

Research Article

PERCEPTUAL LOAD AND VISUOCORTICAL PROCESSING: Event-Related Potentials Reveal Sensory-Level Selection

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Abstract—Behavioral evidence suggests that the processing of parafoveal stimuli decreases as the perceptual demands of a task at fixation increase. However, it remains unclear whether or not this effect of perceptual load occurs during initial sensory-level processing at early stages of visuocortical analysis. Using event-related potential measures, we found that increasing the perceptual load of foveal targets led to a significant decrease in the sensory-evoked response to parafoveal stimuli. Moreover, these effects were observed using two different operational definitions of perceptual load. This result indicates that perceptual load affects the flow of information during the initial stages of visuocortical processing.

Does selection in early visual processing depend on perceptual load? Evidence from reaction time (RT) studies suggests that it may. In particular, when subjects discriminate target stimuli at fixation, response interference from task-irrelevant parafoveal stimuli varies as a function of the perceptual load of the foveal targets. If the perceptual load of targets is low, the parafoveal stimuli have a distracting effect on target processing, but this effect is diminished or absent when the load of targets is high (e.g., Dark, Johnston, Myles-Worsley, & Farah, 1985; Kahneman & Chajczyk, 1983; Miller, 1991; Yantis & Johnston, 1990). Lavie and Tsal (1994) interpreted these load effects within a resource-based model, proposing that (a) visual perception is a limited-capacity process and (b) the perception of task-irrelevant stimuli will proceed only as long as sufficient attentional capacity remains available. According to the model, when perceptual load is increased, target processing consumes a greater percentage of the attentional capacity associated with visual perception, and as a result, the perceptual-level processing of the parafoveal nontargets is reduced (see Lavie, 1995). This model predicts that evidence for load-mediated selection should be observed in visuocortical areas subserving visual perception.

Support for the prediction has come from the domain of neuroimaging. Using functional magnetic resonance imaging (fMRI), Rees, Frith, and Lavie (1997) examined the cortical response to task-irrelevant, parafoveal moving dots as a function of the linguistic complexity—or processing load, in their terms—of a task at fixation. Subjects attended to foveally presented words under two different levels of load. In the low-load condition, they were required to discriminate whether or not words were printed in all capital letters; in the high-load condition, the same word set was presented, but subjects had to discriminate the number of syllables in each word. In both conditions, the parafoveal dots were moving radially toward the edge of the dis-

play, an optic flow field that produced activation in multiple visuocortical areas, including motion-specific area MT (V5). Rees et al. found that when load at fixation was increased, the motion-evoked activity in these visual areas decreased. These results supported Lavie and Tsal (1994), in that the manipulation of processing load led to a systematic reduction in the perceptual processing of the parafoveal stimulation.

Although the data of Rees et al. (1997) provide compelling evidence for the early-selection model of perceptual load, the study leaves two fundamental issues unresolved. First, although linguistic complexity may be a valid operational definition of processing load, it is uncertain whether it is an equally valid definition of perceptual load. Second, Rees et al. used a box-car fMRI design, which integrates cortical activity across multiple stimulus presentations, thereby providing little insight into the temporal sequence of individual stimulus-processing events (see Rugg, 1998). Thus, it remains unclear whether load-related modulations in early visuocortical areas occur during initial sensory input, or whether they are the result of delayed, reentrant feedback. If reentrant modulation proves to be the neural mechanism underlying the effects of load, it would be inconsistent with an early-selection view of perceptual load—because early selection at the cortical level depends on both when and where selection arises, not just where.

To resolve these issues, we used event-related potentials (ERPs), which provide a measure of stimulus-related processing with a millisecond-level temporal resolution (see Coles & Rugg, 1995). Specifically, studies using combined ERP and neuroimaging methodologies have linked the occipital P1 ERP component (latency: ~80–130 ms poststimulus) to sensory-evoked, nonreentrant processing in extrastriate visual cortex (e.g., Heinze et al., 1994; Mangun, Hopfinger, Kussmaul, Fletcher, & Heinze, 1997; Martinez et al., 1999; Woldorff et al., 1997). Moreover, the occipital P1 has been a reliable measure of early selection in vision: The P1 amplitude evoked by a stimulus in an attended location is larger than the P1 evoked by a physically identical stimulus in an unattended location (e.g., Eason, 1981; Mangun & Hillyard, 1991; Van Voorhis & Hillyard, 1977). If perceptual load can mediate attentional selection during the initial stages of visuocortical analysis, the consequences of this selection should be manifest in the P1 response: There should be a reduction in the P1 amplitude for parafoveal stimuli as the perceptual load of foveal targets is increased from low to high. We examined this hypothesis in the following experiments.

