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Attentional Load Asymmetrically Affects Early Electrophysiological Indices of Visual Orienting

Redmond G. O'Connell[1], Dana Schneider[1], Robert Hester[2], Jason B. Mattingley[1] and Mark A. Bellgrove[1]

[1]The University of Queensland, School of Psychology and Queensland Brain Institute, Brisbane, Queensland 4072, Australia and [2]The University of Melbourne, Psychological Sciences, Parkville, Victoria 3010, Australia

Address correspondence to Dr Redmond O'Connell, Trinity College Institute of Neuroscience, Lloyd Building, Trinity College Dublin, Dublin 2, Ireland. Email: reoconne@tcd.ie.

Recent behavioral studies suggest that asymmetries in visuospatial orienting are modulated by changes in the demand on nonspatial components of attention, but the brain correlates of this modulation are unknown. We used scalp-recorded event-related potentials to examine the influence of central attentional load on neural responses to lateralized visual targets. Forty-five participants were required to detect transient, unilateral visual targets while monitoring a stream of alphanumeric stimuli at fixation, in which the target was defined either by a unique feature (low load) or by a conjunction of features (high load). The earliest effect of load on spatial orienting was seen at the latency of the posterior N1 (190–240 ms). The commonly observed N1 enhancement with contralateral visual stimulation was attenuated over the right hemisphere under high load. Source analysis localized this effect to occipital and inferior parietal regions of the right hemisphere. In addition, we observed perceptual enhancement with increasing load within the focus of attention (fixation) at an earlier stage (P1, 90–140 ms) than has previously been reported. These data support the view that spatial asymmetries in visual orienting are modulated by nonspatial attention due to overlapping neural circuits within the right hemisphere.

Keywords: attentional load, event-related potentials, N1, visual orienting, visuospatial asymmetry

Introduction

Although the control of attention typically relies on the complimentary contributions of both cerebral hemispheres, a rich functional imaging and human lesion literature indicates that the right hemisphere plays a dominant role in directing attention toward goal-relevant visual events (Mesulam 1999; Corbetta et al. 2008). The importance of this hemispheric specialization can be seen in patients suffering from left visuospatial neglect due to right parietal damage. These patients fail to orient to left-sided stimuli and typically have their attention captured by sensory events arising toward the right, leading to a pathological gradient of perceptual awareness across space (Heilman et al. 1985; Driver and Mattingley 1998). Most neglect cases arise from damage to right temporoparietal areas, with damage to corresponding regions of the left hemisphere giving rise to mild or transient symptoms (Husain and Rorden 2003; Rorden et al. 2006; Verdon et al. 2010). In addition to their lateralized spatial deficits, right hemisphere patients with neglect often experience significant impairment in nonspatial components of attention, including reductions in information processing capacity and a difficulty sustaining attention (Husain and Rorden 2003). The possibility that these nonspatial deficits are functionally related to the persistence of neglect has motivated further investigation of the interplay between the different components of attention in both healthy and disordered populations.

Recent neuroanatomical models propose that spatial attention relies on 2 distinct but related cortical networks (Husain and Nachev 2007; Corbetta et al. 2008). Intentional shifts of visual attention are directly mediated by a bilateral network of dorsal frontal and parietal regions. Despite the fact that neglect primarily affects attentional functions that have been ascribed to this dorsal network, the condition is most commonly caused by damage to a more ventral collection of frontoparietal regions in the right hemisphere that are associated with nonspatial attentional capacity (Culham et al. 2001; Schwartz et al. 2005; Vuilleumier et al. 2008) and vigilance (Paus et al. 1997; Sturm and Willmes 2001). According to Corbetta et al. (2008), the ventral network serves to bias the dorsal orienting network toward goal-relevant, novel, or unexpected stimuli. In support of this model, a functional magnetic resonance imaging (fMRI) study of stroke patients with lesions that were restricted to the ventral network identified a functional imbalance in the structurally intact dorsal network with decreased activation of right parietal areas and increased activation of left parietal areas (Corbetta et al. 2005). These data suggest that visual orienting is balanced by competitive interactions between the 2 hemispheres and that this balance is partly mediated by inputs from the ventral network. Several studies have shown that this balance is not only disrupted by structural damage but is also affected by increased demands on attentional processes mediated by the ventral network.

Vuilleumier et al. (2008) conducted an fMRI study of patients with right parietal damage but structurally intact early visual areas. Increasing attentional load at fixation caused a reduction in attention-dependent activity in right retinotopic visual areas but produced no changes in left visual areas. Bartolomeo et al. (2000) studied patients whose neglect symptoms had subsided over time. No spatial bias was apparent when participants executed simple speeded responses to lateralized stimuli, but a clear neglect of left space emerged when task difficulty was increased by including rare "catch" trials to which participants had to inhibit their responses. By studying left parietal patients as well as right parietal patients, Peers et al. (2006) suggested that such effects of difficulty are spatially specific by showing that both left and right parietal patients exhibited a rightward selection bias with increasing attentional demand.

Establishing the neural underpinnings of the relationship between spatial and nonspatial factors in the neglect syndrome is complicated by the fact that the underlying brain damage is often widespread and can affect multiple cognitive systems.

Studying these same phenomena in the intact brain therefore has distinct advantages. In contrast to neglect patients, most neurologically healthy individuals exhibit a subtle bias in spatial attention that favors the left side under free viewing conditions (Bowers and Heilman 1980; Nicholls et al. 1999, 2005). A rightward shift of attention can be induced temporarily in healthy participants, however, by increasing the demand on nonspatial attentional resources (Peers et al. 2006; Dodds et al. 2008). To date, there has been little investigation of the neural basis of this behavioral effect.

Event-related potentials (ERP) provide unparalleled temporal resolution in tracing the cortical processes associated with specific events or stimuli and have proven particularly valuable in establishing the precise timing of the neural effects of top-down attention (Luck et al. 2000). Attention amplifies activity in visual centers from a very early stage following stimulus presentation, with signals at attended versus unattended locations being differentiated at or before the latency of the P1 (around 100 ms poststimulus) and extending to the N1 component (around 200 ms poststimulus) and beyond (e.g., Luck 1995; Anllo-Vento et al. 1998; Hillyard et al. 1998; Barnhardt et al. 2008; Kelly et al. 2008). Increasing the commitment of processing resources "within" the region of focused attention has also been shown to enhance visual analysis but starting at the later latency of the N1 (Anllo-Vento et al. 1998; Barnhardt et al. 2008).

