BIOLOGICAL PSYCHOLOGY

ELSEVIER Biological Psychology 43 (1996) 203–226

Effects of lateralized cues on the processing of lateralized auditory stimuli

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Received 3 February 1994; revised 12 January 1996; accepted 12 January 1996

Abstract

We examined the influence of auditory spatial cues on the processing of subsequently presented lateralized auditory target stimuli. In three experiments, effects of the position of the cue on event-related potentials (ERPs) and reaction times (RTs) to the target, which could occur at the same or at a different position to the cue, were examined. In Experiments I and II, stimulus-pairs were delivered via loudspeakers 13° to the right or left of fixation. The cue was task-irrelevant in the sense that it never required a response, whereas the target was task-relevant. In Experiment I, the cue was not informative about the position of the succeeding target, that is, the target was presented at the same or at a different position to the cue with equal probability. In Experiment II, the cue predicted a target with high validity, occurring at the position opposite to the cue. In both experiments, the ERPs to targets presented at the same position as the preceding cue were negatively modulated compared with the ERPs to targets presented at a different position. This negative difference (Nd) between the ERPs to same and different position stimuli occurring between 200–300 ms relative to target onset was also obtained in situations where no overt behavior was required. Effects of cue position on RTs to the target were only observed in Experiment II, being shorter for validly predicted targets. These Nd effects either reflect refractoriness of location-specific exogeneous ERP components or involuntary attentional selection. In order to decide between these alternatives, a third experiment was performed, in which stimulus-pairs were presented via headphones to the left and right ear in attend and ignore condition. An Nd effect was obtained in the attend condition only. The absence of Nd effects in the ignore condition suggests that the Nd obtained in attend condition cannot completely be explained by refractoriness of exogeneous ERP components and thus reflects attentional processes.

Keywords: Event-related potential; ERP; Attention; Perception; Reaction time

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PII S0301-0511(96)05192-7

1. Introduction

The present paper is aimed at illuminating effects of spatial auditory cues on the processing of subsequent auditory stimuli as indicated by event-related brain potentials (ERPs) and reaction times (RTs). A possible consequence of spatial cues is that subsequently presented targets are processed differentially depending on the position of the cue. This means that the cue may lead to some form of stimulus selection according to spatial criteria. It is widely accepted that spatial selection can be elicited when the subject attends voluntarily to a particular position in the environment. As indexed by a vast body of ERP and RT research, stimuli occurring at attended positions are indeed processed differentially from those occurring at unattended or less attended positions (for an overview see, e.g., Näätänen, 1992; Posner, 1980). However, spatial selection occurs not only when subjects voluntarily attend to particular positions but also when attention is captured involuntarily by transient events in the periphery even if they are not informative about the position of a forthcoming target stimulus (Eimer, Nattkemper, Schröger, & Prinz, 1996; James, 1890; Näätänen, 1992; Theeuwes, 1991). Indeed, several behavioral studies revealed effects of uninformative spatial cues on the processing of subsequent lateralized visual target stimuli which may be regarded as a consequence of involuntarily triggered attention since subjects were not instructed to select stimuli presented at 'cued' positions. (e.g., Jonides, 1981; Nakayama & Mackeben, 1989). In the visual modality, the ERP effects of lateralized cues on the processing of subsequent targets have already been illuminated (Eimer, 1994a). In the case of the auditory modality, however, there are no studies exploring the ERP effects of the position of task-irrelevant spatial precues on the processing of succeeding lateralized targets.

RT effects of voluntary spatial attention have been reported in visual (e.g., Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980) and auditory studies (Bédard, El Massioui, Pillon, & Nandrino, 1993; Mazzucchi, Cattelani, & Umiltà, 1983; Mondor & Zatorre, 1995; Murray, Allard, & Bryden, 1988; Robin & Rizzo, 1992; Schröger, 1993; Spence & Driver, 1994) employing transient attention tasks, in which a precue indicates the likely position of the next stimulus on a trial-by-trial basis, but stimuli at all positions were relevant for response. Although there are several studies reporting null effects of auditory spatial attention on behavioral measures (Buchtel & Butter, 1988; Posner, 1978), this may be due to the nature of the task employed (cf. Spence & Driver, 1994), as later studies yielded effects of auditory spatial attention on the processing of auditory stimuli. For example, Spence and Driver (1994) reported faster localization and frequency discrimination of lateralized auditory stimuli when they were preceded by an informative lateralized auditory precue. Most recently, Mondor and Zatorre (1995) demonstrated that tone discrimination is faster when the target tone is preceded by a cue validly predicting the location of the target than when it is preceded by an invalid location cue.

