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The location of preceding stimuli affects selective processing in a sustained attention situation

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Abstract

Event-related potentials (ERPs) were recorded to visual and auditory stimuli in a situation where subjects were required to attend selectively to the left or right side for an entire experimental block and to detect occasional target stimuli at attended locations. Stimuli were presented randomly at attended and unattended locations. In exp. 1, visual and auditory stimuli were presented in separate blocks, while in exp. 2, they were presented together and subjects had to detect visual targets at attended locations. Stimuli at attended positions elicited enlarged sensory-evoked potentials and an enhanced negativity at midline electrodes as compared with unattended stimuli. The latter effect was, however, modulated by the location of the preceding stimulus. At frontocentral electrodes, it was larger for stimuli that were preceded by stimuli at the contralateral side as compared with stimuli preceded by stimuli at the same location. It is argued that this effect may be due to a different amount of processing required for the preceding stimulus. When the predecessor is at a to-be-attended location, it has to be processed more intensively which may interfere with the processing of the next stimulus.

Keywords: Event-related potentials; Visuo-spatial attention; Auditory spatial attention; Processing negativity; Sequence effects

1. Introduction

It is a well-known fact that orientation of attention in space affects the processing of stimuli which are presented at attended or unattended locations. Responses to attended stimuli are usually faster and more accurate than responses to stimuli that are located outside the current focus of attention (cf., Posner et al., 1980; Downing, 1988). In experimental studies which use detection latency or accuracy as dependent variables, the location to be attended is usually indicated at the beginning of each trial by centrally or peripherally presented precues. In contrast, most ERP studies on spatial attention have employed a sustained attention paradigm where the location to be attended was held constant for an entire experimental block. By using this paradigm, distinct ERP differences for attended as compared with unattended locations have been reported. In the auditory modality, attended stimuli elicit an enhanced negativity (called processing negativity or PN) as compared with unattended stimuli. The PN consists of an earlier, frontocentral and a later, frontal part (cf., Hansen and Hillyard, 1983; Näätänen, 1990; Woods, 1990 for an overview). In the visual modality, stimuli at attended locations elicit enhanced early sensory-evoked components at posterior sites (cf., Hillyard et al., 1985; Rugg et al., 1987). This has been interpreted as indicating that spatial attention results in an intraperceptual "sensory gating" that favors perceptual processing of stimuli at attended locations (cf., Hillyard and Mangun, 1987; Mangun and Hillyard, 1990 for an overview). Additionally, enhanced negativities to attended visual stimuli in the time range following the N1 component have also been reported (cf., Harter et al., 1982; Mangun and Hillyard, 1987).

However, a number of problems have to be considered when the effects of spatial attention are investigated by using a sustained attention paradigm. In a situation where the location of attention was held constant for an entire block, no RT benefits could be found for visual stimuli at attended locations (Posner et al., 1980; exp. 1). On the basis of this result, Posner (1980) has argued that the orientation of attention in space is an active process rather than a passive filtering of information, and that it may thus

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not be possible to keep attention focussed at a single position in space for longer periods of time. If this is correct, it is likely that visual stimuli at to-be-attended locations are not truly attended on a proportion of trials when a sustained attention paradigm is used. It is not yet clear whether the same holds for auditory stimuli. Hansen and Hillyard (1988) have shown that in a situation where attention had to be directed to stimulus frequency on the basis of a visual cue, several presentatations of attended tones were needed before ERP effects of attention developed. In contrast, when subjects had to attend to the position of auditory stimuli, attentional ERP modulations were present for auditory stimuli presented immediately after the cue stimulus (cf., Schröger, 1993; Schröger and Eimer, 1993).

Additional problems for studies of spatial attention that employ a sustained attention paradigm may result from the fact that stimuli are usually presented in rapid sequence at two possible locations, one of which has to be attended. More specifically, the selective processing of stimuli may be influenced by the position of the immediately preceding stimulus. When a stimulus is presented at the same location as its predecessor, sensory neurons may still be in a refractory state, possibly resulting in performance costs as well as in an amplitude reduction of ERP components (cf., Woods et al., 1980; Woldorff and Hillyard, 1991).[1]

There may also be less direct influences of the location of preceding stimuli on the processing of subsequent stimuli. In most experiments studying spatial attention, single stimuli are usually presented abruptly at unattended and attended locations. It is known that onset stimuli that are presented against an unstructured background may capture attention automatically, that is, independent of the selective intentions of a subject (cf., Jonides, 1981). Performance benefits for stimuli at recently stimulated locations have been found that may be due to the involuntary capture of attention by abrupt onsets (cf., Müller and Rabbitt, 1989; Nakayama and Mackeben, 1989). When longer intervals between stimuli are used, this initial facilitation for preceded stimuli is replaced by an inhibitory effect that slows the detection of events at recently stimulated locations (cf., Maylor, 1985; Maylor and Hockey, 1987). Indirect electrophysiological evidence for the involuntary capture of attention by abrupt onsets has been reported by Luck et al., (1990). These authors found that enlarged N1 components for stimuli at attended locations as compared to unattended stimuli were present only when the preceding stimulus was presented on the contralateral side. They argued that the N1 enhancement for attended stimuli found in this situation may reflect the re-orientation of attention to the relevant position that was necessary because attention was attracted involuntarily by the preceding stimulus at the irrelevant position. Additionally, Luck et al. (1990) found that target detection was faster and more accurate when targets were preceded by opposite-field stimuli.

In a number of recent experiments, still other sequential effects on the selective processing in a sustained attention situation have been reported. Woods (1990) found that the enhanced negativity (Nd) for tones at attended as compared with unattended locations was larger when the previous stimuli were presented at the attended side. Similar results have been reported by Hansen and Hillyard (1988) and by Wagner et al. (1993) for situations where attended and unattended tones differed with respect to their frequency. These findings have been interpreted as evidence for the assumption that attentional selection between auditory stimuli is easier when a clear sensory representation (attentional trace) of the to-be-attended dimension is available. In contrast to this, Woldorff and Hillyard (1991) found that attentional effects on ERP wave forms were generally larger for auditory stimuli preceded by tones at the opposite ear than for ipsilaterally preceded stimuli.

The present study was designed to further investigate these stimulus sequence effects on ERPs to stimuli at attended and unattended locations in order to study how the position of preceding stimuli influences the selective processing of visual and auditory stimuli. In exp. 1, visual stimuli (letters) and auditory stimuli (tones) were presented in separate blocks. The subject's task was to attend either to the left or right side during an entire experimental block and to detect the occurrence of a target stimulus at the attended side. Since the stimuli were presented randomly at the left or right side, each stimulus was equally often preceded by a stimulus at the same (ipsilateral) position or by a stimulus at the contralateral side. Therefore, ERP effects of spatial attention could be determined separately for ipsilaterally and contralaterally preceded stimuli in order to determine whether the stimulus sequence affects attentional ERP modulations. Additionally, ERP differences between ipsilaterally and contralaterally preceded stimuli could be computed separately for stimuli at attended and unattended locations in order to study how the location of the preceding stimulus is reflected in the ERP wave forms. In exp. 2, visual and auditory stimuli were presented together in single experimental blocks, and the subject's task again was to detect target letters at the attended side. The aim of this second experiment was to determine whether ERP effects of spatial attention and stimulus sequence as well as interactions between these factors are present both for stimuli of the relevant (visual)

[1] An additional problem for ERP experiments on selective spatial attention with short interstimulus intervals is that ERPs may be distorted due to an overlap with ERP responses to preceding stimuli. Woldorff (1993) has recently demonstrated that such overlap effects may be different for ERPs to attended and unattended stimuli, thereby possibly giving rise to artifactual attention effects. These considerations are not directly relevant for the present study, because such artifactual effects are to be expected only at lateral electrodes (or in cross-modal attention experiments where different modalities constitute the attended channel in different blocks).

modality as well as for irrelevant (auditory) stimuli. Because we intended to minimize ERP modulations due to sensory refractoriness and any overlap from ERP responses to preceding stimuli (cf., Woldorff, 1993), the interstimulus intervals (ISIs) between stimuli were chosen rather long (in exp. 1: 700–1100 msec for the visual blocks and 500–900 msec for the auditory blocks; in exp. 2: 950–1050 msec).

2. Experiment 1

2.1. Methods

Subjects

Ten subjects (5 females), aged 20–32 years (mean age 26.7 years), who were participants in an introductory course in cognitive psychophysiology at the University of Munich, took part in the experiment. They received a small amout of money for their participation in the experiment. All subjects were right-handed and had normal or corrected-to-normal vision. The subjects were assumed to be normal from a neuropsychiatric point of view; however, no screening for prior disorders, head injury, concurrent drug use, etc. was conducted.

