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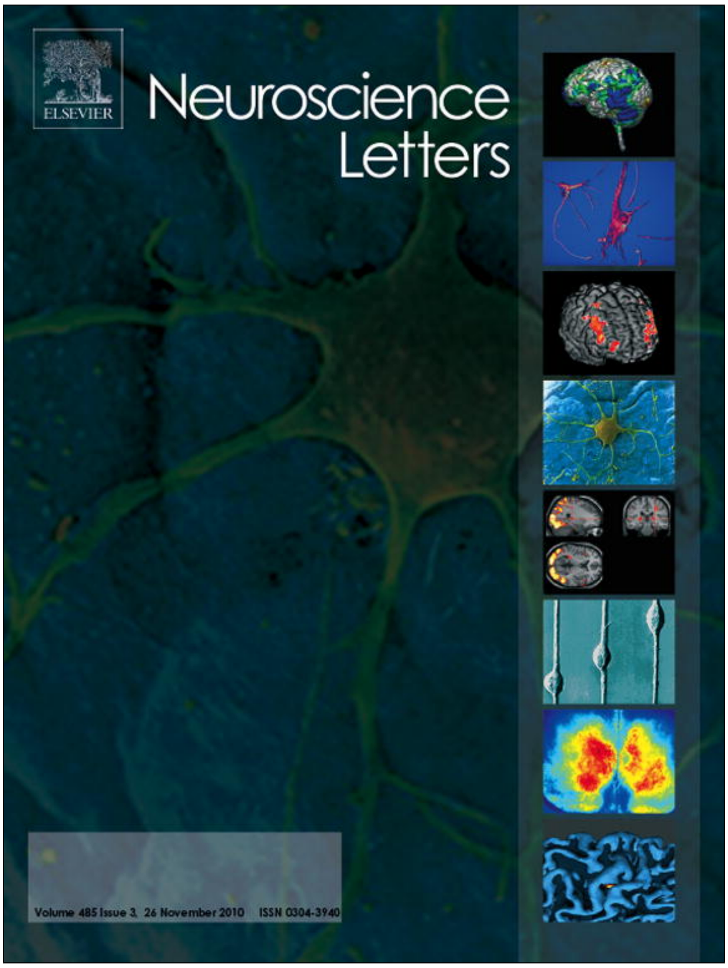

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Perceptual load modifies processing of unattended stimuli both in the presence and absence of attended stimuli

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ABSTRACT

This study explored effects of perceptual load on stimulus processing in the presence and absence of an attended stimulus. Participants were presented with a bilateral or unilateral display and asked to perform a discrimination task at either low or high perceptual load. Electrophysiological responses to stimuli were then compared at the P100 and N100. As in previous studies, perceptual load modified processing of attended and unattended stimuli seen at occipital scalp sites. Moreover, perceptual load modulated attention effects when the attended stimulus was presented at high perceptual load for unilateral displays. However, this was not true when the attended and unattended stimulus appeared simultaneously in bilateral displays. Instead, only a main effect of perceptual load was found. Reductions in processing contralateral to the unattended stimulus at the N100 provide support for Lavie's (1995) theory of selective attention.

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Perceptual load theories of selective attention suggest that increases in perceptual load shift selection from late to early in processing [16,19] and, in the case of visuo-spatial selection, alter the window of processing, reducing processing of unattended stimuli [9,10]. Lavie suggests that perceptual load is determined by the perceptual features and type of perceptual analysis required within an attended display. However, while electrophysiological evidence in support for Lavie's theory has been shown through studies examining processing of unattended stimuli at varying levels of perceptual load, these studies have typically examined processing in the absence of competing attended stimuli [2,5,9,10]. Thus, this study is designed to examine the effects of perceptual load on the processing of unattended stimuli in the presence of competing attended stimuli to determine if changes in processing support Lavie's perceptual load theory of selective attention.

