Blink before and after you think: Blinks occur prior to and following cognitive load indexed by pupillary responses

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Abstract

Pupil dilation and blinks provide complementary, mutually exclusive indices of information processing. Though each index is associated with cognitive load, the occurrence of a blink precludes the measurement of pupil diameter. These indices have generally been assessed in independent literatures. We examine the extent to which these measures are related on two cognitive tasks using a novel method that quantifies the proportion of trials on which blinks occur at each sample acquired during the trial. This measure allows cross-correlation of continuous pupil-dilation and blink waveforms. Results indicate that blinks occur during early sensory processing and following sustained information processing. Pupil dilation better reflects sustained information processing. Together these indices provide a rich picture of the time course of information processing, from early reactivity through sustained cognition, and after stimulus-related cognition ends.

Descriptors: Blinks, Pupil dilation, Cognitive load, Attention, Stroop

This study investigated the extent to which pupil dilation and blinks provide complementary information about the time course of information processing. Assessment of change in pupil diameter provides information about the time course of cognitive information processing. The pupil is larger under conditions of higher attentional allocation, memory use, or interpretation of more difficult material (e.g., Beatty, 1982b). Pupil dilation persists if the demand is sustained (e.g., Beatty, 1982a). For example, as individuals are asked to remember larger numbers of digits, pupil dilation increases proportionally (e.g., Granholm, Asarnow, Sarkin, & Dykes, 1996; Kahneman & Beatty, 1966). Yet, pupil diameter cannot be assessed during blinks, as the pupil is occluded during those events by the eye. Generally, analyses of pupillary responses treat blinks as missing data and fill in estimates of pupil diameter during blinks with an approximation, for example, linear interpolation, which assumes that blinks occur randomly.

Yet, an independent literature suggests that blinks do not occur randomly (Stern, Walrath, & Goldstein, 1984), but rather, blink bursts follow high cognitive load (Fukuda, 1994, 2001; Ohira, 1996) or information processing (Ichikawa & Ohira, 2004), possibly reflecting a release of resources used in stimulus-related cognition (Ohira, Winton, & Oyama, 1998). Eyeblinks have also been observed to be suppressed directly preceding cued information processing, potentially reflecting effects of preparation (Ohira, 1995). Alternately, blinks may occur just after preparation, as very short blink latencies are associated with errors on cognitive tasks, consistent with inadequate preparation (Sirevaag et al., 1999). Transitions between interoceptive mental states associated with closed eyes and more extroceptive states associated with open eyes have been suggested to underlie cognitive modulation of blinks (Marx et al., 2003, 2004).

Cognitive processing associated with blinks can only be measured sporadically (i.e., at the times blinks occur). Initial literature suggests that, by combining these indices, a fuller picture of the time course of information processing can be ob-
tained. Pupil and blink data have been shown to explain independent variance in cognitive load over 10-s intervals (Van Orden, Limbert, Makeig, & Jung, 2001). Initial data further suggests that pupil dilation often follows blinks on a cognitive task (Fukuda, Stern, Brown, & Russo, 2005), potentially suggesting that blinks reflect either initial stimulus processing or preparation for engagement of cognitive resources. Other data suggest that, as difficulty increases, pupil dilation increases but blink rates decrease (Peng, He, Ji, Wang, & Yang, 2006), potentially suggesting that sustained cognitive load is associated with inhibition of blinks.

Other relationships are also possible. For example, blinks are associated with suppression of visual cortex activity (Bristow, Haynes, Sylvester, Frith, & Rees, 2005), which is a contributor to pupil dilation. Light flashes are associated with both blinking and pupillary constriction (Stamper, Lund, Molchany, & Stuck, 2002). Moreover, common aspects of brain function have been associated with both blinks and pupil dilation. For example, an fMRI study of blink patterns suggested that blinks were associated with activity in the medial frontal cortex (Yoon, Chung, Song, & Park, 2005), which has been implicated as central to pupil dilation, via projections to the Edinger Westphal nucleus, which controls the pupillary constrictor muscle (Szabadi & Bradshaw, 1996).