EXPERIMENT 1

The goal of Experiment 1 was to measure the sensory-evoked ERP response to parafoveal, task-irrelevant stimuli (a) as a function of the perceptual load of foveal targets and (b) using a distractor interference paradigm comparable to the paradigms used in behavioral studies of perceptual load. In distractor paradigms, responses to targets at fixation are examined as a function of task-irrelevant stimuli (i.e., distrac-

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tors) presented parafoveally (e.g., Eriksen & Eriksen, 1974). When the task requires a two-choice discrimination of the target, responses are significantly delayed if the distractor is a stimulus that would require the response opposite to the one the target requires (a *response-incompatible* distractor), relative to when the distractor is unrelated to the response options (a *response-neutral* distractor). Behavioral studies of

perceptual load have shown that the effect of the incompatible distractor depends on task load: When load is increased, the incompatible distractor produces less response interference (e.g., Lavie, 1995). Experiment 1 was designed to determine if this decrease in interference is associated with a reduction in the sensory-evoked response to stimuli at the distractor location, as measured by the P1 ERP component.

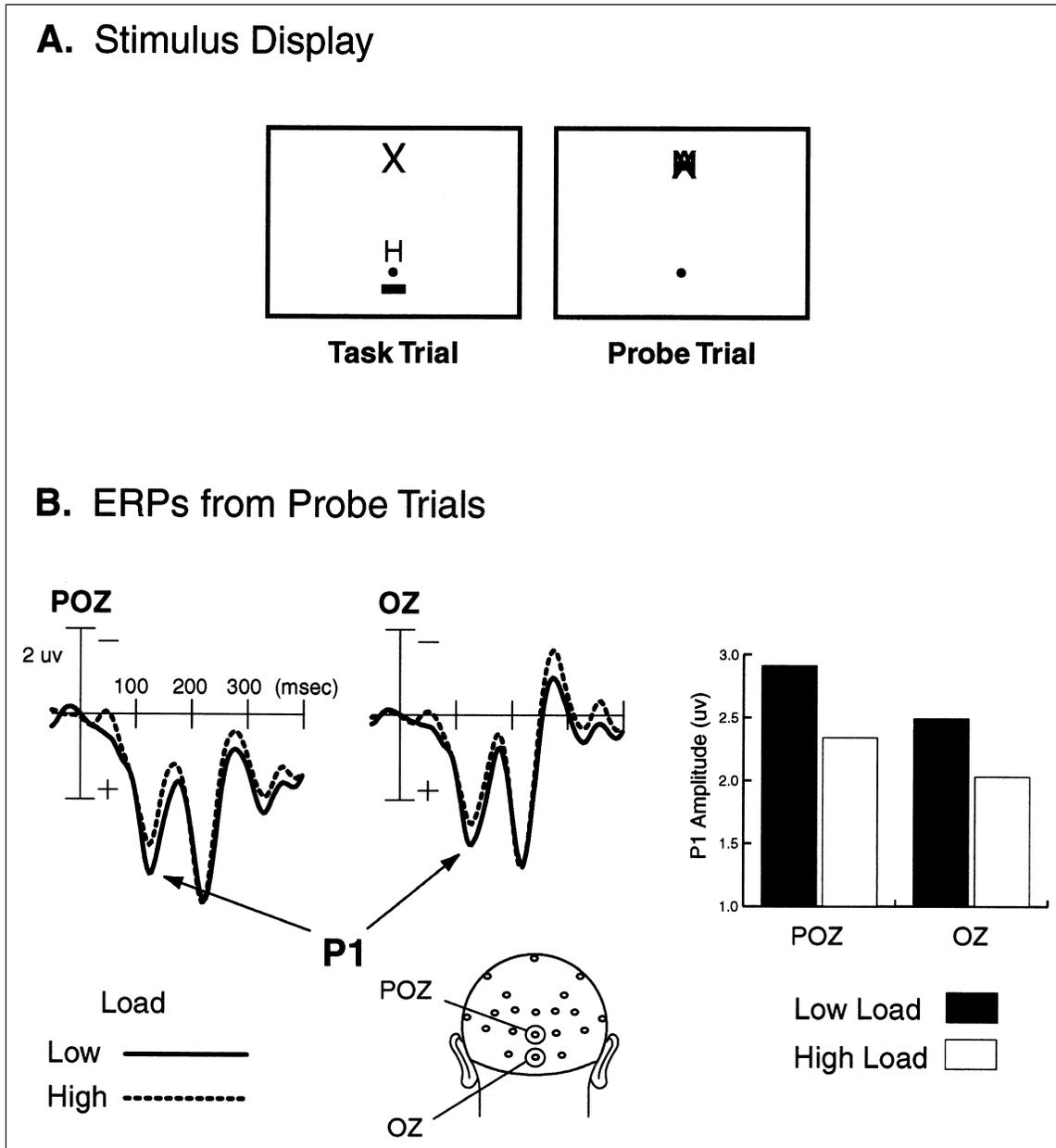


Fig. 1. Stimulus displays (a) and P1 data (b) in Experiment 1. The displays shown are examples of the two different trial types: task (left) and probe (right). In the low-load condition on the task trials, the color of the bar below the fixation dot was discriminated; in the high-load condition, the color and orientation of this bar were discriminated. The P1 data for the probe trials are shown as a function of perceptual load. The event-related potential (ERP) traces are for medial occipital sites POZ and OZ (shown in the bottom illustration), and begin 50 ms prior to stimulus onset. The bar graph shows the mean amplitude of the P1 at each electrode as a function of perceptual-load condition, measured over a 50-ms time window beginning 100 ms after stimulus onset (see Experiment 1 Method).

Method