Effects of voluntary spatial attention on ERPs have also been reported in visual and auditory studies (for review see, e.g., Näätänen, 1992; Woods, 1990), mostly using sustained attention tasks in which attention had to be oriented to one position for an entire series of stimuli. These ERP studies added to our knowledge about spatial attention in several aspects. They demonstrated, for example, that differential processing of stimuli at attended and unattended positions is present even for stimuli not requiring an overt response. Furthermore, they established that selection according to spatial criteria involves several functionally different processes. In the case of sustained auditory spatial attention, auditory stimuli originating from an attended position were found to elicit several negative ERP deflections compared with ERPs to stimuli from unattended positions. They can easily be identified as negative difference (Nd) in the 'attended minus unattended' ERP difference waveforms. These Nds are generated by at least two functionally different processes: an early modality-specific process presumably indicating initial selection and a later unspecific process probably concerned with 'further' processing (Alho, 1992; Alho, Donauer, Paavilainen, Reinikainen, Sams, & Näätänen, 1987; Alho, Sams, Paavilainen, Reinikainen, & Näätänen, 1989; Alho, Teder, Lavikainen, & Näätänen, 1994; Donald & Young, 1982; Giard, Perrin, Pernier, & Peronnet, 1988; Hansen & Hillyard, 1984; Näätänen, 1982, 1990; Näätänen, Gaillard, & Mäntysalo, 1978; Näätänen & Michie, 1979). Distinct effects of spatial attention on auditory ERPs were also obtained in transient attention conditions in which either the relevant or the most likely position was indicated on a trial-by-trial basis (Schröger, 1993, 1994; Schröger & Eimer, 1993). The comparison of the ERPs to stimuli at attended and at unattended positions revealed Nds in the 100–400-ms range.

As mentioned above, behavioral visual studies demonstrated that visual peripheral onsets may cause reflexive, automatic attentional shifts (see, for example, Jonides 1981; Müller & Rabbitt, 1989). Additional ERP evidence for the hypothesis of the attention-capturing potential of lateralized stimuli comes from the visual domain (Eimer, 1994a). In one of Eimer's experiments, targets could occur at the same location as a preceding peripheral cue or in the opposite visual hemifield with equal probability. ERP modulations to visual target stimuli were found to depend on the position of a preceding uninformative spatial cue although (like in a similar auditory RT-study from Simon, Acosta, & Mewaldt, 1975) RTs were not affected by cue position. Same location targets elicited an enhanced negativity between 130 and 300 ms as compared with the ERP elicited by different location targets. This Nd effect was interpreted as reflecting an enhanced processing of same location stimuli due to a "processing bias in favor of cued locations" (Eimer, 1994a, p. 162).

Also in the auditory domain there is some evidence for the attention capturing potential of lateralized stimuli. In the context of research on hemispheric functional asymmetries, Mondor and Bryden (1992a, 1992b) argue that a lateralized tone given prior to the task-relevant stimulus may pull the subject's attention to the cued ear. The effectiveness of the cue is therefore less dependent on the cooperation of the subject than with situations in which verbal (symbolic) cues are employed. These authors (Mondor & Bryden, 1992b, Experiment 3) found that performance was impaired when the symbolic content of the lateralized tone, which was given prior to the relevant sound, was inconsistent with its position, compared with the situation in which the side of the cue and the to-be-attended ear indicated by the cue's pitch were consistent. This result is indeed consistent with the hypothesis that there were involuntary attentional movements to the side of the lateralized tone. In addition, in recent experiments performed by Spence and Driver (1994) there were not only effects of informative spatial auditory cues on the processing of subsequent target stimuli but, most interestingly, localization of the target was speeded even when uninformative spatial cues were employed.