The P1 component has been linked to initial sensory inputs in the fusiform gyrus as well as to suppression of unattended information, which serves to maximize signal levels at attended locations (Luck 1995; Clark and Hillyard 1996; Natale et al. 2006). The N1 has been linked to a higher level stimulus discrimination mechanism, which is also subject to modulation by attention (Vogel and Luck 2000). Dipole modeling and functional imaging studies have highlighted temporoparietal contributions for the N1 (Fu et al. 2005; Natale et al. 2006). These findings suggest that the N1 component indexes processes that are mediated by the ventral attention network that has been directly implicated in the neglect syndrome (Husain and Nachev 2007; Corbetta et al. 2008). Both the P1 and the N1 components show an attentional asymmetry in extrastriate cortex (Miniussi et al. 2002), exhibit preferential enhancement over posterior scalp sites contralateral to the visual field of stimulation (e.g., Hopfinger and West 2006), and are disrupted in cases of unilateral neglect (Driver and Vuilleumier 2001; Marzi et al. 2001).

Here we capitalized on the temporal precision of ERP to determine whether attentional load at fixation can unmask an asymmetry in electrophysiological markers of early visual processing (P1 and N1), particularly within the right hemisphere. Healthy participants were required to detect sudden-onset peripheral stimuli while performing a concurrent attention task at fixation. While the peripheral task never changed, the central task was performed under 3 different levels of attentional load. We had participants monitor a rapid central stream of alphanumeric characters to detect targets defined either by a unique feature (low central-load task) or by a conjunction of features (high central-load task); in a third, no central-load condition, participants fixated the central stream but were not required to monitor the central stimuli or respond to them. By making the peripheral stimuli relevant to task performance, our approach differed from most load designs in which an unattended visual stimulus is included in order to probe participants' ability to filter out distracting information (e.g., Lavie 1995; Rorden et al. 2008). Thus, our design allowed us to examine the effect of nonspatial load on orienting to brief, lateralized target events. In line with evidence from neglect (Corbetta et al. 2005, 2008; Peers et al. 2006), we reasoned that increasing attentional load at fixation should weaken the right hemisphere orienting response for left visual field targets and produce a relative facilitation of processing for stimuli appearing in the right (ipsilateral) visual field. This pattern of results in the intact brain should recapitulate the behavioral results that have been reported in both healthy controls and patients suffering from the neglect syndrome (Russell et al. 2004; Peers et al. 2006; Snow and Mattingley 2006; Dodds et al. 2008).

Materials and Methods

Participants

Forty-nine healthy, right-handed participants volunteered for this experiment. Two participants were excluded due to excessive artifacts in their electroencephalography (EEG) data (>40% data loss) and 2 were excluded due to a technical error relating to response acquisition, leaving a final sample of 45 participants. All participants reported normal or corrected-to-normal vision and no history of psychiatric diagnosis, head injury, or color blindness. All participants gave written informed consent, and all procedures were approved by the ethical review board of The University of Queensland. Ethical guidelines were in accordance with the Declaration of Helsinki. Ages ranged from 18 to 47 years (M = 24 years, standard deviation = 7.3).

Visual Attention Task

Participants were required to detect brief, peripheral visual targets while monitoring a stream of alphanumeric stimuli at fixation for the appearance of a probe item (see Fig. 1). Each trial consisted of a stream of 8 central stimuli during which a single peripheral stimulus (an asterisk of size 30 font) was presented in the left hemifield, right hemifield, or not at all (catch trials) with equal probability. The 3 trial types (left or right peripheral stimuli or no peripheral stimulus) were randomly interspersed throughout each task block. During each trial, participants were asked to indicate when they had detected a peripheral stimulus by making a speeded mouse click response with their right hand. At the end of each trial, they indicated whether the designated central target had appeared by making an unspeeded yes/no response on a keyboard. The task was performed under 3 different conditions of central task load with identical displays used throughout. In the no central-load condition, participants were asked to fixate on the central stimulus stream and to monitor the periphery for the appearance of any stimulus. In the low central-load condition, participants were asked to monitor the central stream for the appearance of any green item within the central stream of red digits (effectively a pop-out event; Treisman and Gelade 1980) while also monitoring for a peripheral target. In the high central-load condition, participants were instructed to monitor the central stream for the appearance of a red "letter" in the alphanumeric stream of red digits (effectively a conjunction search task) while also monitoring for the appearance of a stimulus in the periphery. Relatively greater attention was required in the high than low central-load condition because, in the former, the central target was defined by a specific conjunction of features that were shared by the nontarget stimuli.

Central target items appeared in 50% of trials, and their temporal position within the stream was randomized. To facilitate ERP analysis, peripheral stimuli were only presented at 1 of 2 time points within the central stream: at 800 ms (probe event 3, see Fig. 1) or at 2000 ms (probe event 6). Peripheral stimuli never occurred simultaneously with central targets.

The task was presented on a 29 × 47 cm monitor over a gray background at a viewing distance of 50 cm with display set at a resolution of 1024 by 768 pixels. Each trial started with a central

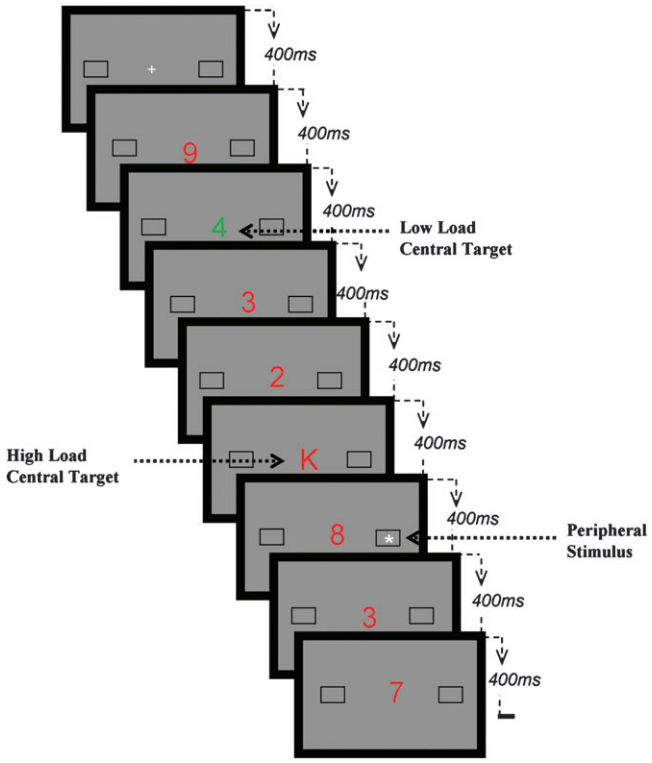

Figure 1. Schematic of a single trial of the visual attention task. Participants monitored a continuous central stream of stimuli at fixation while also monitoring for the appearance of a transient peripheral stimulus that appeared unpredictably to the left, right, or not at all. The task was performed under conditions of no central load (participants ignored the central stream), low central load (detection of a green digit), and high central load (detection of a red letter). Participants were asked to execute a speeded button press in response to peripheral stimuli. Detection of targets appearing within the central stream was assessed at the end of each trial.

fixation cross appearing for 400 ms. The 8 central stimuli were presented in size 30 font for 400 ms each, with no interstimulus interval. The total trial duration was therefore 3200 ms excluding the fixation period. Two 2.5 × 2 cm rectangular placeholders were presented along the horizontal meridian of the visual field at a distance of 16 cm from central fixation in the left and right hemifields. Thus, peripheral stimuli were presented at a visual angle of approximately 24°. Note that for the purposes of our data analysis, it is important to distinguish between a "trial," which refers to a full sequence of 8 central stimuli, and a "probe event," which refers to an individual stimulus within the central stream.

