
Attending to quadrants and ring-shaped regions: ERP effects of visual attention in different spatial selection tasks

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Abstract

Attentional modulations of event-related brain potentials (ERPs) were measured when subjects were cued to attend to a visual quadrant or to a ring-shaped region of visual space to detect infrequently presented targets within the attended region. Spatial attention directed to quadrants was reflected in modulations of sensory-evoked P1 and N1 components at lateral posterior sites and enhanced negativities (Nd) at midline electrodes that started around 150 ms poststimulus. When attention was directed to ring-shaped regions, no modulations of P1 and N1 amplitudes were found, and Nd effects observed at midline electrodes were delayed by about 50 ms. These findings indicate that behavioral effects observed both when attention is directed to contiguous regions and to general areas of visual space may be caused by different underlying processes. Intrapreceptual “sensory gating” mechanisms operating in a way suggested by the notion of an attentional “zoom-lens” may be responsible for the selection of single regions, quadrants, or hemifields. When relevant regions are more complex, spatial selectivity will affect primarily postperceptual processes.

Descriptors: Spatial selectivity, ERPs, Spatial attention, P1, N1

Attention can be oriented voluntarily to regions of visual space independently of overt adjustments of eye or head position, and such attentional orienting processes have profound influences on behavior. Experimental studies of visual–spatial attention often use a trial-by-trial cueing paradigm, in which a cue is presented at the beginning of each trial, indicating the likely location of an upcoming target stimulus within the visual field. Subjects are instructed to direct attention to the cued location while maintaining central fixation, and behavioral performance in trials in which the position of the target is indicated correctly by the cue (valid trials) is compared with performance measured in invalid trials, in which the target appears at an uncued location. Responses on valid trials are usually faster and less error-prone than responses on invalid trials (Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980), and stimuli at cued locations are detected more efficiently than stimuli at unattended positions (Bashinski & Bacharach, 1980; Downing, 1988; Hawkins et al., 1990; Müller & Findlay, 1987). It has been argued that visual–spatial attention can be likened to a “spotlight” that can be moved voluntarily in visual space inde-

pendently of eye movements to select one region for preferential processing (Shulman, Remington, & McLean, 1979; Eriksen & St. James, 1986).

Much research has been devoted to investigating functional properties of this hypothetical attentional spotlight. Behavioral effects of visual–spatial attention vary with the distance of a stimulus from the current focus of attention, reflecting the existence of “attentional gradients” in visual space. Downing and Pinker (1985) found that behavioral costs for targets at incorrectly cued locations become larger with increasing distance from an attended location, and similar findings have been reported by Shulman, Wilson, and Sheehy (1985). The size of the attentional focus can be adjusted in accordance with specific task requirements. LaBerge (1983) had subjects identify a word or the middle letter within a letter string. When the primary task was letter identification, the detection of an occasionally presented probe stimulus was most efficient when the target appeared at the middle position, whereas for word categorization, no such advantage was observed. LaBerge (1983) argued that attention was distributed evenly over all letter locations in the word identification task, but was focused on the central position in the letter identification task.

Although such findings indicate that the distribution of spatial attention in visual space can be modulated by task demands, it is not clear whether simultaneous allocation of attention to two or more nonadjacent locations is possible. Eriksen and Yeh (1985) presented a target and three distractors at the 3, 6, 9, and 12 o'clock position of a virtual circle, and a bar delivered near one possible target location served as precue. Targets appeared with equal probability (40%) at the cued location and at the opposite location. If

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attention could be divided, performance advantages relative to a neutral baseline should be found for both locations. However, benefits were found only for the cued location, and costs were present for the opposite location (see also Posner et al., 1980). The question whether attention can be directed simultaneously to nonadjacent locations has also been investigated in an ERP study by Heinze, Luck et al., (1994) in a task in which participants had to attend to two of four stimulus locations that could be adjacent or separated by an irrelevant location. With adjacent relevant locations, probe stimuli presented at irrelevant positions elicited smaller sensory-evoked components than probes at relevant positions. However, no such attenuation was found for irrelevant probes at the intervening location between the two attended locations, suggesting that sensory responses were not suppressed. According to Heinze, Luck et al. (1994), attention is directed to contiguous areas of visual space. With nonadjacent relevant locations, attention will include the area between these locations.

This apparent inability to allocate attention simultaneously to nonadjacent locations may reflect a basic property of visual-spatial attention. According to a "zoom-lens" account (Eriksen & St. James, 1986), attention can be thought of as expanding or contracting around a single central focus. If this account were the case, performance benefits should be found for all locations included within an attended area. However, some findings suggest that attention can be directed to general regions of visual space in a way not accounted for by a zoom-lens model. Egly and Homa (1984) presented single letters along one of three concentric rings around fixation, and cued letter eccentricity (close, medium, distant) at the beginning of each trial. Identification performance was better than in a control condition in which no advance information was given, suggesting that attention can be directed to ringlike segments of visual space, and that its diameter can be adjusted in accordance with the cue. This hypothesis was further investigated by Juola, Bouwhuis, Cooper, and Warner (1991) in a study that produced results incompatible with a zoom-lens model of spatial attention. Targets and distractors were presented within one of three concentric rings, and subjects were informed at the start of each trial about the most likely eccentricity of the target (80% validity). Response time (RT) benefits for valid trials and costs for invalid trials were obtained. For example, when attention was summoned to the outer ring, RTs were delayed when targets appeared in the middle or inner ring. These findings are problematic for zoom-lens accounts of visual-spatial attention, because they suggest not only that attention can be directed to ringlike areas of visual space, but also that locations included within a currently attended region can be selectively ignored.

The fact that behavioral costs and benefits of visual-spatial attention can be obtained when attention is directed to concentric regions of visual space, excluding the area medial to these regions, and that these effects are similar to the effects observed when attention is directed to single locations, visual hemifields, or quadrants, might suggest that attentional selectivity is functionally equivalent in these conditions. This conclusion would have important consequences for models of visual attention, implying an impressive amount of flexibility and control in the distribution of attention within visual space. It would be premature, however, to base such a conclusion exclusively on evidence from behavioral studies. Attentional effects on performance may reflect selective mechanisms at different processing stages (see Allport, 1993). Visual-spatial attention may influence perceptual processing, so that stimuli at attended locations are analysed more rapidly or intensively (Posner, 1980). Spatial attention may also affect later, postperceptual

processes like response selection (cf. Sperling, 1984). It is conceivable that different mechanisms of attentional selectivity are operative in different spatial selection tasks. To investigate this possibility, performance measures should be complemented with electrophysiological indicators of attentional processing that may allow a more direct access to the mechanisms involved in visual-spatial attention.

In the present study, effects of visual-spatial attention on event-related brain potentials (ERPs) were obtained when attention was directed to ring-shaped areas of visual space and compared with ERPs elicited when attention was directed to quadrants of the visual field. ERP effects of visual-spatial attention are well documented in the literature. Stimuli at attended locations have been found to elicit enhanced sensory-evoked P1 and N1 components at lateral posterior scalp sites as compared with those seen for stimuli at unattended locations (cf., Eason, 1981; Harter, Aine, & Schroeder, 1982; Hillyard & Mangun, 1987; Hillyard & Münte, 1984). These ERP effects start relatively early (around 80 ms to 100 ms post-stimulus), and seem to be generated in extrastriate cortex close to primary visual projection areas (Clark & Hillyard, 1996; Heinze, Mangun et al., 1994). P1 and N1 amplitude modulations may indicate early, intraperceptual sensory gating mechanisms (Mangun & Hillyard, 1990), reflecting a selective influence of spatial attention of visual processing in the ventral stream within the pathways linking V1 to IT cortex (Desimone & Duncan, 1995; LaBerge, 1995; Ungerleider & Mishkin, 1982). In addition to these early effects of visual-spatial attention at posterior sites, additional ERP effects have been found at midline electrodes, at which enhanced negativities can be observed for valid trials compared with invalid trials (Eimer, 1996; Mangun & Hillyard, 1991). These effects usually start about 150 ms after stimulus onset with an initial centroparietal maximum (Nd1) that is followed beyond 200 ms poststimulus by a broadly distributed peak (Nd2). A recent study (Eimer, 1997) showed that these Nd effects are modulated by the distance of unattended stimuli from the current focus of attention, as suggested by the notion of "attentional gradients." Nd1 and Nd2 were largest in amplitude when ERPs in valid trials were compared with ERPs in "invalid far" trials during which stimuli were separated by the horizontal and vertical meridian from an attended location. In contrast to attentional modulations of posterior P1 and N1 components, which are modality-specific, Nd1-Nd2 effects at midline sites have also been observed in attentional cueing experiments in which auditory stimuli were used (Schröger, 1993, 1994; Schröger & Eimer, 1993). Whereas attentional effects of P1 and N1 are likely to reflect selective effects on visual processing within the ventral stream (Clark & Hillyard, 1996; Heinze, Mangun et al., 1994), it is possible that the centroparietal Nd1 effect reflects modality-unspecific activity in parietal cortex related to the control of spatial attention (Eimer, 1998; Eimer & Schröger, 1998).

