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Pupillary responses on the visual backward masking task reflect general cognitive ability

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Abstract

Cognitive processing efficiency requires both an ability to attend to task-relevant stimuli with quickness and accuracy, also while filtering distracting or task-irrelevant stimuli. This study investigated cognitive processing efficiency by using pupillary responses as an index of attentional allocation to relevant target and irrelevant masks on a visual backward masking task. The relationship between attentional allocation on this task and general cognitive ability on the scholastic aptitude test (SAT) was examined in college students ($n=67$). A principle components analysis of the pupillary response waveform isolated a late component that appeared to index the attentional demands associated with processing masks on the backward masking task. This pupillary response index of wasteful resource allocation to the mask accounted for significant variance in SAT scores over and above that accounted for by socio-economic status and target detection accuracy scores. Consistent with the neural efficiency hypothesis, individuals who allocated more resources to processing irrelevant information performed more poorly on cognitive ability tests.

Keywords: Cognitive processing; Pupillary responses; Scholastic aptitude test

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1. Introduction

The neural efficiency hypothesis states that more intelligent individuals process information and solve problems more efficiently (i.e. with less mental effort) than less intelligent individuals (Davidson and Downing, 2000; Haier et al., 1992; Hendrickson, 1982a,b; Schafer, 1982). This hypothesis has received some support in the psychophysiological literature on pupillary responses. The extent of pupil dilation recorded during a cognitive task is a psychophysiological measure of task processing load and resource allocation, with larger pupil dilation reflecting greater processing load or mental effort (Beatty, 1982). Ahern and Beatty (1979) showed an association between pupillary responses and cognitive ability by showing that pupillary responses recorded in college students while they performed a multiplication task were negatively correlated with cognitive ability. That is, college students with lower scores on the scholastic aptitude test (SAT) exhibited greater pupil dilation to the multiplication problems than students with higher SAT scores. Consistent with the neural efficiency hypothesis, they concluded

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that individuals with greater cognitive ability process information with greater efficiency or less mental effort.

One information-processing task tapping speed and efficiency of processing is the visual backward masking task, which has received substantial notoriety in the intelligence literature (for reviews see Deary and Stough, 1996; Deary, 2000). The backward masking task is used to quantify the amount of time that information is passed through the sensory register. This task consists of a rapidly presented target stimulus (e.g. letters or different length lines), a varying length of vacant time (e.g. 20–700 ms) and a masking stimulus that typically completely covers the spatial presence of the target stimulus (Saccuzzo, 1993). Participants are typically asked to identify the target stimuli (e.g. which line is longer or what was the letter). Successful completion of the task, therefore, requires not only efficient processing of the target stimuli, but also the ability to filter the effects of the masking stimulus. Inspection time (IT), the amount of time needed for an individual to reliably perceive the target stimulus, has been touted as the best information-processing measure in terms of having a reliable, substantial correlation with performance on standard tests of psychometric intelligence (Deary and Stough, 1996). This measure derived from the backward masking paradigm accounts for approximately 20% of the variance in intelligence tests (Deary and Stough, 1996; Kranzler and Jensen, 1989; Longstreth et al., 1986; Nettlebeck et al., 1986).

In a previous study, we recorded pupil dilation responses in college students while they performed a visual backward masking task with 33, 50, 67, 117 and 317 ms stimulus onset asynchronies (SOA) between the target and mask stimuli and a no-mask condition (Verney et al., 2001). Pupil dilation was significantly greater during task performance (cognitive load) relative to a condition where participants passively viewed the stimuli (cognitive no-load), and there were no significant differences between SOA conditions during passive viewing of the stimuli (no-load). This finding further validates pupil dilation as an index of cognitive resource allocation. Moreover, significantly greater pupil dilation was found in the longest (317 ms) SOA condition compared to the no-mask condition. Dilation in all other SOA conditions did not exceed that of the no-mask condition. The only difference between the longest SOA condition and the no-mask condition was the presence of the mask. Therefore, this finding suggested that the presence of the mask increased task-processing load beyond that of target detection alone (no-mask condition) only in the longest (317) SOA condition. This finding was consistent with backward masking task models that suggest the mask demands extra processing resources, or a shifting and sharing of stimulus identification resources between the target and mask, only when the mask follows a target by more than approximately 120 ms (Loftus et al., 1988; Michaels and Turvey, 1979; Phillips, 1974).

