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Pupillary responses and processing resources on the visual backward masking task

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Abstract

Task-evoked pupillary responses were recorded during a visual backward masking task as an index of resource allocation. Increased pupillary dilation indicates increased allocation of processing resources to the task. Consistent with numerous studies, detection accuracy increased with longer interstimulus intervals and approximated no-mask accuracy in the 300-ms condition. Pupillary dilation responses were significantly greater during task performance (cognitive load) than during a passive stimulus viewing condition (no-load) and were significantly greater in the 300-ms condition than the no-mask condition. Consistent with models of early visual information processing, the results suggest that the mask demanded extra processing resources when it followed the target by more than 100 ms. Pupillography methods may be useful in evaluating the contribution and timing of resource-demanding processes during early visual information processing.

Descriptors: Information processing, Perception, Attention, Pupillary response, Cognition, Processing resources

The visual backward masking task is a well-studied cognitive task that has been used to investigate the early stages of human information processing. The backward masking paradigm has been used in a wide range of studies, most notably in schizophrenia research (for reviews see Braff, Saccuzzo, & Geyer, 1991; Nuechterlein & Dawson, 1984; Rund & Landro, 1990; Saccuzzo, 1993), and intelligence literature (see Deary & Stough, 1996, and White, 1996, for an overview). The visual backward masking procedure consists of a rapidly presented target stimulus (e.g., letters, or lines of different length), a varying length of vacant time (interstimulus intervals, typically ranging from 20 to 500 ms), and a masking stimulus that typically covers the spatial presence of the target stimulus. The participant is usually asked to decide which of a pair of stimuli were presented as targets (i.e., forced-choice paradigm). Several versions of the visual backward masking task exist (e.g., different spatial, temporal, and energy interactions between target and mask, and monoptic, dichoptic, and binocular setups, critical and standard target durations; see Saccuzzo, 1993, for a thorough explanation), each producing different masking functions and tapping different stages and mechanisms of processing (Breitmeyer & Ganz, 1976; Felsten & Wasserman, 1980; Kahneman, 1968; Michaels & Turvey, 1979; Turvey, 1973).

Although the visual backward masking task has been useful in detecting differences between a variety of participant groups, the cognitive mechanisms underlying group differences remain unclear. Several different cognitive mechanisms contribute to visual backward masking task performance, and methods for identifying which of these mechanisms contribute to the backward masking task deficits of specific participant groups are needed. At least three fundamental mechanisms underlie visual backward masking task performance: integration, interruption (or inhibition), and attentional shifting (or replacement; Breitmeyer, 1984; Breitmeyer & Ganz, 1976; Michaels & Turvey, 1979; Phillips, 1974; Turvey, 1973).

Integration involves the fusing together of the target and the mask representations (or icons; Neisser, 1967), resulting in an indecipherable icon, similar to a double-exposed photograph. Integration is maximal when the target and mask in this scenario are too close, both temporally and spatially, for a clear image of the target to be formed. This overlapping of the target and mask typically occurs at very short interstimulus intervals (e.g., less than 20 ms).

Interruption (or interchannel inhibition) occurs when processing of the target is disrupted by the incoming processing signals of the mask, resulting in only partial processing of the target. Interruption for normal individuals does not occur, or is negligible, at the shortest interstimulus intervals (e.g., less than 20 ms), increases to a maximum between 20 and 70 ms, and then decreases again. The time course when interruption is maximal may vary by task (e.g., earlier for letters than for lines as target stimuli). Michaels and Turvey (1979) suggested that these two mechanisms, integra-

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tion and interruption, interfere with a central processor they called "the constructor," which builds an icon representation of incoming stimuli.

Breitmeyer and colleagues (Breitmeyer, 1984; Breitmeyer & Ganz, 1976) elaborated on this two-factor (integration and interruption) model of masking with regard to transient and sustained visual processing channels. Transient visual pathways (magnocellular tract) transmit information about stimulus onset, offset, and location. Cells involved in this transient visual channel respond quickly to stimuli and are sensitive to the course features of stimuli (low spatial frequency). In contrast, sustained visual pathways (parvocellular tract) respond more slowly to stimuli and are concerned with the fine details of stimuli (high spatial frequency). In this model, the transient visual channels first detect the location and rough image of the target stimulus, and then the sustained visual channels carry out a more detailed analysis. Integration occurs when activity of the target and mask combine in the sustained visual channels, and interruption occurs when the transient activity of the mask disrupts sustained activity of the target.

A third source of masking effects that has been proposed involves the shifting and sharing of processing resources between the target and mask (Loftus, Hanna, & Lester, 1988; Michaels & Turvey, 1979; Phillips, 1974). At 100 ms or more after the target presentation, there is thought to be an additional allocation of processing resources to the identification of stimulus meaning in short-term visual memory (Phillips, 1974). Thus, at this timepoint, stimulus identification resources allocated to identify the meaning of the target must also be used to identify the meaning of the mask (Michaels & Turvey, 1979; Phillips, 1974). Michaels and Turvey referred to this as "replacement," whereby target information is replaced by mask information as the main focus of attention by a central processor called "the algorist." In the time course of early visual processing, this is the first point at which attention as the allocation of processing resources (Hirst & Kalmar, 1987; Kahneman, 1973; Wickens, 1984) is attributed to masking effects. Masking occurs after this timepoint, not because the quality of a single icon is degraded by integration and/or interruption, but because a well-formed target icon and a second well-formed mask icon compete for common stimulus identification resources or algorithms. In addition, the switching or timesharing of resources between the target and mask is itself an algorithm (resource)-demanding process.