In the present study, ERP effects of visual-spatial attention directed to ring-shaped regions of visual space and to visual quadrants were measured in a situation in which single letter stimuli were presented at 12 possible locations along three concentric rings of 1.7°, 2.9°, or 4.1° radius. The to-be-attended region was indicated at the start of each trial by a centrally presented digit cue, and subjects had to respond to infrequently presented target stimuli when these appeared within the attended region. In the Ring condition, the cue indicated which of the three eccentricities (inner, middle, or outer ring) was to be attended. In the Quadrant condition, the cue indicated which quadrant of the visual field (upper or lower left or right) was to be attended. These regions were marked

by grey lines (two concentric circles in the Ring condition, and a horizontal and vertical line in the Quadrant condition) that were continuously present (Figure 1). In all other respects, the two conditions were identical, and subjects received both conditions in counterbalanced order. The aim of this experiment was to study (i) whether functionally equivalent selective mechanisms are operative when attention is directed to contiguous regions or to more complex areas of visual space, and (ii) whether the distribution of visual-spatial attention in the Ring condition is more adequately captured by a zoom-lens account or by a ring model.

Based on prior research (Eimer, 1997), attentional modulations of sensory-evoked P1 and N1 components were predicted for the Quadrant condition. Moreover, enhanced negativities for valid trials at midline electrodes (Nd1, Nd2) were also expected, and these effects should be modulated by the distance of invalidly cued stimuli from the attended quadrant. If the processes underlying the allocation of attention to visual quadrants and to ring-shaped areas of visual space were equivalent, essentially the same effects should be observed in the Ring condition. Systematic dissociations between ERP effects obtained in the Ring and Quadrant conditions would indicate that the respective attentional processes are not identical. If a zoom-lens model was an adequate description of the distribution of attention in the Ring condition, attentional ERP effects should be strongly dependent on stimulus eccentricity. For innermost stimuli, ERP effects of attention should be small, because these stimuli will be inside the attended area regardless of which eccentricity had been cued. For outer stimuli, attentional effects should be large, as these will invariably be located outside the attended region when cued invalidly. No interactions of atten-

tion and eccentricity would be expected if attention could be selectively directed to ring-shaped areas of visual space.

To verify that behavioral effects of spatial cueing comparable to the results reported by Juola et al. (1991) would be obtained under the experimental conditions realized in the Ring condition, an additional behavioral control experiment was conducted that was equivalent to the Ring condition, except that cues predicted target eccentricity with 80% validity and responses were required in valid and in invalid trials.

Methods

Subjects

Sixteen paid volunteers participated in the experiment. Two of the volunteers had to be excluded because of poor eye fixation control in the cue-target intervals of the Quadrant condition. Thus 14 subjects (9 women, aged 22–38 years) remained in the sample. All subjects were right-handed and had normal or corrected-to-normal vision.

Stimuli and Apparatus

Subjects were seated in a dimly lit, electrically shielded, and sound-attenuated cabin, with response buttons under their left and right hands. A computer screen was placed 110 cm in front of the subject's eyes and positioned so that a small fixation cross (subtending a visual angle of about $0.1^\circ \times 0.1^\circ$) was positioned on the subject's horizontal straight-ahead line of sight. The stimulus setup is shown schematically in Figure 1. Uppercase letters M and N served as imperative stimuli, and digits (1–3 in the Ring condition;

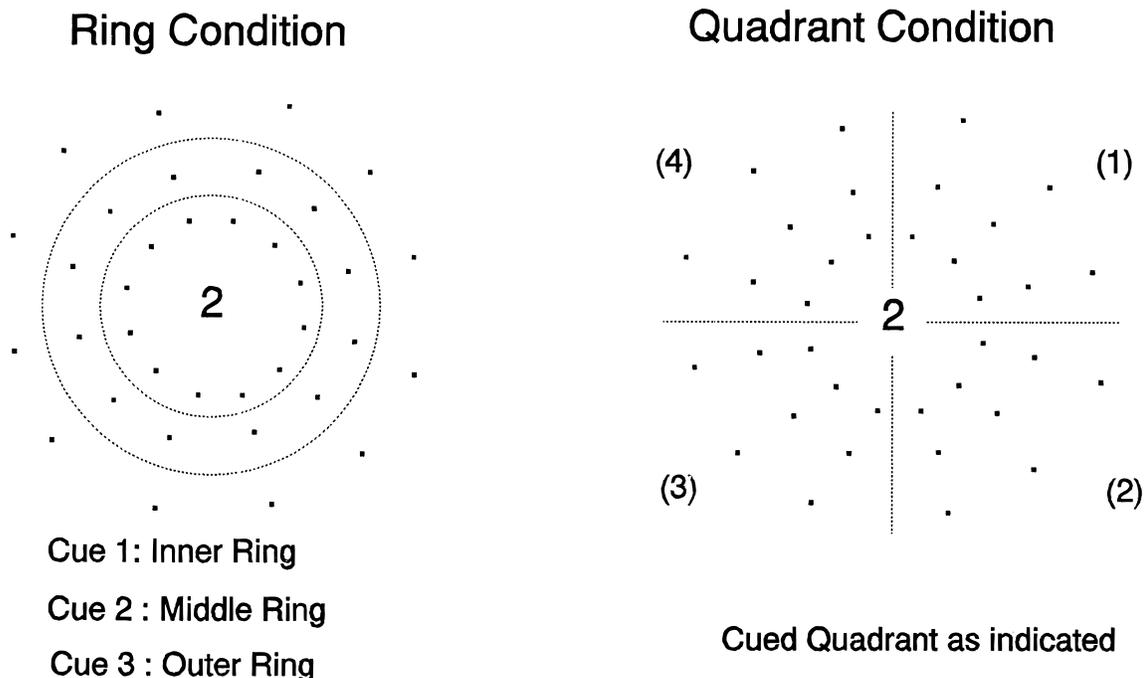


Figure 1. Schematic illustration of the stimulus setup. All stimuli were presented at 1 of 36 possible locations (indicated by the dots) around three virtual circles with a radius of 1.7° , 2.9° , or 4.1° around the screen center. In the Ring condition (left side), two concentric grey circles (2.3° and 3.5° radius) marked the borders of the inner, middle, and outer ring, and a centrally presented digit cue indicated the to-be-attended ring-shaped region. In the Quadrant condition (right side), two grey lines indicated the vertical and horizontal meridian, and a centrally presented digit cue indicated the to-be-attended quadrant.

1–4 in the Quadrant condition) were used as cues. Digits and letters subtended a visual angle of approximately $0.8^\circ \times 0.8^\circ$. All cues appeared at fixation, and imperative stimuli could appear in one of 12 locations along one of three virtual rings of 1.7° , 2.9° , or 4.1° in radius around the fixation cross. In the Ring condition, two concentric circles (2.3° and 3.5° radius) were constantly present. In the Quadrant condition, two lines along the horizontal and vertical meridian of the visual field (sparing the inner $0.9^\circ \times 0.9^\circ$ around fixation) were constantly present. Stimuli were presented in white (letters and digits) or thin grey (lines and circles) against a black background.