The paradigm was based on the design used by Lavie (1995, Experiments 2A and 2B). On each *task trial*, a small colored bar ($0.7^\circ \times 0.2^\circ$) was presented immediately below fixation, in either a horizontal or a vertical orientation, and a target letter ($5^\circ \times 0.75^\circ$) was simultaneously presented immediately above fixation (Fig. 1a). Under the low-load condition, the task required a color discrimination of the bar (purple or green), whereas under the high-load condition, the task required both color and orientation (vertical or horizontal) discrimination (load conditions were blocked). If the bar matched a prespecified color (low load) or color-orientation combination (high load), the subject then had to discriminate the target letter (*A* or *H*) and make a rapid two-choice manual response indicating which letter had been presented. In this sense, the bar represented a go/no-go signal for making the letter discrimination. In the high-load condition, the go signal was counterbalanced between subjects as (a) any green vertical or purple horizontal bar or (b) any purple vertical or green horizontal bar. The two possible colors of the bar and the two orientations were always equiprobable, so within each block of trials, half of the task trials were go trials. Included on two thirds of the task trials was a task-irrelevant letter ($0.92^\circ \times 0.92^\circ$, presented 2.3° above fixation) that was either the same as the target letter (a compatible distractor), the opposite letter (an incompatible distractor), or an *X* (a neutral distractor); the task trials without a distractor were used as an ERP control condition (see Results). The bar, target letter, and distractor (when included) were presented simultaneously for 102 ms.

In addition to these task trials, each block of trials included *probe trials*, when only a task-irrelevant, nonletter stimulus (a superimposition of the *X*, *H*, and *A* distractors) was presented (for 51 ms) in the distractor location. These target-free trials allowed the processing of parafoveal stimulation to be measured as a function of perceptual load in a manner that left the parafoveal ERP unconfounded by foveal stimulation.