Whether brain activity underlying cognitive load is reflected in pupil dilation and blinks on the same time course is less clear though. This study therefore examined relationships between the time course of pupil dilation and blinks in healthy adults on two event-related cognitive tasks known to require different types and time courses of cognitive processing. These included putting digits in order (sustained processing) and a standard Stroop task (conflict resolution). We have previously published pupil dilation data on subsamples of our current sample on both of these tasks (Siegle, Steinhauser, Stenger, Konecky, & Carter, 2003; Siegle, Steinhauser, & Thase, 2004), but have not analyzed the blink data. Our primary question was when blinks occur, with respect to changes in pupil diameter.

To generate a continuously varying index of blink frequency following stimulus onset on the same time course as pupil dilation, we used a probabilistic approach to analyzing when blinks occurred. That is, the proportion of blinks occurring at each sample throughout a trial was recorded to provide a running average of blink frequency on the same time course as pupillary motility. This approach is different from conventional “blinks-per-seconds-long-time-window” approaches and may yield increased sensitivity to the latency of blink bursts. It is conceptually similar to event-related averaging of EOG data (Hackley & Vallee-Inclan, 1999) but can be done without the use of electrodes. Data were analyzed by overlaying plots of blink frequency and changes in pupil diameter and by examining correlations of these waveforms. We hypothesized that blinks would precede and follow pupil dilation on both tasks. Moreover, if pupil dilation indexes occupying of cognitive resources and blinks represent proportional engagement and disengagement of resources, it is expected that increased pupil dilation would be correlated with increased blinks. Using the same logic, pupil dilation is expected to be sustained during tasks requiring sustained load such as putting digits in order, whereas blinks, which only engage the beginning and end of resource recruitment, are not. In contrast, short bursts of cognitive load, as are present on the Stroop task or target detection (used in the latter half of digit-sorting trials), may yield less sustained pupil dilation than blinks.

Method

Participants

Participants were 58 healthy adults recruited from the Pittsburgh community via newspaper and television advertisements and flyers posted in and around the University of Pittsburgh and the University of Pittsburgh Medical Center. Data are reported here for a digit-sorting and Stroop task. Data were of acceptable quality on the digit-sorting task from 55 participants (18 male; 41 Caucasian, 7 African American, 3 Asian, 4 biracial; ages 19–55, $M_{\text{age}} = 31.9$ years [10.9 years]; $M_{\text{duration}} = 15.9$ years [2.8 years]) and on the Stroop task from 54 participants (18 male; 40 Caucasian, 7 African American, 4 Asian, 3 biracial; ages 19–55, $M_{\text{age}} = 32.4$ years [11.0 years]; $M_{\text{duration}} = 15.8$ years [2.9 years]); data was acceptable on both tasks from 51 participants. Data was not included for the remaining participants due to multiple factors, including mechanical failure, excessively noisy pupil or blink data (identified by visual inspection), or participants’ decision to not complete the entire testing session.

All participants had no current or historical Axis I psychiatric disorders, confirmed via a structured diagnostic interview (SCID; First, Spitzer, Gibbon, & Williams, 1996). Participants stated they had no significant eye problems; a subset who were assessed with a hand-held eye chart had normal corrected vision (20/30) with both eyes open; the remainder reported no difficulty reading text on a computer screen much smaller than the text used in the experiment. Participants described no health problems thought to interfere with performance or psychoactive drug intake within the past 6 months. All but 1 participant reported no alcohol abuse in the past 6 months; 1 participant’s data were ambiguous in this regard, and the participant could not be recontacted; their data was included. All participants scored in the normal range on a cognitive screen (NAART-II VIQ ≥ 80; Nelson & Willison, 1991), VIQ: range = 87.76–125.14, $M_{\text{SD}} = 109.6$ (8.1); FSIQ range = 91.9–127.8, $M_{\text{SD}} = 111.3$ (7.38).

Apparatus

Stimuli were displayed in dark gray on a light gray computer screen to minimize dilation to changes in illumination associated with stimulus onset and offset. Participants sat approximately 65.5 cm from the bottom of the stimulus. Stimuli were lowercase letters approximately 1.59 cm high, subtending 1.4° of visual angle. Reaction times were recorded using button presses on a game pad capable of reading reaction times with millisecond resolution. It was modified to contain three buttons, arranged in a triangle, so that respondents’ fingers were nearly equidistant from each possible response. To account for differential response latencies to different buttons, the mapping of game-pad buttons to responses was counterbalanced across participants.