Participants were seated comfortably with their head supported by a chin rest and were instructed to maintain fixation on the central location at all times. Participants were instructed to avoid blinking or moving their eyes during the central stream but were told that they were free to move their eyes during the rest periods between trials. The 3 load conditions were administered in separate blocks (within the same testing session), the order of which was counterbalanced across participants. Each participant completed 300 trials under no central load, low central load, and high central load. A 5-min break was also provided between each load condition.

Data Analysis

Behavioral data were filtered to accept trials in which the peripheral event was detected and for which the central target was correctly identified as being present or absent (for low and high central-load conditions).

Continuous EEG was acquired through the ActiveTwo Biosemi electrode system from 64 scalp electrodes, digitized at 512 Hz. Vertical eye movements were recorded with 2 vertical electrooculogram (EOG) electrodes placed below the left and right eyes, while electrodes at the outer canthus of each eye recorded horizontal movements. Data were analyzed using BESA 5.2. Continuous EEG data were rereferenced offline to the average reference and segmented into epochs of −100 to +900 ms surrounding events of interest. Epochs were baseline corrected relative to the prestimulus interval (−100 to 0 ms), high-pass filtered to 0.3 Hz, and low-pass filtered up to 35 Hz. The continuous EEG was checked manually to exclude any segments with visible eye movement artifacts. If an eye movement was detected during a given trial, the entire trial was rejected from further analysis. To eliminate EOG or other noise transients, any epochs with an amplitude deflection greater than 90 μV were also rejected.

In analyzing the electrophysiological data, the principal goal was to isolate the effects of increasing central task load on visual processing of the peripheral stimuli. To differentiate load effects on central versus peripheral stimuli, the ERP analysis was conducted in 2 stages. Trials without a peripheral stimulus were analyzed first to isolate the effects of attentional load on central stream processing. To account for potential time-on-task or expectancy effects, separate central probe ERP were generated for the third and sixth probe event in the stream. Central targets (green item or red letter) were excluded from these averages to ensure that the 3 load conditions were directly comparable. Next, ERP were generated for trials in which a peripheral stimulus appeared, again with separate averages for peripheral targets coinciding with probe events 3 and 6. Because the peripheral stimuli always appeared simultaneously with a central stream stimulus, a series of difference waveforms ("peripheral difference ERP") were also calculated by subtracting the central stimulus waveform from the peripheral stimulus waveform. This approach allowed us to isolate the activity that was specific to processing of the peripheral stimuli. Only peripheral targets that were correctly identified by participants were included in these analyses. Statistical analyses of the peripheral stimulus ERP components were conducted on the difference waveforms. Note that, unless stated, all the significant main effects and interactions obtained from these analyses of difference waveforms were replicated when we repeated the procedure using the original peripheral stimulus ERP waveforms without any subtraction. For brevity, we report only the former here.

Central stimuli elicited standard visual-evoked components (P1 and N1) as well as a frontocentral positive component (P2f, see Fig. 3). Peripheral targets also elicited P1 and N1 components, as well as a bilateral occipitoparietal P2 and a centroparietal P3, but no P2f was observed (see Fig. 4). The amplitudes and latencies of the P1, N1, and P2 components were analyzed using a region of interest (ROI) approach comprising electrodes PO3, PO7, and O1 for the left hemisphere and PO4, PO8, and O2 for the right hemisphere (for a similar approach, see also Thut et al. 2006). These electrodes were selected because they showed the strongest difference between ipsilateral and contralateral stimuli for the P1, N1, and P2 components in the no central-load condition. Since the P2f and P3 were centrally distributed and showed no effects of peripheral target side, the P2f was analyzed at electrodes FCz and Cz and the P3 was analyzed at electrodes Pz and CPz. The width of the latency window used to measure component amplitudes was based on the duration and spatial extent of each component in the grand average waveform and preliminary peak detection conducted on individual subjects. The following latency intervals were used to determine peak amplitude and peak latency measures: P1 90–140 ms, N1 160–210, P2 270–350 ms, P2f 150–250, and P3 350–600. A large window was used for the P3 due to substantial latency differences across the 3 load conditions (see Fig. 5). The number of trials entered into each participant's ERP average was found to be equal across all levels of load, peripheral target side, and probe event (3 vs. 6) after artifact rejection (M = 38, standard error [SE] = 0.4).

In order to identify the brain regions most affected by the load manipulation, current sources were computed for the peripheral N1 component elicited using standardized low-resolution electromagnetic tomography algorithm (Pascual-Marqui 2002). Sources were mapped onto an average adult brain image from the Montreal Neurological Institute average brain atlas using BESA (version 5.2).

Statistics

Reaction times (milliseconds) for peripheral targets were analyzed using a 3 × 2 × 2 analysis of variance (ANOVA) with factors of central load (no vs. low vs. high), target side (left vs. right), and probe event (3

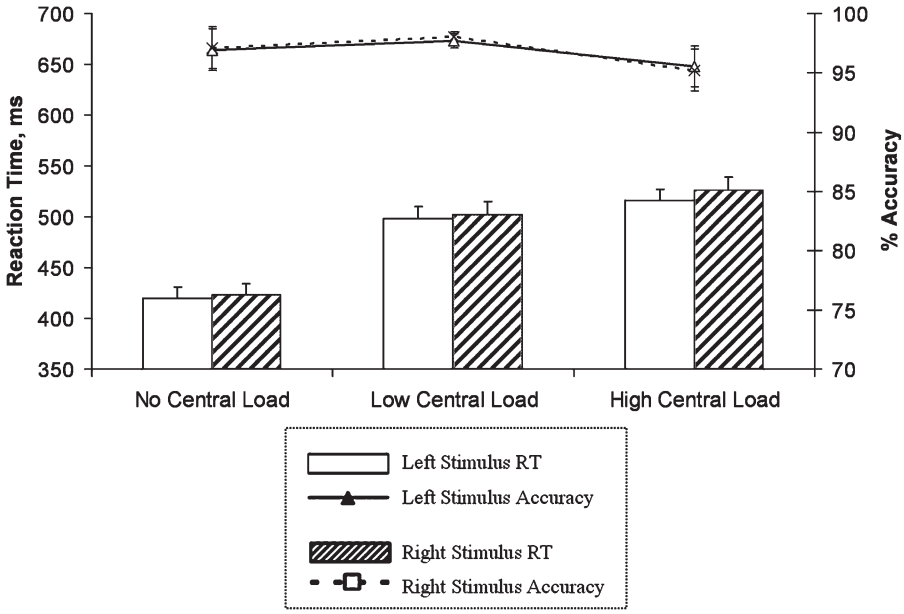

Figure 2. Mean response times and detection accuracy for peripheral targets as a function of load and stimulus side. Faster responses to stimuli appearing in the left visual field were observed at all levels of load, but accuracy was unchanged. Error bars represent SE.

vs. 6). P1, N1, and P2 were analyzed with a 3 × 2 × 2 × 2 ANOVA with factors of load (no vs. low vs. high), target side (left vs. right), probe event (3 vs. 6), and hemisphere (left vs. right). Because of their central distribution, the P2f and P3 were analyzed using only the factors of central load and target side. Main effects and interactions were decomposed using simple planned contrasts. Because there were no significant effects of probe event, we collapsed across the 2 event types (3 and 6) in all the ERP plots (Figs 3, 4, and 6) to facilitate interpretation.