Stimuli, apparatus and procedure

The experiment consisted of 4 blocks in which visual stimuli were presented and 4 blocks in which auditory stimuli were presented. In 2 visual and auditory blocks, subjects were instructed to attend to the left side, in the other 2 visual and auditory blocks they were to attend to the right side. The order in which visual and auditory blocks were delivered was balanced across subjects. The visual blocks consisted of 156 trials. In each trial, an uppercase letter (M or W), subtending a visual angle of $1° \times 1°$, was presented for 100 msec with equal probability in the left or right visual field (6° eccentricity). Subjects were instructed to press a response button with the right hand when a target letter (the letter W) appeared at the attended side. In 144 trials, the non-target letter was presented, and in the remaining 12 trials, the target letter was presented. Thus only 6 responses to target letters at the attended side were required in each block. Randomized sequences of non-target and target letters were presented in the left or right visual field with interstimulus intervals of 700, 900 or 1100 msec.

The auditory blocks consisted of 180 trials. In each trial, a tone (1000 Hz or 1100 Hz, amplitude 80 dB SPL) was delivered via earphones for 50 msec on the left or right side with equal probability. Subjects were instructed to react with their right hand when the target tone (1100 Hz) was presented at the attended side. In 162 trials, the non-target tone was presented, and in 18 trials, the target tone was delivered, resulting in 9 responses to be given in each experimental block. Randomized sequences of non-target and target tones were presented in the left or right ear with interstimulus intervals of 700, 900 or 1100 msec.

The subjects were seated in a dimly lit, electrically shielded and sound attenuated cabin, with response buttons under their right hand. The display was placed 100 cm in front of the subject's eyes and carefully positioned so that the visual stimuli occurred on the subject's horizontal straight-ahead line of sight. Subjects were instructed to maintain their fixation upon a central point. To make subjects familiar with these task requirements, one training block was run at the beginning of the visual and auditory blocks, respectively.

Recording and data analysis

EEG was recorded with Ag-AgCl electrodes from Fz, Cz, Pz, and from OL and OR (located halfway between O1 and T5, and O2 and T6, respectively), all referenced to the right earlobe. The horizontal EOG was recorded from electrodes at the outer canthi of both eyes, the vertical EOG was recorded from electrodes above and beside the right eye. Electrode impedance was kept below 5 kΩ. The amplifier bandpass was 0.10–70 Hz. EEG and EOG were sampled on-line every 7 msec and stored on disk. EEG and EOG were analyzed from stimulus onset until 500 msec after stimulus onset. Trials with eyeblinks (vertical EOG greater than $+/-60$ μV) or horizontal eye movements (horizontal EOG greater than $+/-25$ μV) were excluded from further analysis. Only the EEG data from non-target trials were analyzed. Non-target trials where an overt response was recorded before the onset of the next stimulus (False Alarms) were excluded from analysis.

EEG was averaged separately for the auditory and visual blocks for both Attention conditions (attended vs. unattended), both stimulus positions (left vs. right) and both Preceding conditions (ipsilaterally vs. contralaterally preceded by a stimulus) relative to a 50 msec prestimulus baseline. This procedure resulted in 16 average wave forms for each subject and electrode site, each consisting of maximally 36 trials (visual ERPs) or 40 trials (auditory ERPs). For the ERP wave forms from the visual blocks, mean amplitude values were determined within the following post-stimulus intervals that were chosen with respect to the latencies of the components in the grand averaged ERPs: P1 at occipital electrodes (80–120 msec at electrodes contralateral to the side of the letter, 100–140 msec at ipsilateral electrodes), N1 at occipital electrodes (140–200 msec at electrodes contralateral to the side of the letter, 150–210 msec at ipsilateral electrodes), N1 at midline electrodes (130–190 msec), and a time interval from 220 to 290 msec, where longer-latency effects of spatial attention have been reported and which is termed Nd interval in the Results and Discussion sections. Additionally, P3 amplitude was determined as the maximum positive amplitude between 300 and 500 msec post stimulus. For the auditory blocks, mean amplitudes were determined at midline electrodes for the following intervals: N1 (80–130 msec) and Nd (180–280 msec).

Separate repeated measures analyses of variance were performed on these amplitude values for the following factors: Electrode location; Attention (attended vs. unattended), Preceding (ipsilaterally vs. contralaterally), and stimulus position (left vs. right). For the visual blocks, separate analyses were conducted for occipital electrodes ipsilateral (OI) and contralateral (OC) to the position of the stimulus. When appropriate, a Greenhouse-Geisser adjustment to the degrees of freedom was performed (indicated in the Result section by GG). To test specific interactions between conditions, paired t tests were used. Alpha level was 0.05 for the statistical analyses. Since only very few overt responses were recorded in this experiment, no analyses of overt performance were conducted.

2.2. Results

ERP wave forms to visual stimuli

As expected, stimuli at attended locations elicited enhanced P1 and N1 components at occipital electrodes as compared with stimuli at the unattended side (see Fig. 1, left, top row). This was reflected in an effect of Attention on P1 amplitude at ipsilateral occipital electrodes (F (1, 9) = 7.44; $P < 0.023$) and an almost significant effect at contralateral occipital electrodes (F (1, 9) = 5.00; $P < 0.052$) as well as in an effect of Attention on occipital N1 amplitude at contralateral electrodes (F (1, 9) = 15.35; $P < 0.004$), that almost reached significance at ipsilateral sites (F (1, 9) = 3.92; $P < 0.079$). Almost no difference was obtained for ipsilaterally as compared with contralaterally preceded stimuli for sensory-evoked components at occipital electrodes (see Fig. 1, left, bottom row), except for the fact that at contralateral electrodes, ipsilaterally preceded stimuli elicited a smaller N1 as compared to contralaterally preceded stimuli (F (1, 9) = 5.15; $P < 0.049$). No interaction could be found between Attention and Preceding, thus demonstrating that the preceding relationship had no influence on the attentional modulation of the P1 and N1 components at occipital electrodes.

At midline electrodes, attended letters elicited an enhanced negativity as compared with unattended letters (see Fig. 2, top). In the N1 interval, this effect only approached significance over all electrodes (F (1, 9) = 4.60; $P < 0.060$), but an interaction (Attention × Electrode location: F (2, 18) = 9.24; $P < 0.009$, GG, $\epsilon = 0.618$) indicated a differential Attention effect for single electrode positions. Further t tests revealed that this effect was significant at Cz (t (1, 9) = 3.09; $P < 0.013$) and almost significant at