According to a model proposed by Näätänen (1990, 1992), auditory onsets or offsets may activate a 'transient-detector system' which triggers attentional switches, provided that a variable threshold is exceeded. As inferred from (a) this model regarding auditory transients, (b) the behavioral effects of lateralized tones reported by Mondor and Bryden (1992a, 1992b), (c) the behavioral effects of uninformative spatial precues reported by Spence and Driver (1994), and (d) the visual Nds reported by Eimer (1994a) indicating influences of uninformative spatial cues on the processing of lateralized visual target stimuli, it seems likely that the processing of auditory stimuli may be modulated by the position of a preceding auditory spatial cue. The present study investigated the effects of lateralized auditory cues on the processing of subsequent auditory targets.

The first S1-S2 experiment tested whether differential processing occurred between stimuli preceded by a cue at the same or at a different position. ERPs and RTs to auditory targets, presented either at the same or at a different spatial position relative to a preceding auditory cue, were compared. The cue was task-irrelevant in the sense that it was never connected to a response and that it was not predictive about the position of the target. In one condition, subjects had to respond to the target position. This situation was similar to the previous behavioral study from Simon and colleagues (1975) yielding no RT effects of cue position and the electrophysiological study from Eimer (1994a) also yielding no RT effects but revealing distinct ERP effects of cue position. Therefore, no behavioral effects of stimulus position were to be expected. However, if the lateralized cue triggers attentional switches to the cue position, similar Nd effects as obtained with voluntary transient spatial attention conditions in the auditory (Schröger, 1993, 1994; Schröger & Eimer, 1993) and visual (Eimer, 1993, 1994b, 1995) modality employing informative cues were to be expected. That is, the ERPs to targets presented at the same position as the cue should be negatively modulated compared with the ERPs to stimuli presented at a different position. In an additional control condition, in which position was not relevant at all, there were two kinds of S2 stimuli, namely, a low-probability deviant stimulus and a high-probability standard stimulus. Subjects had to count randomly occurring deviants. This control condition was performed to evaluate whether effects of the cue position on the processing of the subsequent target depend on overt behavior and to evaluate whether they only occur when position is important for response selection.

In a second experiment, the position of the cue was informative about the spatial position of the subsequent target in the sense that it predicted, with high validity, a target occurring at the opposite side. Since the cue was informative about the position of the target, subjects were expected to utilize this stimulus contingency. That is, the information about the forthcoming target stimulus contained in the position of the cue may be expected to induce 'voluntary' attentional switches to the symbolically cued side. Consequently, as in previous studies employing informative cues, RTs to validly cued stimuli were expected to be shorter than RTs to invalidly cued stimuli (Bédard, El Massioui, Pillon, & Nandrino, 1993; Mazzucchi, Cattelani, & Umiltá, 1983; Mondor & Zatorre, 1995; Murray, Allard, & Bryden, 1988; Robin & Rizzo, 1992; Schröger, 1993; Spence & Driver, 1994). On the other hand, the lateralized cue may also be expected to trigger 'involuntary' attentional switches to the physically cued side since it is a transient event. No particular expectations about effects of cue position on the ERPs can be formulated since it is possible that they largely reflect either voluntary or involuntary attention, or it could even be that there are no ERP effects at all.

Unlike experiments employing centrally presented cues, the usage of lateralized cues has the consequence that target stimuli are preceded by a cue presented at the same or at a different location. This means that Nd effects obtained with lateralized cues may, in principle, be due to refractoriness effects on exogeneous ERP components. Such a refractoriness explanation would argue against an interpretation of the Nd effects in terms of involuntary attentional selection. In order to evaluate a simple refractoriness explanation, a third experiment was performed. It was run under an attend condition, in which a response to the position of the target had to be performed, and under an ignore condition, in which subjects were reading a book and were instructed not to pay attention to the auditory stimuli. If comparable Nd effects were present in attend and in ignore conditions, this would argue in favor of the refractoriness hypothesis, whereas larger Nds in the attend as compared with the ignore condition (or the absence of an Nd in the ignore condition) would be in favor of the involuntary attentional selection hypothesis.

2. Experiment I

2.1. Methods

2.1.1. Subjects

Nine paid subjects were employed (3 males; mean age 27.6 years).