Procedure

The experiment consisted of 24 experimental blocks, with 12 blocks in the Ring and the Quadrant condition, respectively. Seven subjects received the Ring condition prior to the Quadrant condition, and this order was reversed for the other seven subjects. In all trials, a cue presented for 200 ms at fixation was followed after an interstimulus interval of 700 ms by a 100-ms presentation of an imperative stimulus. The interval between the offset of an imperative stimulus and the onset of the next cue was 1,500 ms. A fixation cross was presented throughout each block at the central position, except for the 200 ms presentation of the cue. Trials during which an imperative stimulus appeared at a cued location were termed valid, trials during which these stimuli appeared at uncued locations are termed invalid.

In the Ring condition, the two grey circles marked the borders of the inner and middle, and middle and outer ring, respectively. Subjects were instructed to direct their attention to the ring indicated by the cue (1: inner ring; 2: middle ring; 3: outer ring) to detect infrequently presented target letters within the to-be-attended region. Each block consisted of 57 trials. On 45 trials per block, the nontarget letter M was presented, with five trials for each of the nine possible combinations of cued region (1,2,3) and stimulus eccentricity (inner, middle, outer ring). On the remaining 12 trials, the target letter N was presented. On 6 of these trials, it appeared in the cued region and thus required a response, on the other 6 trials, it was presented in an uncued region, and no response was required. The position of each letter within a given ring was determined randomly for each trial. In 6 blocks, subjects were required to press the left button in response to a target within the attended ring, in the other 6 blocks, a right-hand button press was required.

In the Quadrant condition, vertical and horizontal lines marked the borders of the visual quadrants. Subjects were instructed to direct their attention to the quadrant indicated by the cue (1: upper right; 2: lower right; 3: lower left; 4: upper left) to detect target letters within the to-be-attended quadrant. Each block consisted of 68 trials. On 48 trials per block, the nontarget letter M was presented, with 3 trials (one for each eccentricity) for each of the 16 possible combinations of cued quadrant (1,2,3,4) and quadrant of stimulus presentation. On the remaining 20 trials, the target letter N was presented. On 8 of these trials, the letter N appeared within the cued quadrant (and thus required a response), on the other 12 trials, the letter N was presented within an uncued quadrant. The position of each letter within a given quadrant and eccentricity was determined randomly for each trial. In 6 blocks, a left-hand button press was required to targets within the attended quadrant, in the other 6 blocks, a right-hand button press was required.

Subjects were instructed to respond as quickly and accurately as possible to correctly cued target stimuli, to withhold responses to all other stimuli, and to maintain central eye fixation during the

trials. To make subjects familiar with these specific task requirements, two training blocks were run at the beginning of both halves of the experiment.

Recording

Electroencephalograms (EEGs) were recorded with Ag-AgCl electrodes from Fz, Cz, Pz (according to the 10-20 system), from C3' and C4' (1 cm frontally of C3 and C4, respectively), from PL and PR (located halfway between Pz and the ear channel), and from OL and OR (located halfway between O1 and T5, and O2 and T6, respectively).¹ EEG was measured relative to a right earlobe reference. Horizontal electrooculograms (EOGs) were recorded bipolarly from electrodes at the outer canthi of both eyes, vertical EOG was recorded from electrodes above and beside the right eye. Electrode impedance was kept below 5 k Ω . The amplifier band-pass was 0.10–40.0 Hz. EEG and EOG were sampled with a digitization rate of 200 Hz, and stored on disk. The latency of manual responses (if present) was measured on each trial.

Data Analysis

EEG and EOG were epoched offline into periods of 1600 ms, starting 100 ms prior to the onset of the cue, and ending 600 ms after imperative stimulus onset. Trials with eyeblinks (vertical EOG exceeding 60 μ V in the 600-ms interval following imperative stimulus onset) or eye movements (horizontal and vertical EOG exceeding ± 25 μ V in the interval between cue offset and 400 ms after the offset of the imperative stimulus), response errors, or overt responses on nontarget trials were excluded from analysis. After artifact removal, the computer-averaged EOGs obtained in the Quadrant condition was scored for each subject for systematic deviations of eye position in response to cues requiring an attentional shift to the left vs. right (horizontal EOG) or upwards versus downwards (vertical EOG). For two subjects, the maximal residual horizontal EOG deviation exceeded ± 3 μ V, indicating a tendency to move the eyes towards the cued quadrant, and these subjects were disqualified.

For the ERP analysis, only the data from nontarget trials were further analyzed. EEG was averaged separately for both experimental halves for all combinations of cue type (1–3 in the Ring Condition; 1–4 in the Quadrant condition) and stimulus eccentricity (inner, middle, and outer position). In the Quadrant condition, separate averages were computed for stimuli within each of the four quadrants. This procedure resulted in nine average waveforms for each subject and electrode site in the Ring condition, and 48 averages in the Quadrant condition. For the Quadrant condition, averages obtained for each quadrant were collapsed to obtain averages for valid trials and for two types of invalid trials. On “invalid near” trials, the cued and the actual stimulus position were separated by one visual meridian, whereas on “invalid far” trials, the cued and the actual stimulus position were diagonally opposed. This procedure resulted in a total of nine averages per subject for the Quadrant condition (valid, invalid near, and invalid far, for three eccentricities). For the overall analyses of variance (ANOVAs; see below), the averages obtained in the different types of invalid trials were collapsed.

All measures were taken relative to the mean voltage of the 100-ms interval preceding stimulus onset. ERP effects of experimental variables were determined by conducting repeated-measures

¹The C3' and C4' channels were included to obtain the lateralized readiness potential (LRP) as an index of selective motor preparation processes. These data will not be reported in the present article.

ANOVAs on ERP mean amplitude values within four poststimulus time windows (P1: 100–130 ms; N1: 160–210 ms; Nd1: 160–200 ms; Nd2: 200–280 ms). P1 and N1 amplitude effects were analyzed at lateral parietal (PL, PR) and lateral occipital electrodes (OL, OR). Effects within the Nd1 and Nd2 time windows were analyzed at midline electrodes (Fz, Cz, and Pz). Overall repeated-measures ANOVAs were conducted on ERP mean amplitude measures for the following factors: condition (Ring vs. Quadrant), attention (valid vs. invalid), stimulus eccentricity (inner vs. middle vs. outer), and electrode location. Separate ANOVAs were also conducted for the Ring and Quadrant conditions. To test whether effects were modulated by the distance from the current focus of attention, additional ANOVAs were conducted on ERP measures from invalid trials, with distance from focus (near vs. far) replacing attention as factor. When appropriate, Greenhouse–Geisser adjustments to the degrees of freedom were performed. For the RT data obtained in response to validly cued target stimuli, a repeated-measures ANOVA was performed for the factors condition (Ring vs. Quadrant) and stimulus eccentricity.

Control Experiment

Ten paid participants (5 women, aged 21–39 years) received 14 experimental blocks that were identical to the Ring condition, except that the letters M and N were presented with equal probability, and the cue predicted target eccentricity with 80% validity (48 of 60 trials per block were valid). Participants were instructed to maintain central eye fixation during the trials, and to respond with a left-hand or right-hand button press to the letters M and N, respectively, regardless of whether they were presented within the cued or an uncued ring.² A repeated-measures ANOVA was performed on mean RTs for the factors cue validity (valid vs. invalid) and target eccentricity.

Results

Behavioral Performance in the Control Experiment

Mean RTs obtained for the different combinations of cued position and target position are shown in Table 1. Main effects of stimulus eccentricity, $F(2,18) = 26.13$; $p < .001$; $\epsilon = 0.937$, and cue validity, $F(1,9) = 31.06$; $p < .001$, were found. RTs were faster in valid than in invalid trials, and were fastest for innermost, and slowest for outermost stimuli. Eccentricity interacted with validity, $F(2,18) = 8.62$; $p < .002$; $\epsilon = 0.994$, as cue validity effects were larger for the stimuli in the inner ring (32 ms) than for stimuli in the middle and outer rings (16 ms and 19 ms, respectively). However, significant spatial cueing effects were present for all three eccentricities, all $t(9) > 3.25$; all $p < .01$, see Table 1.