In the present study, pupillary responses were recorded during performance of a visual backward masking task in an attempt to index the time course of these resource-demanding components of early visual information processing. Task-evoked pupillary responses reliably index controlled processing resource allocation during cognitive tasks. In a review of pupillometry studies of cognitive processing, Beatty (1982) established that task-evoked pupillary responses reflect within-task, between-task, and between-individual variations in processing demands. Increased processing demands on tasks tapping memory (e.g., digit span), language (e.g., grammatical reasoning, word match, sentence encoding), reasoning (e.g., multiplication), and perception (e.g., discrimination, detection) result in increased pupil diameter. For example, a systematic increase in pupil dilation is observed following the presentation of each to-be-recalled digit on a digit-span recall task (Granholm, Asarnow, Sarkin, & Dykes, 1996), and more difficult multiplication problems (e.g., multiplying pairs of two-digit numbers) result in greater pupillary dilation than less difficult problems (e.g., multiplying pairs of one-digit numbers; Ahern & Beatty, 1979).

The purpose of this study was to investigate the time course of resource-demanding masking mechanisms by using pupillary responses as an index of the extent of processing resources allocated during different masking conditions (17, 33, 50, 100, and 300 ms interstimulus intervals and no-mask conditions) in normal undergraduate students. It was hypothesized that participants would show significantly greater pupillary dilation while performing the visual backward masking task (cognitive load conditions) relative to passive viewing of the stimuli (cognitive no-load conditions). This finding would be consistent with numerous other studies (review by Beatty, 1982) indicating that task-evoked pupillary responses are a valid index of processing resource allocation. We further hypothesized that pupillary dilation responses would be significantly greater in the 300-ms interstimulus interval condition than in the no-mask condition. The Michaels and Turvey (1979) and Phillips (1974) theories hold that an additional allocation of processing resources for identifying the meaning of the mask interferes with target processing only after the mask follows the target by more than 100 ms (i.e., in the 300-ms interstimulus interval condition). Pupillary responses in the no-mask condition index the processing load associated with only target processing, whereas pupillary responses in masking conditions index the processing load associated with both target and mask processing. Thus, if additional processing resources are required for identifying both target and mask only in the 300-ms interstimulus interval condition, this requirement should be reflected in greater pupillary dilation responses in the 300-ms interstimulus interval condition relative to the no-mask condition and other interstimulus interval conditions.

The alternative two-factor account of masking (Breitmeyer & Ganz, 1976), which relies on only integration and interruption, makes different predictions. If a single icon becomes a progressively clearer representation of the target as the effects of integration and interruption diminish with longer interstimulus intervals, then a linear increase in pupillary responses (resource allocation) should be found across increasing interstimulus intervals as clearer targets become available for processing by "the algorist." Further, no interstimulus interval should result in greater pupillary responses than the no-mask condition, if there is no shifting and sharing of resources between the target and mask. Thus, pupillography methods will be used to more directly measure whether a resource allocation mechanism contributes to masking in longer interstimulus intervals.

Method

Participants

Students who responded to advertisements at the University of California, San Diego (UCSD) campus were recruited and consented to participate in the study for monetary compensation. The sample (n = 37) had a mean age of 21.9 years (SD = 3.4), mean education of 15.0 years (SD = 1.9), and were 71.4% female (complete demographic information was not available for two participants). A brief background interview was given to screen participants for factors that potentially affect pupil dilation or cognitive functions (e.g., head injury, substance abuse, diabetes). No participant smoked cigarettes or drank caffeinated beverages within 2 hr before the testing session. Also, none reported any injuries, diseases, or surgeries of the eye. All participants were screened for at least 20/30 visual acuity (corrected or noncorrected) using a Snellen wall chart.

Apparatus

Pupillary responses were recorded from the left eye using a Micromeasurements System 1200 infrared corneal-reflection-pupil-center pupillometer. A video camera sensitive to infrared light and an infrared light source were positioned 20 cm from the participant's eye. Participants were seated comfortably in a lighted room (background luminance = 486 lux) with their chin and forehead stabilized in a headrest. The headrest was used to reduce movement artifact and maintain a distance of 77 cm between the participants' eyes and the computer monitor. Pupil diameter was sampled at 60 Hz, digitized, and saved for offline analysis. A two-button joystick provided the "Right" and "Left" response buttons. A 14-inch Super Video Graphics Adapter (SVGA) monitor controlled by a Dell 386/33 MHz microcomputer was used to administer the backward masking task. This computer and the pupillometer computer were networked to allow precise time locking of pupillary responses with visual backward masking stimulus and response events.