Support for perceptual load theories of selective attention can be found in behavioral studies in which the addition of competing stimuli facilitate early selection preventing processing of distractor stimuli [14,17,18]. Lavie and Fockert [18] argue that increases in perceptual load are derived from increases in the information contained in the attended display rather than changes in factors such as stimulus discriminability. However, there is a growing body of research that argues perceptual load includes stimulus discriminability, affecting sensory perceptual load. In particular, due to the constraints of electrophysiological techniques where changes in the number of stimuli would impair the ability to see changes in perceptual load, in electrophysiological studies, discriminability is the primary operationalization of perceptual load either through changes in stimulus features [2,6,9] or in the duration of presentation [5,9,10]. Moreover, perceptual load has been shown to affect selective attention in a variety of contexts, such as in object and face processing [11,20,27–29], as well as affecting processing cross-modally [15] and in populations with attention deficit hyperactivity disorder [4].

While studies using fMRI provide information with high spatial resolution regarding the effects of perceptual load on processing [32], they cannot provide the temporal resolution of electrophysiological data. Electrophysiological studies have shown that perceptual load can affect neural activity as early as sensory level processing as reflected in changes to the P100 and N100 visual components [5,6,9,10]. Research using fMRI and electrophysiological studies using non-human primates suggest the neurological origins of these components lies in the extrastriate cortex [32]. Moreover, these components have been shown to be influenced both by attention and perceptual load. For example, when presented with a difficult perceptual discrimination (i.e., high perceptual load), processing of unattended parafoveal stimuli as indexed by the P100, is reduced [10]. This suggests changes in activity occur early in processing, and that high perceptual load may result in early selection (as shown by reduced processing of unattended stimuli).

However, despite abundant behavioral research as well as fMRI and electrophysiological studies, an important area of clarification

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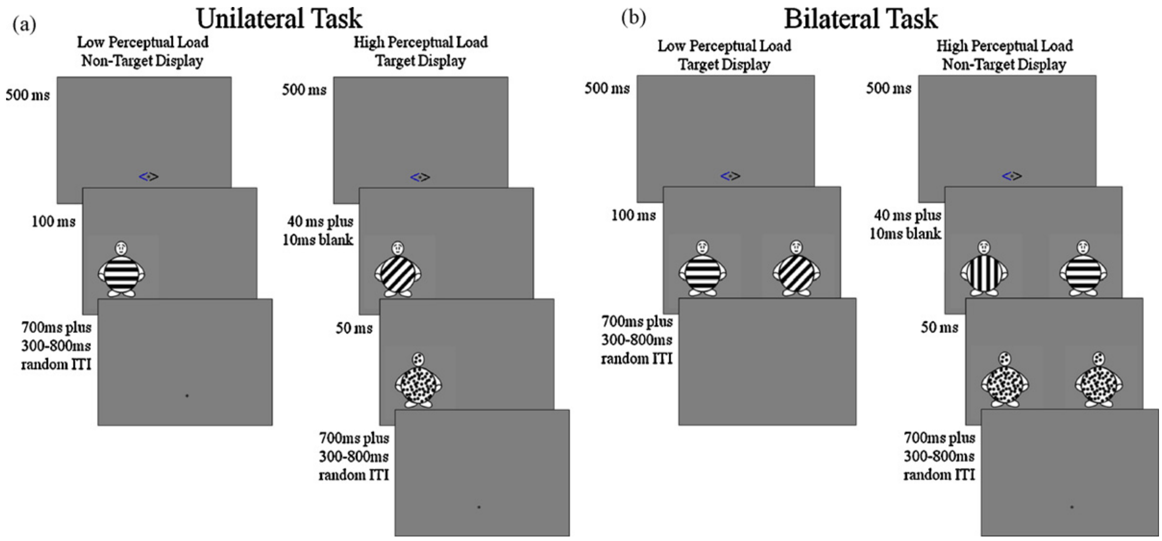

Fig. 1. Stimulus display. (a) Unilateral display and (b) bilateral display.

remains; how is early visual processing of unattended stimuli influenced by perceptual load in the absence of attended stimuli; and how is this effect similar or different when an attended stimulus is present.

