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An ERP study of sustained spatial attention to stimulus eccentricity

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Abstract

Effects of attention on event-related brain potentials (ERPs) were measured when subjects kept sustained attention focused on ring-shaped regions of visual space to detect infrequently presented targets at a given eccentricity. In line with a previous study that employed a trial-by-trial cueing paradigm, no modulations of sensory-evoked P1 and N1 components were found. This suggests that attentional selectivity in complex spatial selection tasks is primarily located at post-perceptual processing levels. Enhanced negativities for attended as compared to unattended stimuli were present between 220 and 380 ms post-stimulus and were followed by an enlarged positivity for attended stimuli in the P3 time range. These effects reflected the distribution of attention in visual space, in part consistent with 'attentional gradient' and 'zoom-lens' models. However, ERPs also suggested the presence of selective mechanisms that exclude irrelevant stimuli located between two simultaneously attended areas. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Directing visual attention to regions of visual space has profound effects on performance. Responses to visual stimuli at attended locations are faster and more accurate than responses to unattended stimuli (Posner et al., 1978, 1980), and stimuli at attended locations are detected more efficiently than stimuli at unattended positions (Bashinski and Bacharach, 1980; Müller and Findlay, 1987; Downing, 1988; Hawkins et al., 1990). These effects of attentional orienting can be

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obtained independently of overt adjustments of eye or head position, and are assumed to demonstrate that visual–spatial attention acts as a 'spotlight' that can be voluntarily moved in visual space to select one region for preferential processing (Shulman et al., 1979; Eriksen and St. James, 1986).

Several lines of research have revealed more specific characteristics of the attentional spotlight. Behavioural 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; Shulman et al., 1985). The size of the attentional focus can be adjusted in accordance with specific task requirements (LaBerge, 1983). Apparently, such adjustments can be surprisingly flexible. Egly and Homa (1984) presented single letters along one of three concentric rings around fixation, and informed participants about the likely eccentricity of the letters (close, medium, distant) at the beginning of each trial. Identification performance was better than in a control condition, where no advance information was given, suggesting that attention can be directed to ring-like segments of visual space of different eccentricities. Juola et al. (1991) presented targets and distractors within one of three concentric rings, and participants were informed at the start of each trial about the most likely eccentricity of the target (80% validity). Response time (RT) benefits for correctly cued locations and costs for invalidly cued locations were obtained. For example, when attention was summoned to the outer ring, RTs were delayed when targets appeared in the middle or inner ring. Juola et al. (1991) argued that attention can be directed to concentric regions of visual space, excluding the area surrounding these regions.

These findings are problematic for a 'zoom-lens' account of visual–spatial attention (Eriksen and St. James, 1986), which assumes that spatial attention operates by the expansion or contraction of a single attentional focus. In this case, attentional benefits should be found for all locations included within an attended area, which was clearly not the case in the Juola et al. (1991) study. In defence of a zoom-lens account, it can, however, be argued that attentional effects on performance can reflect selective mechanisms at different perceptual and post-perceptual processing stages (Allport, 1993). The effects obtained by Juola et al. (1991) may be caused primarily by post-perceptual attentional mechanisms, whereas attention will affect visual–perceptual processing when it can be directed to spatially contiguous regions of visual space. Electrophysiological evidence for this hypothesis comes from a recent ERP study (Eimer, 1999) where participants were cued to attend to a visual quadrant or to a ring-shaped region of visual space in order to detect infrequently presented targets within the attended region. While attentional modulations of sensory-evoked P1 and N1 components at lateral posterior sites were found when quadrants were attended, no such effects were present when attention was directed to ring-shaped regions of visual space[1]. Effects

[1] In a control experiment, Eimer (1999) obtained behavioural effects of spatial attention directed to ring-shaped regions of visual space comparable to the results of Juola et al. (1991), thereby demonstrating that the absence of attentional P1 and N1 modulations was not due to the absence of spatially selective processing in this condition.

of visual–spatial attention on P1 and N1 components are well documented in the literature (c.f. Eason, 1981; Harter et al., 1982; Hillyard and Münte, 1984; Hillyard and Mangun, 1987; Mangun and Hillyard, 1991). These effects are generated in extrastriate cortex close to primary visual projection areas (Heinze et al., 1994b; Clark and Hillyard, 1996), and are assumed to reflect intraperceptual 'sensory gating' mechanisms (Hillyard and Mangun, 1987; Mangun, 1995). The presence of these effects, when attention was directed to visual field quadrants, and their absence, when ring-shaped regions were attended in the Eimer (1999) study suggests that qualitatively distinct attentional mechanisms were involved in these two spatial selection tasks. 'Sensory gating' mechanisms may be responsible for the selection of single regions, quadrants, or hemifields, while the selective processing of more complex spatial regions appears to be located at later, post-perceptual processing stages.