The total pupil dilation response reflects the sum of all processing demands associated with the task. In an attempt to isolate the separate processing demands associated with specific task stimuli (e.g. targets and masks), a principle components analysis (PCA) was computed on the Verney et al. (2001) data set, as well as on pupillary response data sets from two additional backward masking task studies from our lab (Granholm and Verney, 2004; Verney, 2001). PCA is often used as a method of reducing the large number of data time points in psychophysiological data to a small number of meaningful factors. Three factors consistently emerged from the PCA analyses in all three of these studies, which appeared to isolate the specific resource demands associated with target and mask processing. The three factors formed a linear time course of the pupillary response waveform: (1) An early factor from approximately 0 to 0.7 s; (2) a middle factor from approximately 0.7 to 1.5 s; and (3) a late factor from approximately 1.5 to 3.0 s. The middle factor occurred in the time window when peak dilation responses to cognitive task stimuli are commonly found to reflect resource allocation to task performance (e.g. discriminating and evaluating the target lines; Beatty, 1982; Beatty and Lucero-Wagoner, 2000; Steinhauer and Hakerem, 1992). Middle factor dilation was smaller in conditions where target detection was poorest and larger in conditions where target detection was greatest. The middle factor, therefore, was interpreted as reflecting target processing. The late factor was interpreted as reflecting resources allocated to mask processing. In longer SOA conditions (i.e. $> \sim 120$ ms), when the masking stimulus becomes a distinct percept from the target stimulus (Michaels and Turvey, 1979; Phillips, 1974), late factor pupil dilation was significantly greater than in the no-mask condition. We interpreted this difference in the late factor between longer SOA masking conditions (with both target and mask) and the no-mask condition (containing only a target) as reflecting the additional processing demands of the mask. Therefore, the late factor dilation score could be used to measure resource allocation to mask processing.

The present study attempted to replicate and extend Ahern and Beatty's (1979) finding that cognitive task-evoked pupillary responses are negatively associated with general cognitive ability. In contrast to the Ahern and Beatty (1979) study, which used a higher-order processing task (multiplication), the visual backward masking task was used in this study to tap speed and efficiency of processing. This task was thought to be a better test of the neural efficiency hypothesis, because it has been used exclusively for this purpose in the intelligence literature and does not tap cognitive abilities directly measured on the SAT (e.g. math abilities). It was hypothesized that greater cognitive ability (SAT scores) would be associated with greater task detection accuracy. If confirmed, this would replicate previous findings that behavioral measures of information processing efficiency are strongly related to cognitive ability (Deary and Stough, 1996; Kranzler and Jensen, 1989). It was also hypothesized that pupillary dilation responses elicited by the task's non-informational masking stimulus (i.e. inefficient or wasteful mask processing) would significantly add to the prediction in SAT scores above that provided by detection accuracy and socio-economic status (SES). That is, consistent with Ahern and Beatty (1979), greater cognitive ability should be associated with less pupil dilation to the masking stimulus, especially in the longer SOA conditions where resource allocation to the mask is greatest. This finding would be consistent with the neural efficiency hypothesis that individuals with greater cognitive abilities perform tasks with less mental effort and do not wastefully allocate resources to task-irrelevant information (e.g. Cha and Merrill, 1994; Merrill and Taube, 1996; McCall, 1994).

2. Methods

2.1. Participants

Undergraduate male and female students ($n = 101$) were recruited from introductory psychology courses at San Diego State University (SDSU) to participate in a larger study (Verney, 2001; Verney et al., submitted). The Institutional Review Boards at the University of California, San Diego, and San Diego State University approved this study. Participants were offered class credit and monetary compensation for their time and efforts and provided informed consent.

2.1.1. Participant exclusion criteria

Participants in this study were recruited as part of a larger study on cultural differences in intelligence, which required that participants be either Caucasian or Mexican American (Verney, 2001). The race/ethnicity findings are reported elsewhere (Verney et al., submitted). Briefly, pupillary responses and detection accuracy scores on the visual backward masking task in that study were both significantly correlated with Wechsler Adult Intelligence Scale—Revised (WAIS-R) Full Scale IQ scores in a sample of Caucasian participants, but weaker, nonsignificant associations were found in Mexican American participants, even though the two ethnic groups did not differ significantly on detection accuracy or pupillary responses. This differential predictive validity between measures of information processing efficiency and intelligence test scores suggested that the WAIS-R test may contain a cultural component that reduces its validity as a measure of IQ for Mexican American students.

Because specific health factors, such as drug or alcohol abuse, might lead to impairment on cognitive tasks, all participants completed a drug and alcohol use questionnaire and a brief physical and mental health background interview. No subject reported significant patterns of drug or alcohol use. Of the 101 participants who reported to the testing site, 5 individuals were dropped from the study due to medical or physical reasons. One Peruvian student did not meet the criteria for inclusion into that study (Verney, 2001), and thus, was dropped. Twelve participants who presented for the study were excluded from all the analyses due to excessive eye blink artifacts (analyzable trials $<40\%$; $n=2$;), technical difficulties with the eye-tracking instrument ($n=2$), abnormal tonic pupil measurements (resting diameter outliers >3 standard deviations from the mean of all subjects; $n=2$;) or unreasonably poor visual backward masking performance (at-chance no-mask condition or no-mask performance outliers >3 standard deviations from the mean of all subjects; $n=6$). All participants demonstrated at least 20/30 visual acuity (corrected or non-corrected) as assessed by a Snellen wall chart. No participant reported smoking cigarettes or drinking caffeinated beverages within 2 h prior to the testing session. Of the 75 students who qualified for the study, 67 students had SAT scores on record at San Diego State University and provided written consent to obtain access to their records. These students comprised the final sample, which consisted of Caucasian American (53.7%) and Mexican American (46.3%) undergraduate students (52.2% female, mean age $=18.4\pm$ S.D. $=0.9$, mean education $=12.4\pm0.7$). Scores on the combined Verbal and Quantitative SAT ranged from 540 to 1260 total points (mean SAT score $=985.8\pm150.1$). The average family income was reportedly \$46 567 ± \$18 241, the average father's education level was 12.5 ± 3.8 years and the average mother's education level was 12.8 ± 3.4 years.