While studies have looked at processing of unattended stimuli in the absence of attended stimuli [2,3,5–7,9,10], these studies have not looked at processing of the unattended stimuli when attended stimuli are present. Instead, studies that include attended stimuli examine processing when an attended stimulus is superimposed on an unattended stimulus. For example, Mohamed, Neumann, and Schweinberger and co-workers [27] examined the N170, a component related to face processing while participants completed a letter identification task at high or low perceptual load when those letters were superimposed on pictures of faces or houses. Mohamed et al. found that processing of distractor faces was reduced during high perceptual load conditions but that counter-intuitively, processing of house distractors was increased. However, as attended and unattended stimuli could not be spatially separated in this task it is unclear what the contributions of concurrent attended stimulus processing had on unattended stimulus processing. Thus, to better understand the effects of perceptual load on spatial selection, the current study examines processing of spatially distinct attended and unattended stimuli as a function of perceptual load in the presence and absence of attended stimuli.

Sixteen adult participants, (Ages $M = 19.12$, $SD = 1.59$) participated in this study. Participants were recruited from local colleges (Hampshire, Amherst, Smith, and Mount Holyoke Colleges, as well as the University of Massachusetts at Amherst) and were paid $10 for their participation. Six males and 10 females participated, with 13 of the participants being Caucasian, 1 Hispanic, and 2 Asian. Participants were excluded from analysis if they were left handed, had non-correctable visual impairments, were diagnosed with or suspected of having learning disorders, were currently on psychotropic medications, or if they were born prematurely (i.e., less than 36 weeks). Additionally, participants were excluded following initial EEG data reduction if insufficient data for analysis remained (see data analysis and reduction). While twenty participants were recruited, after eliminating participants who met exclusionary criteria or who had insufficient data, 16 participants remained and were used in data analysis.

After completing the consent process all participants completed questionnaires addressing demographic information as well as a brief psychological and medical history.

On each task trial, a small fixation (0.59 × 0.59 degrees) was presented for a random duration between 300–800 ms followed by a cue composed of two arrows (one blue, one black, (2.4 × 1.2 degrees)) for 500 ms. The blue arrow indicated the side to be attended (left or right) and was valid for 60% of the trials. Participants were told that the cue was predictive, but not told the percentage of time the cue would be correct. Following the cue, a unilateral or bilateral display appeared (Fig. 1). Stimuli were presented 18.0 degrees from the fixation, were 8.2 × 7.1 degrees in size, and were composed of either horizontal (non-target), diagonal (target), or vertical (non-target) stripes. Stimuli and masks were equated for luminance, size, and shape. Additionally, analysis of the P100 contralateral to the attended stimulus showed no significant differences between low and high perceptual load, suggesting stimulus equivalency between levels of perceptual load. In the unilateral display the target or non-target stimulus appeared on the attended side of the display when validly cued and unattended side when invalidly cued. In the bilateral display two stimuli appeared, one on each side, with a target or non-target appearing on the attended side and a non-target appearing on the unattended side. In the low load conditions the stimuli appeared for 100 ms. In contrast, in the high load conditions the stimuli appeared for 40 ms followed by a 10 ms blank screen and 50 ms mask. Finally, a fixation appeared for 700 ms during which participants were asked to press the left button on a two-button mouse if a target appeared.