Behavioural Performance in the EEG Study

An effect of condition, $F(1,13) = 19.31$; $p < .001$, was accompanied by an effect of stimulus eccentricity, $F(2,26) = 63.25$; $p < .001$; $\epsilon = 0.866$. Mean RTs in the Ring and Quadrant condition were 600 ms and 552 ms, respectively. Mean RTs for inner, middle, and outer stimuli were 557, 586, and 657 ms in the Ring condition, and 522, 549, and 585 ms in the Quadrant condition. An interaction between condition and eccentricity, $F(2,26) = 7.94$;

²Eye movements were not monitored. Because only the eccentricity, but not the location of targets along the rings was predictable, performance would not benefit from advance eye movements in the cue-target interval. The target duration of 100 ms was short enough to prevent benefits from eye movements following target onset.

Table 1. Mean Response Times for the Nine Different Combinations of Cued Position and Target Position

Cue	Target position		
	Inner ring	Middle ring	Outer ring
1	465 (24)	509 (28)	528 (26)
2	488 (24)	494 (26)	523 (26)
3	505 (27)	511 (26)	506 (26)

Note: Response times in ms (\pm SE). Cued position: 1 = inner ring; 2 = middle ring; 3 = outer ring.

$p < .003$; $\epsilon = 0.874$, indicated that the increase in RTs related to stimulus eccentricity was larger in the Ring condition. Pairwise comparisons showed that these differences within the Ring and Quadrant conditions were all significant, all $t(13) > 3.4$; all $p < .005$. Subjects missed 1.7% and 1.9% of all validly cued targets in the Ring and Quadrant condition, respectively, and the False Alarm rate to nontargets was 3.3% and 1.8% in these two conditions.

Attentional Effects at Lateral Posterior Sites

No main effect of attention was obtained for P1 amplitude, but a significant interaction between condition and attention at occipital electrodes, $F(1,13) = 4.98$; $p < .044$, indicated a differential influence of spatial attention in the Ring and Quadrant condition. Occipital P1 amplitude was larger in valid than in invalid trials in the Quadrant condition, $F(1,13) = 19.0$; $p < .001$, whereas no such effect was present for the Ring condition (see Figure 2). A similar pattern was found at parietal sites, with an attentional effect on P1 amplitude in the Quadrant condition, $F(1,13) = 4.92$; $p < .045$, but not in the Ring condition, although the relevant interaction failed to reach significance, $F(1,13) = 3.31$; $p < .092$. No significant difference was obtained in the Quadrant condition between P1 amplitudes for invalid-near and invalid-far trials.

N1 amplitude at posterior sites was affected by attention, $F(1,13) = 19.11$ and 17.82 ; $p < .001$, for occipital and parietal sites, respectively. Interactions between condition and attention, $F(1,13) = 28.09$ and 23.0 ; both $p < .001$, for occipital and parietal sites, indicated that these effects were different in the Ring and Quadrant conditions (see Figure 2). Whereas no significant attentional effects on N1 amplitude were found in the Ring condition, such effects were clearly present in the Quadrant condition, $F(1,13) = 27.32$ and 27.1 ; both $p < .001$, for occipital and parietal sites. As can also be seen from Figure 2, N1 amplitude was more attenuated in the Quadrant condition for invalid far than for invalid near trials, $F(1,13) = 15.79$ and 9.45 ; $p < .002$ and $.009$, for occipital and parietal sites, respectively.³

Attentional Effects at Midline Electrodes

Figure 3 shows ERP waveforms obtained at midline electrodes in valid and invalid trials and the resulting difference valid-invalid waveforms for the Ring and Quadrant condition. Whereas attentional effects started around 140 ms in the Quadrant condition,

³Stimulus eccentricity also affected N1 amplitude, with largest amplitudes for inner stimuli, and smallest amplitudes for outer stimuli, $F(2,26) = 23.08$ and 3.45 ; $p < .001$ and $.045$; $\epsilon = 0.816$ and 0.941 , for occipital and parietal sites, respectively. However, these effects (not shown in Figure 2) did not interact with condition or attention.

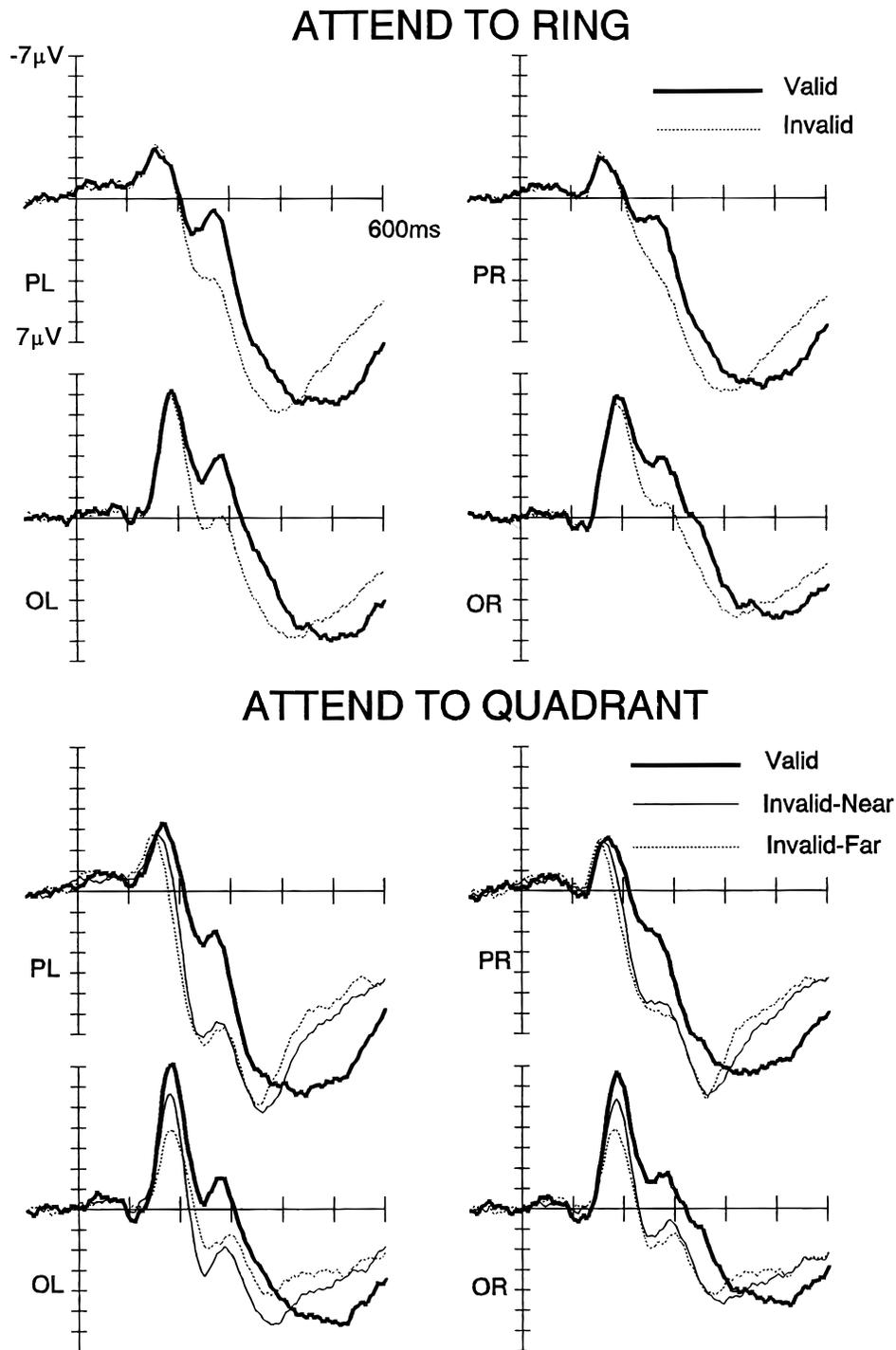


Figure 2. Grand-averaged event-related potentials (ERPs) recorded at lateral parietal and occipital electrodes in the Ring condition (top) and the Quadrant condition (bottom) in valid trials (solid thick lines) and invalid trials (thin lines). For the Quadrant condition, ERPs elicited in invalid near and invalid far trials are displayed separately.