2.2. Apparatus

Pupillometric data were gathered from the left eye via an Applied Science Laboratories Model 4000SU HMO head mounted eye-tracking system during the visual backward masking task performance. This infrared corneal-reflection-pupil-center system sampled pupil area measurements at 60 Hz (approximately every 16.7 ms) and saved the data for subsequent off-line analysis. Pupil area measurements were translated to diameter for consistency with other pupillographic studies. The resolution of the pupillometer was 0.05-mm diameter. A 17-inch super video graphics adapter monitor controlled by a PC was used to administer the visual backward masking task, and the participants used the left and right arrow keys on the keyboard to make their responses.

2.3. Procedure

Following the brief background interview, substance use questionnaire, and visual acuity testing, the visual backward masking task was administered. The Scale of Ethnic Experience (SEE; Malcarne et al., submitted), which provided the participants' socio-economic information (i.e. family income, parent's educational level), was also administered.

2.3.1. Visual backward masking task

The visual backward masking task was implemented on a PC-based system. Participants were asked to identify which of two target lines was longer (i.e. forced-choice paradigm). Target and masking stimuli consisted of black lines on a white background to reduce screen glare effects and minimize changes that could be associated with the pupil light reflex. The target stimulus consisted of two adjacent vertical lines presented in the center of the computer 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 vertically offset in height in one of six different target configurations varying from 2 to 4 cm in offset height (Verney, 2001; Verney et al., 2001). The upper endpoint of the 'short' line could be higher, equal or lower than the upper endpoint of the 'long' line and only one endpoint (either upper or lower) of one target line could be in alignment with the same endpoints of the masking lines. The long and short lines were randomly blocked 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 which completely spatially replaced the target stimulus lines with SOAs of either 50, 67, 100, 134, 317 or 717 ms, or infinity (no-mask condition). These SOAs, 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. Twenty trials were administered for each condition resulting in 140 test trials. The seven SOA conditions were presented in blocks of five trials in the following counterbalanced sequence: 134, no-mask, 67, 100, 317, 717, 50, 134, 717, 317, 50, no-mask, 100, 67, 50, no-mask 717, 100, 317, 67, 134, 317, 50, 67, 717, 134, no-mask, 100 ms. The target and mask had equal duration (16.7 ms; one 60 Hz screen refresh rate). The participants were seated at approximately 61 cm from the computer monitor resulting in 2.79 and 3.75 vertical degrees of visual angle for the target stimulus and masking stimulus, respectively.

A calibration was first conducted to ensure participant-pupillometer agreement on center of visual field. At the beginning of each trial, a blue fixation square (0.85×0.85 cm^2) was presented in the center of the monitor (with a white screen background) for 1 s 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. Instructions were given to press either the right or left arrow keys on the keyboard to indicate which of the two test lines was longer. Both detection accuracy and speed were emphasized with the instruction, 'Try to be as accurate as you can, but also be as fast as you can.' 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 inter-trial interval was set at 3 s. Participants were asked to refrain from blinking during the trial period marked by the two auditory signals (i.e. high and low beeps).

Prior to the test portion of the task, participants were given 21 practice trials. The practice trials began with the easiest conditions; namely, a no-mask trial followed by a 717 ms and a 317 ms SOA trial. The conditions of the remaining 18 trials were randomly blocked. The first 12 practice trials provided computer-automated feedback regarding correctness of the participant's response. Feedback was not provided during the test phase of the study. A moment of rest (≈ 15 s, unless the participant requested a longer break) was allowed after each presentation of 10 trials for the participant to rest and blink their eyes. Each participant was also allowed a few minutes to rest halfway through the test. The entire task (i.e. instructions, practice and test) took typically less than 35 min, with the test portion taking approximately 22 min.

2.4. Data reduction

Graphic displays of raw pupil diameter data were first visually inspected for gross artifacts by a trained technician. Pupillary response data for the individual task trials were divided into 3 s recording epochs triggered by the target onset. Fewer than 4.3% of the test trials were discarded due to major artifacts or excessive eye 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 from baseline was calculated for the artifact-free trials of each SOA condition. Baseline pupil size was defined as the average of five samples of pupil diameter recorded 100 ms prior to each trial onset.

All variables were analyzed for evaluation of assumptions and transformed when necessary to reduce skewness, reduce the number of outliers, and improve the normality, linearity and homoscedasticity of residuals. Bivariate and multivariate outliers were identified through studentized residuals (studentized residual >2) and were dropped. Four participants were dropped as multivariate outliers.