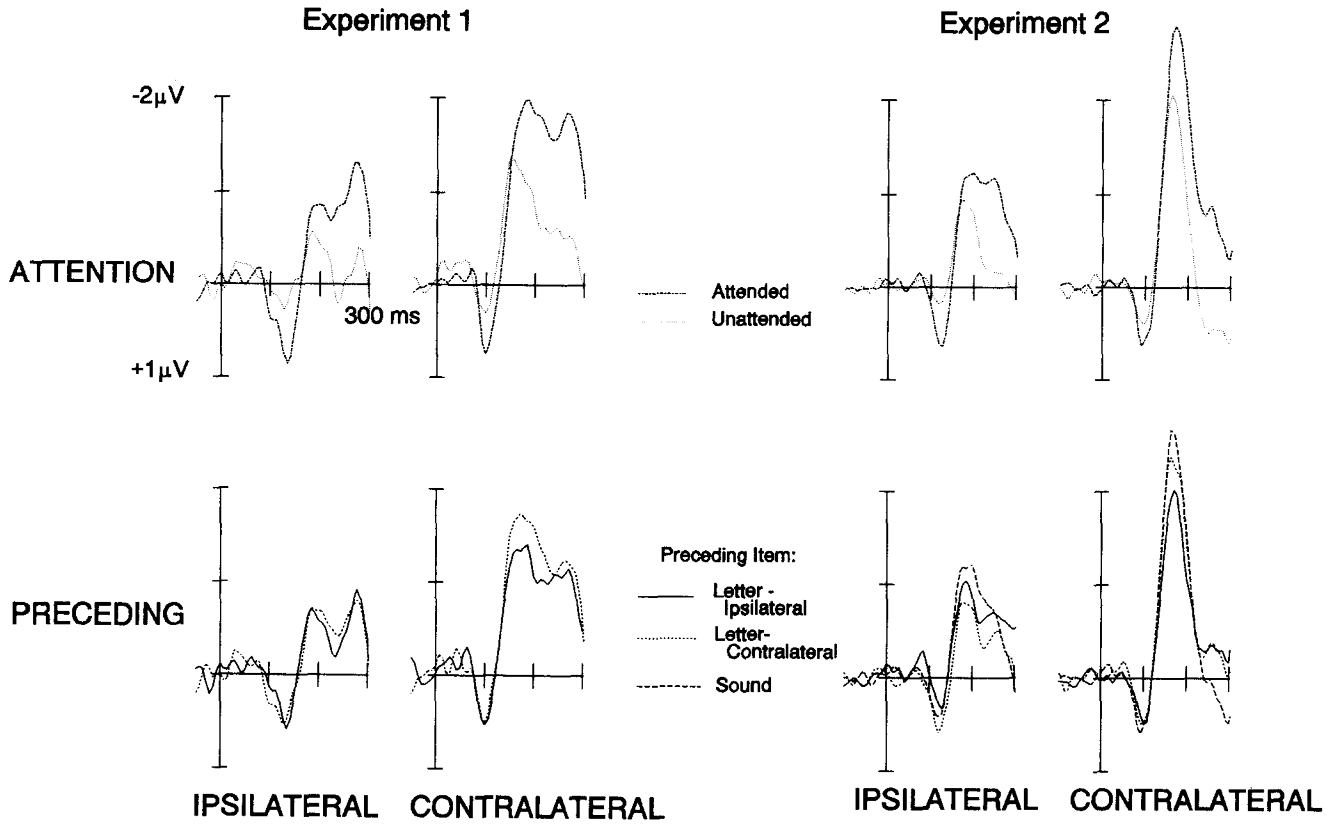

Fig. 1. Grand averaged ERPs elicited by visual stimuli at occipital electrodes ipsilateral and contralateral to the side where the stimulus was presented, exp. 1 (left) and exp. 2 (right). Top row: ERPs to attended and unattended visual stimuli. Bottom row: ERPs to visual stimuli that were preceded by a visual stimulus at the same position, at the contralateral position, or by a sound stimulus (in exp. 2). All wave forms displayed in these and the other figures were digitally low-pass filtered with a cut-off frequency of 40 Hz (24 dB/oct roll-off).

Pz (t (1, 9) = 2.24; $P < 0.052$). In the Nd range, an enhanced negativity for attended as compared with unattended stimuli was found (F (1, 9) = 9.37; $P < 0.014$). Further t tests revealed that this effect was present at Cz and Pz, but failed to reach significance at Fz (interaction Attention × Electrode location: F (2, 18) = 6.73; $P <$ 0.019, GG, $\epsilon = 0.634$). At Fz, however, an indication for an enhanced attentional negativity was found in the case of contralaterally preceded stimuli (see Fig. 2, bottom left), although this effect did not quite reach significance (t (1, 9) = 2.06; $P < 0.069$).

No main effect of Preceding was found in the N1 and Nd ranges. However, a significant 3-way interaction was obtained in the Nd range (Attention × Preceding × Electrode location: F (2, 18) = 7.11; $P < 0.013$, GG, $\epsilon =$ 0.721), which was due to the fact that a significant negative enhancement for ipsilaterally as compared to contralaterally preceded letters was found at Fz in the case of unattended stimuli (t (1, 9) = 2.77; $P < 0.022$; see Fig. 2, bottom right). This effect results in a reduction of the attended-unattended difference for ipsilaterally preceded letters and therefore in the disappearance of a significant Attention effect for ipsilaterally preceded letters at Fz that was noted above. Attended letters elicited a larger P3 than did unattended letters (F (1, 9) = 5.50; $P < 0.044$), and contralaterally preceded stimuli elicited an enhanced P3 when compared with ipsilaterally preceded stimuli. However, a 3-way interaction (Attention × Preceding × Electrode location: F (2, 18) = 5.49; $P < 0.032$, GG, $\epsilon =$ 0.633) indicated that these effects were due to an enlarged P3 for a particular combination of conditions. As is obvious from Fig. 2 (bottom), enlarged P3s were found predominantly for attended contralaterally preceded letters at Cz and Pz.

ERP wave forms to auditory stimuli

As was to be expected, attended stimuli elicited both an enlarged N1 (F (1, 9) = 7.73; $P < 0.021$) and an enhanced negativity in the Nd range (F (1, 9) = 42.95; $P < 0.001$) when compared with stimuli at unattended positions (see Fig. 3, top). Contralaterally preceded tones elicited larger N1 components than ipsilaterally preceded tones (F (1, 9) = 13.99; $P < 0.005$), which is likely to be due to sensory refractoriness in the latter case. In the Nd range, ipsilaterally preceded tones elicited an enhanced negativity as compared with contralaterally preceded tones (F (1,

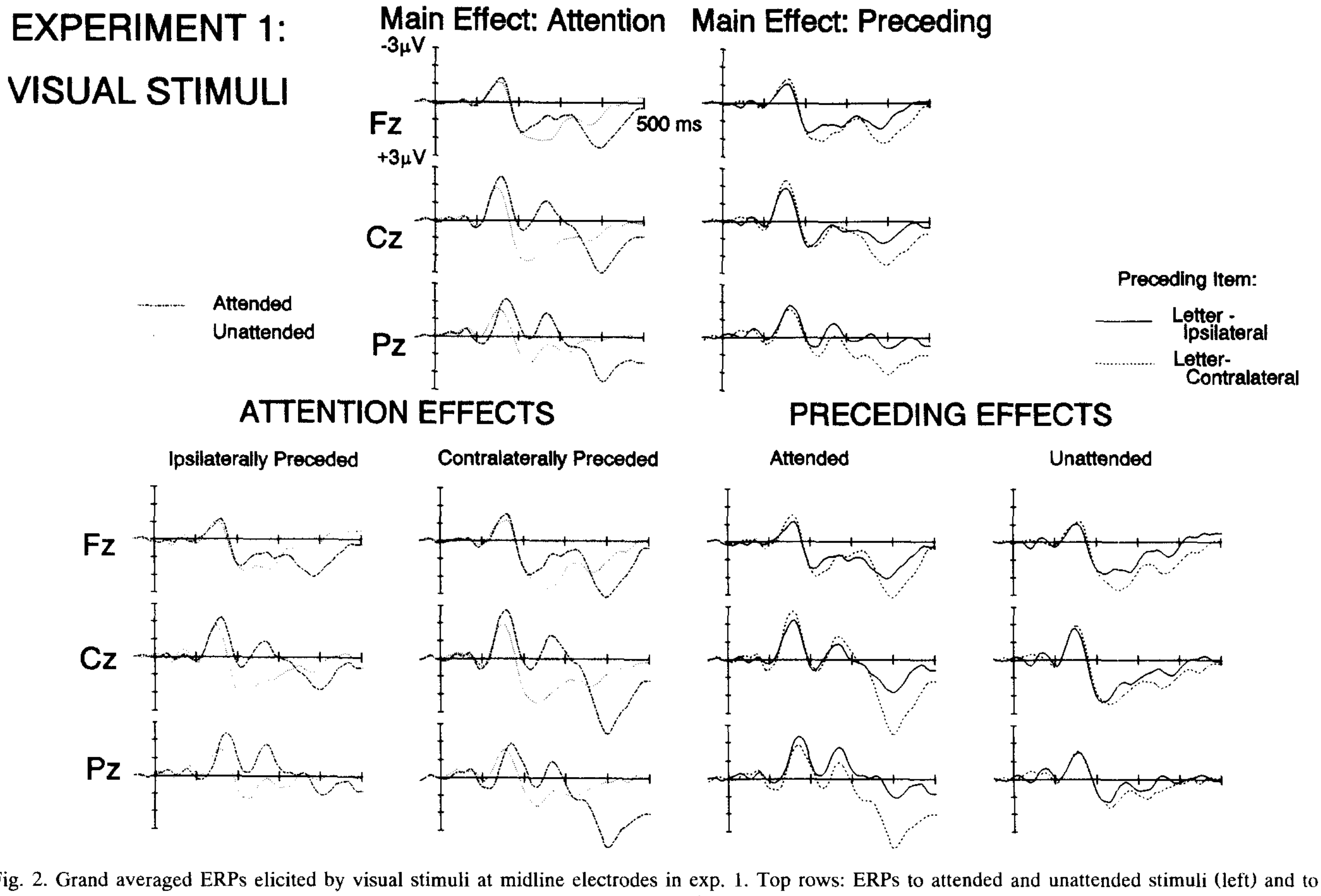

Fig. 2. Grand averaged ERPs elicited by visual stimuli at midline electrodes in exp. 1. Top rows: ERPs to attended and unattended stimuli (left) and to stimuli that were preceded by a stimulus at the same or the contralateral position (right). Bottom rows: ERPs to attended and unattended stimuli displayed separately for the two Preceding conditions (left side), ERPs to ipsilaterally and contralaterally preceded letters displayed separately for attended and unattended stimuli (right side).