Four conditions were created based on the presence of a concurrent unattended stimulus (unilateral vs. bilateral display) and the level of perceptual load (low vs. high); unilateral low perceptual load display, unilateral high perceptual load display, bilateral low perceptual load display, and bilateral high perceptual load display. Conditions were presented in 4 epochs, 2 containing unilateral displays and 2 containing bilateral displays as previous research suggests knowledge of perceptual load is important for perceptual load effects to be seen [5]. Each unilateral display epoch contained 5 blocks of 100 trials, 20% of which were targets. Additionally, there were 200 possible validly cued displays (in which attention was directed to the side of the display on which the stimulus appeared) and 200 invalidly cued displays (in which attention was directed to the side of the display where the stimulus did not appear) that did not contain targets. These displays, presented in the low perceptual load epoch, formed the unilateral low perceptual load display condition, and in high perceptual load epoch formed the unilateral high perceptual load display condition. The low and high percep-

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tual load bilateral display epochs each contained 3 blocks of 100 trials, resulting in 240 displays that did not contain targets. Displays presented in the low perceptual load epoch resulted in the bilateral low perceptual load display condition and in high perceptual load epoch results in the bilateral high perceptual load display condition. As in unilateral displays, targets were present for 20% of the total trials and appeared equally on left and right sides of the display. Participants only responded to target present displays and these were not included in data analyses.

Scalp electroencephalograms (EEGs) were recorded from 32 tin electrodes sewn into a stretchy lycra cap (Electro-cap International). Electrodes were referenced to linked mastoids (re-referenced off-line) and impedances were kept below 5k ohms for all participants. The mastoid reference is preferred with a smaller number of channels as the average reference is not as accurate with this number of electrodes [8]. Data was recorded using a Synamps2 Amplifier with Scan 4.2 software and was digitized at the rate of 500 Hz using a bandpass filter of 1–100 Hz. To ensure eye fixation, the electrooculogram (EOG) was recorded for both vertical (from an electrode inferior to the left eye) and horizontal (from electrodes on both the right and left outer canthus) eye movements.

EEGs were epoched off-line to examine event-related electrophysiological activity for all trials (200 ms pre-stimulus to 1000 ms post-stimulus) and baseline corrected using a baseline of 200 ms pre-stimulus. Trials were eliminated using a computer algorithm if there were significant eye artifacts (defined as amplitudes ±50 μV at vertical or horizontal eye electrodes) or if visual inspection of the trial showed eye movements or significant alpha activity in more than 3 channels (i.e., 10% of total channels). Channels that were consistently bad across the experiment were marked as such and not used in analyses. Participants were eliminated from analyses if there were more than 3 bad channels [30]. The resulting ERPs were used to produce grand-average waveforms for both attended non-target stimuli and unattended non-targets stimuli for each participant for each of the four conditions used in statistical analysis: unilateral low perceptual load display, unilateral high perceptual load display, bilateral low perceptual load display, and bilateral high perceptual load display. Statistical analysis of P100 data was based on average amplitude measured over a 50-msec time window, centered approximately on the peak amplitude of the P100 (100–150 ms post-stimulus) and N100 (150–200 in unilateral displays and 155–205 in bi-lateral displays) seen in the grand-averaged waveforms of the occipital leads O1 and O2. Data from 16 participants were included in analyses with an average of 82.85 trials per condition (SD = 23.40). Data were analyzed using a 2(perceptual load: high vs. low) × 2(direction of attention: left vs. right) × 2 (Electrode O1 vs. O2) repeated measures ANOVA on P100 and N100 amplitude to be consistent with the broader ERP literature. It is important to note, that to appropriately explore differences between unilateral and bilateral displays only components contra-lateral to attended and unattended stimuli were analyzed (i.e., components ipsilateral to attended and unattended stimuli in the unilateral displays were not examined). Additionally, as unilateral and bilateral displays contain very different amounts of visual stimulation, analyses were performed separately for unilateral and bilateral displays. Behavioral analysis examined accuracy rates as defined by the number of total possible trials minus errors of omission and commission.

As anticipated, there was a main effect of display type (unilateral vs. bilateral, $F(1,15) = 11.63$, $p = .004$, $\eta_p^2 = .437$) as well as a main effect of perceptual load (high vs. low, $F(1,15) = 31.94$, $p < .001$, $\eta_p^2 = .680$). Additionally, there was an interaction of display type by perceptual load ($F(1,15) = 19.76$, $p < .001$, $\eta_p^2 = .569$). These findings reflect similar accuracy at low perceptual load for both unilateral ($X = 97.5$, SD = 2.44) and bilateral displays ($X = 98.4$, SD = 1.46). In contrast, accuracy was lower at high perceptual load, but showed greater reductions for bilateral displays (load $X = 79.2$, SD = 3.18) as compared to unilateral displays ($X = 85.5$, SD = 1.92). These data support the effectiveness of the perceptual load manipulation.