A PCA was used to analyze the pupillary response waveform based on the findings from our previous studies (Granholm and Verney, 2004; Verney, 2001). Analysis of variance (ANOVA) was used to analyze the within subjects conditions for detection accuracy and pupillary responses on the visual backward masking task. Dunnett's test was used to protect type-I error in the ANOVA follow-up analyses comparing the masked conditions with the no-mask condition. Finally, a hierarchical regression was used to test our hypotheses

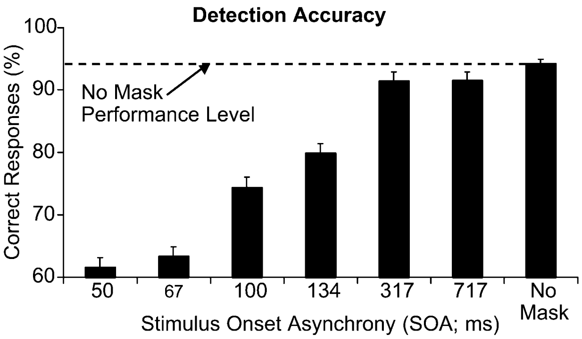

Fig. 1. Detection accuracy scores in percent on the visual backward masking task across all SOA conditions. Error bars are 1 S.E.

that visual backward masking detection accuracy and pupillary responses would account for significant variance in combined Verbal and Quantitative SAT scores over and above that accounted for by SES. Three variables were regressed onto combined SAT scores: (1) *SES* was defined as the average of the categorical variables of family income, father's education level and mother's education level as reported by the participant on the SEE. (2) *Overall detection accuracy* was defined as the total percentage correct for the intermediate and longer SOA conditions (i.e. 100, 134, 317 and 717 ms conditions). To maximize the sensitivity of detection accuracy scores in the regression analyses, conditions with floor and ceiling effects were discarded (based on a 95% confidence interval $\approx$50 and 100%, respectively). Both the 50 and 67 ms SOA conditions were at chance level detection accuracy and performance in the no-mask condition did not differ significantly from perfect accuracy. (3) *Mask pupillary response* was defined as the difference between the late PCA factor of the longer SOA conditions (averaged 317 and 717 ms conditions) and the no-mask condition.

3. Results

3.1. Detection accuracy

Fig. 1 presents detection accuracy for the six SOA masking conditions and the no-mask condition on the visual backward masking task. A one-way ANOVA indicated a significant main effect of condition, $F(6, 61)=97.11$, $P<0.001$, $\eta^2=0.90$. Follow-up analyses (Dunnett's test; $P<0.05$) showed that the early and middle (50–134 ms), but not the longer (317 and 717 ms) SOA conditions were significantly different from the no-mask condition.

3.2. Pupillary response

Fig. 2 presents the averaged raw pupillary responses adjusted to baseline at stimulus onset for the six masking conditions and the no-mask condition across the 3-s window following stimulus onset. To fully and objectively examine the pupillary response waveform across the 3-s trial, and to eliminate the effects of individual differences in resting pupil size and pupil mobility, a varimax rotation PCA was performed on 180 time-points (i.e. 3 s) of the pupil response waveform time-locked to stimulus onset across the seven masked and no-mask conditions for all participants. The same three prominent stable factors found in our larger sample (Verney, 2001) emerged in this sub-sample from that study (Fig. 2),

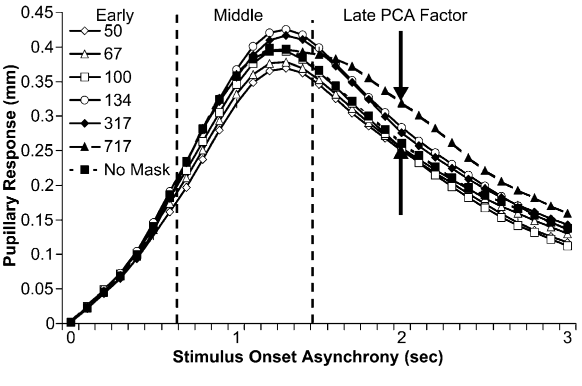

Fig. 2. Averaged raw pupillary responses (mm) adjusted to baseline at stimulus onset with the waveforms divided into the timeframes of the three PCA rotated factors (i.e. early, middle and late PCA factors) for all subjects. The difference between the average of the longer SOA conditions (i.e. 317 and 717 ms conditions) and the no-mask condition for the late factor was used as an index of the amount of attentional allocation devoted to the masking stimulus (mask pupillary response). The arrow indicates resources devoted to the mask in the longest stimulus onset asynchrony.