Pupil dilation was recorded using methods previously described and tested (e.g., Steinhauser, Condray, & Kasparek, 2000). In brief, data were collected using ISCAN RK-406 and ISCAN RK-726 pupillometers. The pupillometers consisted of a video camera and infrared light source pointed at a participant’s eye and a device that tracked the location and size of the pupil using these tools. Pupil size was recorded at 60 Hz and passed digitally from the pupillometer to a computer that stored the acquired data along with signals marking the beginning of trials, the end of fixation, stimulus onset time, and reaction time. The pupillometer’s resolution for a typical participant was better than 0.025 mm pupil diameter. Data collection on the RK-406 was...
managed using EEGSYS (Hartwell, 1995). Data collection on the RK726 was managed using ISCAN’s included software. Both pupillometers were calibrated to the same 2–9-mm artificial pupils, and qualitatively similar condition-related variability on the digit-sorting task was observed in multiple participants from both sites to ensure reliability.

Procedure
At a first appointment, participants were told about the experiment and signed University of Pittsburgh, and if necessary, VA Pittsburgh IRB-approved consent forms. Participants received a brief vision test and the NAART. Within 2 weeks, participants then completed a battery of information processing measures as well as self-report measures not described here. Testing occurred in a moderately lit room (0.56 foot-candles for the RK406, 1.5 foot-candles for the RK726) in which the experimenter was not present. Time of day was not controlled for. The digit-sorting task was always administered as the first task; the order of the other tasks, which included a Stroop task reported here, was counterbalanced across participants.

Tasks

Digit-sorting task. A digit-ordering task similar to that used by MacDonald, Almor, Henderson, Kempler, and Andersen (2001) was examined because it requires sustained cognitive load for up to 5 s in response to a single visual stimulus. Participants completed 36 trials (12 per condition) in which they were instructed to view a fixation mask (1 s), which was replaced by a set of three, four, or five digits (2 s), which was replaced by another fixation mask (5 s). Then, a new “target” digit appeared that was one of the digits that was in the previously presented set and remained on the screen for 10 s. The interstimulus interval was constant. Only two sequences of digits were repeated, both in the three-digit condition, once with the target absent and once with it present. Participants were told that when the digits appeared, they should read them from left to right, sort them in memory (i.e., put them in numerical order), and remember the middle digit in the sorted list. If there were an even number of digits, the higher of the middle digits was to be remembered. Participants were also instructed that when the target appeared, they should push a “yes” or “no” button to indicate whether the target digit was the middle digit from the previous set as quickly and accurately as they could. The order of these buttons was counterbalanced across participants. Labels for these responses were displayed in the upper right hand corner of the monitor. Participants were told they should not use special strategies such as counting the digits by moving their eyes on the screen or sorting only the first few digits, because we were examining the process of sorting items in memory. Participants were instructed to blink as little as possible during the task. Participants reported that following this instruction did not make them uncomfortable. We have previously demonstrated condition-related variation in pupil dilation on this task in a subset of the current sample (Siegle et al., 2004).

A slow-event-related variant of the classic Stroop task (Stroop, 1935) was chosen because it requires a briefer period of cognitive load than digit sorting. Participants completed 36 trials (18 congruent) in which they viewed a fixation mask (row of X’s with vertical prongs over the center) for 1 s followed by a color word for 150 ms, followed by a mask (row of X’s) for 11 s. The interstimulus interval was constant. To achieve a representative number of congruent stimuli, congruent stimuli were repeated six times each, and to allow the maximum differentiation of incongruent pairings, incongruent stimuli were repeated three times each, in a pseudorandom order. Trials were consistently paced. Participants were instructed to push a button for the color in which the word was written (red, green, or blue) as quickly and accurately as possible. The order of these buttons was counterbalanced across participants, and the first letter of each color name was always displayed in the upper right corner of the screen to cue subjects to the button order. Participants were instructed to blink as little as possible during the task. Participants reported that following this instruction did not make them uncomfortable. We have previously demonstrated condition-related variation in pupil dilation on this task in a subset of the current sample (Siegle et al., 2004).