Results

Behavioral Data

Detection accuracy (percent correct) for the central task was analyzed in each of the low and high central-load conditions (note that central target detection was not required in the no central-load condition). Since central target detection was unspeeded, reaction times (RTs) were not analyzed. A robust main effect of central task attentional load was found, $F_{1,44}$ = 44.02, $P < 0.001$, with greater accuracy on the central task under low (M = 97%, SE = 0.004) than high load (M = 94%, SE = 0.007). These results confirm that attentional demands increased at each level of central task load. The side on which a peripheral target appeared had no significant effect on central target detection.

Detection accuracy on the peripheral task was also examined as a function of central load and target side. Accuracy was high in all conditions (no load M = 97, SE = 2; low load M = 98, SE = 0.5; high load M = 95, SE = 1.7), and there were no significant effects of load, side, or probe event. A significant main effect of central load was observed for peripheral target RT, $F_{2,88}$ = 105.3, $P < 0.001$. Responses to peripheral targets in the high-load condition were slower than those in the low-load condition ($P < 0.001$), which in turn were slower than responses in the no-load condition ($P < 0.001$). A significant main effect of target side was also present, $F_{1,44}$ = 6.2, $P < 0.05$, which reflected faster responses to targets appearing on the left (M = 478 ms, SE = 10.3) than on the right side (M = 484 ms, SE = 11.2). Although this effect of target side was numerically small, it confirms a processing advantage for events occurring in the left hemifield. Finally, there was also a significant main effect of probe event, $F_{1,44}$ = 157, $P < 0.001$, which reflected faster responses to peripheral targets appearing later in the trial ($P < 0.001$). There were no significant interactions of load, side, or trial. Figure 2 shows the mean accuracy and RT data for the central and peripheral tasks.

Electrophysiological Data

Effects of Central Load on Peripheral Target Processing

The effects of visual field and central load on ERP components elicited by peripheral target stimuli are illustrated in Figures 3 and 4, respectively. Inspection of the horizontal electrooculogram (HEOG) channels indicated that eye movement traces did not differ between the 3 load conditions. As indicated in Figure 3, some small eye movement activity was apparent after peripheral stimulus onset, but this occurred after the measurement window for the P1 and N1 components (onset around 250 ms).

Peripheral P1 (90–140 ms). There were no significant effects of central load, target side, or probe event ($F < 1$) on peripheral P1 amplitude, but there was a significant main effect of hemisphere, $F_{1,44}$ = 7.6, $P < 0.01$, driven by larger amplitudes over the right than the left hemisphere. There was also a target side by hemisphere interaction, $F_{1,44}$ = 5.6, $P < 0.05$, which reflected enhancement of the P1 over scalp sites contralateral to the visual field of stimulation.

Peripheral N1 (160–210 ms). There were no main effects of central load, target side, probe event, or hemisphere on N1 amplitude, but, as with the P1, there was a significant target side by hemisphere interaction reflecting enhancement by contralateral visual stimulation leading to increased amplitude, $F_{1,44}$ = 7.9, $P < 0.01$, and reduced latency, $F_{1,44}$ = 23.6, $P < 0.01$. An additional, central load by target side by hemisphere interaction was observed, $F_{2,88}$ = 4.8, $P < 0.01$ (see Fig. 5). To