One problem for this interpretation is that spatial attention was manipulated in a trial-by-trial cueing paradigm in the Eimer (1999) experiment. To-be-attended rings were indicated by a precue at the beginning of trials, so that attention had to be shifted to different eccentricities on successive trials. It is plausible to assume that the allocation of spatial attention to ring-shaped regions of visual space is a complex achievement, and that setting and resetting the attentional filter in this task is a time-consuming process. Trial-by-trial cueing may thus have resulted in a reduced level of attentional selectivity. Had participants been allowed to attend to a specific region for a complete block of trials, a better tuning of spatial selectivity to ring-shaped regions may have been achieved. As a consequence, sustained attention to ring-shaped regions may be reflected by attentional P1 and N1 modulations, even though transient attention is not[2]. One aim of the present study was to test this possibility.

As in the Eimer (1999) study, single letter stimuli were presented at twelve possible locations along three concentric rings of 1.7, 2.9, or 4.1° radius. The to-be-attended region was specified at the start of each block, and remained constant for two successive blocks of 240 trials each. These regions were marked by two concentric circles that were continuously present (Fig. 1). Participants had to respond to infrequently presented target stimuli when these appeared within the attended region. In different blocks, participants were instructed to attend to one of the three eccentricities (inner, middle, or outer ring). To investigate effects of spatial selectivity in these different conditions, ERPs to non-target stimuli within attended regions were compared with ERPs to stimuli located in unattended regions. If sustained attention directed to ring-shaped regions affected visual–perceptual processing, this should be reflected in attentional modulations of P1 and N1 amplitudes at posterior electrodes.

[2] It should be noted that Juola et al. (1991), who demonstrated behavioural costs and benefits of attending to ring-shaped regions of visual space, also employed a trial-by-trial cueing paradigm.

Another aim of this experiment was to use ERPs to study the distribution of visual–spatial attention directed to different eccentricities. In the Eimer (1999) study, attention to ring-shaped regions was reflected by enhanced negativities at midline electrodes elicited by stimuli at attended locations relative to unattended stimuli. These effects started around 200 ms post-stimulus and are likely to indicate the attentional processing of potential target stimuli resulting in their identification as non-targets. According to the notion of 'attentional gradients' in visual space, such effects should vary with the distance of an unattended stimulus from the current focus of attention. For example, stimuli in the outer ring may receive some attentional processing when attention is directed to the middle ring, but not when the inner ring is attended. A zoom-lens model of spatial attention predicts that all stimuli inside an attended ring-shaped region are included within the attentional focus. Therefore, attentional ERP effects should interact with stimulus eccentricity. They should be largely absent for innermost stimuli, which will be located within the attentional spotlight regardless of which eccentricity is attended, and large for outer stimuli, because these stimuli will be outside the attentional focus when attention is directed to the inner or middle ring.

Another prediction of the zoom-lens model that was investigated in the present study is the claim that attention can not be simultaneously directed to two non-adjacent eccentricities by excluding the area located between these regions. Participants were instructed to simultaneously attend either to the middle and outer ring, or to the inner and outer ring (excluding the middle ring). ERPs elicited by stimuli in the middle ring were compared between these two conditions. The idea that attention can not be directed to two or more non-adjacent locations is

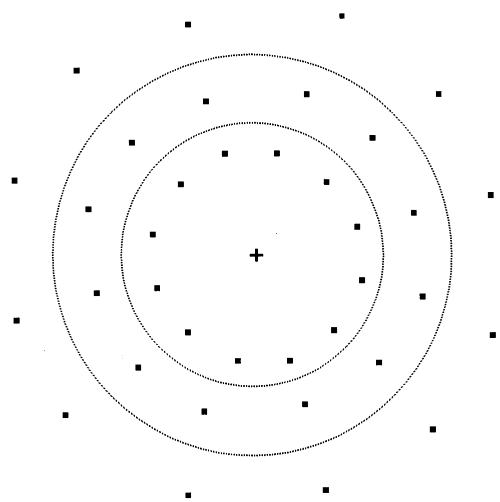

Fig. 1. Schematic illustration of the stimulus setup. All stimuli were presented at one out of 36 possible locations (indicated by the dots) around three virtual circles with a radius of 1.7, 2.9, or 4.1° around the central fixation cross. Two concentric grey circles (2.3 and 3.5° radius) marked the borders of the inner, middle, and outer ring.