Consistent with traditional lateralized attention paradigms the 2(perceptual load: high vs. low) × 2(direction of attention: left vs. right) × 2 (electrode: O1 vs. O2) repeated measures ANOVA for both unilateral and bilateral displays found a significant interaction between the direction of attention and electrode reflecting greater processing contralateral to the direction of attention (unilateral display; $F(1,15) = 7.90$, $p = .013$, $\eta_p^2 = .345$, bilateral display; $F(1,15) = 10.76$, $p = .005$, $\eta_p^2 = .418$; Fig. 2a,b,c,d). However, there were no significant main effects and no other significant interactions which is consistent with previous literature on the effects of perceptual load on early processing [2,6].

Interestingly, there was a significant main effect of load for both unilateral ($F(1,15) = 5.23$, $p = .037$, $\eta_p^2 = .260$) and bilateral ($F(1,15) = 4.81$, $p = .045$, $\eta_p^2 = .243$) displays reflecting reduced processing at high perceptual load (Fig. 2e). There was also a significant interaction between perceptual load, direction of attention, and electrode for unilateral displays ($F(1,15) = 4.80$, $p = .045$, $\eta_p^2 = .242$, Fig. 2a,b) reflecting attention effects (i.e., greater processing contralateral to attended stimuli), that were smaller at high perceptual load as compared to low perceptual load. In contrast, no such interaction was found for bilateral displays ($p > .5$). Instead, only a significant interaction between direction of attention and electrode ($F(1,15) = 8.10$, $p = .012$, $\eta_p^2 = .351$) was found for bilateral displays reflecting greater processing ipsilateral to the direction of attention (Fig. 2c,d).

As in previous studies, both effects of attention and perceptual load were seen in this study. However, there were intriguing differences between effects seen in unilateral as compared to bilateral displays. As in previous studies, attention modulated processing contralateral to stimuli at both the P100 and N100 for unilateral displays and this effect was modulated by perceptual load at the N100 [2,6,9]. Moreover, there was a main effect of perceptual load at the N100 for unilateral displays. In contrast, while bilateral displays also showed attentional effects at both the P100 and N100, this effect was not modulated by perceptual load at the N100. Instead, bilateral displays showed only a main effect of perceptual load.

As in numerous previous studies, this study showed attention effects at the P100 [1,6,13,22–26]. These effects, combined with behavioral performance (reduced accuracy at high perceptual load), suggest the task effectively encouraged participants to direct their attention to the cued hemifield. Additionally, as in previous studies [21] the attention effect for the N100 was different for unilateral as compared to bilateral displays, with greater processing at the N100 contralateral to attended stimuli for unilateral displays and greater processing at the N100 contralateral to unattended stimuli for bilateral displays. Thus, as expected attention effects were seen in both unilateral and bilateral displays, it was possible to look at the effects of perceptual load on attentional effects.

According to Handy and Mangun [9], perceptual load effects are primarily seen at the N100 as the N100 has a larger capacity to show attention effects as compared to the P100. However, it is also possible that effects were seen at the N100 as a result of the high level of discrimination needed at high perceptual load, thus reflecting the discrimination related N100 [12,33,34]. Either explanation is supported by the findings in this study. However, while attentional modulation by perceptual load was seen for unilateral displays, it was not seen for bilateral displays.