Data Selection, Cleaning, and Reduction

Selection of stimuli for analysis. Trials with reaction times below 150 ms were discarded as outliers because it was unlikely these responses were made with regard for the stimulus (digit sorting $M \pm SD = 0.12 \pm 0.47$ s; Stroop $M \pm SD = 0.13 \pm 0.39$ s). Incorrect trials were also eliminated from pupil dilation and blink averages on the digit sorting ($M \pm SD = 2.8 \pm 3.9$ s) and Stroop ($M \pm SD = 1.2 \pm 1.3$ s) tasks.

Calculation of blink waveforms. Blinks were identified as large changes in pupil dilation occurring too rapidly to signify actual dilation or contraction. Specifically, blinks were coded as samples with estimated pupil diameter meeting any of the following criteria: (1) below 1 mm, (2) below the minimum diameter in a subject’s waveform + 0.1 mm, (3) below the median diameter minus 4 mm, or (4) below two times the interquartile range below the 25th percentile (i.e., the Tukey extreme outlier hinge). Blinks were also identified in samples with changes in pupil diameter above 0.4 mm in four samples (0.06 s). Because intervals between blinks of less than 10 samples (0.16 s) were unlikely to represent periods of clear vision, when an interval of less than 10 samples separated two blinks, both blinks and the interval between them were judged to be part of the same single blink.

Samples meeting blink criteria were coded as 1, and samples without blinks were coded as 0. The mean proportion of blinks at each sample within each condition (i.e., number of trials on which blinks occurred at the sample divided by number of trials in the condition) was then calculated to yield condition-related blink-frequency waveforms. A relative proportion was computed as the blink frequency at each sample minus the mean blink frequency in the first 10 samples (0.17 s) preceding the onset of the stimulus (digit sorting, $M \pm SD = 0.11 \pm 0.08$; Stroop task, $M \pm SD = 0.11 \pm 0.18$).

Calculation of pupil dilation waveforms. Data were cleaned using methodology similar to that described by Granholm et al. (1996). Specifically, trials comprised of over 50% blinks (defined as for blink waveforms) were removed from consideration. Linear interpolations beginning four samples before and ending nine samples after a blink replaced blinks throughout the data set. This technique prevented interpolation to poor pre- and post-blink pupil estimates due to partial lid closures. Linear trends in pupil dilation calculated over blocks of 20 trials were removed from pupil dilation data to eliminate effects of slow drift in pupil dilation.
diameter that were not related to trial characteristics. The average pupil diameter in the 10 samples (0.17 s) preceding the onset of the stimulus was subtracted from pupil diameter after stimulus onset to produce pupil dilation difference score indices. Stimulus selection and data cleaning procedures resulted in the elimination of $Md = 4$ trials, $M (SD) = 5.9$ trials (5.8 trials) on the digit sorting task and $Md = 3$ trials, $M (SD) = 4.8$ trials (6.8 trials) on the Stroop task.

### Determination of windows of significant differences

Contrasts on pupil dilation were examined via statistical tests at each point along pupil dilation and blink waveforms. To control type I error for this large number of tests, Guthrie and Buchwald’s (1991) technique was used, as we have done in our previous publications on pupil dilation in these data sets (Siegle, Steinhauser, Stenger, et al., 2003; Siegle et al., 2004). Briefly, this technique involves using Monte Carlo simulations to estimate the number of consecutive significant differences long enough to be judged to not have occurred by chance with $p < .05$ given the temporal auto-correlation of the data. Thus, contiguous sample-by-sample tests are considered replications. As we have previously noted, simulations suggested that windows of 35 significant consecutive tests significant at $p < .1$ (0.56 s) would yield windows of differences significant at $p < .05$.

Effects of condition for the Stroop task (differential response to congruent vs. incongruent stimuli) were examined using paired $t$ tests. Effects of condition on the digit sorting task were examined using multivariate ANOVAs, which are not subject to violations of sphericity, at each sample. All of these tests were performed at each point along the relevant waveforms. When results are reported for an entire time window, they represent tests of the mean pupillary or blink responses in a window of consecutive significant differences.

For direct comparisons of the relative magnitude of blink and pupil proportions, data were rescaled into standard-deviation units by dividing the relative change in millimeters or blink proportion from the prestimulus baseline values by the standard deviation of these changes over the entire waveform. The resulting waveforms were compared using paired $t$ tests along the waveform, subject to the same Type I error correction methods as for condition-related comparisons.

Throughout the article $p$ values representing statistical significance are reported exactly unless they are below .005, in which case they are reported as $p < .005$.