their onset was clearly delayed in the Ring condition. This delay was reflected in the results obtained within the Nd1 interval (160–200 ms poststimulus). Main effects of attention, $F(1,13) = 12.73$; $p < .003$, and eccentricity, $F(2,26) = 10.14$; $p < .003$; $\epsilon = 0.647$, were accompanied by Condition \times Attention and Electrode location \times Attention interactions, $F(1,13) = 23.46$; $p < .001$; and $F(2,26) = 12.35$; $p < .001$; $\epsilon = 0.717$. Moreover, a three-way

interaction was obtained, Condition \times Attention \times Electrode location: $F(2,26) = 6.91$; $p < .013$; $\epsilon = 0.632$. Significant interactions between condition and attention were obtained at all midline sites, all $F(1,13) > 8.5$; all $p < .012$. Subsequent analyses showed that attention affected ERPs at all midline sites in the Quadrant condition. The Nd1 effects obtained at Fz were significantly smaller than the effects obtained at Cz and Pz (see Figure 3). In contrast,

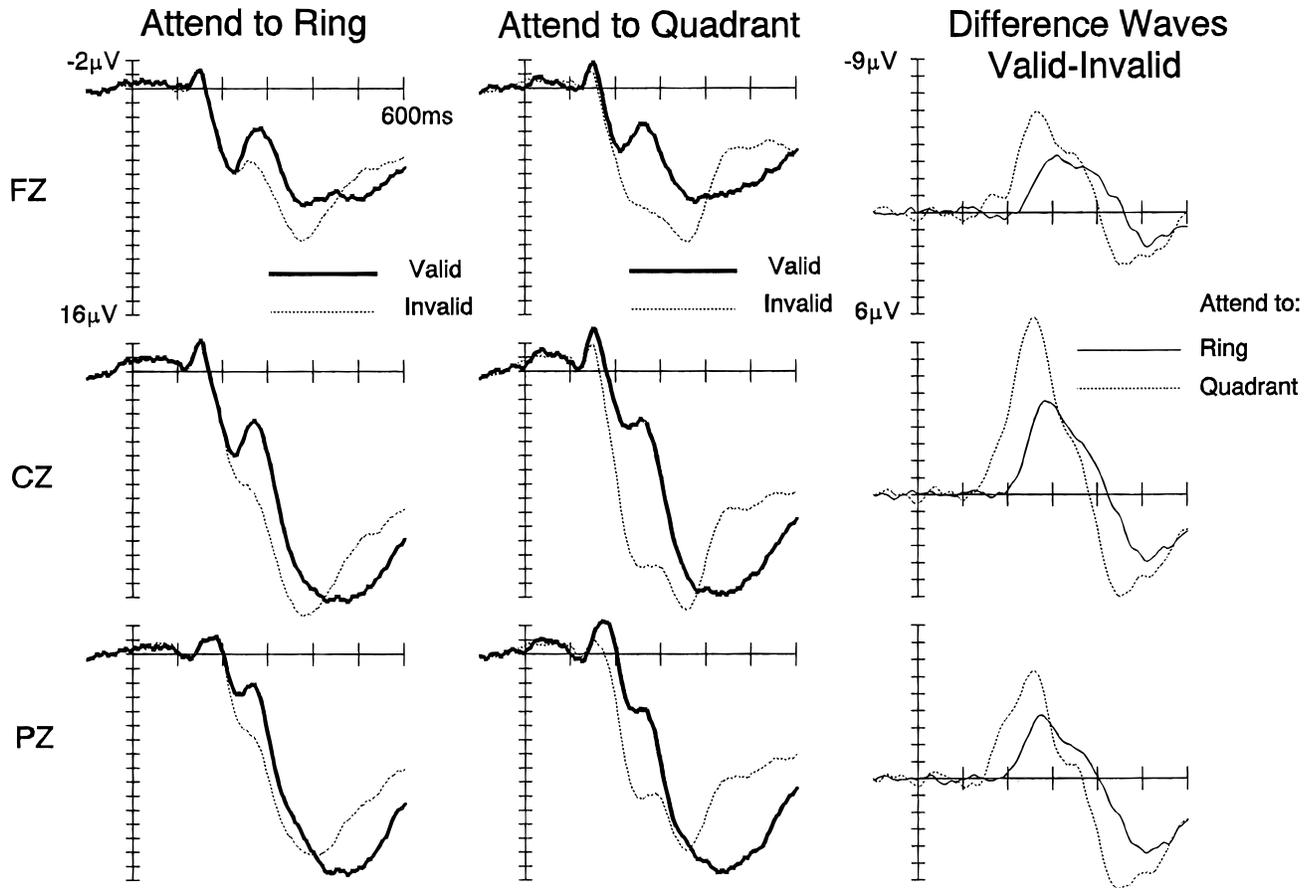


Figure 3. Left and middle: Grand-averaged event-related potentials (ERPs) recorded at midline electrodes in the Ring condition (left) and the Quadrant condition (middle) in valid trials (solid thick lines) and invalid trials (thin dashed lines). Right: Difference waveforms obtained by subtracting ERPs for invalid trials from ERPs for valid trials in the Ring condition (solid lines) and the Quadrant condition (dashed lines).

no attentional effects were present in the Nd1 interval for the Ring condition. As can be seen from Figure 4 (right side), the Nd1 effects obtained in the Quadrant condition were larger in the valid-invalid far than in the valid-invalid near difference waveforms. Significant differences between invalid near and invalid far trials were present at Cz and Pz, both $F(1, 13) > 7.05$; both $p < .020$, but not at Fz.

In the Nd2 interval (200–280 ms poststimulus), effects of attention, $F(1, 13) = 46.63$; $p < .003$, were accompanied by Condition \times Attention and Electrode location \times Attention interactions, $F(1, 13) = 52.2$; $p < .001$; and $F(2, 26) = 20.87$; $p < .001$; $\epsilon = 0.941$. Again, a three-way interaction was obtained, Condition \times Attention \times Electrode location: $F(2, 26) = 23.8$; $p < .001$; $\epsilon = 0.957$. Spatial attention affected ERPs at all midline electrodes, all $F(1, 13) > 30.0$; all $p < .001$. However, Attention \times Condition interactions, reflecting larger Nd2 effects in the Quadrant than in the Ring condition (see Figure 3), were also present at all midline sites, all $F(1, 13) > 28.8$; all $p < .001$. Additional t tests revealed significant attentional effects in the Nd2 interval at all midline sites in both experimental conditions, all $t(13) > 3.3$; all $p < .006$. Attentional effects were modulated by stimulus eccentricity in the Nd2 time range, as evidenced by an Attention \times Eccentricity interaction, $F(2, 26) = 10.7$; $p < .001$; $\epsilon = 0.784$, and a three-way interaction, Attention \times Condition \times Eccentricity: $F(2, 26) = 9.78$;

$p < .001$; $\epsilon = 0.946$. Figure 5 shows mean valid-invalid difference amplitudes obtained in the Nd2 interval for single midline sites and different eccentricities in the Ring and Quadrant condition. Whereas eccentricity showed no systematic effect in the Quadrant condition, attentional effects were affected strongly by eccentricity in the Ring condition. Nd2 effects were largest for outer stimuli, and smallest for innermost stimuli. This pattern can also be seen in Figure 4 (left side), in which valid-invalid difference waveforms obtained at single midline sites in the Ring condition are displayed separately for stimuli located within the inner, middle, and outer ring. Here, latency differences also become visible, as Nd2 effects started earlier for outermost stimuli than for middle and inner stimuli. The onset of attentional effects for the outermost stimuli in the Ring condition (Figure 4, left) is still delayed by about 30 ms as compared with the Quadrant condition (Figure 4, right).