Unilateral displays show high perceptual load reduced attention effects at the N100. This reduction appears to be the result of a smaller N100 contralateral to the attended stimulus at high perceptual load (Fig. 2a,b,c,d). While some studies have found greater

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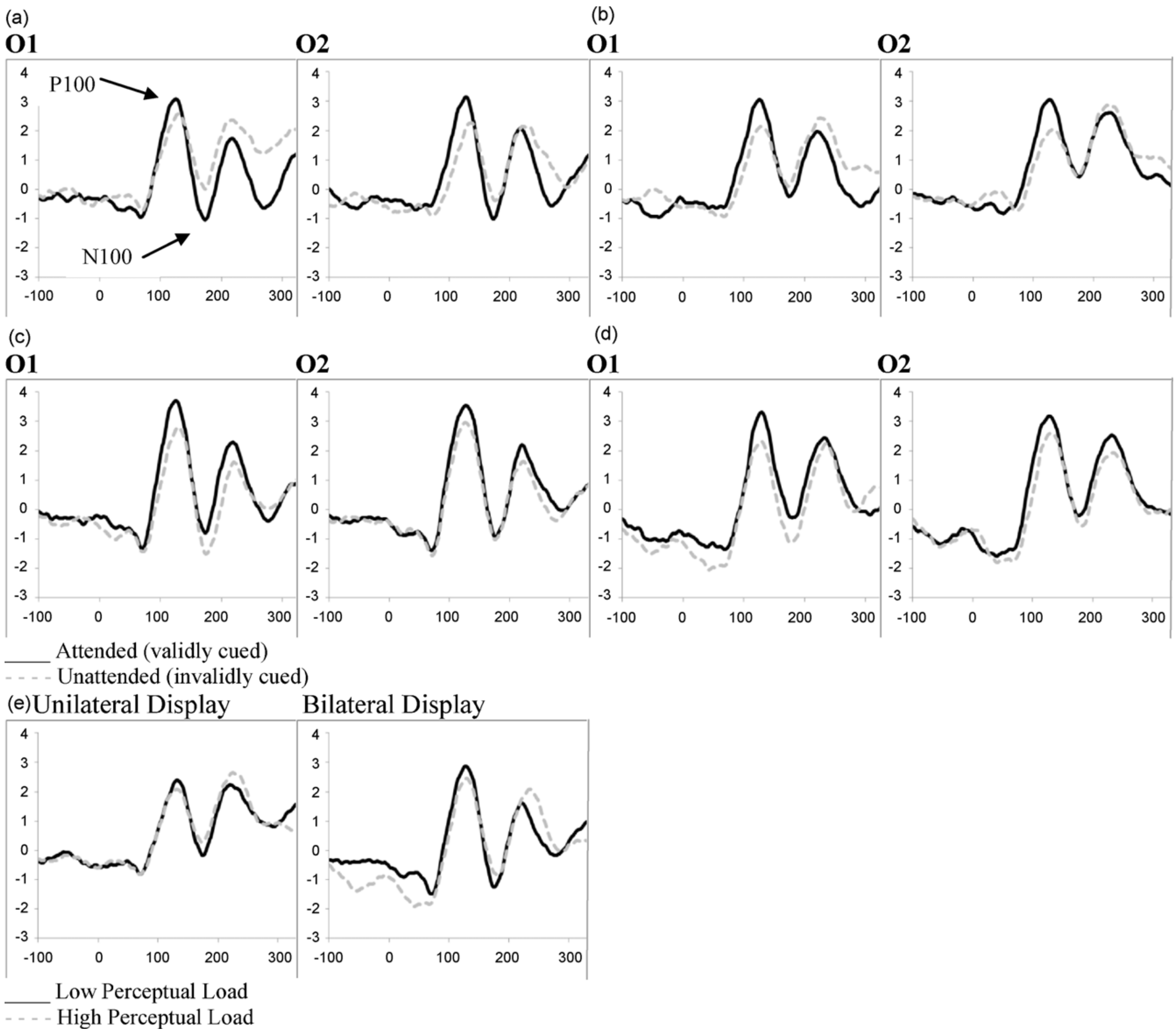