### Results

#### Digit-Sorting Task

As expected, mean harmonic mean reaction times did not differ significantly between conditions via multivariate repeated measures analyses of variance, $M (SD)$ reaction times: three digits: 1266.7 ms (507.6 ms), four digits: 1254.5 ms (466.3 ms), five digits: 1314.6 ms (555.7 ms), $F(2,51) = 1.86$, $p = .17$. The same was true for accuracy when both $d'$ and percent correct were considered (percent correct reported here because performance was near ceiling, inflating $d'$ for many participants), $M (SD)$ percent correct, three digits: 94% (17%), four digits: 93% (11%), five digits: 91% (18%), $F(2,51) = 1.07$, $p = .35$.

Figure 1a,b shows the pupil and blink proportion waveforms for each condition (three, four, or five digits) for the digit sorting task. Both blinks and pupil diameter displayed clear task-timing related variation. For blinks, condition-related variation was significantly different in the window from 1.10 to 3.93 s following stimulus onset, $F(2,39) = 3.19$, $p = .05$, which was during the digit sorting period. As shown in the figure, blinks were inhibited compared to the prestimulus blink rate more for the four- and five-digit conditions than the three-digit condition. Pupil dilation displayed condition-related differences throughout the trial.

![Figure 1](image_url)

**Figure 1.** Blink frequency and pupil dilation in response to the digit sorting task ($n = 55$). Panel a shows the proportion of blinks at each sample for each condition. Panel b shows pupil dilation in each condition. In panels a and b significant condition-related differences are highlighted below the x-axis (light = $p < .1$, dark = $p < .05$). Both blinks and pupil dilation reflected clear task- and condition-related variation. Panel c shows z-scored overlays of the blink and pupil dilation data and reveals that blinks frequently preceded and followed periods of pupil dilation.
from 2.18 to 9.60 s, \( F(2,39) = 19.60, p < .005 \), and then from 9.68 to 16.35 s, \( F(2,39) = 6.41, p < .005 \). Figure 1c shows blinks and pupil diameter superimposed. These data suggest that an initial decrease in blink frequency occurred as stimulus-related pupil dilation was beginning. A burst of blinks occurred shortly before peak pupil dilation. Pupil dilation was sustained compared to blinks throughout the digit-sorting interval for the three-digit condition, 4.02 to 8.02 s, \( t(54) = -3.76, p < .005, d = -0.51 \), the four-digit condition, 3.68 to 7.77 s, \( t(54) = -4.86, p < .005, d = -0.65 \), and the five-digit condition, 3.60 to 10.93 s, \( t(54) = -6.95, p < .005, d = -0.94 \). Blinks again decreased as the target came on concurrent with pupil dilation, and were then sustained following target identification while pupil dilation decreased, particularly in the four-digit condition, 13.18 to 15.27 s, \( t(54) = 2.78, p = .01, d = 0.38 \), and 16.85 to 18.00 s, \( t(54) = 2.82, p = .01, d = 0.38 \). The peak of the blink waveform in the 1–5-s window was significantly earlier than the peak of the pupil dilation waveform in the four-digit condition, \( t(54) = 4.92, p < .005, D = 46.05 \text{ ms}, d = 0.66 \), and the five-digit conditions, \( t(54) = 8.57, p < .005, D = 75.36 \text{ ms}, d = 1.16 \), but there were no significant differences in the three-digit condition.

To better understand what aspects of pupil dilation were most strongly related to blinks, we correlated the mean blink waveforms in each condition with the mean pupil dilation waveform and its first and second derivatives as well as the absolute value of these derivatives. If blinks parallel pupil dilation, high correlations would be expected with the pupil dilation waveform. If they precede or follow cognitive load, high correlations would be expected with the lowest absolute values of the second derivative, representing periods of constant pupil diameter, that is, times at which the pupil is not responding to a stimulus. As shown in Table 1, though all correlations were small, the most reliable associations in all three conditions were with the absolute value of the second derivative.