9) = 5.72; $P < 0.040$). Additional t tests revealed that this effect was present only for unattended stimuli (see Fig. 3, bottom right). This was reflected in an interaction between Attention and Preceding (F (1, 9) = 13.08; $P < 0.006$). The fact that unattended ipsilaterally preceded tones elicited an enhanced negativity was also reflected in the observation that the enhanced negativities for attended as compared to unattended stimuli were more pronounced for contralaterally than for ipsilaterally preceded stimuli (see Fig. 3, bottom left), although this effect remained significant in the latter case. In the visual blocks, enhanced negativities for ipsilaterally preceded stimuli at unattended locations could be found only at Fz, whereas for auditory stimuli this effect was present at all midline electrodes. As an additional difference from the experiment employing visual stimuli, no P3 effect could be obtained for any combination of task conditions (see Fig. 3).

2.3. Discussion of experiment 1

In experiment 1, the effects of spatial attention on ERP wave forms that were reported in previous studies using a sustained attention paradigm have been successfully replicated. Attended visual stimuli elicited larger sensory-evoked potentials at occipital electrodes, and also an enhanced negativity at midline electrodes in the N1 and Nd intervals. Attended auditory stimuli elicited an enhanced negativity in the N1 and Nd intervals when compared with unattended stimuli. In contrast to the results reported by Luck et el. (1990), the enhancement of the occipital N1 component for attended visual stimuli was not affected by the position of the preceding stimulus. The N1 effect was obtained both for contralaterally as well as for ipsilaterally preceded visual stimuli. The ISIs employed in the present experiment were more than twice as long than in the Luck et al. (1990) study, where ISIs ranging from 310 msec to 450 msec were employed. It is thus conceivable that in the present experiment, attention may be oriented back to the relevant position after the presentation of a stimulus an an irrelevant location, but prior to the presentation of the next stimulus.

Both at occipital and at midline electrodes, the position of the preceding stimulus affected the ERP wave forms for auditory as well as visual stimuli. First, there was evidence

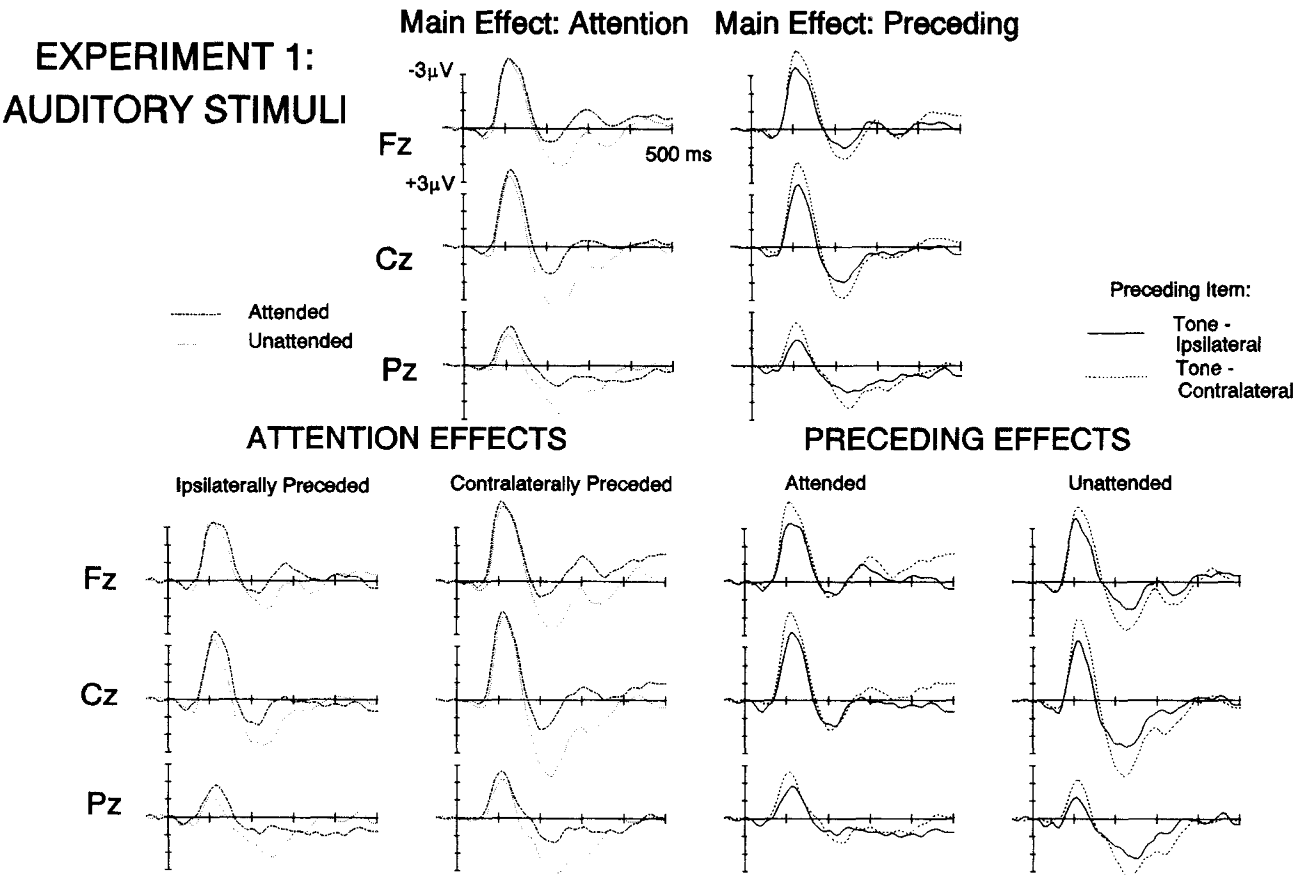

Fig. 3. Grand averaged ERPs elicited by auditory stimuli at midline electrodes in exp. 1. Top rows: ERPs to attended and unattended stimuli (left) and to stimuli that were preceded by a stimulus at the same or the contralateral position (right). Bottom rows: ERPs to attended and unattended stimuli displayed separately for the two Preceding conditions (left side), ERPs to ipsilaterally and contralaterally preceded auditory stimuli displayed separately for attended and unattended stimuli (right side).

for sensory refractoriness in the case of ipsilaterally preceded stimuli, as these stimuli elicited a smaller auditory N1 at midline electrodes and a smaller visual N1 at contralateral occipital electrodes. Moreover, ipsilaterally preceded auditory stimuli (at midline electrodes) as well as ipsilaterally preceded visual stimuli (at Fz) elicited an enhanced negativity in the Nd range when compared to contralaterally preceded stimuli. However, these effects were present only when these stimuli were presented at the unattended side. This was most evident for auditory stimuli (see Fig. 3, bottom), but could also be observed for visual stimuli at Fz.[2] This effect may either be due to a selective negative enhancement for unattended stimuli preceded by a stimulus at the same position, or to an enhanced positivity for unattended stimuli whose predecessor was located contralaterally. On the basis of Fig. 3, it is conceivable that the latter possibility was responsible for this effect in the case of auditory stimuli. Enhanced positivities for unattended auditory stimuli have been found in a number of previous studies (Alho et al., 1987; Berman et al., 1989; Michie et al., 1990). Alho et al. (1987) suggested that this positivity reflects the suppression of processing of irrelevant stimuli. If this interpretation is correct, it may be concluded on the basis of the present results that the suppression of stimuli at irrelevant locations is more successful when the preceding stimulus was presented at the contralateral (attended) location. This may also account for the finding reported by Woods (1990) that attentional Nd effects were larger for stimuli preceded by attended as compared with unattended stimuli.