Fig. 2. Effects of perceptual load on attention for unilateral displays contralateral to the non-target stimulus for (a) low perceptual load displays and (b) high perceptual load displays, as well as for bilateral displays contralateral to the non-target stimulus for (c) low perceptual load displays and (d) High Perceptual Load Displays. Effects of perceptual load on unattended stimulus in (e) unilateral and bilateral displays.

attention modulation at high perceptual load [2], attention effects at the N100 vary as a function of task and stimulus factors [6,9]. For example, Handy and Mangun [9] showed differences in the N100 as a function of the probability of the cue, with lower probabilities resulting in smaller differences between attended and unattended stimuli (i.e., valid cue probability of 1 vs.75). In this task, the probability of a correct cue was only 6, lower than in previous studies of this type. Thus, in this study it is likely that at high perceptual load a more distributed attention was utilized to compensate for this lower probability to attain a high level of performance, while at low perceptual load this strategy was not necessary, resulting in a reduced attention effect at high perceptual load.

In addition to modulation of attention by perceptual load, overall a perceptual load effect was seen with reduced processing at the N100 at higher levels of perceptual load (Fig. 2e). These findings are consistent with Lavie's [16] theory of selective attention that suggests that processing of an unattended stimulus should be reduced in the presence of an attended stimulus at high perceptual load. Additionally, the P100 effects support this theory, showing similar processing contralateral to the attended stimulus at low and high levels of perceptual load.

In contrast to unilateral displays, bilateral displays showed modulations in processing as a function of perceptual load at the N100, but did not show any modulations of attention by perceptual load. The N100 was reduced at high perceptual load as compared to low perceptual load (Fig. 2e). Importantly this was true for processing contralateral to the unattended stimulus. As noted previously, this is consistent with Lavie's model of selective attention and is similar to unilateral displays, as well as to previous studies of effects of perceptual load on unattended parafoveal stimuli [10]. In contrast, the absence of modulatory effects on attention by perceptual load in bilateral displays is intriguing and there are several potential explanations that should be examined further.

First, it is possible that bilateral displays are at a higher level of perceptual load than unilateral displays even at low perceptual load. Thus, bilateral low perceptual load displays may already show modulations of attention by perceptual load, and increased perceptual load may have exceeded the ability for the N100 to show additional effects. However, this is unlikely to be the case as unilateral and bilateral displays under low perceptual load conditions showed ceiling behavioral effects (performance exceeding 97%) and effects of increased perceptual load on attentional processing have

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not been shown in the absence of behavioral changes [2,5,9,10]. Thus it is unlikely that bilateral displays exhaust the N100's ability to show modulation of attention by perceptual load.

Alternatively, it is possible that perceptual load effects on attention were not seen as a result of differences in the way attention effects are expressed in bilateral displays. N100 attention effects are typically reduced for bilateral displays and instead reflect changes at the P100 that carryover into the N100 timeframe [21]. It is therefore possible that attention effects at the N100 do not reflect additional modulations in attention beyond the P100 leaving only effects of perceptual load. This explanation appears likely, as subtractions of unattended from attended stimuli suggest a positivity beginning at approximately 80–100 milliseconds that continues through the N100 timeframe (approximately 150–200 ms) and is consistent with studies of attention modulations using bilateral displays [21,31].

Finally, one of the limitations of this study was that the perceptual load manipulation utilized changed sensory perceptual load (i.e., target discrimination). This type of manipulation may affect processing differently than other types of changes such as the inclusion of additional attended information. Thus, future studies should explore alternative manipulations of perceptual load.

Overall, findings from this study suggest that reductions in processing contralateral to unattended stimuli as a function of perceptual load are similar in unilateral and bilateral displays, supporting Lavie's [16] perceptual load theory of selective attention. However, this study also raised important differences in unilateral as compared to bilateral displays. Possibly due to the nature of attention modulations at the N100, modulatory effects on attention were only seen for unilateral displays. Thus, while perceptual load influences processing with and without an attended stimulus present, the presence of both an attended and unattended stimulus alters how perceptual load influences processing at the N100.

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