**Stroop Task**

As expected, mean harmonic mean reaction times were slower for incongruent than congruent trials via multivariate repeated measures analyses of variance, \( M (SD) \) reaction times: congruent: 985.0 ms (457.8 ms), incongruent: 1144 ms (492.6 ms), \( F(1,52) = 84.22, p < .005 \). Though most participants performed nearly perfectly, accuracy was marginally lower when both \( d' \) and percent correct were considered (percent correct reported here because performance was near ceiling, inflating \( d' \) for many participants), \( M (SD) \) percent correct, congruent: 98% (11%), incongruent: 96% (9%), \( F(1,52) = 3.76, p = .06 \).

Figure 2a,b shows the pupil and blink proportion waveforms for each condition for the Stroop task. As in the digit-sorting task, both blinks and pupil diameter displayed clear task-timing-related variation. Blinks did not show condition-related variation.

### Table 1. Associations of Mean Blinks with Pupil Dilation and Its Derivatives

<table>
<thead>
<tr>
<th>Condition</th>
<th>Index</th>
<th>( t(54) )</th>
<th>( p )</th>
<th>( D )</th>
<th>Effect size (Cohen’s ( d ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congruent</td>
<td>pupil</td>
<td>6.12</td>
<td>&lt;.0005</td>
<td>.27</td>
<td>0.83</td>
</tr>
<tr>
<td>Congruent</td>
<td>( d_{\text{pupil}} )</td>
<td>-1.74</td>
<td>.09</td>
<td>-0.05</td>
<td>-0.23</td>
</tr>
<tr>
<td>Congruent</td>
<td>( d_{\text{pupil}}^2 )</td>
<td>-2.88</td>
<td>.01</td>
<td>-0.01</td>
<td>-0.39</td>
</tr>
<tr>
<td>Congruent</td>
<td>abs(( d_{\text{pupil}} ))</td>
<td>-2.14</td>
<td>.04</td>
<td>0.05</td>
<td>0.29</td>
</tr>
<tr>
<td>Incongruent</td>
<td>pupil</td>
<td>6.23</td>
<td>&lt;.0005</td>
<td>.27</td>
<td>0.84</td>
</tr>
<tr>
<td>Incongruent</td>
<td>( d_{\text{pupil}} )</td>
<td>-4.34</td>
<td>&lt;.0005</td>
<td>-0.10</td>
<td>-0.59</td>
</tr>
<tr>
<td>Incongruent</td>
<td>( d_{\text{pupil}}^2 )</td>
<td>-2.85</td>
<td>.01</td>
<td>-0.01</td>
<td>-0.38</td>
</tr>
<tr>
<td>Incongruent</td>
<td>abs(( d_{\text{pupil}} ))</td>
<td>1.49</td>
<td>.14</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>Incongruent</td>
<td>abs(( d_{\text{pupil}}^2 ))</td>
<td>-7.71</td>
<td>&lt;.0005</td>
<td>-0.07</td>
<td>-1.04</td>
</tr>
</tbody>
</table>

\( \text{aCorrelations significant at } p < .05 \) controlling for Type I error following a Bonferroni correction (\( p < .003 \) uncorrected for digit sorting, \( p < .005 \) for the Stroop task) are highlighted in boldface. \( d_{\text{pupil}} \) is the first derivative of pupil diameter. \( d_{\text{pupil}}^2 \) is the second derivative of pupil diameter.
whereas the pupil did respond to Stroop condition: Incongruent words were associated with increased pupil diameter 1.85 to 3.27 s following trial onset, \( t(53) = 3.25, p < .005 \). Difference \( (D) = 0.03 \text{ mm}, d = 0.44 \). As shown in the figure, the peak of the blink waveform was earlier for the congruent compared to the incongruent condition, when peaks in the time window between 1.0 and 3.5 s were examined, \( t(53) = -2.34, p = .02, D = 11.35 \text{ ms}, d = 0.31 \). Figure 2c shows relative changes in blinks and pupil diameter superimposed. Although peak pupil diameter increased more than peak blink percentage for incongruent trials in the 1.85–2.60-s window, \( t(53) = -2.45, p = .02, d = -0.33 \), as in the digit-sorting data, the blink rate was increased following the response whereas pupil dilation was not for both congruent trials from 3.35 to 6.93 s, \( t(53) = 4.13, p < .005, d = 0.56 \), and from 9.93 to 12.00 s, \( t(53) = 3.54, p < .005, d = 0.48 \). For incongruent trials from 3.52 to 12.00 s, \( t(53) = 4.84, p < .005, d = 0.66 \).