2.1.2. Stimuli and apparatus

Sound pairs were presented via loudspeakers either 13.3° to the right or 13.3° to the left of fixation. The first sound of the pair (S1) was a bandbass filtered white noise with frequency limits of 1000 and 2000 Hz. The second sound of the pair (S2) was a bandbass filtered white noise with frequency limits of 1 and 1000 Hz. Each sound lasted 100 ms, the silent inter-stimulus intervals (ISI; offset of S1 to onset of S2) were 300, 500 or 700 ms. The inter-trial interval (offset of S2 to onset of the next pair) was 2 s. The loudspeakers from which the sounds were delivered were fixed on the left and on the right side of a display placed 100 cm in front of the subjects, straight-ahead line of sight. Sounds had an intensity of about 80 dB SPL at head position (measured with an impulse sound level meter from Rhode & Schwarz). Subjects were seated in a reclining chair in an electrically and acoustically shielded cabin.

2.1.3. Procedure

In the first phase of the experiment, 10 blocks each consisting of 120 trials (i.e., sound pairs) were run. S2 required a button-press response with the right index finger when it was delivered from the right loudspeaker, and a button-press response with the left index finger when it was delivered from the left. The probability that the two sounds within a pair were delivered from the same position was 0.5. The sounds were delivered with equal probability from the left and right speakers. The different ISIs (300, 500 and 700 ms) had equal probability. In the second phase of the experiment, two blocks (each containing 180 trials) were run in which S2 occasionally was reduced in sound pressure level by an amount of 25 dB SPL ($p = 0.10$). Subjects were asked to count these infrequently occurring events, irrespective of the position from which they were delivered. In these blocks, the constant ISI was 500 ms. S2 that were delivered from the same side as S1 are referred to as 'same position stimuli' and contralaterally presented S2 are referred to as 'different position stimuli'. Subjects were instructed to respond as quickly and accurately as possible. They were asked to maintain central fixation.

2.1.4. Recording

The EEG was recorded from 3 channels with Ag-AgCl electrodes. Recordings were made from electrode sites, Fz, Cz, Pz, all referenced to the right mastoid. The horizontal and vertical EOG were recorded from electrodes at the outer canthi of both eyes and from an electrode above the right eye, respectively. The EEG was amplified with a filter-bandwidth of 0.10–70 Hz and stored on a computer disc (sampling rate was 160 Hz). The recordings were epoched off-line into periods of 800 ms, including a pre-stimulus baseline of 100 ms relative to the onset of S2. Trials with either EOG exceeding ± 115 μV or with EEG exceeding ± 50 μV relative to the baseline were rejected from further analysis to avoid artifacts resulting from eye blinks or movements.

2.1.5. Data analysis

Averaging was conducted for same and for different position stimuli, separately for the three different ISIs. Frequencies higher than 30 Hz were digitally filtered (24 dB/octave). Difference waves were computed by subtracting the ERPs to different position stimuli from the ERPs to same position stimuli ('same-different' waves). Mean amplitudes of the ERPs to same and different position stimuli were computed unattended positions (Eimer, 1993, 1994b, 1995; Schröger, 1993, 1994; Schröger & Eimer, 1993). In the case of informative cues, Nd effects may be interpreted as waves). To establish the presence of the Nd1, one-tailed paired t-tests between the mean amplitudes of same and different position ERPs were performed at Pz where the Nd1 usually is the most prominent; to establish the presence of the Nd2, t-tests were performed at Cz where the Nd2 has its largest amplitude (cf. Schröger, 1993, 1994; Schröger & Eimer, 1993). Repeated measures analyses of variances (ANOVAs) were performed with Position (levels: same, different), ISI (levels: 300, 500, 700 ms), and Electrode Site (levels: Fz, Cz, Pz) as within-factors, separately for the mean amplitudes in the Nd1- and Nd2-intervals. In the counting condition, ERPs to standard stimuli were computed accordingly. ANOVAs were performed with Position and Electrode Site as within-factors. However, only significant main effects of Position and interactions including Position as one factor will be reported.

RTs shorter than 100 ms and longer than 700 ms were excluded from further analysis. RTs of each subject were averaged, separately for same and different position stimuli, for left and right stimuli, and for the different ISIs. A repeated measures analysis of variance was performed with Position, ISI, and Side of Presentation (levels: left, right) as within-factors. For all ANOVAs, Greenhouse-Geisser corrections were performed when appropriate. Post-hoc contrasts were performed with the Scheffé test. Alpha-level was 0.05 for all statistical analyses.