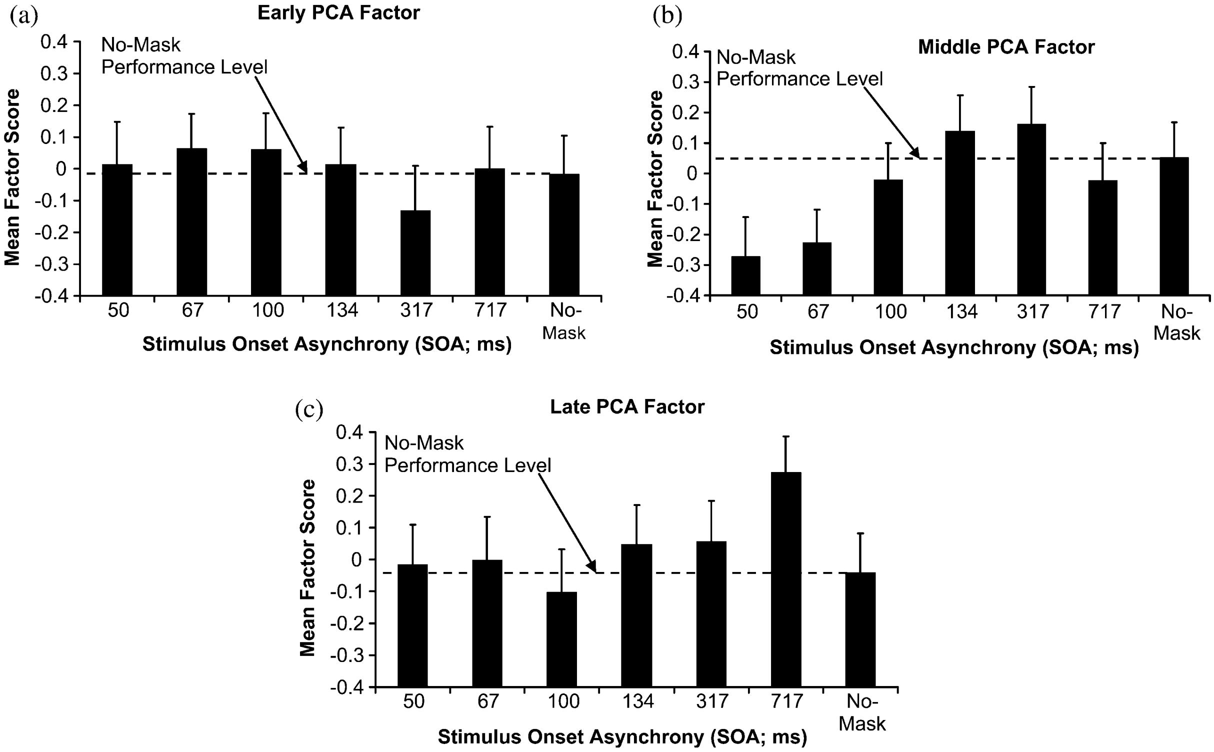

Fig. 3. PCA mean factor scores for the pupillary responses on the visual backward masking task across all SOA conditions in the early PCA factor (top left), the middle PCA factor (top right) and the late PCA factor (bottom). Larger PCA mean factor scores indicate greater pupillary dilation response. Error bars are 1 S.E.

accounting for 95.3% of the variance in the pupillary response data. As indicated by the squared multiple correlations, all factors were internally consistent and well defined by the data (the lowest of the squared multiple correlations for factors from data was 0.67). The PCA divided the pupillary response waveform into three time-dependent components: (1) An early component from 0 to 0.7 s (the third rotated factor; eigenvalue = 5.8); (2) A middle component from 0.7 to 1.53 s (second rotated factor; eigenvalue = 20.8); and (3) A late component from 1.53 to 3.0 s (first rotated factor; eigenvalue = 68.7). As described above, we interpreted the middle factor as indexing target processing and the late factor as indexing mask processing, especially in the longer SOA conditions when the masking stimulus becomes a distinct percept from the target stimulus.

Fig. 3 presents the early, middle and late PCA mean factor scores for the pupillary responses in the six masking conditions and the no-mask condition. A 3 (PCA factor) × 7 (masking condition) ANOVA conducted on the factor scores resulted in significant effects for condition, $F(6, 61) = 4.10$, $P < 0.01$, $\eta^2 = 0.29$ and the PCA factor × condition interaction, $F(12, 55) = 4.73$, $P < 0.01$, $\eta^2 = 0.51$, but not for PCA factor, $F(2, 65) = 0.07$, ns, $\eta^2 = 0.00$. A one-way ANOVA conducted on the early factor scores did not show a significant SOA effect, $F(6, 61) = 1.40$, ns, $\eta^2 = 0.12$, suggesting comparable early factor score amplitude in all conditions.

A one-way ANOVA conducted on the middle factor scores resulted in a significant condition effect, $F(6, 61) = 12.81$, $P < 0.01$, $\eta^2 = 0.56$. Follow-up analyses (Dunnett's test; $P < 0.05$) showed that the middle factor amplitude in the no-mask condition was significantly greater than the responses in the 50 and 67 ms SOA conditions, 50 ms vs. no-mask, $t(66)=3.63$, $P<0.01$, 67 ms vs. no-mask, $t(66)=3.75$, $P<0.01$. This finding was consistent with our interpretation of the middle factor as indexing resources allocated to target processing. That is, greater resources were allocated to target processing in the no-mask and longer SOA conditions, where target detection accuracy was high, than in the two shortest masking conditions where target detection was at chance performance.

A one-way ANOVA conducted on the late factor scores also resulted in a significant SOA effect, $F(6, 61)=3.52$, $P<0.01$, $\eta^2=0.26$. Follow-up analyses (Dunnett's test; $P<0.05$) showed that the late factor amplitude in the no-mask condition was significantly less than in the 717 ms condition, $t(66)=3.41$, $P<0.01$. This finding is consistent with our interpretation of the late factor as indexing resources allocated to the masking stimulus. That is, in the longest SOA, where the mask is thought to demand the most attention (Michaels and Turvey, 1979; Phillips, 1974), late factor amplitude was significantly greater than in the no-mask condition.