supported by behavioural evidence (Posner et al., 1980; Eriksen and Yeh, 1985) and by ERP data (Heinze et al., 1994a). In the latter study, participants had to attend to two of four stimulus locations that were either adjacent or separated by an irrelevant location. With adjacent relevant locations, probe stimuli presented at irrelevant positions elicited smaller P1 components than probes at relevant positions. No such attenuation was found for irrelevant probes at the intervening position between attended locations, suggesting that when attention is directed to non-contiguous areas of visual space, it will necessarily include the area between these locations. If this was the case, no differences in the ERPs elicited by middle ring stimuli should be observed between the attend middle and outer ring and attend inner and outer ring conditions. In contrast, if these stimuli could be selectively decoupled from early or later stages of attentional processing when attention is directed to the inner and outer ring, systematic ERP differences should be obtained.

2. Methods

2.1. Participants

Fourteen paid volunteers (ten female, aged 22–36 years) participated in the experiment. All participants were right-handed and had normal or corrected-to-normal vision.

2.2. Stimuli and apparatus

Participants were seated in a dimly lit sound attenuated cabin, with response buttons under their left and right hands. A computer screen was placed 110 cm in front of the participant's eyes. A small central fixation cross (subtending a visual angle of about $0.1 \times 0.1°$) was positioned on the participant's horizontal straight-ahead line of sight. Uppercase letters M and N, subtending a visual angle of approximately $0.8 \times 0.8°$, served as stimuli. These letter stimuli could appear in one of twelve locations along one of three virtual rings of 1.7, 2.9, or 4.1° in radius around the fixation cross. The fixation cross and two concentric circles (2.3 and 3.5° radius), marking the borders of the inner and middle, and middle and outer ring, were constantly present throughout the experimental blocks (see Fig. 1 for a schematic illustration of the stimulus setup). Letter stimuli were presented in white, and the circles were presented in thin grey against a black background.

2.3. Procedure

The experiment consisted of ten experimental blocks, each consisting of 240 trials. After 120 trials, a resting period was included, and participants could initiate the subsequent run of 120 trials with a right-hand button press. Letter stimuli were presented for 100 ms, and the intertrial interval was 1000 ms. On 180 trials per block, the non-target letter M was presented with equal probability in the inner, middle, and outer ring. On the remaining 60 trials, the target letter N was presented, again equiprobably in the inner, middle, and outer ring. The position of each letter within a given ring was determined randomly for each trial.

Participants were instructed to direct their attention to one ring-shaped region (attend one ring) or simultaneously to two regions (attend two rings) and to respond with a button press whenever they detected the target letter N within the attended region/regions. The to-be attended region and the required response side (left versus right) was specified prior to each block on the computer screen. Five different attention conditions were run, consisting of two successive blocks. Response side was varied between blocks. In three conditions, participants were instructed to direct their attention to the inner, middle, or outer ring-shaped region. In the remaining two conditions (attend two rings), they had to attend to two of the three regions (attend middle and outer ring; attend inner and outer ring). The order in which these five conditions were delivered was randomised for each participant.

Participants 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 them familiar with these specific task requirements, two training blocks were run at the beginning of the experiment.

2.4. Recording

EEG was recorded with Ag–AgCl electrodes from Fz, Cz, Pz, C3, and C4 (according to the 10–20 system), from PL and PR (located halfway between Pz and the ear channels), and from OL and OR (located halfway between O1 and T5, and O2 and T6, respectively). EEG was measured relative to a right earlobe reference. Horizontal EOG was 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 kΩ. The amplifier bandpass was 0.10–40 Hz. EEG and EOG were sampled with a digitisation rate of 200 Hz, and stored on disk. The latency of manual responses (if present) was measured on each trial.

2.5. Data analysis

EEG and EOG were epoched off-line into periods of 700 ms, starting 100 ms prior to stimulus onset. Trials with eyeblinks (vertical EOG exceeding 60 μV in the 600 ms interval following imperative stimulus onset) or eye movements (horizontal EOG exceeding ± 25 μV in the 400 ms interval after stimulus onset), response errors, or overt responses on non-target trials were excluded from analysis. The ERP analysis was conducted exclusively on the data from non-target trials. EEG was averaged separately for all combinations of the five attention conditions and stimulus eccentricities, resulting in 15 average waveforms for each participant and electrode site. All measures were taken relative to the mean voltage of the 100 ms interval preceding stimulus onset. Effects of experimental variables on P1 and N1 components were determined at lateral parietal and occipital electrodes by analysing ERP mean amplitude values within post-stimulus time windows centred on the components' mean latencies (P1: 90–130 ms; N1: 150–200 ms). Further analyses were conducted separately for midline and lateral electrodes on the basis of mean amplitude values obtained within five successive 40 ms time windows between 180 and 380 ms post-stimulus, as well as in the P3 latency range (400–550 ms post-stimulus).