Visual Backward Masking Stimuli and Procedure

A computer program (written by S.P.V.) was used to administer the visual backward masking task, which consisted of 30 pretest trials, 120 test trials, and 30 posttest trials. The reason for the inclusion of pre- and posttest trials was twofold: (1) to provide for a "cognitive no-load" condition, as participants were asked to simply view the stimuli without responding during pretest and posttest trials, and (2) to investigate whether habituation of the pupillary response would be observed over the course of the testing session. The test trials constituted a "cognitive load" condition in which the participants were asked to identify which of two target lines was longer (i.e., forced-choice paradigm). The target stimulus consisted of two adjacent vertical lines presented in the center of the screen, 1.7 cm apart. For every trial, one of the two lines (right or left) was longer than the other (2.7 vs. 2 cm) and offset vertically in height in one of six different target configurations. The upper endpoint of the "short" line could be higher, equal, or lower than the upper endpoint of the "long" line, and the short line could be either the right or left line. Also, only one endpoint (upper or lower) of one target line could be in alignment with the same endpoints of the masking lines. In this manner, the effects of apparent movement or flicker as a mask-breaking cue may be reduced (Alexander & Mackenzie, 1992). The long and short lines were blocked randomly in series of 12 trials (so that each of the six offset configurations was presented twice in every sequence of 12 trials). The masking stimulus was comprised of two 4-cm long, parallel lines that completely replaced (spatially) the target stimulus lines.

The target and masking stimuli were separated by intervals of 17, 33, 50, 100, or 300 ms, and a no-mask condition was included as a control. These interstimulus intervals, comprising a typical range in the backward masking literature, were bounded by the 60-Hz refresh rate of the monitor and were timed to display in accordance with the top of the refresh cycle. In the test condition (i.e., cognitive load), the six interstimulus interval conditions were presented in blocks of five trials in the following counterbalanced sequence: 100, 33, 50, 300, no-mask, 17, 100, no-mask, 300, 17, 50, 33, 17, no-mask, 50, 300, 33,100, 300, 17, 33, no-mask, 100, 50 ms. For the pre- and posttest conditions (i.e., cognitive no-load), the six interstimulus intervals were presented in blocks of five trials each for a total of 30 trials; the pretest sequence was 17, no-mask, 50, 300, 33, 100 ms, and the posttest sequence was 100, 33, 300, 50, no-mask, and 17 ms. In this study, the target and mask had equal duration (17 ms; one 60-Hz screen refresh rate), and the relationship between interstimulus interval and stimulus onset asynchrony is simply interstimulus interval = stimulus onset asynchrony + 17 ms. The target stimulus and masking stimulus were displayed at 2.01 and 2.97 degrees of visual angle with luminance measured at 5.7 and 6.1 lux, respectively.

At the beginning of each trial, a green fixation square (0.85 × 0.85 cm, 0.63 degrees of visual angle, and 7 lux) was presented in the center of the monitor (with a black screen background) along with a high-pitched tone (1500 Hz for 500 ms). The fixation square and tone served as visual and auditory cues to warn the participant to prepare for the trial's target stimulus. When the participant's left pupil was detected as fixating on the green square for at least 200 ms, evidenced by a calibration (prior to testing) of participant-pupillometer agreement on the center of the visual field, the program would terminate the fixation square and administer the target stimulus. Instructions were given to press either the right or left response buttons to indicate which of the two test lines was longer. Both detection accuracy and speed were emphasized in the instructions. Three seconds after the onset of the target stimulus, a low-pitched tone (800 Hz for 500 ms) functioned as an auditory cue signaling the end of the trial. The intertrial interval was 3 s. Participants were asked to refrain from blinking during the trial period between the two auditory signals marking the beginning and ending of the trial (i.e., high and low tones respectively). If the participant did not respond with a button press within 3 s, a warning sound (alternating 1500- and 800-Hz tones) prompted the participant to make a response.

Before the test portion of the task, the participant was given 24 practice trials. The practice trials began with the easiest interstimulus interval conditions, namely, two no-mask trials followed by two 300-ms interstimulus interval trials. The interstimulus interval durations of the remaining 20 trials were blocked randomly. For the first half of the practice, computer-automated feedback was provided regarding correctness of participant's response. Feedback was not provided during the test phase of the study. Because the computer required time to periodically save strings of data, participants were prompted to blink or rest their eyes after each presentation of six trials before continuing with the next set. In addition, participants were allowed time to rest (participant determined the length of resting time) halfway through the test. The entire task (i.e., instructions, practice, pretest, test, and posttest) took typically less than 35 min, with the test portion taking about 20 min.

Data Reduction

Graphic displays of raw pupil diameter data were first inspected visually for gross artifacts by a trained technician. Six participants were excluded from all the analyses because of excessive eyeblink artifacts ($n = 1$), technical difficulties ($n = 2$), or abnormal tonic (resting diameter; $n = 2$) or phasic (event changes in diameter; $n = 1$) pupil measurements (outliers > 2 *SD*). Across all 31 remaining participants, fewer than 7.1% of the test trials, 4.8% of the pretest trials, and 5.6% of the posttest trials were discarded due to major artifacts or excessive blinking. A computer algorithm was used to remove eye blinks and other minor artifacts from other trials by linear interpolation. A 7-point smoothing filter was then passed over the data. For each participant, an average pupillary response was then calculated for the artifact-free trials of each interstimulus interval condition within the cognitive load and no-load conditions.