An unexpected finding was that contralaterally preceded visual stimuli at attended sides elicited an enlarged P3 at central and parietal electrodes. This effect could not be due to the fact that this specific situation was less likely than the other task combinations. Attended and unattended as well as ipsilaterally and contralaterally preceded stimuli appeared equally often, and for the auditory blocks, where an analogous experimental situation was realized, no P3 effect could be observed. The nature of this P3 effect thus remains unclear. However, the central question of the present research whether the Preceding relationship modulates attentional effects in a sustained attention paradigm may have found a tentative answer. At midline electrodes, these effects seem to be more pronounced for stimuli that are preceded by a stimulus at the contralateral location and smaller for ipsilaterally preceded stimuli. Before further explanations for this effect are considered, it should first be confirmed within another experimental setting. Therefore a second experiment was conducted to further study the effects observed in exp. 1 and to gain further insight into the processes underlying these effects.

[2] Therefore, the enhanced negativity for ipsilaterally preceded auditory stimuli cannot simply be explained by refractoriness of the P2 generators, since it did not occur in the case of attended tones.

3. Experiment 2

In experiment 2, auditory and visual stimuli were presented together in single experimental blocks. The direction of attention was again kept constant for an entire block. The sounds were task irrelevant, since subjects had to detect a visual target at the attended location. They were included to test whether the processing of stimuli in an irrelevant modality may also be affected by the direction of visuo-spatial attention or by the location of preceding stimuli.

In experiment 1, a rather small number of trials per subject were the basis for the averaged wave forms. This fact may have been specifically relevant for the visual wave forms, where less clear-cut results could be obtained than for the auditory ERPs. In experiment 2, the total number of trials was increased to ensure that reliable ERP wave forms could be computed for each experimental condition. Moreover, RTs to target letters that may also indicate a differential processing of ipsilaterally and contralaterally preceded and unpreceded stimuli were measured in experiment 2.

3.1. Methods

Subjects

Twelve paid subjects (8 females), aged 18–29 years (mean age 24.3 years) took part in the experiment. All subjects were right-handed and had normal or corrected-to-normal vision. As before, no neuropsychiatric screening was conducted.

Stimuli, apparatus and procedure

The experiment consisted of 24 blocks. In half of the blocks, subjects were instructed to attend to the left side, in the other half they were to attend to the right side. Each attend-left block was followed by an attend-right block. The blocks consisted of 162 trials. In 18 trials, a target letter (W) was presented, in 72 trials, a non-target letter (M) was presented, and in 72 trials, a sound stimulus was delivered. The letters subtended a visual angle of $1° \times 1°$ and were presented for 200 msec in the left or right visual field (6° eccentricity). The sounds were delivered from one of two loudspeakers that were fixed at the left and right side of the computer display. They consisted of a 50 msec burst of white noise (5 msec rise- and fall-time). Randomized sequences of letters (non-targets and targets) and sounds were presented with equal probability on the left or right side with interstimulus intervals of 950, 1000 or 1050 msec. Subjects were instructed to press a response button with the right hand when the target letter (the letter W) appeared at the attended side.

In all other respects, the experimental situation was identical to exp. 1.

Recording and data analysis

EEG recording and rejection criteria were identical to exp. 1. The EEG wave forms recorded for non-target stimuli were averaged separately for visual and auditory stimuli for the conditions Attention (attended vs. unattended), Preceding (ipsilaterally or contralaterally preceded by a letter or a sound), and stimulus position (left vs. right) relatively to a 100 msec prestimulus baseline. This procedure resulted in 32 ERP wave forms for each subject and electrode site. The average maximum number of single trials contributing to one ERP wave form was 108. For the auditory stimuli, only the ERP wave forms to sounds preceded by letters (either ipsi- or contralaterally) were analyzed. Mean amplitude values were determined separately for the ERPs elicited by letters and the ERPs elicited by sounds. For the visual ERPs, these values were determined within the following post-stimulus intervals that were chosen with respect to the latencies of the components in the grand averaged ERPs: P1 at occipital electrodes (75–115 msec at electrodes contralateral to the side of the letter, 95–135 msec at ipsilateral electrodes), N1 at occipital electrodes (140–200 msec at electrodes contralateral to the side of the letter, 150–210 msec at ipsilateral electrodes), N1 at midline electrodes (140–190 msec), and the Nd interval (210–290 msec). Additionally, P3 amplitude was determined as the maximum positive amplitude between 300 and 500 msec post stimulus. For the auditory stimuli, mean amplitudes were determined at midline electrodes for the following intervals: N1 (90–140 msec), P2 (160–240 msec), and N2 (260–320 msec).

Repeated measures analyses of variance were performed separately for letter and sound stimuli on these amplitude values for the following variables: Electrode location, Attention (attended vs. unattended), Preceding (for visual stimuli: ipsi- vs. contralaterally preceded a letter vs. a sound; for auditory stimuli: ipsi- vs. contralaterally preceded by a letter), and stimulus position (left vs. right). When appropriate, a Greenhouse-Geisser adjustment to the degrees of freedom was performed (indicated in the Results section by GG). To test specific interactions between conditions, paired t tests were used. RTs to target letters were analyzed for effects of Preceding and stimulus position. Target trials with RTs exceeding 1000 msec were regarded as errors.

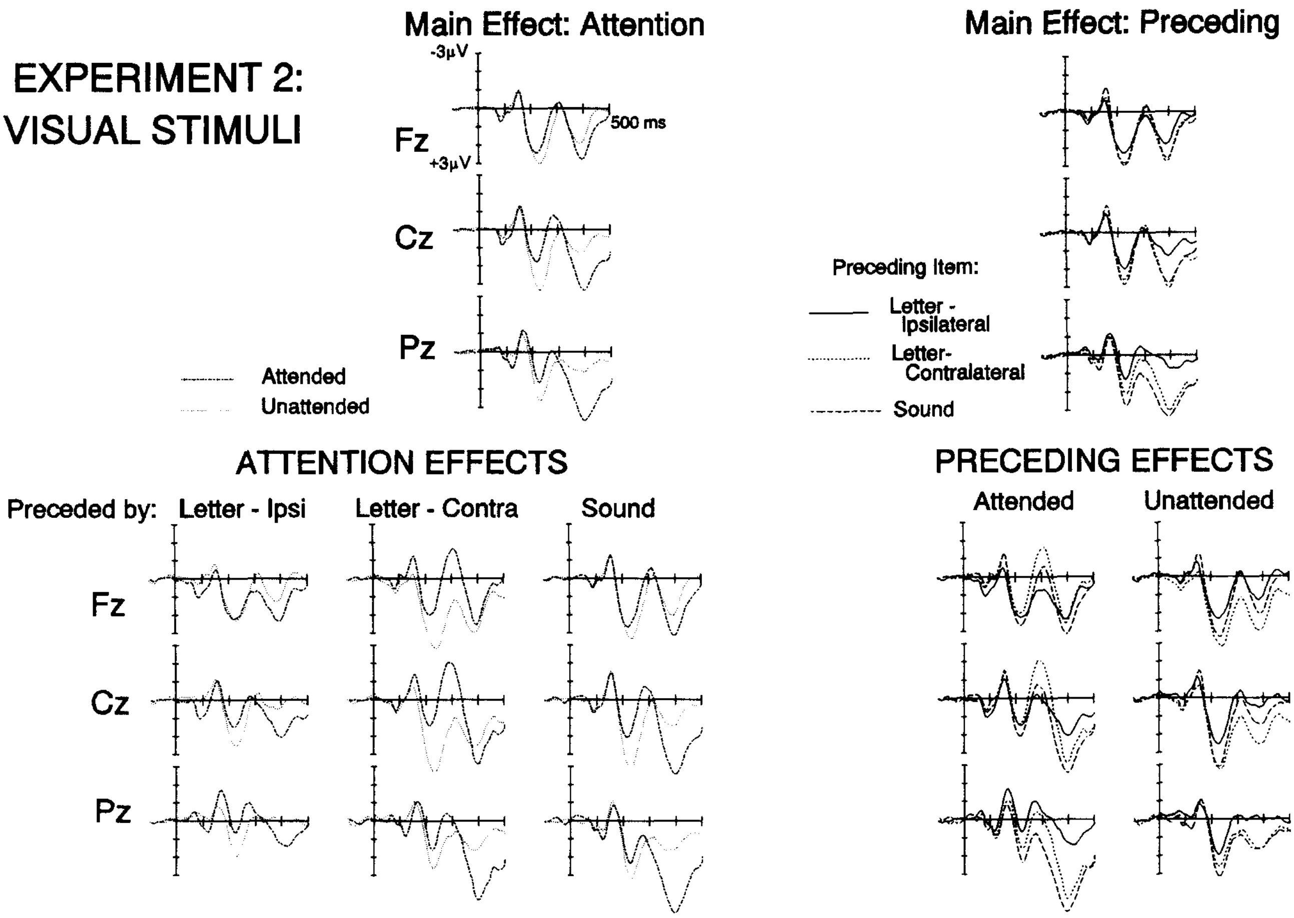

Fig. 4. Grand averaged ERPs elicited by visual stimuli at midline electrodes in exp. 2. Top rows: ERPs to attended and unattended stimuli (left) and to stimuli that were preceded by a visual stimulus at the same or the contralateral position or by a sound stimulus (right). Bottom rows: ERPs to attended and unattended stimuli displayed separately for 3 Preceding conditions (left side), ERPs to stimuli preceded by letters at ipsilaterally and contralaterally positions or by sounds displayed separately for attended and unattended stimuli (right side).