ERPs obtained in the attend one ring and attend two rings conditions were analysed separately. For the attend one ring conditions, repeated measures ANOVAs were conducted on ERP mean amplitude measures for the factors attention (attended versus unattended, collapsed over both unattended eccentricities), stimulus eccentricity (inner versus middle versus outer), electrode location (Fz versus Cz versus Pz, for midline sites; central versus parietal versus occipital, for lateral posterior sites), and recording hemisphere (left versus right, for lateral posterior electrodes only). To test specific effects of attentional allocation on ERP waveforms, separate ANOVAs were conducted for single eccentricities and different types of unattended trials. For the attend two rings conditions, ERPs obtained for stimuli presented within the middle ring were analysed for the factors attention (attended: attend middle and outer ring; unattended: attend inner and outer ring), electrode location, and hemisphere. When appropriate, Greenhouse–Geisser adjustments to the degrees of freedom were carried out.

3. Results

3.1. Behavioural performance

In the attend one ring conditions, RTs to inner, middle, and outer stimuli were 529, 579, and 607 ms, resulting in a main effect of eccentricity ($F(1,13) = 22.3$; $P < 0.001$; $\varepsilon = 0.69$). Participants missed 2.9, 8.9 and 13.2% of targets presented in the inner, middle, and outer ring. False alarm rate was 1.4%. In the attend two rings conditions, RTs were 564 ms to inner ring targets and 580 ms to middle ring targets. RTs to outer ring targets were 584 and 611 ms in the attend middle and outer ring and attend inner and outer ring conditions, respectively, and this difference was significant ($t(13) = 2.7$; $P < 0.02$). Participants missed 10.4% of all targets, and false alarm rate was 3.3%.

3.2. ERP effects of spatial attention — attend one ring

Fig. 2 shows the overall effects of spatial attention directed to ring-shaped areas. Grand-averaged ERP waveforms to stimuli at attended and unattended locations, collapsed across stimulus eccentricities, are presented together with the resulting attended–unattended difference waveforms (bottom). No modulations of P1 and N1 components at lateral parietal and occipital sites are visible in Fig. 2. The absence of any attentional enhancement of sensory-evoked components was confi-

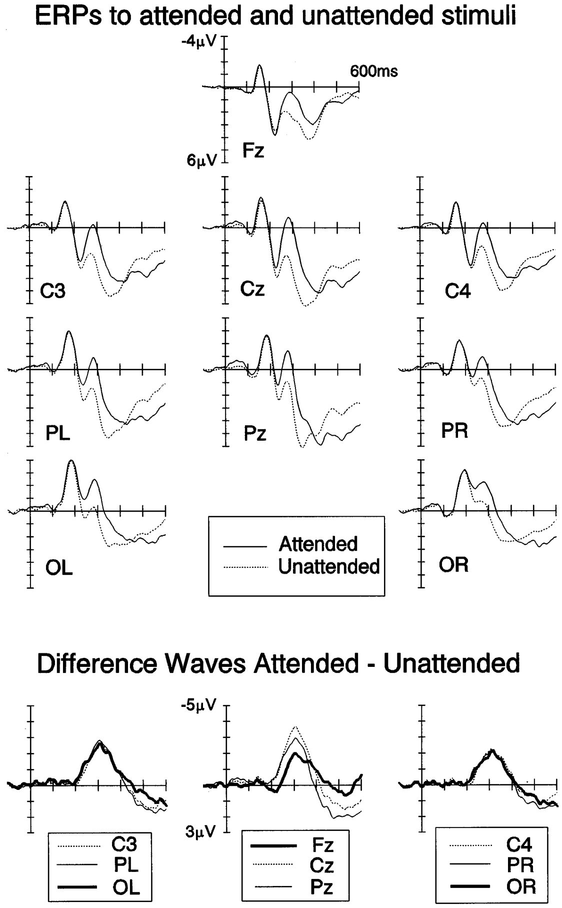

Fig. 2. Grand-averaged ERPs recorded at midline and lateral electrodes to stimuli in the attended ring (solid lines) and stimuli within unattended rings (dashed lines) in the attend one ring conditions. Bottom: difference waveforms obtained by subtracting ERPs to unattended stimuli from ERPs to attended stimuli.

rmed by statistical analyses, revealing that attention had no effect whatsoever on P1 and N1 amplitudes at lateral posterior electrodes (both $F < 1$). There were no significant interactions between attention and other experimental factors in the P1 and N1 analysis windows.