Typically, pupillary responses to cognitive tasks with visual displays, such as the visual backward masking task, exhibit a bimodal waveform consisting of an initial constriction response to the increased display luminance and a subsequent dilation response under cognitive load. Cognitive load can both reduce the magnitude of the initial peak constriction phase and increase peak dilation in the later phase. The pattern of pupil response across the whole of the 3-s trial was chosen as the primary measure because (1) it is based on 180 recorded samples, providing greater reliability and less variability than a peak measure, (2) it provides a better index of sustained resource allocation, which is not reflected in a single peak value, and (3) it incorporates resource allocation effects on the peak constriction of the pupillary light reflex, which can be reduced when recorded under cognitive load relative to no-load conditions (Gavriysky, 1991). The total pupil response, therefore, is a better index of total resource allocation, because it reflects the total duration of resource allocation and resource allocation effects on both peak constriction and peak dilation. Nonetheless, we examined peak constriction amplitude, peak dilation amplitude, and peak-to-peak measures for comparability with previous pupillary response studies and to examine the effects of light and cognitive load on these different components.

Six dependent measures were calculated for each interstimulus interval and the no-mask condition. (1) Detection accuracy was defined as the percentage correct out of 20 trials for each interstimulus interval condition. (2) Baseline pupil size was defined as the average of five samples of pupil diameter recorded 100 ms prior to each trial onset. (3) Total pupil response was defined as the difference between pupil diameter at baseline and the average of all pupil samples recorded for 3 s after display onset. (4) Peak constriction amplitude was defined as the difference between baseline and the smallest pupil diameter occurring between 200 and 1,500 ms after trial onset. (5) Peak dilation amplitude was defined as the difference between baseline and the largest pupil diameter occurring between 500 and 2,000 ms after trial onset. (6) Peak-to-peak dilation response was defined as the difference in amplitude from the peak constriction to the peak dilation. Our a priori hypotheses require a comparison of adjacent interstimulus intervals and a comparison of each of the masked interstimulus interval conditions with the no-mask condition. To accomplish these comparisons, a one-way multivariate analysis of variance (MANOVA) was used to investigate detection accuracy and total pupil response across all interstimulus interval conditions, and planned contrasts (Fisher LSD test, two-tailed, $\alpha = .05$) compared each interstimulus interval condition with the other intervals, as well as with the no-mask (i.e., standard) condition.

Results

Detection Accuracy

Figure 1 presents detection accuracy for the five interstimulus interval masking conditions and the no-mask condition. A one-way MANOVA conducted on the percentage of correct responses showed a significant main effect of interstimulus interval, $F(5,26) = 74.35$, $p < .001$, with an effect size, η^2, of .93. Detection accuracy was significantly higher in the no-mask condition than in all interstimulus interval conditions (Fisher's LSD; p at least $< .05$) and all other pairwise comparisons were also significant (p at least $< .01$), except for 17 versus 33 ms ($p > .05$).