3.3. Relationship between pupillary response and detection accuracy

If the late factor indexes mask processing load, then the difference between masked and no-mask conditions on late factor scores (e.g. 317 ms SOA—no-mask and 717 ms SOA—no-mask late factor difference scores) should be inversely correlated with detection accuracy. That is, more wasteful allocation of resources to masks should be associated with less efficient target processing. These late (mask) factor difference scores were significantly inversely correlated with detection accuracy in the 317 ms, $r(65)=-0.34$, $P<0.01$ and the 717 ms, $r(65)=-0.33$, $P<0.01$, SOA conditions, but not in any other condition. In addition, if the middle factor indexes target processing, the extent of dilation on the middle factor should be positively correlated with target detection. Detection accuracy was significantly positively correlated with dilation on the middle factor in the 717 ms SOA condition, $r(65)=0.32$, $P<0.01$, but not in any other condition. In longer SOA conditions, therefore, participants who allocated more resources to targets and less to masks showed more accurate target detection.

3.4. Cognitive ability

SAT scores were significantly correlated with SES, $r(65)=0.60$, $P<0.01$, overall detection accuracy, $r(65)=0.36$, $P<0.01$ and mask pupillary response, $r(65)=-0.46$, $P<0.01$. Participants who scored higher on the SAT were from higher SES backgrounds, detected more target stimuli during the visual backward masking task, and exhibited less dilation to the masking stimulus in the longer SOA conditions than participants who scored lower on the SAT. SES was significantly correlated with overall detection accuracy, $r(65)=0.39$, $P<0.01$ and mask pupillary response, $r(65)=-0.31$, $P<0.01$. Participants who were from higher SES backgrounds detected more target stimuli and allocated less attention to the masking stimulus in the longer SOA conditions than did participants who were from lower socio-economic backgrounds. Overall detection accuracy was also significantly correlated with mask pupillary response, $r(65)=-0.42$, $P<0.01$. Participants who detected more target stimuli exhibited less dilation to the masking stimulus in the longer SOA conditions than did participants who detected fewer target stimuli.

The results of the hierarchical regression are presented in Table 1. Step 1 of the regression showed that SES accounted for significant amount of variance in SAT scores, $R^2=0.366$, $F(1, 65)=37.46$, $P<0.01$, Adjusted $R^2=0.356$. Step 2 added overall detection accuracy and resulted in a significant model, $R^2=0.384$, $F(2, 64)=19.96$, $P<0.01$, adjusted $R^2=0.365$; however, the change in R^2 was not significant, $\Delta R^2=0.018$, $F(1, 64)=1.92$, ns. Overall detection accuracy did not account for significantly greater variance in SAT scores over that accounted for by SES.

Step 3 of the regression added mask pupillary response and resulted in a significant model, $R^2=0.422$, $F(3, 62)=17.07$, $P<0.01$, adjusted $R^2=$

Table 1
Hierarchical regression predicting SAT scores

Model	Variable	Full model regression statistics				Hierarchical regression statistics				
		β	t value of β	Semi-partial, sr^2	F value of sr^2	R^2	F value of R^2	ΔR^2	F value of ΔR^2	Adjusted R^2
Step 1	SES	0.50**	4.84	0.205**	23.40	0.366**	$F(1, 65)=37.46$			0.356
Step 2	Det. Acc.	0.05	0.42	0.001	0.01	0.384**	$F(2, 64)=19.96$	0.018	$F(1, 64)=1.92$	0.365
Step 3	Mask PR	−0.28**	2.77	0.064**	7.35	0.448**	$F(3, 63)=17.07$	0.064**	$F(1, 63)=7.35$	0.422

Note: $^{**}P<0.01$; SES, socio-economic status; Det. Acc., overall detection accuracy; Mask PR, mask pupillary response.

0.422, and the change in R^2 over Step 2 was also significant, $\Delta R^2 = 0.064$, $F(1, 63) = 7.35$, $P < 0.01$. The addition of the mask pupillary response uniquely accounted for 7.3% of the variance in SAT scores above that of SES and detection accuracy. SES significantly accounted for 20.5% and mask pupil response accounted for 6.4% of the full model variance in SAT scores, while overall detection accuracy accounted for a nonsignificant 1.8% of the variance in SAT scores.

4. Discussion

A psychophysiological measure, pupillary response, was used in conjunction with a behavioral measure, detection accuracy, on the visual backward masking task to investigate the neural efficiency hypothesis that individuals with greater cognitive ability process information more efficiently than individuals with lower cognitive ability. As predicted, a pupillary response component that likely indexed attentional allocation to the masking stimulus significantly added to the prediction of SAT scores by uniquely accounting for 6.4% of variance in SAT scores above and beyond that accounted by SES and detection accuracy. This finding is consistent with the hypothesis that individuals who wastefully allocate attention to irrelevant information, the masking stimulus in this study, have lower scores on standardized cognitive ability tests (e.g. Cha and Merrill, 1994; Merrill and Taube, 1996; McCall, 1994). Thus, this study replicated and extended the findings of Ahern and Beatty (1979) and supported the neural efficiency hypothesis.