Behavioral performance was measured as a function of target load and distractor type; manual responses were made with the thumbs, each signaling one of the target letters, with thumb-target mapping counterbalanced across subjects. The intertrial interval was randomly varied between 1,500 and 1,800 ms. Within each load condition, each block of trials contained 72 task and 24 probe trials presented in random order. Subjects were run in eight blocks in each condition, in a counterbalanced fashion.

Scalp potentials were recorded from 29 tin electrodes mounted in a custom elastic cap. All electroencephalographic (EEG) activity was recorded relative to the left mastoid, amplified with a band-pass of 0.1 to 100 Hz (half-amplitude cutoffs), and digitized on-line at a sampling rate of 256 samples per second. To ensure proper eye fixation, we also recorded vertical and horizontal electro-oculograms (EOGs), the vertical EOG from an electrode inferior to the right eye and the horizontal EOG from an electrode on the right outer canthus. Off-line, computerized artifact rejection was used to eliminate trials during which detectable eye movements ($>1^\circ$), blinks, muscle potentials, or amplifier blocking occurred. For each subject, ERPs were averaged into 3,000-ms epochs, beginning 1,500 ms before stimulus onset. Subsequently, all ERPs were algebraically referenced to the average of the left- and right-mastoid signals, and filtered with a low-pass Gaussian filter (10-Hz half-amplitude cutoff) to eliminate high-frequency artifacts in the waveforms. The resulting ERPs were then used to produce the grand-averaged waveforms presented in this article. Statistical analysis of the P1 data was based on a mean amplitude measure over a 50-ms time

Table 1. Mean reaction times (in milliseconds) for target responses in Experiment 1

Perceptual load	Distractor		Difference
	Incompatible	Neutral	
Low	546 (78)	531 (73)	15
High	736 (93)	740 (99)	-4

Note. Standard deviations are in parentheses.

window, centered approximately on the peak latency in the grand-averaged waveform (100–150 ms poststimulus). Ten subjects participated.

Results

Behavior

The effect of the incompatible distractor on target responses varied as a function of perceptual load (Table 1). This was confirmed by an omnibus repeated measures analysis of variance (ANOVA), which showed a significant load-by-distractor interaction, $F(1, 9) = 12.16$, $p < .01$. When load was low, RTs to targets were slower when the incompatible distractor was present than when the neutral distractor was present, $t(9) = 3.16$, $p < .05$, two-tailed. In contrast, when load was high, RTs did not significantly differ when the incompatible distractor was present relative to when the neutral distractor was present, $t(9) = 1.58$, $p > .10$, two-tailed. Only data for neutral and incompatible distractors were analyzed because prior studies of load and distractor interference have not attempted to interpret the effects of compatible distractors on target responses as it is difficult to separate effects of response-based facilitation and feature-based priming.

ERPs

The amplitude of the P1 measured on probe trials decreased with perceptual load (Fig. 1b). This effect was confirmed in an omnibus repeated measures ANOVA, which showed that the P1 amplitudes at midline occipital electrode site OZ and midline parietal-occipital site POZ were significantly greater in the low-load condition than in the high-load condition, $F(1, 9) = 6.63$, $p < .05$.¹

Discussion

Consistent with the model of Lavie and Tsal (1994), the P1 data indicate that the sensory-evoked response in early visuocortical processing was reduced for task-irrelevant, parafoveal stimuli when the perceptual

1. As a control, ERPs were derived for the foveal targets that were presented without a distractor. The P1 amplitude for these targets did not change with perceptual load, $F(1, 9) = 1.31$. This finding eliminates the concern that the decrease in P1 amplitude seen at the distractor location was simply due to a reduction in the sensory-evoked response of the P1 caused by a constriction of the pupil under the high-load condition (see Beatty, 1982). That is, if the pupil response was causing the ERP effect, the foveal ERPs should have also shown a decrease under the high-load condition.

load of foveal targets was high. Moreover, the behavioral evidence shows that response interference associated with the incompatible distractor decreased with the increase in load. Taken together, the results support the position that the effects of perceptual load on attentional selection arise during the initial stages of visuo-cortical processing.