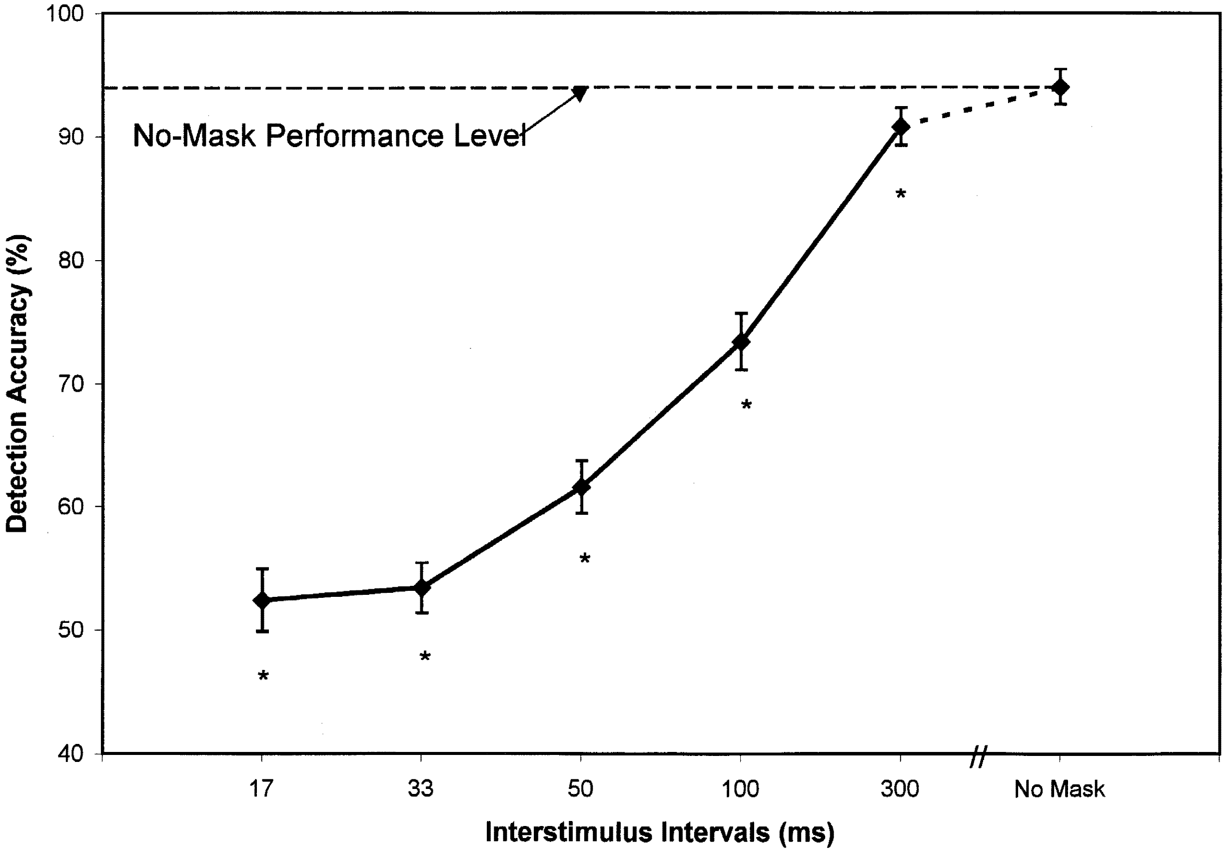

Figure 1. Percentage of correct responses for the five interstimulus interval and no-mask conditions in the cognitive load condition. Error bars are ± 1 *SE*. $*p < .05$ versus the no-mask condition.

Pupillary Response

Cognitive no-load condition. A 2 (pretest vs. posttest) × 6 (interstimulus interval) MANOVA on total pupillary response scores was conducted to investigate possible differences between the cognitive no-load conditions. The main effect for interstimulus interval was not significant, $F(5,26) = 1.23$, *ns*, nor was the interaction between test condition and interstimulus interval significant, $F(5,26) = .60$, *ns*. Surprisingly, there was no evidence of habituation of pupillary responses over time in the testing session. In contrast, pupillary responses were significantly greater in the posttest ($M = 0.046$ mm; $SD = .121$ mm) relative to pretest ($M = 0.022$ mm, $SD = .105$ mm) condition, $F(1,30) = 4.56$, $p < .05$, $\eta^2 = .54$. This finding suggests that, despite instructions to just passively view the stimuli, participants appeared to continue to engage in the task in the posttest condition to a greater extent than they did before they had experience with the task in the pretest conditions. Therefore, only pretest trials were used to constitute a cognitive no-load condition.

Cognitive load vs. no-load condition. Figure 2A presents the average pupillary response across participants for the six interstimulus intervals in the cognitive load and no-load conditions. Typical for pupillary responses during cognitive tasks with visual displays, Figure 2A shows bimodal pupillary response waveforms consisting of an early very small peak constriction response to the low luminance of the display followed by a peak dilation response to cognitive load. Consistent with the study hypotheses, dilation appeared to be greater in the cognitive load relative to the no-load condition and appeared to be greatest in the 300-ms interstimulus interval in the cognitive load condition.

These observations were confirmed in a 2 (cognitive load vs. no-load) × 6 (interstimulus interval) MANOVA carried out on the total pupil response scores. The main effect for cognitive load versus no-load conditions was significant, $F(1,30) = 81.84$, $p < .001$, $\eta^2 = 1.00$, and the interaction between test condition and interstimulus interval was significant, $F(5,26) = 2.99$, $p < .05$,