3.2. Results

Behavioral performance

Reaction times were significantly influenced by the factor Preceding (F (3, 33) = 6.34; $P < 0.007$). Further t test revealed that RT latencies to stimuli that were preceded by a letter at the same location were significantly longer (503 msec) as compared with the other Preceding conditions (481 msec to letters preceded by a sound at the same side, and 474 msec to target letters preceded either by a letter or a sound at the contralateral side). No difference was found for the RTs to target stimuli on the left and on the right side (487 vs. 485 msec). Subjects missed a target letter on 2% of the target trials and gave an erroneous response on 0.2% of the non-target trials.

ERP wave forms elicited by visual stimuli

Similar to exp. 1, attended letters elicited enhanced P1 and N1 components at occipital electrodes (see Fig. 1, right, top row). These effects were found to be highly significant both at ipsilateral and at contralateral sites (F (1, 11) = 9.27; $P < 0.011$ and F (1, 11) = 11.19; $P < 0.007$ for contra- and ipsilateral P1 amplitude; F (1, 11) = 43.58; $P < 0.001$ and F (1, 11) = 10.04; $P < 0.009$ for contra- and ipsilateral N1 amplitude). An effect of Preceding at occipital sites was again found for the contralateral N1 amplitude (F (3, 33) = 6.56; $P < 0.008$, GG, $\epsilon = 0.584$). The N1 to stimuli ipsilaterally preceded by a letter was smaller than the N1 to stimuli that were contralaterally preceded by a letter, while the N1 to sound-preceded letters (collapsed over ipsilateral and contralateral sounds) was largest (see Fig. 1, right, bottom row). As in exp. 1, no interaction (Preceding × Attention) was found for the occipital N1 component.

As can be seen in Fig. 4 (top), attended letters tended to elicit an enhanced negativity as compared with unattended letters at midline electrodes in the N1 range (F (1, 11) = 4.53; $P < 0.057$), and this effect was highly significant in the Nd range (F (1, 11) = 16.05; $P < 0.002$). Main effects of Preceding were present only at Pz, where letters ipsilaterally preceded by letters elicited an enhanced negativity as compared with stimuli preceded by contralateral letters or sound-preceded stimuli both in the N1 and Nd intervals (interactions Preceding × Electrode location: F (6, 66) = 8.03; $P < 0.004$, GG, $\epsilon = 0.280$; and F (6, 66) = 12.41; $P < 0.001$, GG, $\epsilon = 0.412$, respectively).

Additionally, interactions between Attention and Preceding were obtained that were significant in the Nd interval (F (3, 33) = 5.85; $P < 0.010$, GG, $\epsilon = 0.632$) and approached significance in the N1 range (F (3, 33) = 3.02; $P < 0.065$, GG, $\epsilon = 0.714$). Moreover, these were accompanied by highly significant 3-way interactions (Attention × Preceding × Electrode location: F (6, 66) = 9.95; $P < 0.001$, GG, $\epsilon = 0.566$; and F (6, 66) = 17.85; $P < 0.001$, GG, $\epsilon = 0.661$, for the N1 and Nd intervals, respectively). In exp. 1, similar patterns were traced back to larger negativities for unattended ipsilaterally preceded as compared to contralaterally preceded stimuli at frontal sites (in the case of visual stimuli) or at all midline electrodes (for auditory stimuli). As can be seen from Fig. 4 (bottom), an analogous result was obtained in the present experiment at Fz and Cz. Again, Attention effects were largest for stimuli preceded by a letter at the contralateral side. They were missing when the stimulus was ipsilaterally preceded by a letter (see Fig. 4, bottom left). These observations were confirmed for the N1 and the Nd interval by planned comparisons using t tests. For sound-preceded letters (collapsed over ipsilateral and contralateral sounds), smaller, but significant, attentional effects were present at Fz (in the Nd range) and at Cz (both in the N1 and Nd range). When the effect of Preceding is plotted separately for attended and unattended stimuli (Fig. 4, bottom right), it becomes obvious that at unattended positions, stimuli that were preceded by a letter at the same location elicited an enhanced negativity as compared with letters preceded by a contralateral letter, while for attended positions, this effect reverses: here enhanced negativities are elicited in the latter condition.[3] A similar tendency was already visible in the corresponding visual and auditory ERPs in exp. 1 (cf., Figs. 2 and 3). However, the pattern found at Pz was rather different from the effects observed at frontocentral electrodes: here letters preceded by ipsilateral letters elicited an enhanced negativity both when they were attended (in the N1 and Nd intervals) and when they were unattended (in the Nd interval).

For P3 amplitude, main effects were obtained both for Attention (F (1, 11) = 9.26; $P < 0.011$) and for Preceding (F (3, 33) = 14.34; $P < 0.001$, GG, $\epsilon = 0.505$), indicating that attended stimuli elicited a larger P3 than unattended stimuli, and that the P3 to letters preceded by ipsilateral letters was smaller than to stimuli preceded by a contralateral letter or a sound (see Fig. 4). Again, a highly significant 3-way interaction (Attention × Preceding × Electrode location: F (6, 66) = 16.25; $P < 0.001$, GG, $\epsilon = 0.479$) was obtained that was due to the fact that – similar to exp. 1 – an enlarged P3 was elicited most notably at central and parietal electrodes by attended stimuli that were preceded by a contralateral letter (or by an irrelevant sound stimulus), whereas the P3s elicited by unattended letters and by attended letters that were preceded by a letter at the same location were significantly smaller.

[3] These relationships were further investigated with planned comparisons using paired t tests. For attended stimuli, letters preceded by a letter at the contralateral position were found to elicit an enhanced negativity in the Nd interval as compared with stimuli preceded by letters at the same location and to tone-preceded stimuli both at Fz and at Cz. In the case of unattended stimuli, however, ERPs to stimuli preceded by a letter at the contralateral position were less negative than the ERPs for the other Preceding conditions.

ERP wave forms elicited by auditory stimuli

No differences were to be found between ERP wave forms to letter-preceded sounds presented at the attended and at the unattended side (see Fig. 5, top left). However, a rather different picture emerges when the effects of Attention on auditory ERPs were analyzed separately for sounds that were either ipsilaterally or contralaterally preceded by a letter. Here significant differences become visible for frontal and central electrodes (see Fig. 5, bottom left) that are similar to the effects obtained for visual stimuli. When sounds were preceded by a letter at the contralateral side, sounds at attended sides elicited an enlarged negativity as compared with sounds at unattended sides. As evidenced by t tests, this effect was manifested in an enhanced N1 at Fz and Cz, a smaller P2 at Fz, and in an enhanced N2 at Fz and Cz. For sounds that were preceded by an ipsilateral letter, this effect reversed: now sounds at the unattended side tended to elicit enlarged negativities as compared with sounds at attended positions. Subsequent t tests revealed that this effect approached significance in the N1 interval at Fz and Cz, and was significant for the P2 interval at Fz, and for the N2 interval both at Fz and Cz. This pattern was reflected in interactions between Attention and Preceding that were significant in the N1 and N2 intervals (F (1, 11) = 11.68; $P < 0.006$; F (1, 11) = 11.43; $P < 0.006$) and approached significance in the P2 interval (F (1, 11) = 4.04; $P < 0.070$). In contrast to these effects at frontal and central electrodes, no such effect could be obtained at Pz. The differential effects of Attention for different Preceding conditions and different electrode sites were thus also reflected in significant 3-way interactions (Attention × Preceding × Electrode location) in the N1 interval (F (2, 22) = 9.80; $P < 0.004$, GG, $\epsilon = 0.658$), the P2 interval (F (2, 22) = 12.35; $P < 0.001$, GG, $\epsilon = 0.710$), and the N2 interval (F (2, 22) = 17.69; $P < 0.001$, GG, $\epsilon = 0.627$). These effects are also visible when the Preceding effects are plotted separately for sounds at attended and unattended sides (see Fig. 5, bottom right): for stimuli at unattended locations, ipsilaterally preceded sounds elicited an enhanced negativity at frontocentral leads when compared with contralaterally preceded sounds, while for stimuli at attended locations, the opposite effect is present.