Effects of distance from the attentional focus on invalid trial ERPs in the Nd2 interval were determined separately for the Quadrant and Ring condition. In the Quadrant condition, attentional effects were again more pronounced in the valid-invalid far difference waveforms (Figure 4, left). Significant differences between invalid near and invalid far trials were present at Cz and Pz, both $F(1, 13) > 11.9$; both $p < .004$, but not at Fz. For the Ring condition, invalid trials with imperative stimuli presented in the inner or outer ring were classified as invalid near when the neigh-

DIFFERENCE WAVES

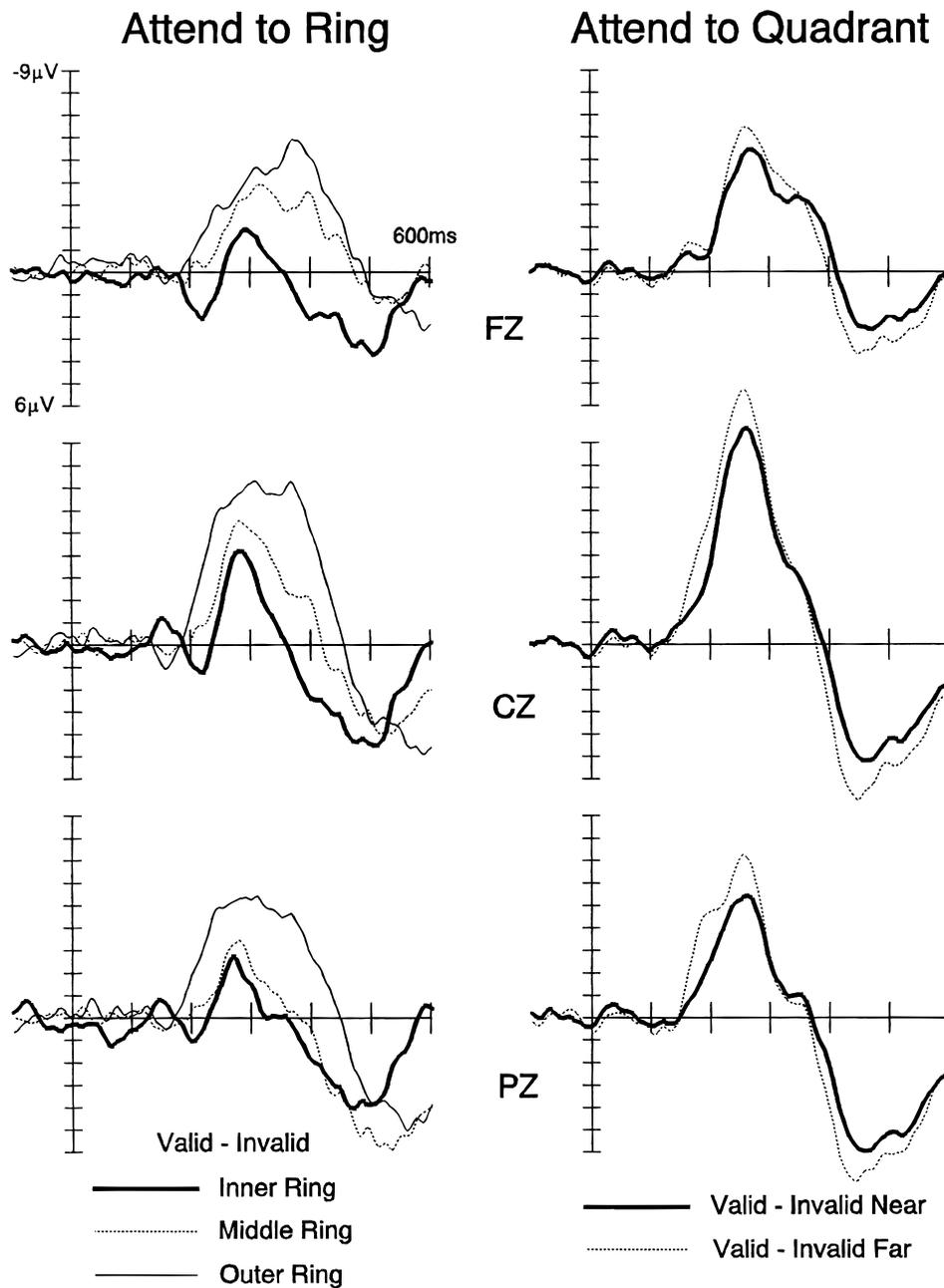


Figure 4. Left: Difference waveforms obtained at midline electrodes in the Ring condition by subtracting event-related potentials (ERPs) for invalid trials from ERPs for valid trials, displayed separately for stimuli presented in the inner ring (solid thick lines), the middle ring (dashed thin lines), and the outer ring (solid thin lines). Right: Difference waveforms obtained at midline electrodes in the Quadrant condition by subtracting ERPs for invalid near trials from ERPs for valid trials (solid thick lines) and by subtracting ERPs for invalid far trials from ERPs for valid trials (dashed thin lines).

boring eccentricity was cued (e.g., when an outer stimulus was preceded by an “attend middle” cue), and as invalid inner when the more distant eccentricity was cued (e.g., when an outer stimulus was preceded by an “attend inner” cue). Significant differences between these two types of invalid trials were obtained, $F(1, 13) = 17.91$; $p < .001$, and this effect interacted with eccentricity, $F(1, 13) = 8.67$; $p < .011$. The underlying pattern of results re-

sponsible for these effects is shown in Figure 6, in which valid-invalid difference waveforms obtained in the Ring condition are shown for different eccentricities and the two possible invalid cues. The differences between invalid near and invalid far trials are clearly more pronounced for stimuli within the outer ring than for the innermost stimuli. Another analysis on ERPs elicited in the Nd2 interval in the Ring condition was conducted for invalid stim-

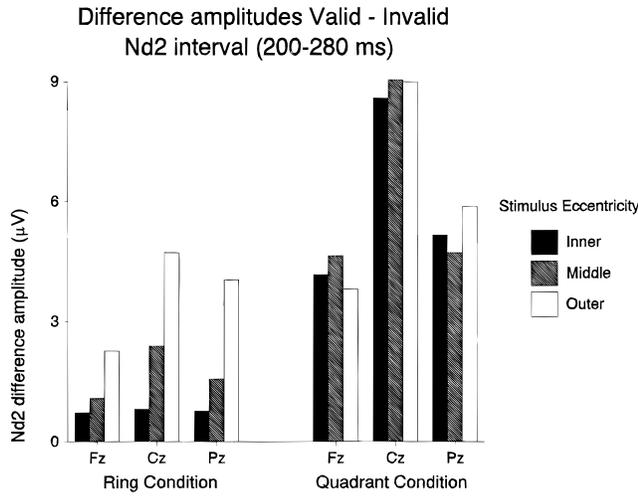


Figure 5. Mean valid–invalid difference amplitude at midline electrodes in the Nd2 interval (200–280 ms poststimulus), shown separately for the Ring condition (left) and the Quadrant condition (right), and all stimulus eccentricities.

uli presented in the middle ring. ERPs were more negative for invalid trials during which an “attend outer” cue was presented than for trials where the innermost region was cued, $F(1,13) = 28.34$; $p < .001$. This difference is reflected in Figure 6 (middle) as larger attentional Nd2 effects in the attend middle–attend inner (AM-AI) difference waveforms as compared with the attend middle–attend outer (AM-AO) waveforms.

