig. 2).<sup>60</sup> The eye camera (providing a view of the participant and their eye) together with the scene camera (providing a view of what the participant is looking at) (Fig. 2) enabled continuous monitoring of participant adherence in real time. Blink activity was detected using the open source eye tracking software Pupil v2.0 (Pupil Labs GmbH), based on the visibility of the pupil, as previously described.<sup>27,60</sup> Briefly, the Pupil software assigns a quality measure for the detected pupil in each video frame, referred to as pupil confidence. The pupil confidence value indicates how accurately the edge of the detected pupil fits an ellipse (range, 0 [no fit] to 1 [good fit]).<sup>27,60</sup> Blinks are assumed to occur during pupil confidence drops evident when the pupil is obscured; thus, pupil confidence is a proxy measure for blink detection.<sup>60</sup> Blink data was extracted from the eye tracker recordings using Pupil software Player module (Pupil Labs GmbH) as CSV files.<sup>27</sup> Blink rate (number of blinks per minute) and interblink interval (the time between the end of one blink to the start of the following blink) data were estimated using Pupil software blink detection algorithm as described elsewhere.<sup>27</sup> Interblink interval data were determined from the timestamp details of the blink onset and offset identified by the Pupil software blink detection algorithm, and so not an inverse of blink rate.<sup>27</sup>

For the reading from a smartphone task (repeats 1 and 2), data from the first 3 minutes of video recording were discarded and the remaining 12 minutes were used for the analysis to allow for adjustment and adaptation to wearing the headset as recommended.<sup>61</sup> Complete recordings (15 minutes) were analyzed for all other tasks, because the participants continued with each of the subsequent tasks without removing the headset.

### Repeatability of Blink Measurements

Participants completed the reading from smartphone task with maximum screen brightness twice at separate study visits occurring 2 days apart at the same time of day (between 10 AM and 11 AM). The time of the day was controlled because the blink rate has been reported to exhibit diurnal variation (higher in the evening).<sup>62</sup>

### Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics (version 26, 2019; Armonk, NY, USA). A linear mixed model with fixed effect of task and mask wear and their interactions was used to examine differences in blink parameters between tasks and the effect of mask wearing on the differences in blink parameters. A separate linear mixed model

with the fixed effect of time was used to compare differences in blink parameters across time, within each task. Another model with fixed effects of task, time, and mask wear was used to examine the differences in ocular surface symptoms across tasks and time. All models included a random effect for individual to account for repeated measures within persons. Model-estimated means were obtained and post hoc pairwise comparisons were performed between tasks, between each minute within each task duration, and between pretask and post-task symptoms within each task; *P* values were corrected for multiple comparisons by a Bonferroni adjustment. Spearman's bivariate correlation was used to examine associations between blinking and changes in ocular surface symptoms, and ocular surface and tear film indices; the *P* values for the correlations were adjusted for multiple comparisons using the one-step Bonferroni method. The statistical approach suggested by Bland and Altman was used to examine repeatability of blink rate and interblink interval. The coefficient of repeatability (CoR =  $1.96 \times \text{SD}$  of differences between the two repeats), mean difference (bias) between repeats and limits of agreement (limits of agreement = bias  $\pm$  CoR) were calculated, and paired *t*-tests were used to examine agreement between repeats.<sup>33</sup> Significance was established at a *P* value of 0.05 or less.

## RESULTS

Twenty-four participants with normal ocular surface health completed the study. Participants were aged 18 to 40 years (mean,  $28.6 \pm 6.3$  years), 67% were female, and comprised different ethnicities: African (38%), South Asian (21%), Middle Eastern (17%), East Asian (12%), and Caucasian (12%). Fourteen participants wore a surgical mask during data collection.

Thirteen data points were excluded, where more than 60% pupil confidence values were less than 0.6, as per the manufacturer's recommendation<sup>27</sup>: three from the printed text task, one from smart TV, five from smartphone, two from smartphone (50% brightness), and two from smartphone (more complex text). Ocular surface symptoms and clinical signs reported by participants who had excluded data points were within the range of other participants.