As can be seen from Fig. 5 (top right), the ERP wave forms to sounds preceded by ipsilateral and contralateral letters were almost identical, except for the fact that at Pz, the ERPs to sounds preceded by ipsilateral letters tended to

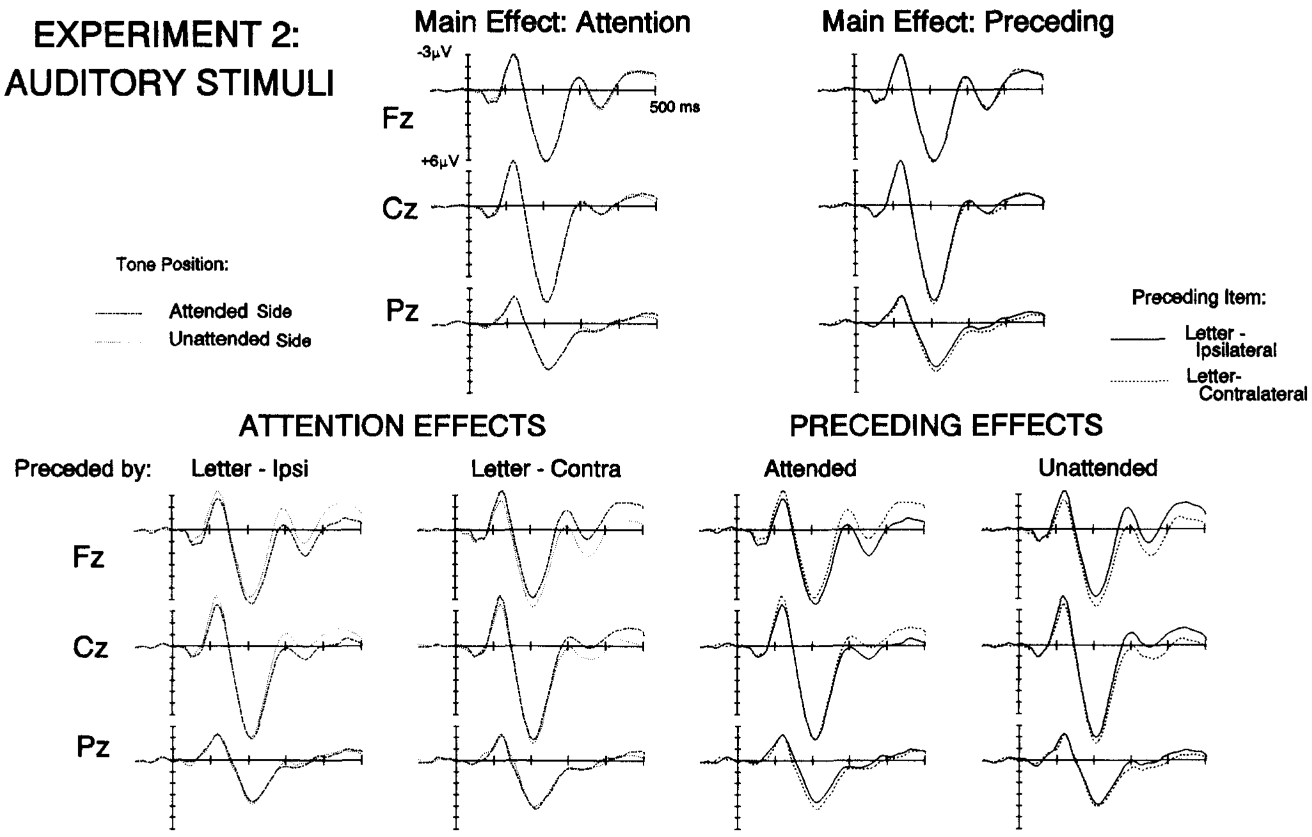

Fig. 5. Grand averaged ERPs elicited by auditory stimuli that were preceded by visual stimuli at midline electrodes in exp. 2. Top rows: ERPs to attended and unattended sounds (left) and to sounds that were preceded by a visual stimulus at the same or the contralateral position (right). Bottom rows: ERPs to attended and unattended sounds displayed separately for sounds preceded by a letter at the same or the contralateral position (left side); ERPs to ipsilaterally and contralaterally preceded sounds displayed separately for attended and unattended stimuli (right side).

be more negative, resulting in a smaller P2 and a N2 enhancement. The latter effect, however, failed to reach statistical significance.

3.3. Discussion of experiment 2

As can be seen from the grand averaged EOG wave forms in Fig. 6, subjects were generally able to maintain central fixation after the presentation of lateralized stimuli. Experiment 2 thus confirmed that covert shifts of visuospatial attention are associated with enhanced sensory-evoked potentials at posterior sites and an enhanced negativity beyond 200 msec at midline electrodes for attended as compared with unattended stimuli. More interestingly, the main findings from exp. 1 were successfully and more clearly replicated in the present experiment. The assumption that the attentional effects reported for the sustained attention paradigm are modulated by the location of the preceding stimulus was clearly confirmed.

At midline electrodes, large attentional effects were visible when visual stimuli were preceded by contralateral letters, while these effects were smaller for sound-preceded letters and virtually disappeared at Fz and Cz for letters preceded by ipsilateral letters. This effect may be due both to an enhanced negativity for ipsilaterally preceded letters at unattended and to a reduced negativity for these stimuli at attended locations. The observation that attended stimuli elicited smaller N1 components and less negativity in the Nd range at Fz and Cz when they were preceded by a letter at the same position as compared with the other Preceding conditions (see Fig. 4, bottom right) fits well with the finding that RTs were significantly delayed for (attended) target stimuli preceded by an ipsilateral letter. At Pz, however, stimuli preceded by ipsilateral letters elicited an enhanced negativity both when they were attended and when they were unattended. In the case of unattended letters, stimuli preceded by a contralateral letter or by a sound elicited more positive-going ERP wave forms in the Nd interval than did letters preceded by an ipsilateral letter (see Fig. 4). This is similar to the effects found for auditory stimuli in exp. 1, possibly reflecting a suppression of processing for irrelevant stimuli. As in exp. 1, a differential modulation of P3 amplitude was found at central and parietal sites. At attended locations, stimuli preceded by contralateral letters again elicited an enlarged P3. When attended stimuli were preceded by sounds, a similar P3 enhancement was observed.

At first sight, it seemed to make no difference whether sounds were presented at attended or unattended sides (see Fig. 5, top), as no main effect of Attention was present for the auditory ERPs. This finding contrasts with the results from a similar experiment by Hillyard et al. (1984), where enhanced negativities for auditory stimuli presented at attended locations were found in a situation where attention was directed to visual stimuli. In contrast to the present study, Hillyard et al. (1984) used very short ISIs (250–450 msec), which may have produced more strictly focussed spatial attention and may thus have resulted in attentional effects for irrelevant auditory stimuli. Moreover, in the Hillyard et al. (1984) study the probability of auditory stimuli was 50%, whereas tones were less frequent than visual stimuli in the present study.