A late PCA component of the pupillary waveform was found in this study, which appeared to isolate the amount of resource allocation to mask processing. The PCA factor structure found in the present study was replicated in the other two data sets (Granholm and Verney, 2004; Verney et al., 2001), suggesting stability of the factor structure across psychiatric and non-psychiatric samples, different stimulus presentations (i.e. white stimuli on dark background vs. dark stimuli on white background) and different ethnic backgrounds (i.e. Caucasian and Mexican American). The PCA divided the pupillary response waveform into three meaningful factors. The middle factor occurred in the time window when peak dilation responses to cognitive tasks are typically found to reflect task processing load (Beatty, 1982; Beatty and Lucero-Wagoner, 2000; Steinhauer and Hakerem, 1992). Middle factor amplitude in the shortest (i.e. 50 and 67 ms) SOA conditions was significantly smaller than in the no-mask condition, and detection accuracy was at chance in these brief SOA conditions. Middle factor amplitude was much greater in longer SOA and no-mask conditions, where detection accuracy was nearly perfect. That is, the middle factor showed less dilation in brief SOA conditions, where target images were not yet fully formed (Breitmeyer, 1984; Breitmeyer and Ganz, 1976) and target detection was poor, but showed greater dilation when targets were fully formed and accurately detected. This pattern of results suggests that the middle factor indexed target processing.

In contrast, late factor amplitude was significantly greater in the longest (717) SOA condition relative to the no-mask condition. Models of early visual information processing suggest that, in longer SOA conditions, the masking stimulus becomes a distinct percept from the target stimulus and stimulus identification resources must be shifted and shared between targets and masks (Michaels and Turvey, 1979; Phillips, 1974). Therefore, the finding of greater late factor amplitude in the longest SOA condition (distinct target and mask percepts) and the no-mask condition (only target percept) suggests that the late factor indexed the additional processing demands of the mask. Furthermore, the difference between longer SOA and no-mask condition late factor amplitude was significantly inversely correlated with detection accuracy. Participants who allocated more resources to masks showed less accurate target detection. In contrast, middle factor amplitude was significantly positively correlated with detection accuracy in longer SOA conditions. Participants who allocated more resources to target detection showed more accurate target detection. Taken together, these findings suggest that allocating more resources to mask processing comes at the cost of fewer spare resources for accurate target processing. Importantly, this pattern of results was found only in longer SOA conditions, when competition between targets and masks for stimulus identification resources is thought to be greatest (Michaels and Turvey, 1979; Phillips, 1974).

It is important to stress that middle and late factor amplitudes did not simply reflect psychophysical aspects of the stimuli, rather than active cognitive processing of targets and masks. In Verney et al. (2001), participants passively viewed the visual backward masking task stimuli, and were told not to process them in any way (cognitive no-load condition). Pupil dilation responses were significantly smaller in this no-load condition, relative to the cognitive load condition when participants made judgments about target line length. Moreover, middle and late factor scores did not differ significantly between any SOA and no-mask conditions in the no-load condition. Simply viewing targets and masks in rapid succession, regardless of whether they were perceived as single (or merged) or separate percepts, did not produce the pattern of results for the middle and late factors found in this study. Rather, the middle and late factors reflected the active cognitive processing of targets and masks, respectively.

The early PCA factor was initially interpreted in our other studies (Granholm and Verney, 2004; Verney et al., 2001) as indexing a light reflex response to change in display light. In both of those studies, a bright target stimulus was presented on a dark background and a brief constriction response was found in the time window when pupillary light reflexes are typically observed (Loewenfeld, 1999). However, in the present study, dark stimuli were presented on a bright background and a dilation response, not a constriction, was observed in the time window of the early factor (Fig. 2). This is not consistent with a light reflex interpretation of the early factor. A model proposed by Steinhauer and Hakerem (1992), which describes the contributions of parasympathetic and sympathetic components to overall pupillary dilation during cognitive tasks, may provide an alternative interpretation of the early factor. The early factor occurred in a time window when early dilation to a cognitive task is thought to result from inhibition of parasympathetic pathways leading to relaxation of the sphincter pupillae (Steinhauer and Hakerem, 1992). When there is light in the visual display of a cognitive task, a pupillary light reflex may be observed in this time window, which is primarily due to activation of parasympathetic pathways leading to constriction of the sphincter pupillae (Loewenfeld, 1999). Regardless of whether an initial dilation or constriction is observed, the first factor may reflect an early, rapid parasympathetic contribution to the waveform. In the Steinhauer and Hakerem (1992) model, slower contributions to pupil dilation during cognitive tasks (e.g. to middle and late factor scores in this study) are due to sympathetic activation of the dilator pupillae. The PCA factor structure we have found in three studies, regardless of display luminance, all identified an early factor that ended at approximately the same time point that parasympathetic contributions subside and the sympathetic component begins to dominate in the Steinhauer and Hakerem (1992) model. This study was not, however, designed to investigate this model. Future studies could help delineate the parasympathetic and sympathetic contributions to the PCA factors found in this study by blocking the parasympathetic and sympathetic systems separately during backward masking task performance and observing the impact on the different PCA factors.