Baseline ocular surface symptoms and clinical assessments are presented in Table. Examination room temperature was maintained at  $21.9 \pm 0.7^\circ\text{C}$ .

### Differences in Blink Parameters Between Tasks

There were significant differences in blink rate ( $F = 29.94$ ,  $P < 0.001$ ) and interblink interval ( $F = 38.32$ ,  $P < 0.001$ ) between tasks. The blink rate was lower and the interblink interval was longer during all reading tasks compared with conversation ( $P < 0.001$ ) and walking indoors ( $P < 0.001$ ) (Fig. 3). There were no significant differences in the blink rate or interblink interval between conversation and walking indoors, or between any of the reading tasks. Interactions between tasks and mask wear were not significant, indicating that mask wear did not have an effect on the differences in blink rate ( $P = 0.65$ ) or interblink interval ( $P = 0.72$ ) between tasks. Blink rate and interblink interval remained unchanged throughout measurement duration for each task ( $P > 0.05$ ) (Fig. 4).

### Differences in Ocular Surface Symptoms Before and After a Task and Association With Blinking

Ocular surface symptoms (IOSS) pretask and post-tasks differed between tasks ( $F = 4.69$ ,  $P < 0.001$ ). Symptoms worsened after reading from a smartphone when text was more complex ( $P = 0.01$ ) or at 50% brightness ( $P = 0.02$ ), and from a smart TV ( $P < 0.001$ ), but did not change during other tasks (Fig. 5). There was no evidence that mask wearing influenced these differences (mask wear  $\times$  task  $\times$  time interaction,  $P = 1.00$ ). These changes in symptoms were not associated with blink rate or interblink interval ( $\rho = -0.09$  to  $0.41$ ,  $P = 1.00$ ) (Supplementary Table S1). There were no associations between blinking and baseline ocular surface symptoms (Ocular Surface Disease Index, Symptoms Assessment in Dry, Dry Eye Questionnaire 5, IOSS), tear film, and other clinical indices ( $\rho = -0.01$  to  $0.45$ ,  $P = 1.00$ ) (Supplementary Table S2).

### Repeatability of the Blink Rate and Interblink Interval

The group mean blink rate for participants while reading from a smartphone was  $10.6 \pm 10.4$  blinks/min for the first repeat and  $11.3 \pm 10.4$  blinks/min for the second repeat. The interblink interval was  $10.3 \pm 9.7$  seconds and  $9.7 \pm 11.2$  seconds for the first and second repeats, respectively.

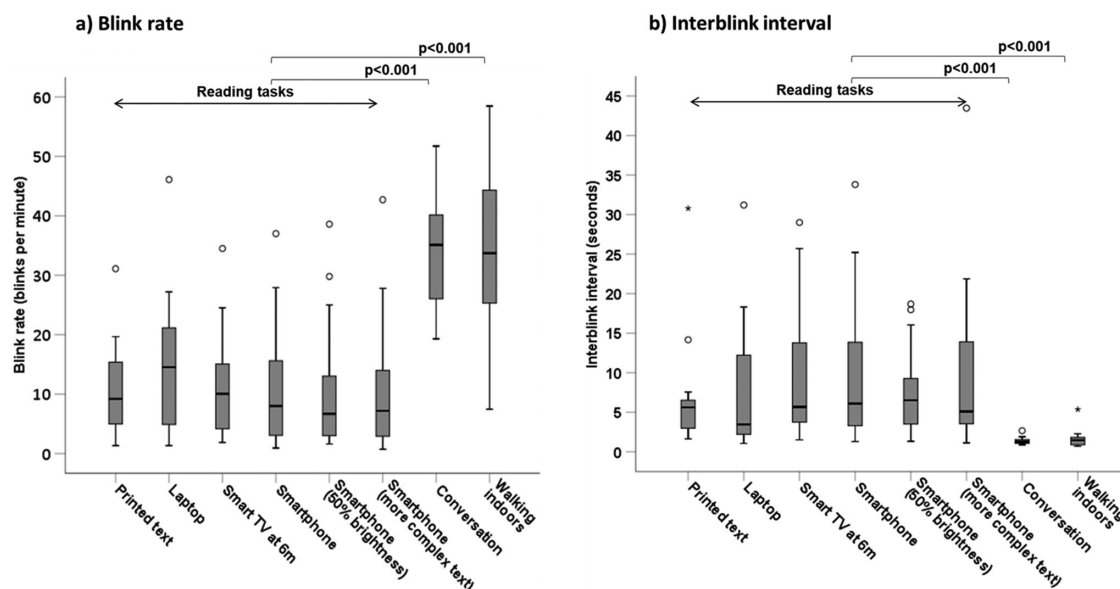
TABLE. Baseline Ocular Surface Symptoms and Clinical Assessments for 24 Students With Healthy Eyes