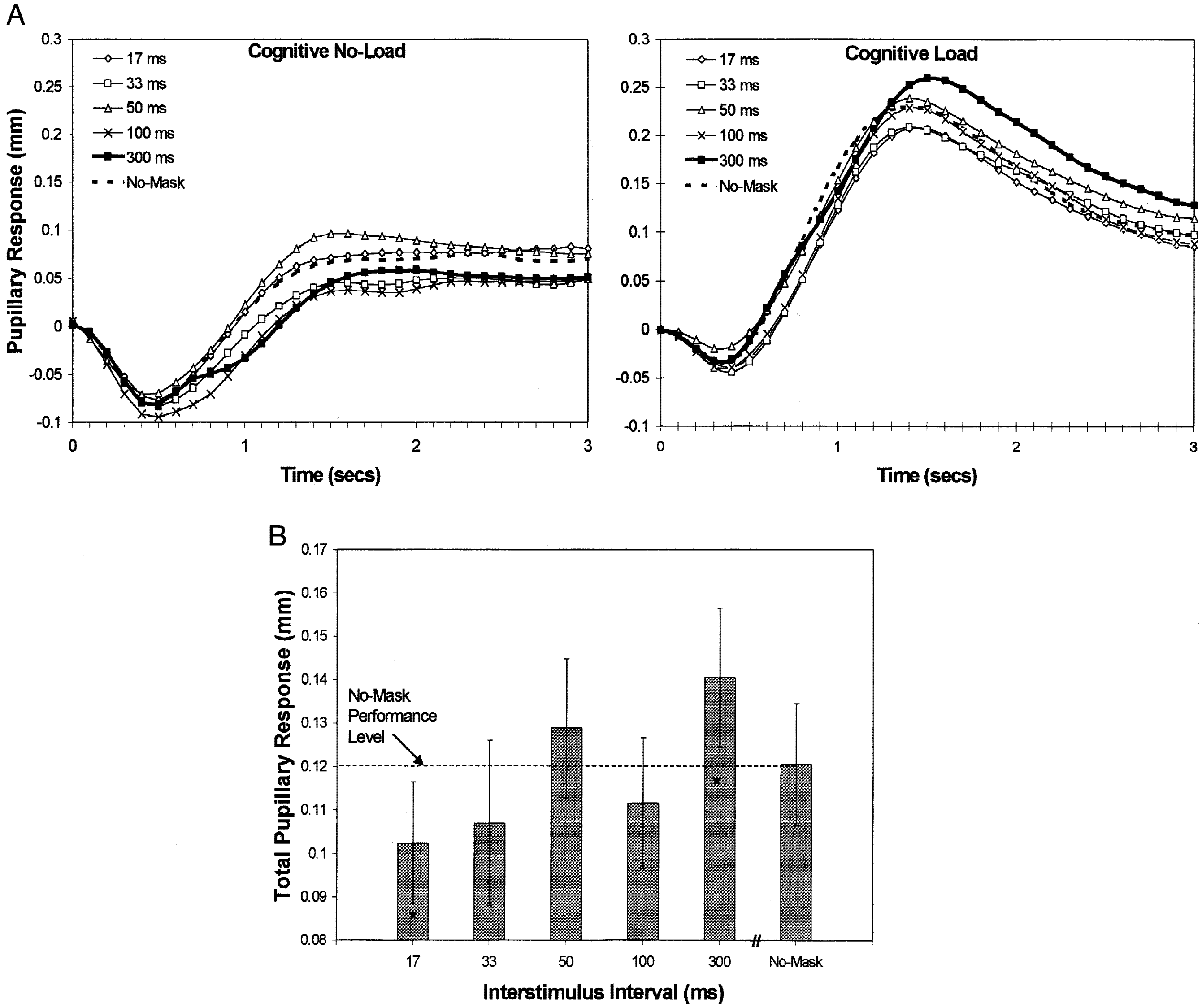

Figure 2. Pupillary responses for the five interstimulus interval and no-mask conditions: (A) raw pupillary responses (mm) within the cognitive no-load and cognitive load conditions; (B) total pupillary response (mm) in the cognitive load condition. Error bars are ± 1 *SE*. $^*p < .05$ versus the no-mask condition.

$\eta^2 = .77$, but the main effect for interstimulus interval, $F(5,26) = 1.75$, *ns*, was not significant.

Effect of interstimulus interval on pupillary responses. Figure 2B presents the total pupillary responses for all interstimulus intervals in the cognitive load condition. A one-way repeated-measures MANOVA conducted in the cognitive load condition on total pupillary response resulted in a significant effect for interstimulus interval, $F(5,26) = 6.73$, $p < .001$, $\eta^2 = .56$. Pupillary responses elicited in the 300-ms interstimulus interval condition were significantly larger (Fisher's LSD) than most other conditions, 17 versus 300 ms, $t(30) = -3.85$, $p < .001$; 33 versus 300 ms, $t(30) = -3.70$, $p < .001$; 100 versus 300 ms, $t(30) = -2.58$, $p < .05$; and 300 ms versus no-mask, $t(30) = 2.08$, $p < .05$; with the only exception being in the 50-ms interval condition, 50 versus 300 ms, $t(30) = -1.52$, *ns*. Greater total pupillary responses were also found in the 50-ms condition than in the two earlier interstimulus interval conditions: 17 versus 50 ms, $t(30) = -3.44$, $p < .01$; 33 versus 50 ms, $t(30) = -2.66$, $p < .05$ (with a statistical trend for 50 vs. 100 ms, $t(30) = 1.96$, $p < .10$). Lastly, the no-mask condition was found to have greater total pupil responses than the 17-ms condition, 17 versus no-mask, $t(30) = -2.04$, $p < .05$.

A one-way repeated-measures MANOVA was also calculated for the cognitive no-load condition on total pupil response. The main effect for interstimulus interval was not significant, $F(5,26) = 1.69$, *ns*, indicating that all interstimulus intervals elicited a similar amount of total pupil response when participants were instructed to view the stimuli passively.

Other pupillometric measures. To provide information for comparison with other published pupillary response experiments, several other common pupillary response variables were explored in the cognitive load condition: baseline pupil size, peak dilation amplitude, peak constriction amplitude, and peak-to-peak measures (see Table 1). No significant differences were found in a one-way repeated-measures MANOVA for baseline pupil size across the six interstimulus interval conditions in the cognitive load condition, $F(5,26) = .93$, *ns*.