Discussion

The present experiment investigated whether selective attention directed to visual field quadrants and to more complex areas of visual space was reflected in equivalent ERP modulations, indicating functionally similar underlying mechanisms, and how attention is distributed in response to cues summoning it to ring-shaped regions of the visual field. The ERP results obtained in the Quadrant condition confirmed findings from previous research (Eimer, 1997). Visual–spatial attention affected the amplitudes of posterior sensory-evoked P1 and N1 components, with larger P1 and N1 amplitudes for stimuli within an attended quadrant. These effects suggest that spatial attention directed to a quadrant of visual

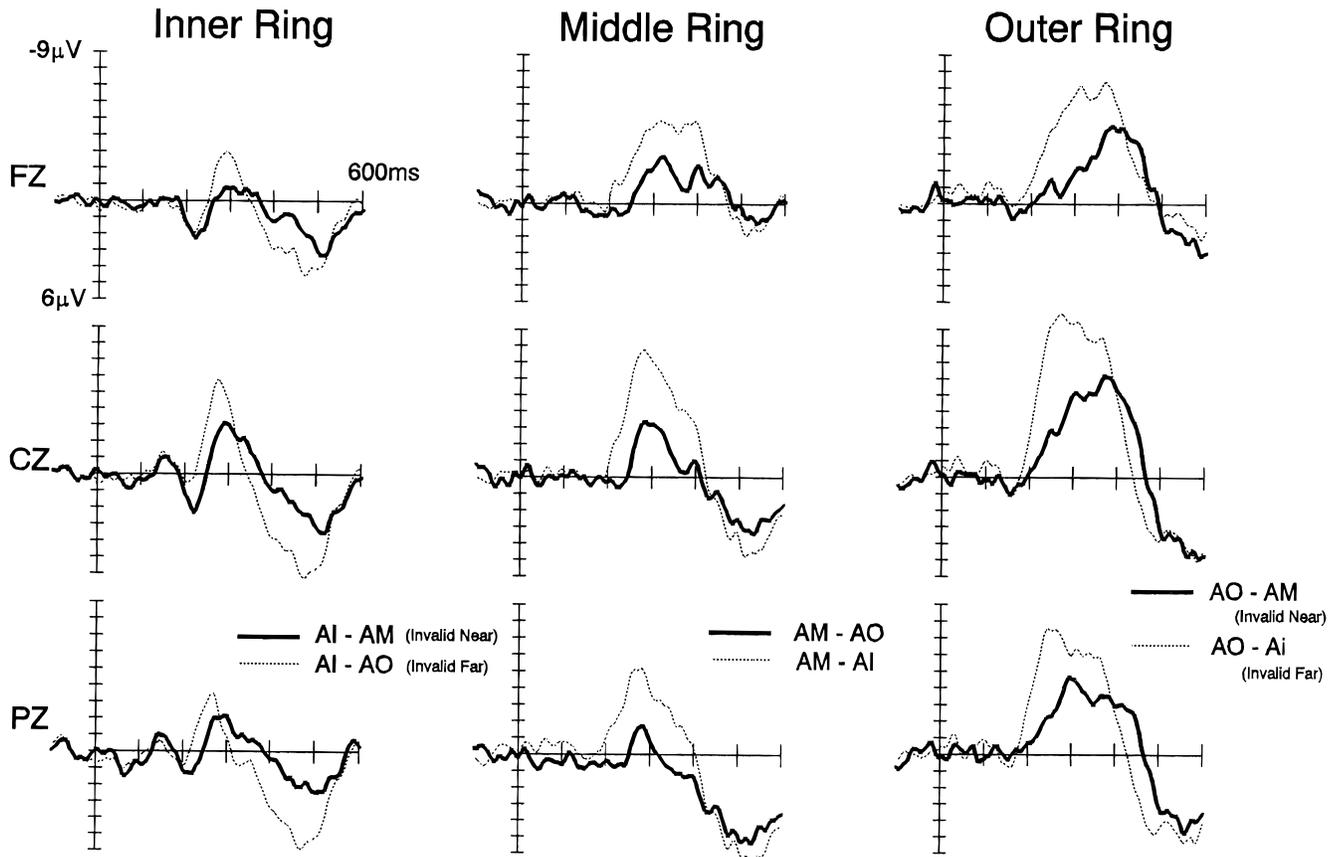


Figure 6. Difference waveforms obtained at midline electrodes in the Ring condition for stimuli presented in the inner, middle, and outer ring by subtracting event-related potentials (ERPs) for invalid trials from ERPs for valid trials. The respective valid–invalid comparisons are indicated (AI = attend inner; AM = attend middle; AO = attend outer), and invalid trials marked as “invalid near” and “invalid far” where appropriate.

space affects perceptual processing of attended and unattended information, presumably reflecting “sensory gating” processes in the ventral stream. In addition, enhanced negativities for attended as compared with unattended stimulus locations were found at midline electrodes. As in previous studies, these effects started around 150 ms poststimulus and were initially larger at centroparietal than at frontal sites. Evidence for a gradient of visual–spatial attention was also obtained, as attentional effects on the posterior N1 component (Figure 2, bottom) and on midline ERPs (Figure 4, right) were modulated by the distance of invalid stimuli from the currently attended quadrant. These effects were larger for invalid stimuli located diagonally opposite to the attended region than for invalid stimuli separated by just one visual meridian from the attended quadrant. In contrast, no difference between invalid near and invalid far trials were found for P1 amplitude, confirming previous findings (Eimer, 1997). This may reflect a differential sensitivity of the P1 and N1 generator processes for the distribution of attention within the visual field.

A very different pattern of results was obtained in the Ring condition. In contrast to the Quadrant condition, no attentional modulations of posterior P1 and N1 components were observed (Figure 2, top), and the effects of spatial attention on midline ERPs were delayed, starting around 200 ms poststimulus (Figure 3, right). The presence of attentional P1 and N1 modulations in the Quadrant condition, and their absence in the Ring condition, reflected by Attention \times Condition interactions, indicates that the attentional processes elicited in these two conditions are not equivalent. If attentional effects on sensory-evoked components reflect intraperceptual sensory gating mechanisms, one may conclude from the present findings that spatial attention selectively affects early visual processing when it is directed to visual field quadrants, but not when it has to be allocated to ring-shaped areas of visual space. This interpretation would be consistent with the findings of Heinze, Luck et al. (1994). The fact that RTs to validly cued targets were about 50 ms faster in the Quadrant condition than in the Ring condition may also suggest that different, presumably more efficient selective mechanisms were active in the former case.

Alternatively, the fact that attentional ERP modulations were earlier and larger in the Quadrant condition may simply reflect the attenuation or complete absence of spatially selective processing in the Ring condition. Because there were three rings and four quadrants, attending to a ring involved a larger spatial area and more potential target locations than attending to a quadrant. Moreover, in contrast to Juola et al. (1991), who obtained behavioral effects of attending to stimulus eccentricity when presenting targets simultaneously with distractors, single letters were presented as targets in the present study. The results obtained in the behavioral control experiment, however, demonstrate clearly that spatial attention does affect response latencies in the Ring condition, thus ruling out the idea that the lack of attentional modulations of P1 and N1 amplitudes in this condition is due to the absence of spatially selective processing. In this control study, significant cueing effects were observed for all three eccentricities, thus confirming the finding of Juola et al. (1991) that directing attention to ring-shaped areas of visual space affects behavioral performance. In addition, a main effect of target eccentricity was present, reflecting the fact that in contrast to Juola et al. (1991), letter size was not increased for more peripheral targets.