As can be seen in Fig. 2, attended stimuli elicited an enhanced negativity at midline and lateral electrodes relative to unattended stimuli starting around 200 ms post-stimulus. This was followed by a larger positivity for attended stimuli in the P3 latency range. Statistical analyses substantiated these observations. Between 220 and 380 ms post-stimulus, enhanced negativities elicited by attended as compared with unattended stimuli were reflected in main effects of attention at midline sites (all $F(1, 13) > 6.5$; all $P < 0.025$) as well as lateral electrodes (all $F(1, 13) > 12.8$; all

$P < 0.005$). Interactions of these effects with eccentricity will be discussed later. For midline electrodes, attention × electrode location interactions were found between 220 and 340 ms (all $F(2, 26) > 4.9$; all $P < 0.03$; $0.53 < \varepsilon < 0.72$), as attentional negativities were smaller and delayed at Fz relative to Cz and Pz (see Fig. 2, bottom). In fact, no effect of attention was present at Fz in the 220–260 ms interval. At lateral recording sites, attention × hemisphere interactions were obtained between 260 and 340 ms (both $F(1, 13) > 7.1$; both $P < 0.02$). As can be seen from Fig. 2, attentional negativities tended to be larger over the left than over the right hemisphere.

An enhanced positivity for attended stimuli was present in the P3 latency range, reflected in main effects of attention at midline electrodes ($F(1, 13) = 10.7$; $P < 0.01$) as well as at lateral sites ($F(1, 13) = 11.6$; $P < 0.005$). Attention × electrode location interactions were present at midline and lateral electrodes ($F(2, 26) = 20.0$ and 4.6; $P < 0.001$ and 0.04; $\varepsilon = 0.62$ and 0.66, respectively). Enhanced positivities to attended stimuli were present at Cz and Pz (both $F(1, 13) > 7.9$; both $P < 0.02$), but not at Fz (see Fig. 2). At lateral sites, significantly enlarged positivities were found at central and parietal sites (both $F(1, 13) > 7.8$; both $P < 0.02$), but not occipitally.

Fig. 3 shows attended–unattended difference waveforms at midline sites for different stimulus eccentricities. Attentional negativities elicited by inner ring stimuli were delayed relative to stimuli in the middle and outer rings. This was reflected in an attention × eccentricity interaction in the 220–260 ms measurement interval ($F(2, 26) = 4.1$; $P < 0.03$; $\varepsilon = 0.90$). Subsequent paired t-tests revealed significant attentional effects at Cz and Pz for stimuli presented in the middle and outer rings

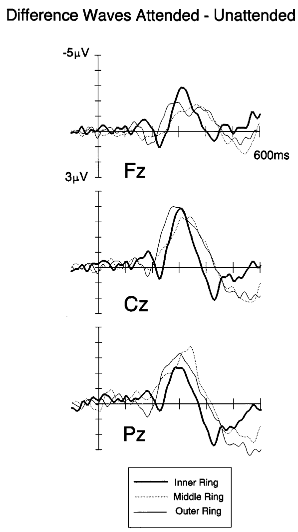

Fig. 3. Difference waveforms obtained at midline electrodes in the attend one ring conditions by subtracting ERPs to unattended stimuli from ERPs to attended stimuli, separately for stimuli presented in the inner ring (solid thick lines), the middle ring (dashed thin lines), and the outer ring (solid thin lines).