In the congruent condition, the peak latency for blinks was 16.5 ms earlier than for pupil dilation, \( t(53) = 3.01, p = .004, d = 0.41 \); differences were not significant for the incongruent condition.

As for the digit-sorting task, correlations of blinks and pupil diameter waveforms, shown in Table 1, suggested that blinks were reliably associated with pupil dilation and negatively with the absolute value of the second derivative of pupil dilation.

**Sensitivity Analyses**

To understand the extent to which blink and pupillary responses were a function of variation in reaction times, Figure 3 presents reaction-time-locked waveforms analogous to Figures 1c and 2c. As shown in the figure, the qualitative patterns of reactivity are similar as for the stimulus-locked data for both tasks. On the digit-sorting task, blinks peaked before pupil dilation in the four- and five- digit conditions and, again, were sustained following the target compared to the pupillary response. Similarly, on the Stroop task, blinks peaked earlier and were sustained following the reaction time compared to pupil dilation in both conditions.

**Discussion**

Blinks and pupil dilation have both been associated with cognitive load. This study used a new approach to quantifying blink rates over time to examine their temporal association in healthy adults on two cognitive information processing tasks. Results suggested that the time course of blinks and pupil dilation were moderately correlated. Yet these measures were not redundant. On both tasks, results were consistent with a burst of blinks peaking before the pupillary response and occurring most reliably during times in which the pupillary response was neither accelerating nor decelerating, potentially signifying that blinks flank periods of change in cognitive load. As the peak pupil dilation is delayed from neural and muscular activity by up to 0.5 s, blinks may, as reported in previous reports, precede peak cognitive load indexed by pupil dilation (Fukuda et al., 2005). Sustained cognitive load was accompanied by sustained pupil dilation but not sustained blinks. Yet blinks were sustained following peak cognitive load in both tasks, consistent with the idea that blinks represent the end of cognitive processing and a releasing of information from working memory (Ichikawa & Ohira, 2004).

**Figure 2.** Blink frequency and pupil dilation in response to the Stroop task \((n = 54)\). Panel a shows the proportion of blinks at each sample for each condition. Panel b shows pupil dilation in each condition. In panels a and b significant condition-related differences are highlighted below the x-axis \((light = p < .1, dark = p < .05)\). The onset and offset of stimuli are marked with vertical lines in panels a and b. Both blinks and pupil dilation reflected clear task-related variation, but only pupil dilation shows condition-related variation. Panel c shows z-scored overlays of the blink and pupil dilation data and reveals that blinks frequently followed periods of pupil dilation.

Our supplementary data, available online at [http://www.pitt.edu/~gsiegle/siegle-pupilblinks-SupplementaryMaterial.pdf](http://www.pitt.edu/~gsiegle/siegle-pupilblinks-SupplementaryMaterial.pdf), present a number of additional analyses suggesting the following: (1) Cross-correlations of the entire blink and pupil waveforms are consistent with our primary analyses. Additionally, they suggest that blinks occurring at stimulus onset were correlated with pupil dilation throughout the trial on the digit-sorting task and in the 4–10-s window on the Stroop task. (2) Results did not differ qualitatively between the two employed pupilometers. (3) Results were not strongly affected by eye position, although some data coded as blinks may have actually been vertical eye movements. Removal of high velocity eye movements did not change the observed results qualitatively.
Together these data are consistent with previous studies suggesting that blinks and pupil dilation provide nonredundant but related indices of information processing (Van Orden et al., 2001). They additionally suggest that blinks may be especially sensitive to the onset and offset of stimulus-related information processing whereas pupil dilation may be most sensitive to sustained information processing. Also, as blinks appeared to be increased in the prestimulus time window on the digit-sorting task (Figure 1a) and as a fixed interstimulus interval was employed, blinks may be sensitive to preparatory effects, which could be examined in a future study that varied the predictability of stimulus onset times.