A one-way repeated-measures MANOVA on peak dilation amplitude in the cognitive load condition resulted in a significant effect of interstimulus interval, $F(5,26) = 6.88$, $p < .001$, $\eta^2 = .57$. Consistent with the total pupillary response measures, the 300-ms interstimulus interval condition elicited significantly greater peak dilation amplitude than any other condition; 17 versus 300 ms, $t(30) = -3.95$, $p < .001$; 33 versus 300 ms, $t(30) = -4.49$, $p < .001$; 50 versus 300 ms, $t(30) = -2.29$, $p < .05$; 100 versus 300 ms, $t(30) = -2.34$, $p < .05$; and a trend for 300 versus no-mask, $t(30) = 1.88$, $p < .10$. An interesting pattern was also noted in the 50-ms interstimulus interval condition, with this condition eliciting greater peak dilation responses than the 17-ms condition, $t(30) = -3.35$, $p < .05$ and the 33-ms condition, $t(30) = -2.72$, $p < .05$. The no-mask condition also elicited greater peak dilation responses than the 17-ms condition, $t(30) = -2.17$, $p < .05$.

A one-way repeated-measures MANOVA on peak constriction amplitude in the cognitive load condition resulted in a significant effect for interstimulus interval, $F(5,26) = 3.66$, $p < .05$, $\eta^2 = .41$. The 50-ms interstimulus interval condition showed significantly less constriction than most other interstimulus interval conditions as follows (Fisher's LSD): 17 versus 50 ms, $t(30) = 2.17$, $p < .05$; 33 versus 50 ms, $t(30) = 3.81$, $p < .001$; 50 versus 100 ms, $t(30) = 2.68$, $p < .05$; 50 versus 300 ms, $t(30) = 2.50$, $p < .05$; with a trend for 50 ms versus no-mask, $t(30) = -1.65$, $p < .10$.

A one-way repeated-measures MANOVA was conducted in the cognitive load condition on the peak-to-peak pupil response, which removes the constriction component from peak dilation. This analysis resulted in a significant effect for interstimulus interval, $F(5,26) = 6.38$, $p < .001$, $\eta^2 = .55$. Pupillary responses in the 300-ms interstimulus interval condition were again greater than in any other condition (Fisher's LSD); 17 versus 300 ms, $t(30) = -3.19$, $p < .01$; 33 versus 300 ms, $t(30) = -4.52$, $p < .001$; 50 versus 300 ms, $t(30) = -3.71$, $p < .001$; 100 versus 300 ms, $t(30) = -1.88$, $p < .10$ (trend); 300 ms versus no-mask, $t(30) = 2.04$, $p < .05$. No other comparisons among the interstimulus interval conditions were significant. Thus, consistent with the study hypothesis, significantly more cognitive resources were allocated in the 300-ms condition than in the other interstimulus interval conditions.

Discussion

Consistent with numerous other studies (e.g., reviewed in Beatty, 1982), pupillary dilation responses were significantly larger under cognitive load than during passive viewing of the stimuli (cognitive no-load). This finding provides further validation of pupillary response as a measure of controlled processing resource allocation. Consistent with our prediction, pupillary responses were signifi-

Table 1. *Pupillary Response Variables for the Five Interstimulus Intervals and No Mask Condition in the Cognitive Load Condition*

	Interstimulus interval (ms)					
Dependent Measure	17	33	50	100	300	No mask
Baseline pupil size (mm)	5.20 (1.03)	5.20 (1.02)	5.18 (1.03)	5.22 (1.01)	5.18 (1.04)	5.20 (1.03)
Peak dilation amplitude (mm)	.234 (.120)	.232 (.153)	.262 (.124)	.250 (.129)	.283 (.140)	.259 (.113)
Peak constriction amplitude (mm)	−.058 (.069)	−.060 (.066)	−.036 (.057)	−.059 (.076)	−.049 (.052)	−.049 (.062)
Peak-to-peak dilation amplitude (mm)	.293 (.134)	.293 (.145)	.298 (.117)	.309 (.132)	.332 (.141)	.308 (.117)

Note: Values given as means, with *SD*s in parentheses.

cantly larger in the 300-ms interstimulus interval condition than in the no-mask condition. This finding suggests that the mask demanded additional processing resources in the 300-ms condition. Moreover, the peak-to-peak measure, which removes constriction amplitude from peak dilation, showed a stepwise increase in pupil dilation for the 300-ms condition, whereby dilation was significantly greater in the 300-ms condition than in any other interstimulus condition. This pattern of results cannot be explained by only a two-factor account of masking (Breitmeyer & Ganz, 1976) at longer interstimulus intervals. Rather, these results are consistent with a shifting and sharing of resources between the target and mask at longer interstimulus intervals (Michaels & Turvey, 1979; Phillips, 1974).

One assumption underlying attentional shifting in current masking models is that shifting occurs only after the mask stimulus becomes sufficiently distinct from the target, at which time resources are allocated to evaluate the mask as a separate percept. This hypothesis could be tested in a two-pulse temporal resolution task, in which two stimuli are presented with varying interstimulus intervals and participants report whether they saw one or two stimuli. Greater resource allocation (pupillary dilation) should be found in interstimulus interval conditions in which participants report separate percepts. Further, if the mechanism of interference between the target and mask is the amount of stimulus identification resources attracted away from the target by the mask, then manipulations that increase the information load and processing demands of the mask (e.g., words vs. nonsense stimuli) should interfere more with target detection (see Michaels & Turvey, 1979) and should result in greater resource allocation (pupillary responses).