Although the design of Experiment 1 closely replicated prior behavioral studies, the way in which perceptual load was manipulated raises an important issue. Like Rees et al. (1997), we based the load manipulation on a qualitative change in processing demands—discriminate target color versus discriminate both color and orientation. As a

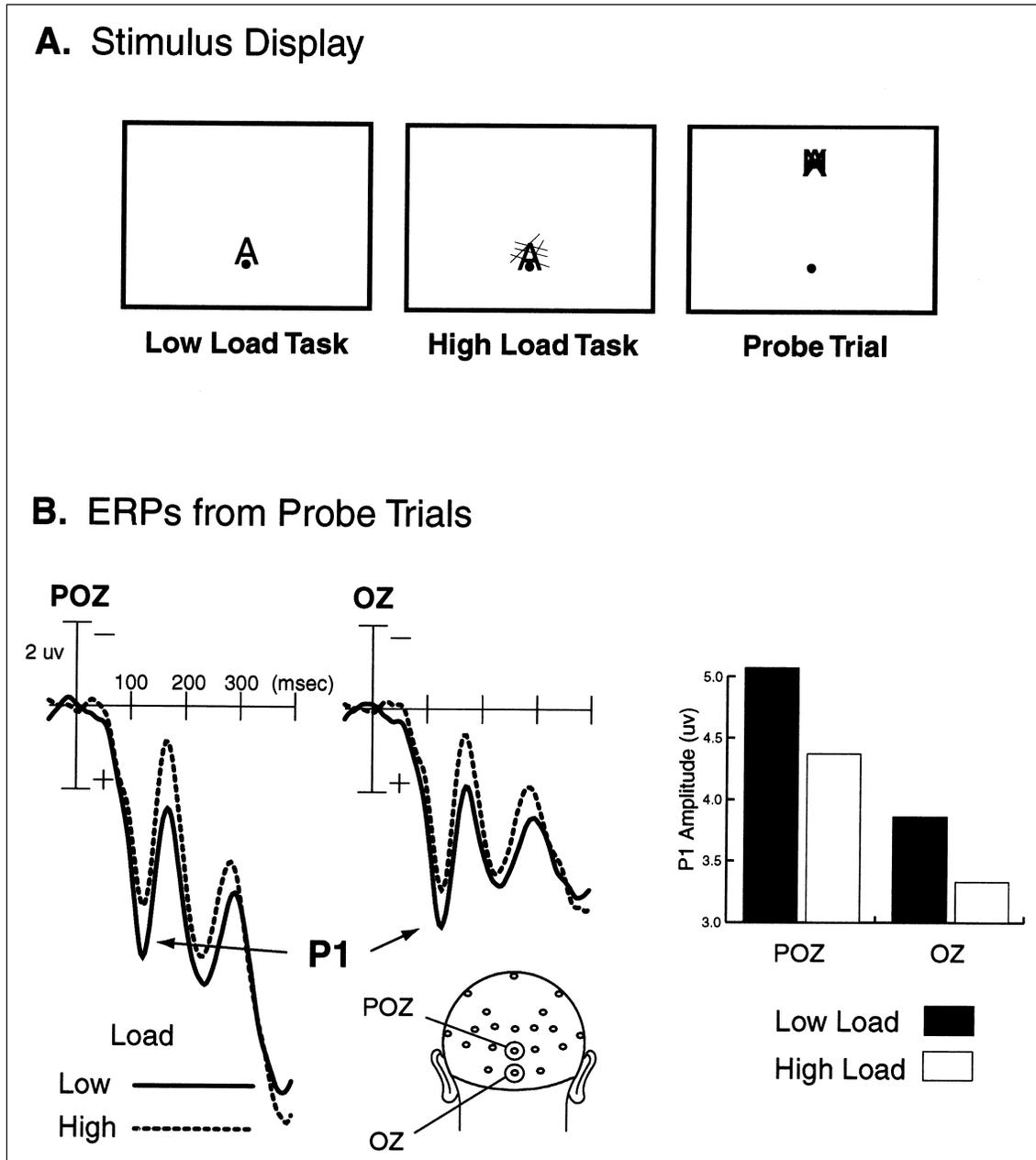


Fig. 2. Stimulus displays (a) and P1 data (b) in Experiment 2. The displays shown are examples of low-load task trials (left), high-load task trials (middle), and probe trials (right). The perceptual-load manipulation was based on varying the target's signal-to-noise ratio. The P1 data for the probe trials are shown as a function of perceptual load. The event-related potential (ERP) traces are for medial occipital sites POZ and OZ (shown in the bottom illustration), and begin 50 ms prior to stimulus onset. The bar graph shows the mean amplitude of the P1 at each electrode as a function of perceptual-load condition, measured over a 50-ms time window beginning 100 ms after stimulus onset (see Experiment 1 Method).

result, it remains to be shown whether the early visuocortical effects of perceptual load can also arise under conditions in which the task remains constant, but there is a quantitative change in the processing demands associated with it. That is, it is unclear whether the ERP effects reported in Experiment 1 depend on differences between qualitatively distinct tasks, or whether they can occur when an overall increase in load is placed on a specific perceptual-level process (see Handy, 2000). To examine this issue, we performed a second experiment.

EXPERIMENT 2

The goal of Experiment 2 was to measure the sensory-evoked ERP response to parafoveal stimuli as a function of the perceptual load of a foveal task that remained constant across different load conditions. Specifically, we employed a design similar to that of a previous study (Handy & Mangun, 2000), in which we required subjects to discriminate a letter target that had its signal-to-noise ratio varied between load conditions. In the low-load condition, single target letters were presented at fixation; in the high-load condition, the same foveal target letters were presented, but for shorter durations and with masking stimuli presented at target offset (Fig. 2a). This manipulation increased the perceptual load for the latter condition by decreasing the target signal strength (via a reduction in target duration) and by adding noise (the mask).