Variables	Value
Ocular surface symptoms (score)	
IOSS (0–10)	$1.9 \pm 1.6$ (0–5)
DEQ-5 (0–22)	$5.9 \pm 4.1$ (0–16)
SANDE (0–100)	$18.1 \pm 22.9$ (0–81)
OSDI (0–100)	$15.1 \pm 16.6$ (0–61)
Tear film	
Lipid layer thickness (nm)*	$43.0 \pm 18.8$ (20–75)
Tear meniscus height (mm)	$0.29 \pm 0.08$ (0.17–0.47)
Noninvasive tear break-up time (s)	$10.3 \pm 6.7$ (3.4–22.9)
Cornea white light staining (grade)	0 (0–0)
Meibomian gland evaluation (grade)	
Eyelid telangiectasia (grade)	0 (0–2)
Expressibility (No. of expressible glands)	2 (0–3)
Expressibility (amount of pressure applied)	2 (0–3)
Expressed meibum quality (grade)	0 (0–1)
Cornea staining - fluorescein (0–15)	0 (0–0)
Conjunctival staining - Lissamine green (0–15)	0 (0–2)
Meibography	
Meibomian gland area loss (score)	1 (0–3)
Meibomian gland morphological pattern present:	
Dilation	13 (54%)
Shortening	18 (75%)
Tortuosity	14 (58%)

\* Data for 21 participants only included because lipid layer thickness values measuring above the upper cut-off of 100 interferometric color units (ICU) were not displayed by the instrument for three participants.

Data are presented as mean  $\pm$  SD (range) and median (range). Higher eye symptom questionnaire scores indicate worse discomfort.

DEQ-5, Dry Eye Questionnaire 5; OSDI, Ocular Surface Disease Index; SANDE, Symptoms Assessment in Dry Eye.



**FIGURE 3.** (a) Blink rate and (b) interblink interval during various tasks of 15 minutes' duration, measured using a wearable eye tracking headset (Pupil Labs GmbH) for 24 students with healthy eyes. Note that data from the first 3 minutes of the smartphone task were discarded and the remaining 12 minutes used for analysis. Data are presented as median and interquartile range. Open circles represent mild outliers (measurements  $>1.5$  to  $3.0$  times the interquartile range) and stars represent extreme outliers (measurements  $>3$  times the interquartile range).

There was no significant difference between two repeated measurements for blink rate ( $P = 0.62$ ) or interblink interval ( $P = 0.55$ ). The Bland and Altman plots for blink rate and interblink interval showing the bias and limits of agreement are presented in Figure 6. The CoR was calculated to be  $\pm 12.4$  blinks/min for blink rate and  $\pm 18.8$  seconds for the interblink interval.