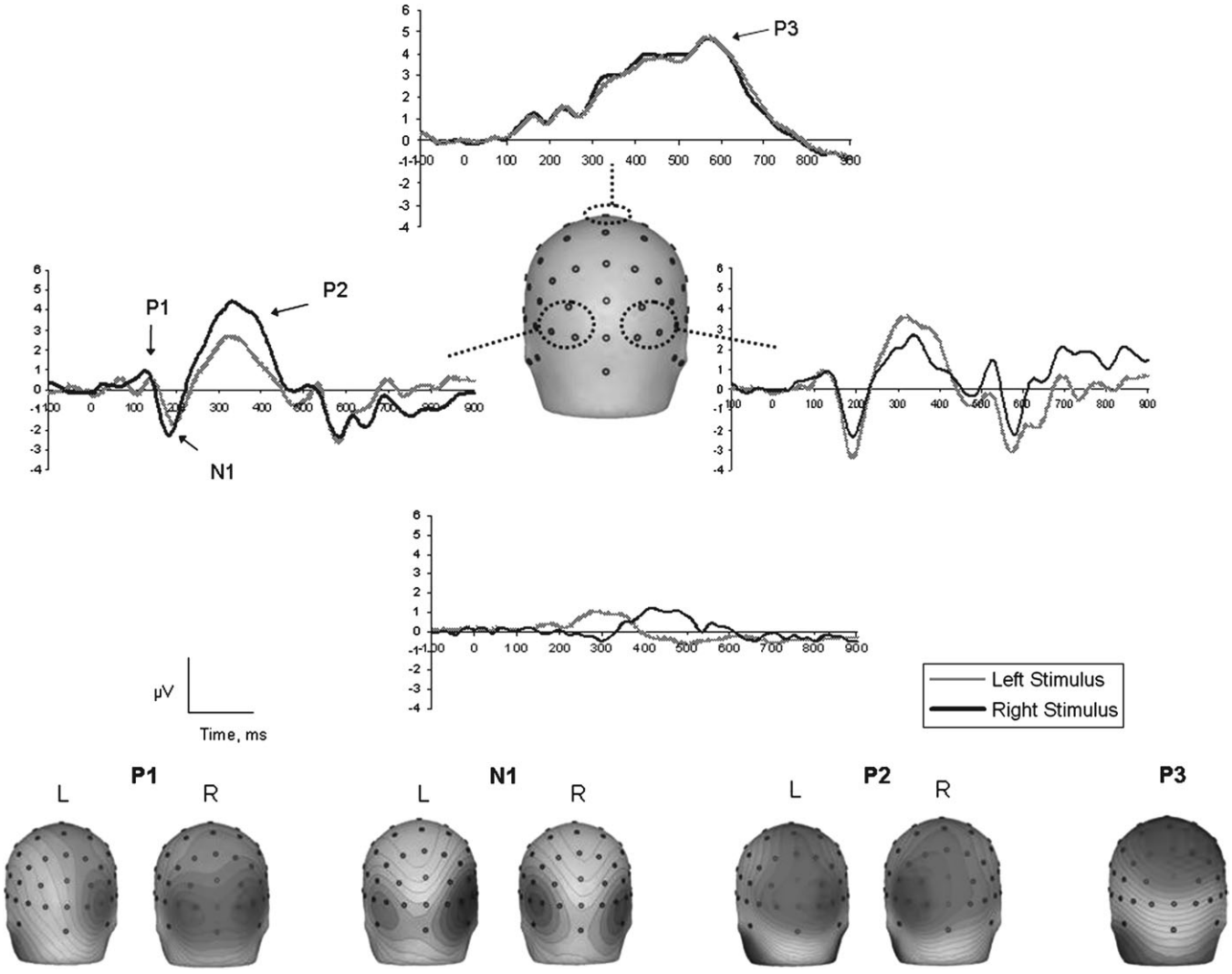

Figure 3. Grand average ERP waveforms elicited by peripheral targets over left and right hemispheric ROIs during the no-load condition. Relative enhancement of the P1, N1, and P2 was seen over the hemisphere contralateral to the visual field of stimulation. The centroparietal P3 component was not affected by stimulus side.

further explore this interaction, additional central load by target side ANOVAs were conducted separately for the left and right hemisphere ROIs. A significant load by side interaction was indicated for the right hemisphere, $F_{2,88} = 3.4$, $P < 0.05$, but not for the left hemisphere, $F_{2,88} = 0.2$, $P = 0.8$. Planned contrasts indicated that the right hemisphere interaction resulted from an increase in processing of right hemifield stimuli and decrease in processing of left hemifield stimuli between high and no central-load conditions ($P < 0.05$).

Peripheral P2 (270–350 ms). There was a significant main effect of central load on the amplitude of the peripheral P2, $F_{2,88} = 10.4$, $P < 0.001$ (planned contrasts high < low, $P < 0.001$, low < no, $P < 0.001$). The main effect of hemisphere approached significance, $F_{1,44} = 3.9$, $P = 0.055$, and indicated larger amplitudes over the left hemisphere. There was a strong side by hemisphere interaction, again reflecting contralateral enhancement, $F_{1,44} = 36.9$, $P < 0.0001$.

P3 (350–600 ms). There was a significant main effect of central load on P3 peak amplitude, $F_{1,44} = 7.9$, $P < 0.01$ (planned contrast high < low central load $P = 0.06$; low < no central load, $P < 0.01$). There was also a significant main effect of probe event, $F_{1,44} = 4.2$, $P < 0.05$, with P3 amplitude decreasing from probe event 3 to probe event 6. P3 peak latency was significantly delayed by increasing central load, $F_{1,4} = 26.1$, $P < 0.001$ (planned contrast high vs. low load $P = 0.3$; low load > no load, $P < 0.01$).

Effects of Central Load on Central Stream Processing

The analysis of central stream processing allowed us to explore the effects of attentional load on stimulus-driven responses at a single foveal location. Trials in which no peripheral stimulus appeared were analyzed in order to isolate processing specific to the central stream (see Fig. 6).

Central P1 (90–140 ms). A significant main effect of central load on P1 amplitude was observed, $F_{2,88} = 5.4$, $P < 0.01$, with P1 amplitudes increasing as a function of load (high > low, $P < 0.05$, low > no, $P < 0.01$). There were no main effects of probe event or hemisphere. Latency also increased significantly with load, $F_{2,88} = 6.35$, $P < 0.01$ (planned contrasts, high > low, $P = 0.4$, low > no, $P < 0.05$), but there were no other significant main effects or interactions.