Method

On each task trial, a letter, either an *A* or an *H*, was presented at fixation. The letters were drawn with white lines 0.06° thick, and were 0.86° wide by 0.86° tall. In the low-load condition, the letter was presented for 102 ms. In the high-load condition, the letter was presented for a briefer duration, and was immediately followed by a patterned mask. The mask consisted of a set of randomly oriented white lines of various lengths, 0.06° thick, contained within a 1° square area. The onset of the mask coincided with the offset of the target, and their summed durations equaled 102 ms. The ratio of the target duration to the mask duration was varied between trial blocks (depending on the subject's performance) in order to maintain task difficulty; the aim was to keep task performance as close to 75% correct as possible. The ratios of target/mask durations (in milliseconds) used were 17/85, 34/68, and 51/51. In each block, there were 60 task trials, 30 with an *A* and 30 with an *H*.

In addition to these task trials, each block of trials included 20 probe trials, which consisted of the same parafoveal ERP stimulus that was used in Experiment 1. The location of this parafoveal stimulus remained unchanged, and its duration was 102 ms. Each trial block contained a total of 80 trials, with the order of trial types (task or probe) randomly varied within and between blocks. The intertrial interval was randomly varied between 1,500 and 1,800 ms. Each subject completed six blocks of trials in each of the two load conditions, with order counterbalanced across subjects. All electrophysiological recordings and analyses were identical to those of Experiment 1. Eight subjects participated.

Results

RTs were shorter in the low-load condition than in the high-load condition (Table 2), an effect that was confirmed by an omnibus repeated measures ANOVA, $F(1, 7) = 11.73, p < .05$. As in Experiment

Table 2. Mean reaction times and standard deviations (in milliseconds) for target responses in Experiment 2

Perceptual load	Reaction time	SD
Low	458	64
High	526	85

1, the amplitude of the P1 for the parafoveal stimulus decreased with perceptual load (Fig. 2b). An omnibus repeated measures ANOVA again showed that the P1 amplitudes at electrode sites OZ and POZ (time window: 100–150 ms poststimulus) were significantly greater in the low-load condition than the high-load condition, $F(1, 7) = 8.54, p < .05$.