We found some evidence of resource allocation at shorter interstimulus intervals. In the 50-ms condition, greater total pupil response, greater peak dilation amplitude, and smaller constriction amplitude were found relative to shorter interstimulus intervals. These results might indicate attentional shifting or some other form of resource allocation even in early stages of visual information processing. Indeed, recent studies have reported that top-down resource allocation functions can modulate early backward masking effects (Ramachandran & Cobb, 1995). The 50-ms condition is in the middle of the interstimulus interval range when interruption is thought to maximally degrade the target icon (Michaels & Turvey, 1979). Thus, the increased dilation found at this interval might result from the increased processing load that is imposed on stimulus identification resources by having to decipher a degraded icon. However, dilation in the 50-ms condition was not greater than the no-mask condition, which suggests that identifying a degraded target icon in the early interstimulus interval conditions was not more resource demanding than identifying a clear target icon in the no-mask condition.

Another possibility is some type of psychophysical interference with the light reflex when two light stimuli onset with a 50-ms interstimulus latency. The increased dilation in the 50-ms condition was present in the early constriction component of the pupillary response but not in the dilation component when constriction was removed from peak dilation in the peak-to-peak analysis. This finding suggests that the larger total pupillary response found in the 50-ms condition was due to inhibition of the pupillary light constriction reflex, rather than the later peak dilation component. Larger dilation due to inhibition of the light reflex was also observable (Figure 2) in the cognitive no-load condition (although not statistically significant). Taken together, these findings suggest that the larger total pupil dilation found in the 50-ms condition was due to inhibition of the light reflex even when no cognitive operations were required. This deduction may suggest a more peripheral mechanism related to interference with the light reflex by light stimuli with this onset asynchrony. These speculations about the findings in the 50-ms condition should be viewed with caution, because these are post hoc interpretations of a finding that may be due to chance.

Surprisingly few resources were allocated in the 17-ms interstimulus condition. In this condition, there was a clear dissociation between level of performance and pupillary responses (resource allocation) to the task. Detection accuracy was poorest in this condition, suggesting greatest task difficulty, but pupillary responses were smallest in this condition, suggesting lowest resource demands. Poor detection accuracy in this condition suggests that the target icon was severely degraded. It is logical to hypothesize that a more severely degraded icon should have placed higher demands on stimulus identification resources. However, severely degraded icons in shorter interstimulus intervals demanded fewer resources (smaller pupillary responses) than clearer icons in longer intervals. It is possible that so little information was provided by the fused target-mask stimulus in the 17-ms condition that few processing resources were devoted to identifying these stimuli. As more target information became available in longer interstimulus intervals, more resources were devoted to target identification. Pupillary responses were greater in the 17-ms cognitive load condition than in the 17-ms no-load condition, suggesting that even the 17-ms condition did demand some resources. Although it is possible that this increased dilation in the cognitive load condition was due to the processing demands of having to decipher a degraded icon, this effect also might be due to resource demand associated with response organization and rapid motor responding in the cognitive load condition, which was not required in the no-load condition.

Pupillography methods may be a useful tool to test hypotheses about the relative processing demands and processing mechanisms underlying different task conditions, as well as normal individual differences and abnormal breakdown in specific cognitive processes. For example, the visual backward masking task has been used extensively to examine the information processing impairments of patients with schizophrenia, who show impaired detection accuracy relative to nonpsychiatric comparison participants at interstimulus intervals between 100 and 500 ms. It has been hypothesized that this visual backward masking deficit may be due to slowed or reduced resource allocation during post-iconic identification of stimulus meaning (Braff et al., 1991; Green, Nuechterlein, & Mintz, 1994). This hypothesis could be tested using this pupillography paradigm. Such resource allocation impairments in patients with schizophrenia should be evidenced by smaller pupillary responses in patients relative to controls in 100–500-ms interstimulus interval conditions.

Finally, this study illustrates one of the strengths of using both behavioral (e.g., accuracy) and psychophysiological (e.g., pupillary response) measures to investigate information processing models. In this study, processing resource allocation and task difficulty level could be separated in a theoretically meaningful way. The accuracy data suggested that the 300-ms and no-mask conditions were psychometrically easier than the other interstimulus interval conditions and, yet, these conditions had greater resource demands. Difficulty measures and psychophysiological measures of resource allocation do not always yield the same pattern of results across processing load conditions. In the present study, resource demands were highest in conditions in which performance levels were also highest. In addition, different amounts of resources may be allocated by different participants or in different conditions to achieve the same level of performance. Thus, more direct measures of resource allocation should be used to address questions regarding resource-dependent mechanisms. The data we present confirm prior expectations about the time course of resource-dependent mechanisms in early visual information processing using pupillary responses as a more direct measure of resource allocation.

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