Differences between attentional ERP modulations in the two experimental conditions may also reflect the fact that the average distance separating stimuli at uncued locations from the currently attended area was smaller in the Ring condition than in the Quad-

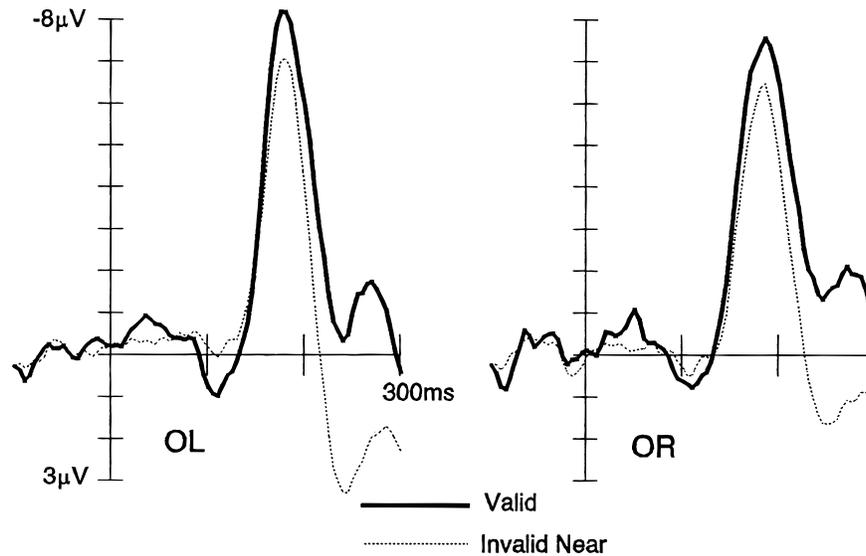
rant condition. For example, with attention cued to the inner ring, unattended stimuli would be separated from the border of the attended region (demarcated by the inner grey circle) by 0.6° or 1.8° . For most invalid trials in the Quadrant condition, this distance would be considerably larger (see Figure 1). The differential attentional modulations of sensory-evoked components obtained in the Ring and Quadrant conditions may therefore simply reflect a spatial gradient of attentional selectivity. If the absence of attentional modulations of P1 and N1 amplitudes in the Ring condition resulted from the fact that the distance between attended and unattended locations was generally too small for spatially selective effects on sensory-evoked ERP components to be observed, such effects should also be absent in the Quadrant conditions whenever uncued stimuli appear close to the attended region. This possibility was investigated by comparing ERPs elicited in the Quadrant condition by inner stimuli (1.7° eccentricity) in valid and invalid near trials (Figure 7, top). In these latter trials, the average distance of unattended stimuli from the border of the attended quadrant was about 1.2° . As can be seen from Figure 7 (top), attentional modulations of occipital P1 and N1 components were still present, and subsequent ANOVAs confirmed that attention significantly affected P1 amplitude, $F(1, 13) = 6.09$; $p < .028$, and N1 amplitude, $F(1, 13) = 8.14$; $p < .014$. Even with average distance between attended and unattended regions held constant, attentional effects on sensory-evoked components were restricted to the Quadrant condition, suggesting that different mechanisms of attentional selectivity are operative in these two spatial selection tasks.

If the Nd1 effect reflects the presence of spatial “expectation gradients” in parietal cortex (LaBerge, 1995) that are set up in response to a precue, its absence in the Ring condition suggests that spatially selective preparatory processes are efficient when attention can be directed to contiguous regions of visual space, but not when more complex regions are relevant. According to LaBerge (1995; see also LaBerge & Brown, 1989), the function of parietal “attentional gradients” is to control spatially selective processing in the ventral stream. The absence of attentional effects on P1 and N1 amplitude in the Ring condition may thus be a consequence of the fact that spatial orienting is less selective in response to cues directing attention to ring-shaped areas of visual space.

The pattern of attentional ERP modulations obtained in the Ring condition also allows some inferences with respect to the distribution of attention in response to a cue summoning it to ring-shaped regions of visual space. Whereas a ring model would assume that regions medial to the currently attended ring can be excluded from attentional processing, a zoom-lens account would hold that attention will necessarily include all locations medial to the attended area, resulting in Attention \times Eccentricity interactions. Pronounced attentional ERP effects should be elicited by outer stimuli, whereas such effects should be small for inner stimuli. The ERP pattern observed at midline electrodes is in line with a zoom-lens account. As can be seen in Figures 4 (left) and 5, attentional effects were largest for outer and smallest for innermost stimuli. The effects of attention observed for stimuli presented in the middle ring also support the zoom-lens model. The model predicts larger effects when valid trials are compared with invalid trials during which the inner ring was cued (because the middle ring would be outside the narrow attentional focus), and small effects when valid trials are compared with trials with an attend outer cue. This pattern was indeed observed (Figure 6, middle panel).

According to most advocates of a zoom-lens model, the concentration of attentional resources is inversely proportional to the

Attend to Quadrant Innermost Stimuli



Valid - Invalid Difference Waveforms Outer Ring Cued

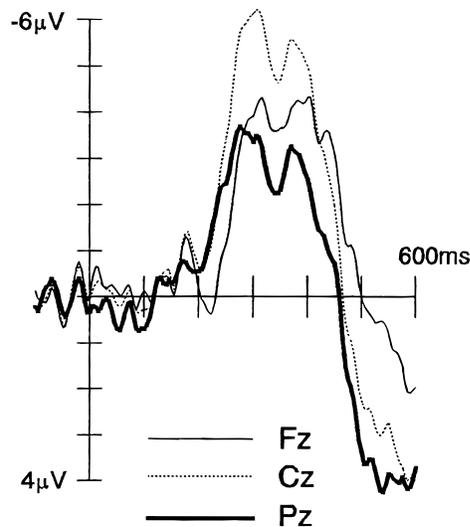


Figure 7. Top: Grand-averaged event-related potentials (ERPs) recorded at lateral occipital electrodes OL and OR in the Quadrant condition to innermost stimuli (1.7° eccentricity) in valid trials (solid thick lines) and invalid near trials (thin lines). Bottom: Difference waveforms obtained at midline electrodes in the Ring condition following an “attend outer ring” cue, obtained by subtracting ERPs for invalid trials (where stimuli appeared at the middle or inner position) from ERPs for valid trials.

size of an attended region (Eriksen & St. James, 1986). This finding may explain the presence of attentional effects for stimuli presented within the inner ring. If attentional processing was generally more efficient after an attend inner than an attend outer cue, graded effects of attentional cueing should be observed for stimuli presented in the inner ring. The fact that the increase of RTs to

validly cued targets with increasing stimulus eccentricity was more pronounced in the Ring condition would be in line with this idea. It should be noted that the attentional ERP effects observed for inner stimuli were small and delayed as compared with stimuli at larger eccentricities (Figure 4). Moreover, that there is little experimental evidence to demonstrate that the assumption of an

verse relationship between focus size and processing efficiency is more than just intuitively plausible (see Posner et al., 1980, Experiment 5; LaBerge, 1983; or McCormick & Klein, 1990, for examples in which this relationship does not hold).

The main finding of the Juola et al. (1991) study that favored a ring model of visual-spatial attention was that RT costs were obtained when targets appeared at locations included by an attended ring. The ERP results discussed so far supported a zoom-lens model and could not account for such behavioral effects. To find out whether there are ERP modulations that do reflect the type of spatial selectivity captured by the ring model, ERPs obtained in valid trials should be compared with ERPs elicited by invalidly cued stimuli that are located within the attended ring, while holding the size of the attended area constant. In this type of comparison, validity will be necessarily confounded with stimulus eccentricity, which was the reason why it was not included in the original analyses. However, because no main effects of eccentricity or interactions including this factor were present for ERP amplitudes in the Nd2 interval, an additional analysis was conducted for trials where the outer ring was cued. Valid trials were compared with invalid trials during which an attend outer cue was followed by imperative stimuli presented in the middle or inner ring. According to a zoom-lens model, no attentional effects should be present, because the size of the attended area would be constant, and invalidly cued medial stimulus locations would be lo-

cated within this area. Figure 7 (bottom) shows difference waveforms obtained at midline electrodes by subtracting ERPs obtained for stimuli preceded by an invalid attend outer cue from ERPs to validly cued outer stimuli. A main effect of attention, $F(1, 13) = 9.14$; $p < .01$, was obtained in the Nd2 interval, presumably reflecting the activity of a spatially selective mechanism beyond the attentional zoom-lens. Such a process may operate to exclude stimuli medial to a currently relevant area from attentional processing, and may thus be responsible for behavioral effects observed by Juola et al. (1991). The fact that the corresponding ERP effects became visible beyond 200 ms poststimulus suggests that such a mechanism selectively modulates the activity of processing stages subsequent to perceptual analysis.

Overall, the present study has qualified behavioral evidence showing that attention can be directed to general areas of the visual field, excluding regions surrounded by attended areas. The processes underlying attentional selectivity in such a situation are likely to be different from the processes responsible for the selective processing of contiguous regions of visual space. In the latter case, attention has a modulatory influence on early perceptual stages of visual processing, whereas the selective effects of attending to more complex spatial configurations seem to be confined to later, postperceptual stages of information processing.

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