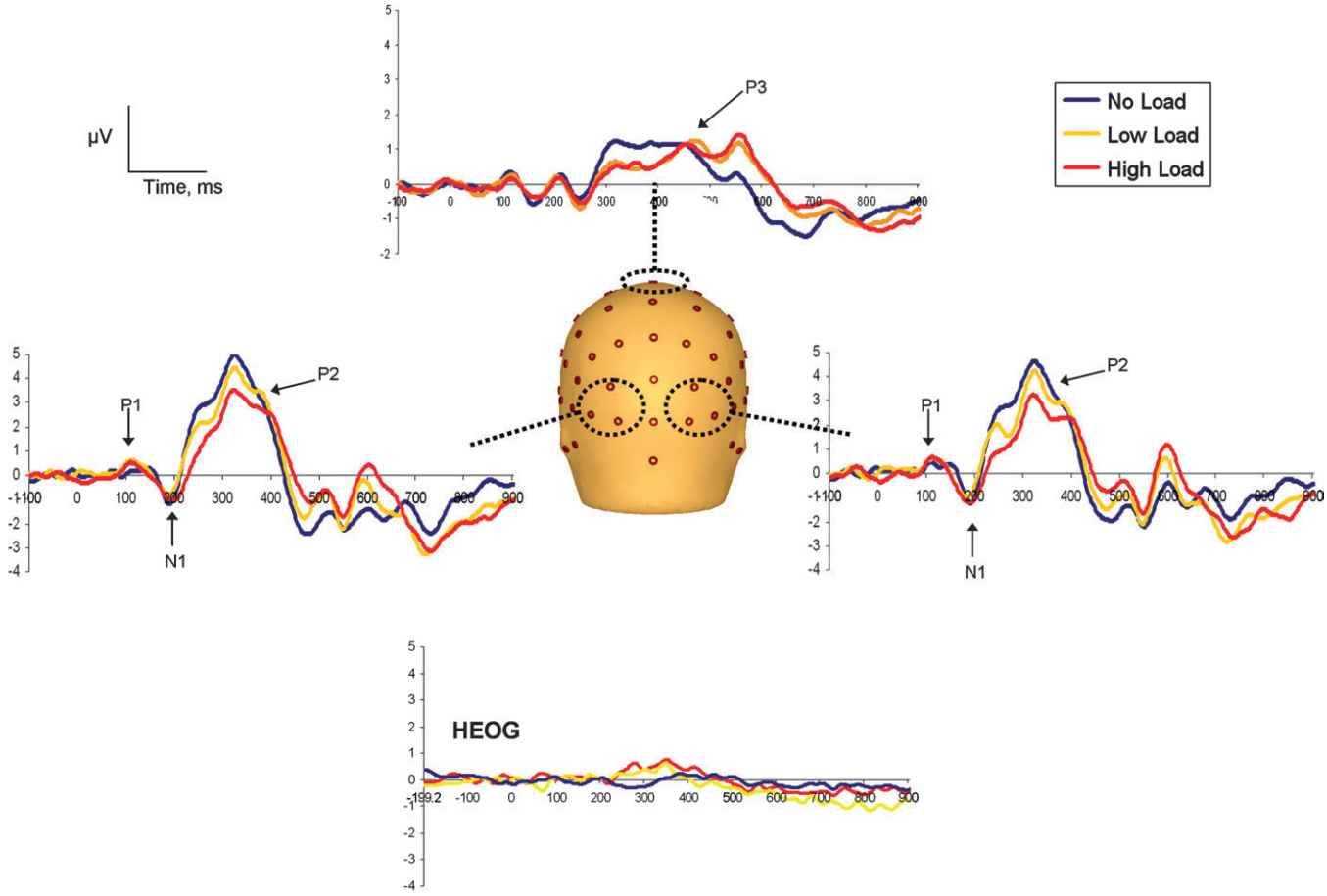

Figure 4. Grand average difference ERP waveforms isolating processing of peripheral targets as a function of central attentional load. The difference waveform was generated by subtracting activity elicited by central stimuli that were not accompanied by a peripheral stimulus from the activity elicited by concurrent presentation of central and peripheral stimuli. This plot is a combined average for all peripheral stimuli regardless of visual field in order to highlight the basic load effects on component amplitudes. While the early P1 and N1 were unaffected, increased central load produced a significant attenuation of the occipital P2 component and a delay in the peak latency of the centroparietal P3. The HEOG channel data confirm that eye traces were equivalent across the 3 conditions.

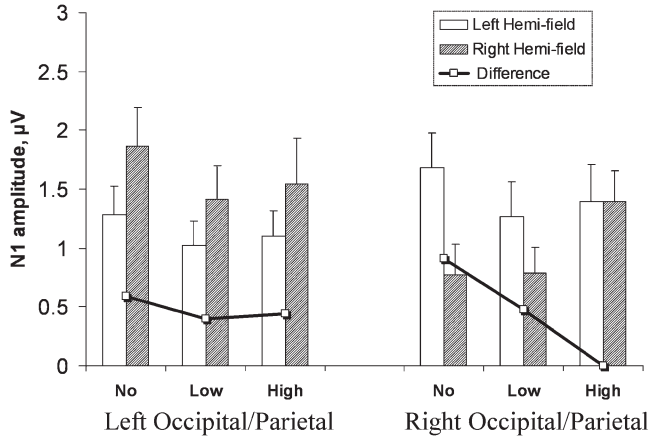

Figure 5. Absolute amplitude of N1 elicited by peripheral stimuli as a function of load, hemisphere, and stimulus side. The difference plot shows a contralateral enhancement over each hemisphere (contralateral stimulus amplitude minus ipsilateral amplitude) under no central load. Increasing attentional load specifically affected spatial selection in the right hemisphere. Under high load, there was a decrease in contralateral N1 over the right hemisphere accompanied by an increase in the ipsilateral N1. This finding suggests that increasing central load produces a rightward shift of the attentional field.

Central N1 (160–210 ms). There was a significant main effect of central load on N1 amplitude, $F_{2,88} = 6.1$, $P < 0.01$ (planned contrasts, high vs. low, $P = 0.6$; low > no, $P < 0.05$). There was also a main effect of hemisphere on amplitude driven by a strong right hemisphere dominance, $F_{1,44} = 34.7$, $P < 0.001$.

P2f (150–250 ms). The P2f component was seen in the central stimulus waveforms only and was largest over frontal scalp sites. A main effect of central load was seen for this component, $F_{2,88} = 4.6$, $P < 0.05$. Planned contrasts confirmed that P2f amplitude was larger in the high-load than in the no-load condition ($P < 0.05$), but there was no difference between the high- and low-load conditions ($P = 0.8$).

Source Analysis

As a further confirmatory step, we employed source analysis to explore the central load by target side by hemisphere interaction that was observed for the N1 component. To isolate the load-specific effects, we created 2 new difference waveforms by subtracting the no central-load peripheral difference ERP from the high central-load peripheral difference ERP for each of the left and right hemifield stimuli separately. The source analysis indicated that the central load manipulation produced a marked increase in activation of right superior