When the Predecing relationship was taken into account, however, effects similar to those reported for the visual stimuli were obtained at Fz and Cz for the task-irrelevant sounds. When sounds were preceded by contralateral letters, sounds presented at the attended side elicited an enlarged negativity in the N1, P2 and N2 intervals, while

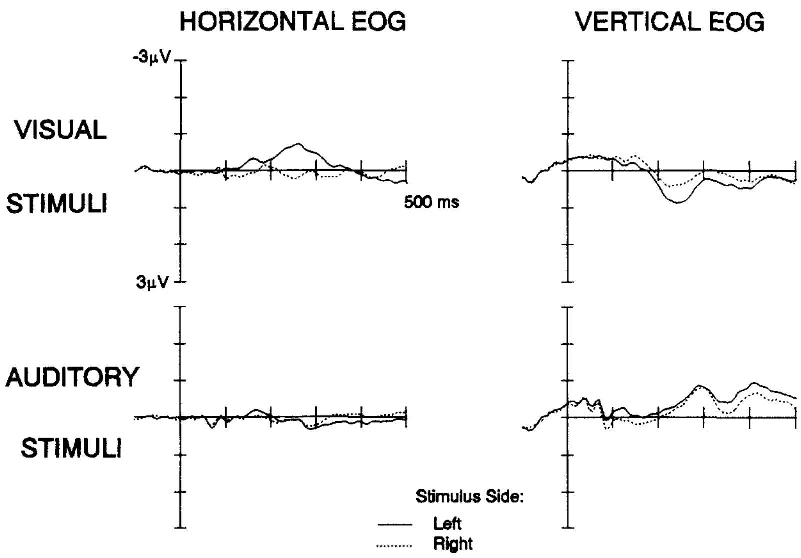

Fig. 6. Grand averaged horizontal (left side) and vertical (right side) electrooculogram (EOG) recordings in response to the presentation of stimuli at the left and the right side, exp. 2. Top row: horizontal and vertical EOGs in response to left and right visual stimuli. Bottom row: horizontal and vertical EOGs in response to left and right auditory stimuli.

in the case of ipsilaterally preceded sounds, the reverse effect was obtained. This effect may be due to an enhanced negativity for ipsilaterally preceded sounds presented at unattended positions, and to an enhanced negativity for contralaterally preceded auditory stimuli at attended positions.

To summarize, exp. 2 brought further evidence that the attentional modulations of ERP wave forms that are found in a sustained attention situation are influenced by the position of immediately preceding stimuli. This was even the case for the ERP wave forms for auditory stimuli in a situation where these stimuli were completely task irrelevant.

4. General discussion

The present experiments brought converging evidence that ERP differences for stimuli at attended and unattended locations in a sustained attention paradigm are modulated by the position of the immediately preceding stimulus. When stimuli are presented at the same location as their predecessors, only small negative enhancements for attended as compared with unattended stimuli were observed. When they were presented contralateral to their predecessors, larger attentional effects were measured. For visual stimuli, this effect was present at frontal electrodes (in exp. 1) or at frontocentral sites (in exp. 2). It seems to be due to the fact that at unattended positions, ipsilaterally preceded stimuli elicit an enhanced negativity, while at attended locations, these stimuli elicit less negative ERP wave forms than contralaterally preceded stimuli. For relevant auditory stimuli (in exp. 1), this effect was observed at all midline electrodes. A strikingly similar phenomenon was visible in the frontocentral ERP wave forms to the task-irrelevant sound stimuli that were included in exp. 2.

Enlarged attentional effects for contralaterally preceded stimuli have already been reported by Luck et al. (1990) and Woldorff and Hillyard (1991). In the latter study, the Nd elicited by attended-ear tones was found to be larger for tones preceded by a tone in the unattended ear. This effect was present in the N2 range and may be regarded as equivalent to the differential Nd effects reported in the present study. Luck et al. (1990) used visual stimuli and found that the stimulus sequence affected the attentional modulation of the N1 component at posterior sites. In the experiments reported here, no such interactions between stimulus sequence and spatial attention were found at lateral occipital electrodes. However, larger attentional effects for contralaterally preceded visual stimuli were present in exp. 2 at frontocentral electrodes in the N1 interval. It is unclear whether the posterior N1 effects reported by Luck et al. (1990) are similar to the frontocentral N1 effects found in the present study.

Several different explanations may be formulated for the finding that ERP effects of spatial attention are enhanced for contralaterally as compared to ipsilaterally preceded stimuli. It may be possible that the abrupt appearance of a stimulus captures attention automatically, and that attention is partially kept at that position until the next stimulus turns up. If this were the case, ipsilaterally preceded stimuli at unattended locations may thus not really be unattended, since attention will still be partially focussed at these locations. This may account for the observed enhanced negativity for ipsilaterally as compared with contralaterally preceded stimuli at unattended locations. However, in the present experiments, the ISIs were rather long, so that subjects should have been able to re-orient their attention back to the position where targets had to be detected even if it had been attracted involuntarily by stimuli at the unattended side. Moreover, the hypothesis of an involuntary attentional capture leaves unexplained the finding from exp. 2 that when visual or auditory stimuli were presented at attended locations, stimuli preceded by a letter at the same position elicited less negativity than contralaterally preceded stimuli at Fz and Cz. Similarly, this hypothesis cannot explain the RT costs found in exp. 2 for targets that were preceded by a letter at the same position. If attention was captured by the preceding stimulus regardless of the current direction of attention, opposite results were to be expected. The finding that at Pz, enhanced negativities for ipsilaterally preceded stimuli were found both at attended and unattended locations, is in line with the "attentional capture" hypothesis. It may thus be possible that two distinct processes are active in parallel, leading to differential ERP effects at anterior and posterior sites (see below). However, both for the RT effects and for the ERP modulations at frontocentral electrodes, alternatives to the explanation referring to an involuntary capture of attention by preceding stimuli need to be considered.

The finding that RTs to target stimuli that are preceded by an ipsilateral letter are delayed as compared to contralaterally preceded targets confirms previous results that have been reported by Woods et al. (1992, exp. 2). This effect is consistent both with the assumption that attentional orienting to recently stimulated locations is inhibited and with the hypothesis that the perceptual processing of ipsilaterally preceded targets suffers due to sensory refractoriness. Both explanations postulate processing costs for ipsilaterally as compared with contralaterally preceded stimuli that are independent of the direction of attention. Therefore, neither explanation can account for the fact that ipsilaterally and contralaterally preceded stimuli yielded rather different frontocentral ERP effects depending on whether they were presented at attended or unattended locations.

As a starting point for a more convincing explanation of these effects, it has to be recognized that in a sustained attention situation, processing requirements are not identical for stimuli at attended and unattended sides. Because stimuli at unattended locations are always response-irrelevant, they may receive only superficial analysis, while stimuli at attended locations, which are potential targets, have to be identified in order to decide whether an overt response is to be given or not. These different processing requirements are presumably reflected in the negative enhancements for attended as compared with unattended stimuli. However, this difference may also affect the processing of the next stimulus. For stimuli that were preceded by (potentially relevant) attended stimuli, less processing capacity may be available than for stimuli which predecessor was presented at an unattended, irrelevant location. Given these assumptions, most of the findings from exp. 1 and exp. 2 can be explained without too much difficulty. The finding that RTs to targets preceded by ipsilateral letters were delayed may be due to the fact that in this case, the preceding item was a potentially relevant visual stimulus, while in the other cases, the preceding stimulus was either of the irrelevant modality or at the irrelevant position. The finding that visual stimuli preceded by ipsilateral letters elicited an enhanced negativity at frontocentral electrodes when unattended, while negative enhancements to contralaterally preceded letters were found for attended stimuli can be explained by the fact that in both situations, the predecessor was presented at the irrelevant side and thus required less processing. A similar explanation can be given for the pattern observed with the irrelevant sound stimuli in exp. 2. Here contralaterally preceded sounds at the attended side and ipsilaterally preceded sounds at the unattended side elicited enhanced negativities. In both cases, the preceding letter was presented at the irrelevant side, while in the other cases, the preceding visual stimulus was located at the relevant side and thus required further processing. Taken together, these assumptions imply that when a stimulus is preceded by a potentially relevant stimulus at the attended side, processing costs may result, that are reflected in systematic modulations of ERP wave forms.

It may be considered whether this explanation can also account for the fact that enhanced P3 components were recorded for attended visual stimuli when they were not preceded by an ipislateral letter. In other words, enlarged P3s were found in situations where a potentially relevant stimulus was presented and no further processing of the preceding stimulus was necessary (because it was presented on the irrelevant side or was of the irrelevant modality). The enlarged P3 may thus reflect attended processing that is unaffected by residual processing of the preceding item. However, this description can not account for the fact that no such P3 effect turned up in exp. 1 when auditory stimuli were used.

Although the explanation developed in the last paragraph may explain both the ERP effects at frontocentral midline electrodes and the RT results of exp. 2, it leaves open the question why rather different ERP modulations were obtained at Pz, where ipsilaterally preceded stimuli elicited an enhanced negativity even when they were presented at attended locations and thus were preceded by a potentially relevant stimulus. It may be considered whether the differential ERP effects for frontocentral and parietal electrodes that were found in the present experiments are a reflection of two independent, but overlapping processes, one dealing with an ongoing processing of potential targets, the other possibly connected to an involuntary capture of spatial attention by onset stimuli. Additional research is necessary to further distinguish between these two hypothetical processes and to explore in more detail how the processing of stimuli in a sustained spatial attention situation is affected by the location of preceding stimuli.

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