## DISCUSSION

A wearable eye tracking headset can be used to measure blinking reliably in a variety of real-life settings and was found to be repeatable from day to day. The blink rate was consistently decreased and the interblink interval was longer during various reading tasks, including reading from printed text, a laptop, a smart TV at 6 m, and a smartphone, compared with conversation or walking, irrespective of reading task difficulty, screen brightness, viewing distance, or device used. Changes in the blink rate and interblink interval occurred immediately upon starting tasks and did not change throughout the 15-minute task duration. No relationship was apparent between blinking and ocular surface comfort or clinical signs.

The blink rate during reading (mean for all reading tasks,  $10.7 \pm 9.7$  blinks/min) and conversation ( $32.4 \pm 12.4$  blinks/min) in this study aligns with previous findings of a slower blink rate while reading printed text and on a computer (pooled mean,  $7.9 \pm 3.3$  blinks/min) than during conversation in adults (mean, 21 blinks/min)<sup>4</sup> and in children (20.5 blinks/min).<sup>27</sup> A lower blink rate has been consistently reported with computer or smartphone reading and gaming relative to conversation<sup>28,63,64</sup> and rest or primary gaze.<sup>5,7,12-14,59,65</sup> The blink rate while reading on a smartphone (10.6 blinks/min) is similar to a previously reported mean of 8.9 blinks/min within 1 minute of gaming on a smartphone<sup>28</sup> and a median of 12.5 blinks/min

within 10 minutes of reading on a smartphone.<sup>50</sup> A lower blink rate during reading tasks compared with conversation and walking is as expected, because tasks involving higher cognitive demand and concentration are associated with a slower blink rate compared with tasks of a lower cognitive demand.<sup>4,5,8,9,66,67</sup>

The interblink interval measured during conversation in this study ( $1.5 \pm 0.6$  seconds) is shorter compared with the only previously reported value of  $6 \pm 3$  seconds in healthy adults.<sup>68</sup> The interblink interval has not been measured previously during reading or walking. Other reports were during rest, predetermined gaze, or steady fixation, and viewing a game or movie on computer with reported mean interblink interval values ranging from 3 to 10 seconds.<sup>15,18,19,68-71</sup> As with the blink rate, the interblink interval has been speculated to be unconsciously adjusted depending on the importance of perceived visual information—prolonged with greater cognitive demand.<sup>70</sup>

Enabled by the portability of the wearable eye tracking headset, this study was the first to report a blink rate while walking. Blinking during walking did not differ from that during conversation. A previous study speculated that the cognitive demand during conversation compares with that during orientation simulated in a laboratory, similar to walking.<sup>72</sup>

Blinking was not affected by the type of device used in this study. These results align with previous reports that the blink rate remains unchanged when an identical reading task is performed in print and on any type of digital device.<sup>8,9,11,65,73,74</sup>

Text complexity did not modulate the effect of reading on blinking in this study, in agreement with a previous study that compared blink rate while reading regular words with reordered mirrored images of the same words.<sup>67</sup> In contrast, another study found a small decrease in the blink rate during complex reading compared with noncomplex reading on