2.2. Results of Experiment I

2.2.1. RT data

Table 1 contains the mean RTs of Experiment I for the factors Position and ISI. The ANOVA revealed a significant main effect for the factor ISI ($F(2,16) = 15.40$, $p < 0.002$, $\epsilon = 0.61$; Scheffé's critical difference = 18 ms). That is, the RTs with an ISI of 300 ms tended to be slower as compared with RTs when the ISI were 500 ms or 700 ms (328 ms vs. 311 and 312 ms, respectively). There was also a significant Position × ISI interaction ($F(2,16) = 12.35, p < 0.001, \epsilon = 0.99$), which was mainly due to slower RTs to same compared with RTs to different position stimuli (320 vs. 305 ms) with the 700-ms ISI (Scheffé's critical difference = 8 ms). The main effects of Side of Presentation and Position as well as the remaining two-way and three-way interactions were not statistically significant.

2.2.2. ERP data

Figure 1 shows the ERPs to same and different stimuli, separately for the 300-, 500- and 700-ms ISIs. Figure 2 shows the corresponding 'same-different' subtraction waves. Generally, the ERPs to same position stimuli were negatively modulated compared with the ERPs elicited by different position stimuli, or, vice versa, there was an enhanced positivity in the ERPs to different position stimuli compared with those to same position stimuli. This effect was largest between 200 and 300 ms at central electrode sites. It occurred in the condition in which subjects had to respond to position and in the control condition, where subjects had to count intensity decrements of S2.

2.2.3. Response to position

In the Nd1-interval, the ERPs revealed a negative modulation for ERPs to same

Table 1
Mean reaction times (ms) and corresponding standard errors to same and different position stimuli for the different ISIs (Experiment I)

	ISI (ms)					
	300		500		700	
	Mean	(S.E.)	Mean	(S.E.)	Mean	(S.E.)
Same position	326	(13)	311	(12)	320	(15)
Different position	330	(12)	312	(13)	305	(13)

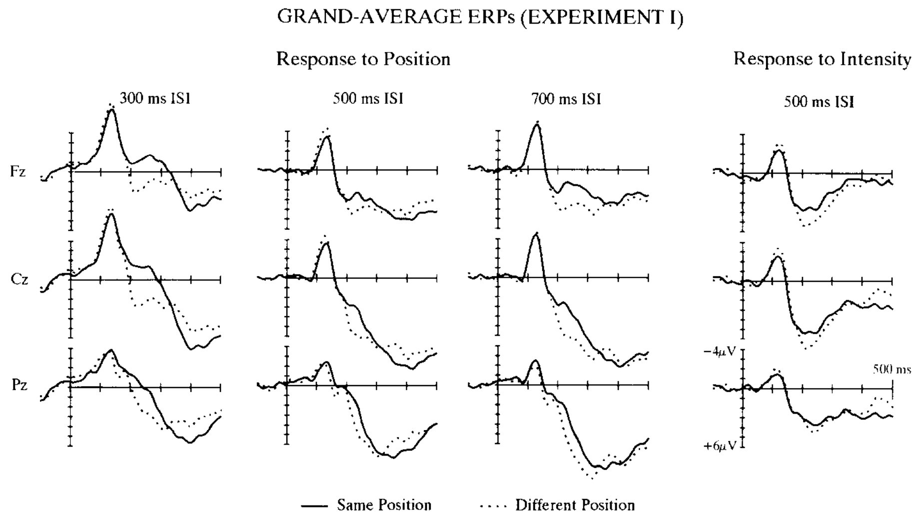

Fig. 1. Grand-average ERPs elicited by same and different position stimuli, separately for the different ISI conditions and response requirements (Experiment I).