A few other studies have shown that the wasteful allocation of resources to distracting or irrelevant information is associated with poorer performance on cognitive tests (Cha and Merrill, 1994; McCall, 1994; Merrill and Taube, 1996). This study replicates those findings. One possible explanation for this finding is that individuals with lower cognitive ability actively and routinely process stimuli before determining the information to be irrelevant. Thus, the mask, as a separate, distinct percept in the longer SOA conditions (Michaels and Turvey, 1979; Phillips, 1974), would demand more resources for such individuals to process it. This might be due to reduced active selection of relevant information or reduced filtering of irrelevant information in individuals with lower cognitive ability relative to individuals with higher cognitive ability. Theories of this type of information processing efficiency emphasize not only selectively encoding the relevant information, but also actively inhibiting the irrelevant information (e.g. Neill, 1977; Neill and Westberry, 1987; Neill et al., 1995; Tipper, 1985; Tipper and Cranston, 1985). The ability to quickly automate the processing of irrelevant information by individuals with higher cognitive abilities is another related possibility. Automatic processing requires minimal mental effort while controlled processing requires resources (Schneider and Shiffrin, 1977). The smaller pupillary responses in individuals with higher cognitive abilities may reflect greater or faster automation of mask inhibition, while the larger pupillary responses in individuals with lower cognitive abilities may reflect a failure to automatically dismiss the mask, requiring the use of controlled processing to determine its identity and relevance. Further research is needed to investigate these possible mechanisms and to determine the role of processing irrelevant information in cognitive abilities.

Performance on the backward masking task has reliably been shown to substantially correlate with measures of cognitive ability (reviewed by Deary and Stough, 1996; Kranzler and Jensen, 1989). This study, however, did not find detection accuracy to be a significantly correlated to SAT scores in the presence of SES. A weak relationship between detection accuracy and SAT scores has been previously reported (Longstreth et al., 1986). Although greater detection accuracy was significantly correlated with higher SAT scores, this relationship was not significant when controlling for SES or in the context of the more powerful pupillary response predictor. A few possibilities for this discrepancy exist. For the average participant (i.e. freshman college status), the SAT would have been administered 1–2 years prior to the lab testing for this study. The long time period between measures would likely diminish the correlation between them. In addition, the SAT was designed to be an achievement measure, and as such, may be less effective at tapping the ‘intelligence’ construct than measures of cognitive ability (e.g. IQ tests) that have been used in most previous studies. Achievement tests such as the SAT have nonetheless been closely associated with general intelligence (Reschly, 1990). Also, the administration of the masking task in this study differs from most studies because the PC-based stimulus presentation limited display rates to those bound by a 60 Hz refresh cycle. In contrast, most previous studies have utilized a tachistiscope-administered task. The refresh cycle also determined the use of a standard target exposure duration procedure in this study rather than an individually determined critical stimulus duration (CSD) procedure and measurement of IT as the dependent variable, as in the most studies investigating the relationship between masking performance and cognitive ability. Target duration for the CSD procedure in IQ studies has typically ranged from approximately 10 ms to a few hundred millisecond (Deary and Stough, 1996). Michaels and Turvey (1979) in their early studies outlining masking effects reported no significant differences between target durations of 10, 20 and 50 ms in a sample of healthy college students. The target duration used in this study (i.e. 16.7 ms), therefore, is consistent with most studies using a CSD procedure and the lack of association between detection accuracy and SAT scores is not likely due to the standard target duration procedure used in this study. Detection accuracy on the same computerized, standard target exposure visual backward masking task used in this study did significantly predict IQ scores (i.e. WAIS-R, Full Scale scores; Wechsler, 1981) in our larger study (Verney, 2001; Verney et al., submitted).

The combination of a psychophysiological measure, indexing attentional allocation to the task, with traditional behavioral measures, indexing individual performance level, is a powerful approach to study cognitive mechanisms involved in human information processing and the breakdown of processing with illness. For example, we examined pupillary responses during the backward masking task in schizophrenia (Granholm and Verney, 2004). Relative to healthy controls, patients with schizophrenia were found to over-allocate attentional resources to the irrelevant masking stimulus (i.e. greater late factor amplitude in longer SOA conditions) and under-allocate resources to the relevant target stimulus (i.e. smaller middle factor amplitude). This attentional allocation problem in patients with schizophrenia might account, in part, for more general cognitive and intellectual deficits found in schizophrenia, given the finding from the present study that lower general cognitive ability was associated with this type of allocation problem. We have also used this paradigm to investigate cultural bias in cognitive ability assessment (Verney et al., submitted). Psychophysiological measures, such as pupillary responses, and early visual information-processing tasks, such as the backward masking task, appear to be less influenced by cultural and social learning factors associated with other cognitive measures (Deary and Stough, 1996). We found differential validity in predicting WAIS-R scores from these measures between Caucasian American and Mexican American students, suggesting that the WAIS-R test contains a cultural component that reduces the validity of the WAIS-R as a measure of cognitive ability for Mexican American students (Verney et al., submitted). Information processing and psychophysiological approaches, therefore, may be helpful in developing culture-fair cognitive ability measures and in better understanding information processing deficits and abilities in both psychiatric and non-psychiatric populations.

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