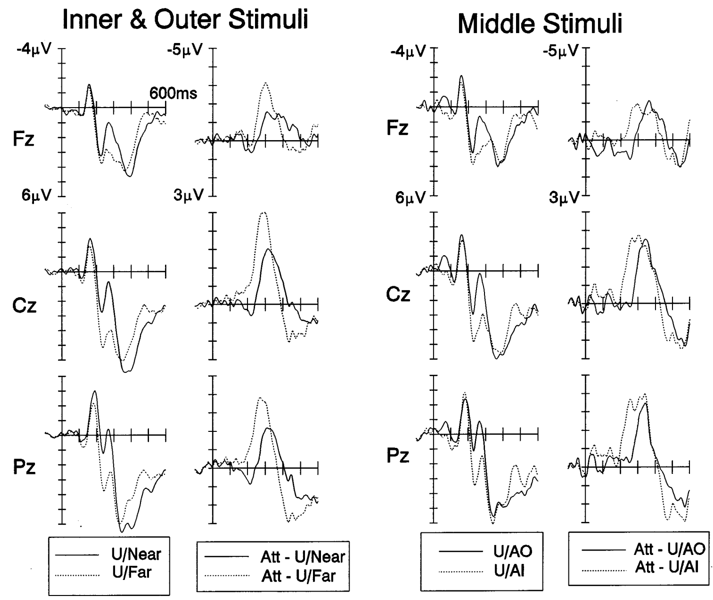

Fig. 4. Left panels. Left: grand-averaged ERPs recorded in the attend one ring conditions at midline electrodes to 'unattended/near' (U/Near; solid lines) and 'unattended/far' (U/Far; dashed lines) stimuli, collapsed across inner ring and outer ring stimuli. Right: difference waveforms obtained at midline electrodes for inner and outer stimuli by subtracting from ERPs for attended trials either unattended/near ERPs (Att-U/Near; solid lines) or unattended/far ERPs (Att-U/Far; dashed lines). Right panels. Left: grand-averaged ERPs recorded for unattended middle stimuli in the attend one ring conditions at midline electrodes when attention was directed to the outer ring (U/AO; solid lines) or to the inner ring (U/AI; dashed lines). Right: difference waveforms obtained at midline electrodes for middle ring stimuli by subtracting from ERPs for attended trials either ERP waveforms obtained when the outer ring was attended (Att-U/AO; solid lines) or ERPs obtained when the inner ring was attended (A-U/AI; dashed lines).

(all $t(13) > 2.4$; all $P < 0.03$), but not for inner ring stimuli (both $t(13) < 0.2$) in this time interval. No attention × eccentricity interactions were present at lateral sites. Fig. 3 also suggests that these attentional negativities were preceded by enhanced positivities for stimuli at attended locations, most notably at Fz. However, these ERP modulations were not statistically reliable.

Additional analyses were conducted for different types of unattended trials. Unattended stimuli presented in the inner or outer ring were termed 'unattended/near', when the neighbouring eccentricity was attended (e.g. an inner stimulus in an 'attend middle ring' block), and 'unattended/far' otherwise (e.g. an inner stimulus under 'attend outer ring' instructions). As can be seen from Fig. 4 (left), ERPs to unattended/near stimuli were more negative than unattended/far ERPs, and this was reflected in significant differences between these two types of stimuli between 220 and 300 ms (both $F(1, 13) > 10.9$; both $P < 0.01$). In the 300–340 ms interval, this effect approached significance ($F(1, 13) = 4.1$; $P < 0.07$)[3]. In the P3 time range,

[3] The difference between unattended/near and unattended/far trials apparent in Fig. 4 (left) in the N1 time range was not statistically reliable.

unattended/near ERPs were significantly more positive than unattended/far ERPs ($F(1, 13) = 16.4$; $P < 0.001$). These differences between unattended trials also become apparent when attended–unattended difference waveforms are displayed separately for the two types of unattended trials (Fig. 4). Attentional negativities start earlier and subsequent positivities are more pronounced in the attended–unattended/far difference waves relative to the attended–unattended/near waveforms. A similar analysis was conducted for unattended middle stimuli. When attention was directed to the outer ring, ERPs were more negative between 220 and 300 ms ($F(1, 13) = 18.1$ and 15.9; $P < 0.001$ and 0.002, respectively) and more positive in the P3 time range ($F(1, 13) = 5.3$; $P < 0.04$) than when the inner ring was attended (Fig. 4, right). This was reflected in delayed attentional negativities and attenuated positivities in attended–attend outer ring difference waves relative to attended–attend inner ring difference waveforms.

3.3. ERP effects of spatial attention — attend two rings

Fig. 5 shows ERPs for attended and unattended middle ring stimuli obtained in the attend middle and outer ring and attend inner and outer ring conditions. No attentional effects were found for P1 and N1 amplitudes at lateral posterior