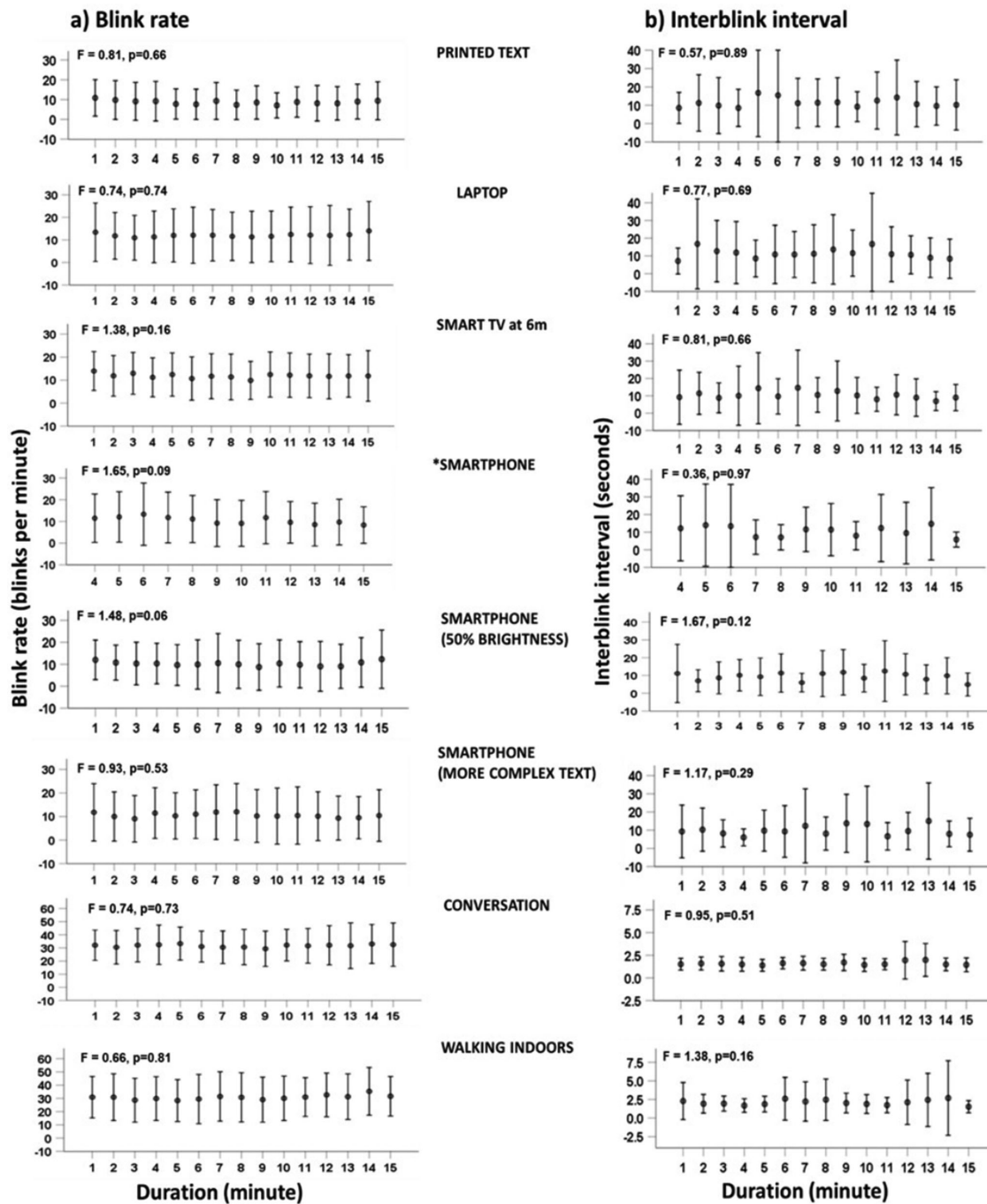


FIGURE 4. (a) Blink rate and (b) interblink interval during various tasks of 15 minutes duration, measured using a wearable eye tracking headset (Pupil Labs GmbH) for 24 students with healthy eyes. The tasks include six reading tasks (printed text, laptop, smart TV at 6 m, smartphone, smartphone at 50% brightness, smartphone more complex text), and two nonreading tasks (conversation, walking indoors). \*Note, data from the first three minutes of the smartphone task were discarded and the remaining 12 minutes used for analysis.

tablet and printed text.<sup>8</sup> Other studies<sup>3,5,10,65</sup> that report a reduced lower while reading complex text on a computer, tablet, or printed text did not directly compare texts of differing complexities. The likely high reading comprehension ability level of university student participants may have limited this study's ability to demonstrate an effect of text complexity.