Discussion

In Experiment 2, perceptual load was manipulated by varying target signal-to-noise ratio in a letter-discrimination task. The amplitude of the P1 ERP component evoked by the task-irrelevant, parafoveal stimuli decreased with increases in load, a pattern that replicated the results of Experiment 1. This finding suggests that the effect of perceptual load on early visuocortical processing, as indexed by the amplitude of the P1, reflects the overall consumption of attentional capacity. The implications of these findings are discussed in the next section.

GENERAL DISCUSSION

The results presented here suggest that perceptual load can modulate attentional selection early in visuocortical processing. In both experiments, when the perceptual load of the foveal tasks was high, there was a reduction in the sensory-evoked occipital P1 response for task-irrelevant parafoveal stimuli, relative to the respective low-load conditions. Providing the temporal resolution of load-related stimulus processing that was previously unavailable, these findings demonstrate that load-mediated selection can occur as early as extrastriate cortex, by approximately 90 to 100 ms after stimulus onset. Interestingly, this ERP evidence was obtained on trials on which no task-relevant stimuli were present, indicating that the load-related effects on the P1 carried over from task-relevant trials. Three lines of evidence converge on a model wherein perceptual load affects the capacity associated with attending to visual locations.

First, the carryover of the load effect from task-relevant to task-irrelevant trials directly parallels the manner in which perceptual load influences the endogenous orienting of spatial attention. In particular, previously we (Handy & Mangun, 2000) used ERPs to demonstrate that when attention was cued to the most likely location of an impending parafoveal target, the amount of attention subjects allocated to the cued location increased with the perceptual load of the target items. The P1 evoked by stimuli in the expected target location was larger when perceptual load was high than when perceptual load was low. In a similar vein, the current data suggest that increasing the load of foveal targets decreases the amount of residual attentional capacity available for allocation to task-irrelevant parafoveal locations. Taken together, this ERP evidence is consistent with a model in which (a) spatial attention is allocated prior to stimulus onset and (b) a greater

proportion of this capacity is allocated to the expected target location—either foveal or parafoveal—when perceptual load is high than when it is low. The model predicts that the influence of load on spatial attention depends on whether or not subjects can anticipate the load of an impending target: P1 effects that are observed when load is held constant across trial blocks (Experiments 1 and 2; Handy & Mangun, 2000) should be eliminated if load is randomly varied within blocks, because subjects would not be able to systematically allocate their spatial attention prior to target onset as a function of target load. We are currently examining this hypothesis.

Second, using fMRI, Smith, Singh, and Greenlee (2000) recently found that attending to fixation suppresses non-stimulus-related activity in extrastriate neurons representing parafoveal locations, relative to when attention is in a more diffuse state. Smith et al. interpreted this finding as evidence that spatial attention can reduce the baseline level of activity in neurons that have receptive fields in nonattended visual locations (see also Sommers, Dale, Seiffert, & Tootell, 1999). The data presented here are consistent with the findings of Smith et al., in that increased load at fixation led to a reduction in the sensory-evoked extrastriate response to parafoveal stimulation—the predicted effect if load was increasing the percentage of spatial attention capacity allocated to fixation. However, whether our results were due to a reduction in the baseline level of activation for parafoveal locations rather than a reduction in the amount of stimulus-related activity above prestimulus baseline levels (i.e., reduced sensory gain) remains an open question.

Finally, although the current data do not discount the possibility that perceptual load influences the capacity associated with feature- or object-based attention, the possibility that object-based effects explain the P1 behavior observed here seems unlikely when ERP evidence from other studies is considered. A recent investigation of combined stimulus expectancies found that when subjects were cued to the most likely location and form of an impending target, the P1 was affected only by the location expectancy—effects related to the form expectancy arose in later ERP components (Handy, Green, Klein, & Mangun, in press). Similar results have been reported in ERP studies of hierarchical feature selection, which have shown that if subjects simultaneously attend to the location and color or motion of targets, the P1 is modulated by attention to location, but not by attention to the other stimulus attributes (e.g., Anllo-Vento & Hillyard, 1996; Hillyard & Münte, 1984). In all of these ERP studies, despite active attention to nonspatial object features, P1 effects were unique to spatial attention. In sum, the present findings are most consistent with a model in which the effects of load on early visuocortical processing reflect modulations of the capacity for attending to visual locations.

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