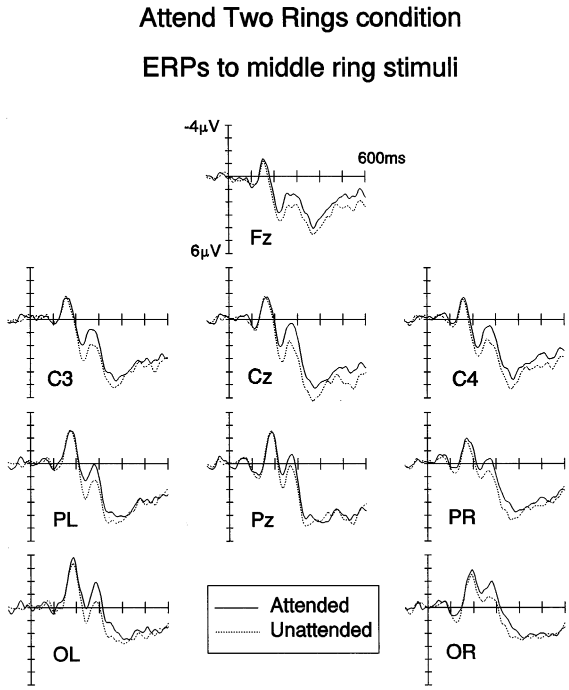

Fig. 5. Grand-averaged ERPs recorded at midline and lateral electrodes in the attend two rings conditions to middle ring stimuli when attention was directed to the middle and outer ring (attended; solid lines) and to the inner and outer ring (unattended; dashed lines).

electrodes (both $F < 1$). Beyond 200 ms post-stimulus, ERPs were more negative when attention was directed to the middle and outer ring than when inner and outer stimuli were attended, and middle ring stimuli ignored. This observation was substantiated by statistical analyses revealing significant effects of attention between 220 and 260 ms at midline sites ($F(1, 13) = 6.6$; $P < 0.025$) and lateral electrodes ($F(1, 13) = 5.6$; $P < 0.04$). In the 260–300 ms interval, these effects were almost significant at midline and lateral sites ($F(1, 13) = 3.6$ and 4.0; $P < 0.08$ and 0.07, respectively).

4. Discussion

Participants were instructed to attend to a ring-shaped region of visual space throughout an experimental block in order to detect infrequent target stimuli within an attended region, and ERPs were recorded to attended and unattended non-target stimuli presented at three different eccentricities. The aim of this study was twofold: First, it was investigated whether sustained attention to ring-shaped regions of visual space would result in modulations of sensory-evoked P1 and N1 components, indicating that spatial attention affected early, visual–perceptual processes. Second, ERPs to attended and unattended stimuli were compared under different attention instructions to study the distribution of spatial attention across the visual field.

With respect to the first issue, the results were clear-cut: Effects of visual–spatial attention on posterior P1 and N1 amplitudes were entirely absent. It may be argued that the absence of these effects was due to the fact that ERPs were averaged across all stimulus positions within a given ring, and thus included stimuli presented ipsilaterally and contralaterally to lateral electrodes as well as stimuli presented in the upper and lower visual field. This procedure may have attenuated or even eliminated lateralised attentional effects or effects sensitive to the vertical position of stimuli within the visual field. However, the fact that reliable P1 and N1 modulations have been obtained with stimulus positions and averaging procedures identical to the present study when attention was directed to visual field quadrants (Eimer, 1999) renders this possibility unlikely. The absence of attentional modulations of P1 and N1 amplitudes in the present study where attention was directed to ring-shaped regions of space is in line with the negative results obtained by Eimer (1999). It was argued that the absence of attentional modulations of sensory-evoked components in this study may have been due to the fact that attention was manipulated on a trial-by-trial basis, thereby reducing the efficiency of spatial selectivity tuned to ring-shaped regions of visual space. In the present experiment, participants kept attention focused on a specific region for two successive experimental blocks. The lack of any ERP evidence for intraperceptual 'sensory gating' demonstrates that the difference between transient and sustained attention is not critical for the presence or absence of such effects. This finding thus strengthens the conclusion that mechanisms of spatial selectivity in complex tasks, like attending to ring-shaped regions of space, are primarily located at post-perceptual processing stages.

Although attention did not affect P1 and N1 components, ERP effects were observed at longer latencies. Enhanced negativities were elicited by attended as compared with unattended stimuli between 220 and 380 ms post-stimulus. This effect is likely to reflect the attentional processing of potentially response-relevant letter stimuli at attended locations. In contrast to frontal processing negativities observed by Karayanidis and Michie (1996) in a combined location and colour selection task, attentional negativities were found to be earlier and more pronounced at central and posterior electrodes than at Fz. In the P3 latency range, ERPs were more positive for attended relative to unattended stimuli, most notably at Pz. The P3 component is usually interpreted as a measure of stimulus evaluation and classification duration (Kutas et al., 1977), suggesting that the P3 effect obtained for attended stimuli indicates their successful identification as non-targets[4]. Variations of these effects across the different attention instructions can provide information about the distribution of visual attention when it is directed to different eccentricities. 'Attentional gradients' were reflected in the fact that ERPs to 'unattended/near' stimuli (inner and outer stimuli delivered when the middle ring was attended) were more similar to ERPs to stimuli at attended locations than 'unattended/far' ERPs (elicited by inner ring stimuli when the outermost ring was attended, and by outer stimuli when the inner ring was attended). Accordingly, attentional effects started earlier and were more pronounced, when ERPs to attended stimuli were compared to ERPs elicited by unattended/far stimuli (Fig. 4, left).