Screen brightness did not affect the blink rate in the present study. Another study found decreased blink-

ing while reading from computer with high screen brightness compared with low screen brightness.<sup>75</sup> The higher blinking with low screen brightness under standard background luminance was speculated to be caused by increased glare discomfort.<sup>21,75</sup> An effect of screen brightness on the blink rate may not be expected; because in the photopic range, the eye and visual system constantly and rapidly adapt to luminance changes.<sup>76</sup>



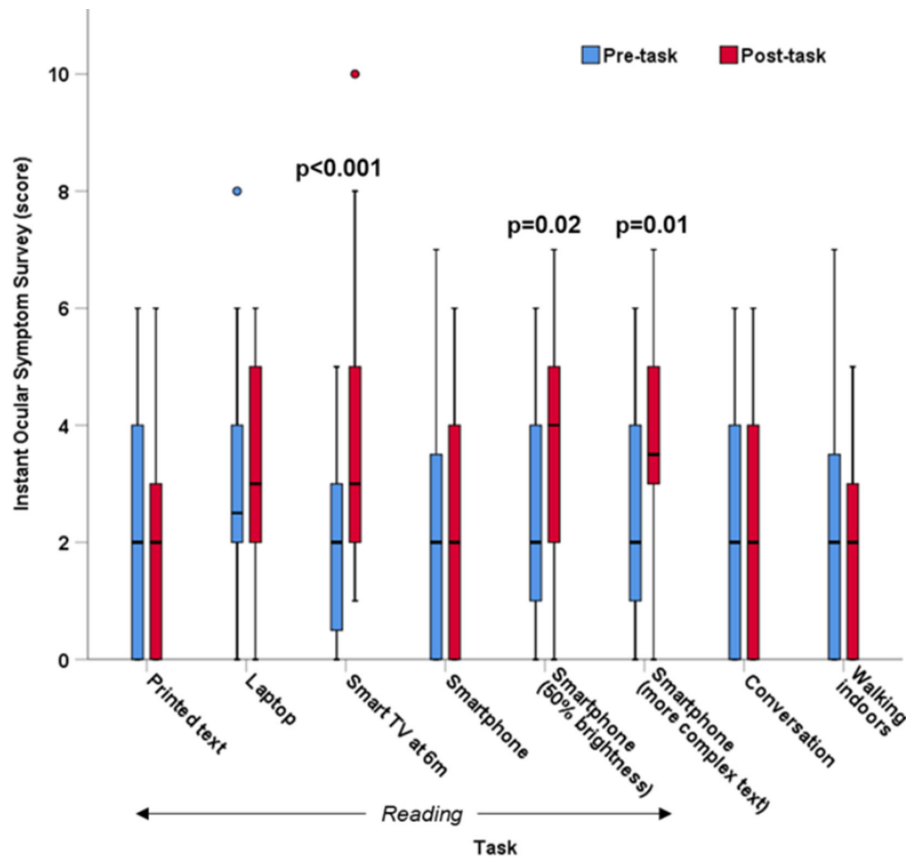


FIGURE 5. Ocular surface symptoms of discomfort and dryness scores (median and interquartile range) measured using the IOSS before and after various tasks of 15 minutes duration for 24 students with healthy eyes. Note, data from the first three minutes of the smartphone task were discarded and the remaining 12 minutes used for analysis. Higher IOSS scores indicate worse discomfort. Blue and red circles represent mild outliers (symptom scores  $> 1.5$  to  $3.0$  times the interquartile range).