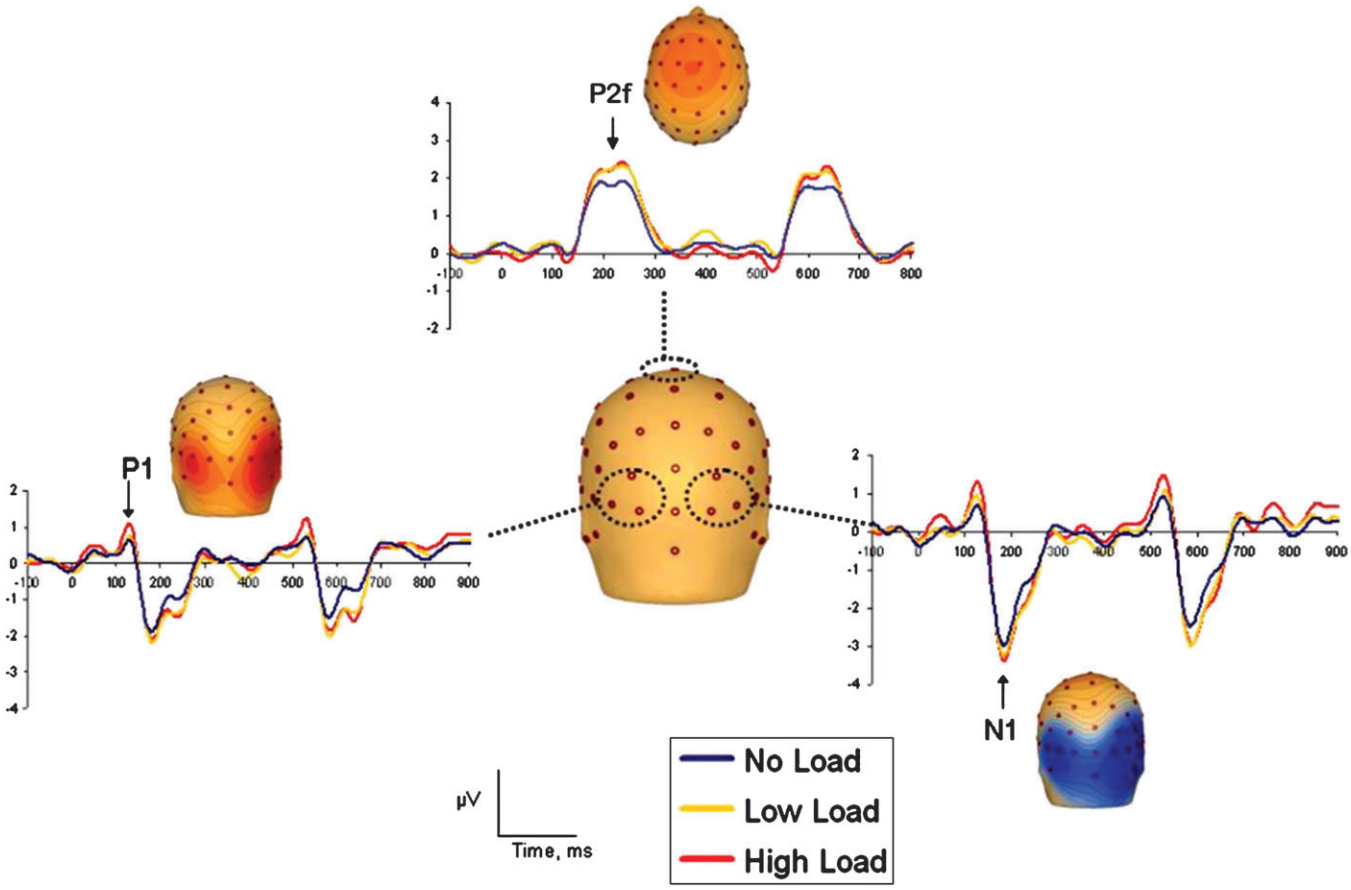

Figure 6. Grand average ERP time locked to the onset of a central stimulus when no peripheral target was presented. Central stimuli were presented every 400 ms; thus, in this 1000 ms segment, there are 2 instances of the classic P1/N1 visual-evoked potential. Accompanying scalp topographies demonstrate the occipital focus for both of these components. The amplitude of both the P1 and the N1 increased as a function of attentional load suggesting increased visual attention to central stimuli. An additional frontocentral component (P2f) also increased in amplitude with central load.

occipital and inferior parietal cortex in response to right hemifield stimulation. The load effects were not clearly lateralized during left hemifield stimulation (see Fig. 7). Thus, although central attentional load reduced the contralateral orienting response within occipitoparietal cortex in both the left and the right hemispheres, the increase in ipsilateral processing was specific to the right hemisphere.

Discussion

Although many attentional load paradigms entail attending to one stimulus channel while ignoring others (e.g., Schwartz et al. 2005; Rorden et al. 2008), the present paradigm explored how orienting toward peripheral target stimuli is affected by increasing attentional demands at fixation. As expected, increasing the attentional demands of the central task produced an increase in the commitment of attentional resources to the central location as evidenced by significantly enhanced early visual processing (P1 and N1) of central probes and a corresponding slowing of response times to peripheral targets. The diminished processing of peripheral stimuli with increasing central load was further confirmed by the attenuation of the peripheral P2 and P3 components. In addition, we found that central task load had an asymmetric effect on the peripheral N1 component. Specifically, the processing advantage for left hemifield stimuli observed over right hemisphere electrodes was diminished with increasing central load. Within the right hemisphere, this effect was driven by a reduction in the N1 amplitude elicited by contralateral stimuli and a concomitant increase in N1 amplitude elicited by ipsilateral stimuli. The equivalent effect was not seen over left hemisphere electrodes.

These findings accord well with studies that have shown that a subtle neglect-like pattern of behavior can be induced in neurologically healthy participants by increasing nonspatial attentional load (Peers et al. 2006; Dodds et al. 2008). Furthermore, our findings are consistent with reports of disruption to the N1 component in patients suffering from the neglect syndrome (Driver and Vuilleumier 2001; Marzi et al. 2001). To our knowledge, this is the first study to provide neurophysiological evidence that increasing nonspatial attentional load specifically affects spatial orienting subserved by right hemisphere brain networks.

Effects of Attentional Load on Spatial Attention

Under the no-load condition, the contralateral N1 elicited by peripheral stimuli was relatively enhanced over both hemispheres, but as load increased, this contralateral orienting response became specifically attenuated over the right hemisphere. This effect resulted from suppression of the contralateral N1 together with a concomitant increase in responsiveness to ipsilateral stimuli with central load. This finding is consistent with existing neuroanatomical models in which asymmetries

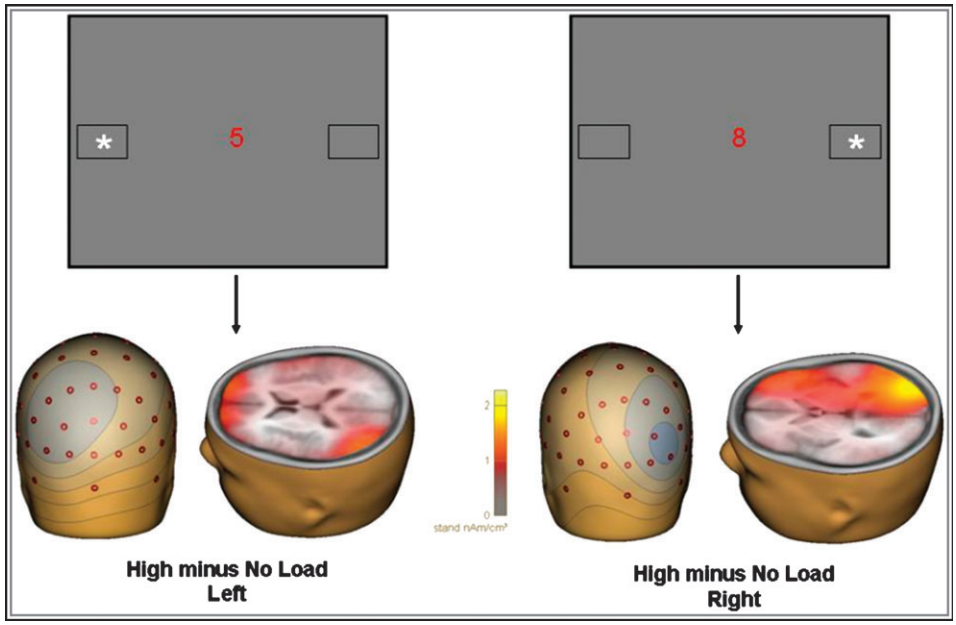

Figure 7. ERP source analysis for the N1 using the standardized low-resolution electromagnetic tomography algorithm method to identify brain regions most affected by increasing attentional load. Sources were identified after subtracting no-load ERP from high-load ERP for left and right peripheral targets. Increasing attentional load was associated with a clear increase in activation within right inferior occipitoparietal regions in response to ipsilateral (right hemifield) stimuli.

within the dorsal orienting network are mediated by the right lateralized ventral attention network (Husain and Nachev 2007; Corbetta et al. 2008).