There are multiple other potential explanations for the blink burst at the beginning of trials. For example, as there was a predictable interstimulus interval, participants may have blinked at the beginning of trials simply to moisten their eyes or to better focus on the stimulus. These explanations may be slightly less likely, as blinks occurred directly after auditory stimuli in a previous study (Fukuda, 1994). The blink burst could also have occurred before peak pupil dilation if blinks and pupil responses reflect similar underlying processes; because blinks are a function of striate muscles and the pupil is controlled by smooth muscles, the pupil has a more sluggish impulse response. Its response would therefore peak later than blinks. This interpretation would specifically help to explain why the blink burst no longer preceded peak pupil dilation in the response-aligned data. Allowing for a delays of blinks and pupil dilation from neural activity would explain why neither index peaked before the reaction time. a: Digit-sorting task. b: Stroop task. Figure 3. Z-scored overlays for pupil dilation and blinks for reaction-time-aligned condition means. In each panel, 0 is the reaction time. a: Digit-sorting task. b: Stroop task.

A number of factors may qualify observed results. Having instructed participants to blink as little as possible could significantly have altered their natural blinking pattern on the tasks, particularly if they intentionally tried to not blink during the times the stimulus was present on the screen. The use of two different pupillometers could have but was unlikely to have influenced the data, given that results are qualitatively similar for each pupillometer (Supplemental data, Figure 3). Generalization of the observed results could be limited to slow-event-related tasks that provoked relatively low levels of cognitive load and affective engagement: Increasing processing load, for example, with faster trials, or inducing heightened states of arousal could change the observed relationships. As performance was near-perfect on both tasks, examination of relationships of pupil dilation and blinks to performance was not possible. Our sample was generally quite healthy and well educated; the extent to which results generalize to a broader population also must be explored. Data were collected at 60 Hz. Potentially more subtle phenomena (e.g., blinks occurring before or after very small quick changes in pupil diameter) could be detected with a faster sampling rate, though there is no theoretical reason to suspect this happened.

Additionally, blinks in this experiment were detected as large deviations from usual pupillary motility, measured with an infrared
pupillometer. There are reasons other than blinks that a pupillometer might fail to register good data such as large head or, potentially, eye movements. Future research using electrode-based measures of blinks could more specifically try to separate these effects. Although there is no theoretical reason to believe that vertical eye movements on tasks with centrally fixated stimuli would be systematic (as opposed to conjugate lateral eye movements, which have been associated with cognitive load; Bakan & Strayer, 1973; Gur, 1975) but were not observed to be associated with blinks in this study, we did find a significant association of blinks with estimated small upward changes in eye gaze (see supplementary data), which did not confound the primary findings. Potentially this association is due to partial lid closure effects on gaze occurring directly before blinks, which resolve after blinks. If this phenomenon is replicable under a design specifically created to understand these effects, it could represent an interesting area for future research. Such a role would be supported by literature on brain activity associated with saccades (e.g., Dyckman, Came- hong, Clementz, & McDowell, 2007).

These limitations notwithstanding, this study brings together two sometimes disparate literatures, one stemming from observations of what happens when the eyes are closed and one stemming from observations exclusively regarding when the eyes are open. Results suggest that blinks and pupil dilation may be thought of as complementary. Pupil dilation and blinks are easy and noninvasive to measure. The increasing availability of these measures from infrared eye trackers makes them particularly useful as adjunctive measures during functional neuroimaging (e.g., Harrison, Singer, Rotstein, Dolan, & Critchley, 2006; Siegle, Steinhauser, Stenger, et al., 2003; Urry et al., 2006). Pupillometry studies inherently measure blinks but, traditionally, remove them from consideration as part of the data preprocessing. Rather, we suggest that it may be useful to analyze blinks in the same time-dependent way that pupil dilation is examined. Examining the proportion of blinks at each sample during a trial allows precise quantification of when blinks generally occur following a stimulus, potentially yielding a more nuanced portrait of the time course of cognitive load than traditional blink measures. Reporting on blinks and pupil dilation in the same manuscript can provide convergent validity for explanations involving the time course of cognitive load, from preparation, onset of load, peak processing, and the offset of or recovery from cognitive load.

REFERENCES


Blinks and pupil dilation


**SUPPORTING INFORMATION**

The following supporting information for this article is available online:

**Figure 1.** Cross-correlations of blinks and pupil dilation.

**Figure 2.** Cross-correlations of blinks and pupil dilation.

**Figure 3.** Results analogous to primary figures 2c and 3c, but separated by pupilometer.

**Figure 4.** Results with high velocity periods not counted, analogous to primary figures 2c and 3c.

This material is available as part of the online article.

(Received April 10, 2007; Accepted October 15, 2007)