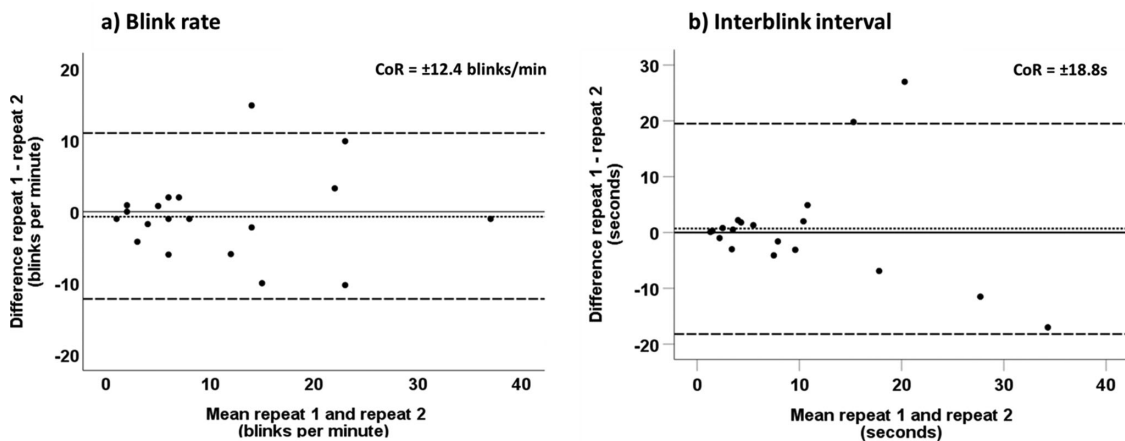


FIGURE 6. Differences between (a) blink rate and (b) interblink interval measured using the wearable eye tracking headset (Pupil Labs GmbH) during two repeats plotted against their mean for 24 students with healthy eyes, while reading easy book series on a smartphone for 12 minutes. The dotted line shows a bias of (a)  $-0.7$  blinks/min ( $P = 0.62$ ) and (b)  $0.7s$  ( $P = 0.55$ ). The dashed lines represent the limits of agreement of (a)  $+11.7$  to  $-13.1$  blinks/min and (b)  $+19.5$  to  $-18.2s$ .

The presentation of the reading tasks at near or distance did not impact blinking in this study. There was no effect on blinking in this study of reading letters of a smaller angular size on a smart TV at 6 m compared with those of a larger angular size while reading from a smartphone, laptop, or

printed text. A previous study reported a lower blink rate during reading text printed in a small font compared with viewing a picture; however, the effect was not modulated by induced accommodative and convergence visual demand.<sup>77</sup> Another previous study reported a decreased blink rate

while reading text set at 100% font display on a desktop and an increased blink rate while reading the same text set at 330% expanded font display from the same desktop distance.<sup>9</sup> A relationship between screen viewing distance and blink rate has not been reported previously. The direction of the gaze during tasks may also modulate blink behavior. Tasks involving a down gaze, such as reading on printed text and smartphone, may be less likely to trigger blinking compared with tasks involving an upward (e.g., smart TV at 6 m)<sup>21,69</sup> or primary gaze.<sup>67</sup> An upward gaze direction could lead to ocular surface area exposure, thereby stimulating blinks.<sup>9,21,78</sup>

The impact of task on the blink rate and interblink interval in this study was immediate and remained unchanged throughout the task duration, in agreement with earlier work. A study that investigated the blink rate each 30 seconds over the course of 10 minutes reading on a tablet also found no changes in the blink rate.<sup>8</sup> A study using the same eye tracker device in school-aged children similarly found a rapid slowing of the blink rate and lengthening of the interblink interval, which occurred within the first minute of gaming on a smartphone, and these parameters remained further unchanged throughout 1 hour of gaming.<sup>28</sup> A study in adults found no difference in blink rate over the course of 1 hour of gaming on a smartphone.<sup>79</sup> An intervention study in adults found an increase in rate of incomplete blinks from 1 to 60 minutes of smartphone reading, but no change in the rate of complete blinks.<sup>80</sup>

Ocular surface symptoms of dryness and discomfort worsened when reading on a smartphone with 50% screen brightness, more complex text on a smartphone, and reading on a smart TV at 6 m, but there was no association between these changes in ocular surface symptoms and the blink rate or the interblink interval. In agreement with this study, previous studies have shown that ocular surface symptoms of dryness and discomfort are worsened after as few as 12 to 20 minutes of reading story books or compiled words from fiction novels.<sup>74,81,82</sup> In addition, a previous study reported both increased eyestrain symptoms and ocular surface symptoms after reading from a smartphone for 1 hour.<sup>80</sup> Whereas previous studies in adults did not find direct associations between symptoms and blink rate during digital device use, similar to this study,<sup>3,11,22</sup> an increased occurrence of incomplete blinking has been implicated in the worsening of ocular surface symptoms while reading on a computer or smartphone.<sup>11,22,80,83</sup> Complete blinking is essential to the replenishment of the tear film and maintenance of ocular comfort,<sup>84</sup> and incomplete blinking can potentially impact dry eye symptoms.<sup>85,86</sup> Blink amplitude was not characterized in the current study, but its usefulness as a possible marker of ocular surface health warrants exploration.