The asymmetric effects of load on N1 amplitude were not accompanied by an equivalent behavioral trend. Changes in spatial asymmetry with increasing load have been reported in unilateral neglect (Lavie and Robertson 2001; Peers et al. 2006), but these effects appear to be more difficult to replicate in neurologically healthy participants. For example, Peers et al. (2006) reported a clear decrease in detection accuracy for stimuli appearing in the left visual field in neglect patients when the difficulty of a spatial task was increased by the addition of a nonspatial dual-task element. When Dodds et al. (2008) used an identical paradigm with healthy participants, they observed no significant change in bias, although a possible interaction with time-on-task was highlighted. The severe capacity limitation associated with neglect makes patients susceptible to the effects of attentional load, whereas a greater increase in load may be required to challenge the right hemisphere's dominance of lateralized responses in the healthy brain. Although the use of simple suprathreshold unilateral stimuli may have limited our ability to detect subtle behavioral effects, robust asymmetries in electrophysiology under load were observed. Increased interference by ipsilesional distractors is common following damage to right parietal regions, which in turn might underlie the phenomenon of extinction (Marzi et al. 2001; Geeraerts et al. 2005; Snow and Mattingley 2008). Our N1 data suggest that participants are more likely to be susceptible to distraction by stimuli in the right visual field under conditions of high load. An interesting issue for future work, therefore, will be to examine whether nonspatial load impacts on attentional bias in tasks involving bilateral presentations. The unique temporal sensitivity of our ERP measures allowed us to observe a subtle electrophysiological asymmetry in the absence of any overt behavioral change.

Previous source dipole modeling of the N1 has highlighted a collection of generators within lateral occipital and temporoparietal regions (De Sanctis et al. 2008; Fu et al. 2008; see also Natale et al. 1996). The N1 arises from synchronous activity within multiple brain areas, and it is likely that different experimental manipulations will selectively affect different generators (Miniussi et al. 2002). In the present study, the no versus high central-load contrast revealed that the modulation of the N1 by load was driven by an increased responsiveness to right hemifield stimuli originating in an inferior occipitoparietal region of the right hemisphere. The inferior parietal lobe has been identified as a key locus of overlap between the dorsal and the ventral attention networks (Husain and Nachev 2007; Corbetta et al. 2008) and may act as a critical intermediary between these 2 systems. Damage to the right inferior parietal lobe is common in cases of neglect, which could account for the co-occurrence of spatial and nonspatial deficits in this syndrome (Mort et al. 2003).

Peripheral stimuli elicited 2 additional later positive waveforms that have been associated with higher cognitive stages of stimulus processing, the occipitoparietal P2 and the centroparietal P3. As in the case of the P1, the amplitude of the P2 varied as a function of load and to an equal degree over the 2 hemispheres. The P3 component has been widely studied and is broadly taken to reflect the efficiency of resource allocation for a relevant stimulus (Polich and Criado 2006). Here, both the peak latency and the mean amplitude of the P3 were negatively affected by attentional load. This P3 result is consistent with our finding of longer reaction times with load and suggests slower information processing due to competition between separate stimulus channels. The P3 was the only component that was affected by the onset time of the peripheral target. P3 latency, which reflects stimulus classification speed (Polich and Criado 2006), decreased significantly when the peripheral target appeared later in the trial (probe event 6 vs. probe event 3). This result likely reflects increased target expectancy toward the end of the trial and is consistent with the decreases in reaction time that were observed. It should also be noted

that while previous work has reported equivalent P1 and N1 amplitudes when stimuli are selected on the basis of nonspatial features, such as color or shape (Hillyard and Anllo-Vento 1998; Vogel and Luck 2000), the later P2 and P3 effects may arise in part from the different stimulus discrimination requirements at each level of load (O'Donnell et al. 1997).

Nonspatial Effects of Attentional Load

Analyzing the central stimuli using trials in which no peripheral stimulus was presented allowed us to explore the effects of attentional load on processing at a single attended location. We found that both of the early visual components elicited by central stimuli (i.e., the P1 and N1) increased in amplitude as a function of central load. Consistent with the observation that peripheral target RTs increased with load, the central P1 result points to a suppression of perceptual processing outside of fixation as the demands of the central task increase (Luck 1995; Frey et al. 2010).

Since participants were not required to attend to the central task in the no-load condition, any relative perceptual facilitation seen under low or high load is likely to have a spatial component as attention must be redistributed to include the central location. Previous ERP work has indicated that one can selectively focus on bilateral peripheral locations while attenuating responses to central stimuli (Muller et al. 2003). Miniussi et al. (2002) have also shown that the P1 and N1 are enhanced when attention is focused at the center of gaze as opposed to being divided across the 2 visual fields. In the present paradigm, the low- versus high-load comparison provides a purer measure of modulation within the focus of attention, since responses were required to specific classes of stimuli appearing at the central location in both conditions. Enhancement of the central P1 component with increasing levels of load, but identical visual stimulation, clearly indicates that increasing the allocation of resources at an already attended location can modulate activity within extrastriate cortex. The extent to which the depletion of nonspatial attentional resources contributed to the central N1 result is more difficult to determine because there were no significant differences between the low- and the high-load conditions. The N1 is modulated by spatial attention and is also enhanced when stimulus discrimination is required at an attended location (Vogel and Luck 2000). Both of these factors could have contributed to the increase in central N1 with load.

Modulation of the P1 by attentional load has been observed previously in spatial selection tasks when comparing processing at attended versus unattended locations (Handy et al. 2001; Fu et al. 2008), but the earliest reported load effects within the focus of attention have been at the latency of the later N1 component (Barnhardt et al. 2008). A distinguishing feature of the present study was that attention was diffusely distributed across the visual field in anticipation of a peripheral target event, whereas the study of Barnhardt et al. (2008) employed a paradigm in which participants were required to monitor a single spatial location. The relative amount of attentional resources available to be devoted to that single location is likely to have been very high, perhaps raising the threshold above that at which attentional load manipulations take effect. Previous work has suggested that the attentional enhancement indexed by the P1 and N1 is more prominent during relatively demanding tasks (Luck 1995; Fu et al. 2009). In the present data, the diffusion of attention across the visual field is likely to have reduced the availability of resources at the central location. We argue that this reduced capacity necessitated top-down enhancement of perception at an earlier processing stage to effectively compensate for the increasing attentional demands.

As noted previously, our load paradigm differs from those often used in behavioral investigations of Lavie's (1995) model of selective attention because our peripheral stimuli were always task relevant. Lavie's model predicts that processing of distractor stimuli will decrease with increases in the load of a target task due to the reduced availability of attentional resources. Although not the primary focus of this study, our findings add a further dimension to this literature by demonstrating that increased central load causes a decrease in the processing of peripheral stimuli even when these events occur at task-relevant locations. An interesting question for future work will be to directly compare the behavioral and electrophysiological effects of increasing load at fixation on relevant versus irrelevant peripheral stimuli within the same paradigm.

In summary, we have undertaken an in-depth neurophysiological analysis of the interaction between nonspatial attentional load and visual orienting to peripheral stimuli. Increasing load at fixation disrupted the neural response of the right hemisphere to unilateral peripheral stimuli. We argue that this asymmetry arises from a weakening under load of the dominance of the right hemisphere for both spatial and nonspatial components of attention. Our electrophysiological data in healthy subjects may help to explain the coexistence of both spatial and nonspatial deficits in patients with acquired damage to the right cerebral hemisphere.

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