The differences observed between different types of unattended middle ring stimuli are consistent with a zoom-lens model, which predicts that the middle ring will be included within the attentional focus when the outermost ring is attended, but not when attention is directed to the inner ring. In line with this, ERPs to unattended middle stimuli were less similar to attended ERPs when the inner ring was attended than when attention was directed to the outer ring, and this was reflected in large attentional effects in the attend middle ring–attend inner ring difference waveforms (Fig. 4, right). According to a zoom-lens account of visual–spatial attention, innermost stimuli will receive attentional processing regardless of which eccentricity is attended, and stimuli in the middle ring will be attended when attention is directed to the middle as well as to the outer ring. Effects of attention should thus be completely absent for inner stimuli, and no differences should be found for middle ring stimuli in the attend middle ring–attend outer ring difference waveforms. The results obtained in this study were not in line with these predictions. Although attentional effects were delayed for stimuli presented within the

[4] Fig. 3 suggests that attended inner ring stimuli elicited a shorter-latency P3 than stimuli in the middle or outer ring. This was reflected in a significant attention × eccentricity interaction ($F(1,13) = 5.1$; $P < 0.02$; $\varepsilon = 0.82$) in a post-hoc analysis conducted on mean amplitude values at midline sites between 380 and 450 ms post-stimulus. An enhanced positivity was elicited by attended inner stimuli within this interval ($F(1,13) = 4.6$; $P < 0.05$), but not by middle and outer stimuli. As stimulus identification should be faster for stimuli presented close to fixation than for more eccentric locations, this observation is in line with the interpretation of P3 as a measure of the duration of stimulus evaluation processes.

inner ring relative to middle ring and outer ring stimuli (Fig. 3), and for middle ring stimuli in the attend middle ring–attend outer ring difference waves (Fig. 4, right), these effects were nevertheless clearly present. It is possible to explain the presence of attentional ERP modulations under these conditions by assuming that the concentration of attentional resources is inversely proportional to the size of an attended region (Eriksen and St. James, 1986). Attentional processing will thus be most efficient when the inner region is attended and least effective when attention is directed to the outer ring. While this assumption can reconcile the above findings with a zoom-lens model, the possibility remains that these effects also reflect mechanisms of spatial selectivity not accounted for by this model.

The zoom-lens account was put to a more rigid test in the attend two rings conditions. Attention was directed to the middle and outer ring, or to the inner and outer ring, excluding the intervening middle region, and ERPs elicited by middle ring stimuli were compared between these conditions. A zoom-lens model predicts that the size of the attended area is identical in both conditions, covering all three eccentricities. With the size of the attentional focus held constant and the irrelevant region located between two attended eccentricities under attend inner and outer ring instructions, no ERP differences should be found between attention conditions for middle ring stimuli. In line with the results of Heinze et al. (1994a), no attentional effects were found for P1 and N1 amplitudes. However, larger negativities were elicited beyond 200 ms post-stimulus by middle ring stimuli when attention was directed to the middle and outer ring than when the middle region was to be ignored (Fig. 5). Notably, these effects were smaller and shorter-lived than the attentional effects observed in the attend one ring conditions, and were not followed by an enhanced positivity for attended stimuli. One may tentatively interpret these effects as reflecting a subset of spatially selective processes able to exclude irrelevant stimuli located between attended regions from full attentional processing. These processes may also be responsible for behavioural effects like those observed by Juola et al. (1991).

In summary, the present study confirmed that attention directed to ring-shaped areas of visual space has no effect on sensory-evoked ERP components, even under sustained attention conditions, suggesting that behavioural effects observed in such complex spatial selection tasks are likely to result from post-perceptual attentional processes rather than attentional modulations of sensory stages. Beyond 200 ms post-stimulus, differences in ERPs elicited by stimuli at attended and unattended eccentricities indicated that the allocation of attention to regions of visual space can be more flexible than suggested by a simple zoom-lens model of visual–spatial attention.

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