The day-to-day repeatability of blink rate was CoR  $\pm 12.4$  blinks/min; this finding sets the smallest measurable difference in blink rate in longitudinal studies. A closer inspection of the limits of agreement in Figure 6 suggests that CoR may differ with magnitude of blink measurement. Therefore, the CoR was calculated separately for blink rate values higher than 10 blinks/min. Repeatability was better with blink rates of 10 blinks/min or less (CoR,  $\pm 5.4$  blinks/min), but less reliable at more than 10 blinks/min (CoR,  $\pm 18.8$  blinks/min) (Supplementary Table S3). Previous studies intending to report repeatability of blink rate do not provide a standard repeatability measure to enable comparison with the present

findings.<sup>6,18,29,30</sup> These findings suggest that blink repeatability may be better during reading than conversation and walking. These results provide a basis on which to estimate sample size in future studies.

As for the blink rate, the repeatability of interblink interval was better for values of less than 10 seconds (CoR,  $\pm 3.9$  seconds) and poorer for longer interblink interval values (CoR,  $\pm 29.6$  seconds) (Supplementary Table S3). The overall CoR for interblink interval is higher compared with the normal range previously reported.<sup>19</sup> No studies have previously examined the repeatability of the interblink interval.

The strengths of this study lie with measurement of blinking in situ without the need for head restraint. Also, the blink rate and interblink interval were compared between various tasks on differing devices, controlling for complexity, viewing distance, direction of gaze, and luminance, within one study. Based on these results, in situ measurements of blinking parameters may not be feasible in a small proportion of participants owing to poor pupil detection confidence, the causes of which require further investigation. Poor pupil confidence unrelated to blinks can occur when using the wearable headset owing to extreme gaze angles or pupil obscuration by eyelashes.<sup>60</sup> Excluded data in the current study were likely unrelated to gaze angle, because no extreme gaze angles were observed by the continuous eye monitoring during data collection. Future studies should explore whether this limitation is uniquely related to participant's eye characteristics (e.g., long eye lashes).<sup>60</sup>

Incomplete blinking has been reported as an important marker of ocular surface symptoms during reading on smartphone or computer,<sup>9,11,80</sup> as well as during driving.<sup>87</sup> Future studies using the wearable eye tracker will enable examination of blink amplitude in situ during various task and conditions.

## CONCLUSIONS

The blink rate was decreased and the interblink interval increased during reading compared with conversation and walking. Changes in the blink rate and interblink interval were immediate and sustained for all tasks, suggesting that blinking is a rapidly responsive marker of changes. The similarity in the blink rate and interblink interval response during a variety of reading tasks, including on a smartphone, suggests that the lower blink rate during reading is not driven by the type of device used, viewing distance, screen brightness, or duration or complexity of task, but rather is intrinsic to the task of reading itself. There was no apparent relationship between changes in blinking and ocular surface comfort or signs.

The blink rate measured using a wearable device in situ was repeatable from day to day. The current study established solid foundations for the usefulness of blinking as a repeatable and responsive marker of ocular surface health when measured in situ. Future research should explore its usefulness in the settings of dry eye diagnosis and monitoring of treatment effectiveness.

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**Data Availability Statement:** The datasets generated during and/or analyzed during the current study are available in the Mendeley Data repository, <https://data.mendeley.com/drafts/j63x6bxj8k>, Doi:10.17632/j63x6bxj8k.1

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