position stimuli at Pz. The differences in mean amplitudes at Pz between same and different position stimuli in the Nd1-interval were −0.84, −0.93, and −0.92 μV for the 300-, 500-, and 700-ms ISIs, all being statistically different from zero (*t*-values = 2.29, 2.51 and 1.97, *p*-values < 0.05). The parietal topography of the Nd1 was reflected in a significant Position × Electrode Site interaction of the ANOVA ($F(2,16) = 21.05, p < 0.001, \epsilon = 0.97$; Nd1 at Fz, Cz, and Pz: 0.29, 0.07, −0.89 μVs; Scheffé's critical distance = 1.21 μV). In the Nd2-interval, the ERPs to same position stimuli were negatively modulated compared with the ERPs to different position stimuli. The differences in mean amplitudes at Cz between same and different position stimuli in the Nd2-interval were 3.31, 1.66, and 2.40 μV for the 300-, 500- and 700-ms ISI. These Nd2 amplitudes were statistically different from zero (*t*-values = 6.55, 2.29 and 4.36, *p*-values < 0.01). The ANOVA yielded a main effect of Position ($F(1,8) = 28.45, p < 0.001$) and a position × ISI interaction ($F(2,16) = 4.40, p < 0.046, \epsilon = 0.74$; Scheffé's critical distance = 1.41 μV) indicating that the Nd2 amplitudes differed between the ISI conditions. The mean Nd2 amplitudes (collapsed across midline electrodes) in the 300-, 500- and 700-ms ISI conditions were −2.66, −1.40, and −2.19 μV, respectively. Although the smallest Nd2 occurred with an ISI of 500 ms, it was not statistically different from the Nd2 obtained with an ISI of 300 or 700 ms.

2.2.4. Response to intensity (control condition)

There were no statistically significant effects in the Nd1-interval. In the Nd2-interval, the ERP to same position stimuli were negatively modulated compared with the ERPs to different position stimuli. However, at Cz the ERP difference of −1.11 only approached significance ($t = 1.80$, $p = 0.055$); the Fz difference of −1.39 was significant ($t = 3.59$, $p < 0.01$). The ANOVA revealed a marginal significant main effect of Position ($F(1,8) = 4.29$, $p < 0.072$) and a significant Position × Electrode Site interaction ($F(2, 1) = 5.10$, $p < 0.032$, $\epsilon = 0.75$).

2.3. Discussion of Experiment I

2.3.1. RT data

The finding of prolonged RTs with an ISI of 300 ms compared with RTs when the ISIs were 500 ms and 700 ms is consistent with results from experiments using variable-ISI in simple reaction experiments. Usually, simple RT is longest after the shortest ISI (for review, see Niemi & Näätänen, 1981). This effect seems to be due to the highest uncertainty of presentation of the response stimulus with the shortest ISI and to increasing probability of stimulus presentation with longer intervals. A similar decrease of RT with increasing ISI was also reported in recent studies employing spatial auditory cues (Mondor & Zatorre, 1995; Spence & Driver, 1994) where it was interpreted as "a temporal advantage for targets at longer SOAs" (Spence & Driver, 1994, p. 559) or it seemed to be possible "that the cue acts non-specifically to alert the participant that a target is about to be presented" (Mondor & Zatorre, 1995, p. 392). The RT difference between same and different position stimuli when the ISI was 700 ms is similar to data from visual experiments where RTs to same position stimuli were prolonged compared with those to different position stimuli, which were interpreted as reflecting an 'inhibition of return' (Maylor & Hockey, 1985; Posner, Rafal, Choate, & Vaughan, 1985; Woods, Alho, & Algazi, 1992). However, such interpretation should be handled with caution since this concept refers to the visual modality. There was no Position main effect with RT as dependent variable. This absence of RT effects was also found in other auditory (Simon et al., 1975) and visual (Eimer, 1994a) studies employing uninformative lateralized cues. However, there were distinct ERP effects indicating that same and different position stimuli were processed differentially.

2.3.2. ERP data

The observed Nd effects (Figs. 1 and 2) reflect processing differences between same and different position stimuli. Before interpreting them as a result of involuntary attentional selection, alternative hypothesis have to be considered. There are two possible alternative hypotheses: the Nd effects could be due to differential resolution times of the contingent negative variation (CNV), or due to location-specifity of exogeneous ERP components (e.g., the P2) leading to a differential state of refractoriness of the ERP components elicited by same and different position stimuli. The hypothesis of differential CNV resolution times is not very likely since differential CNV resolution times should have been accompanied by corresponding latency differences in behavioral measures (McCallum, 1988; for a similar argument, see also, Mangun & Hillyard, 1991, p. 1068).

The hypothesis of a simple refractoriness mechanism according to which neurons

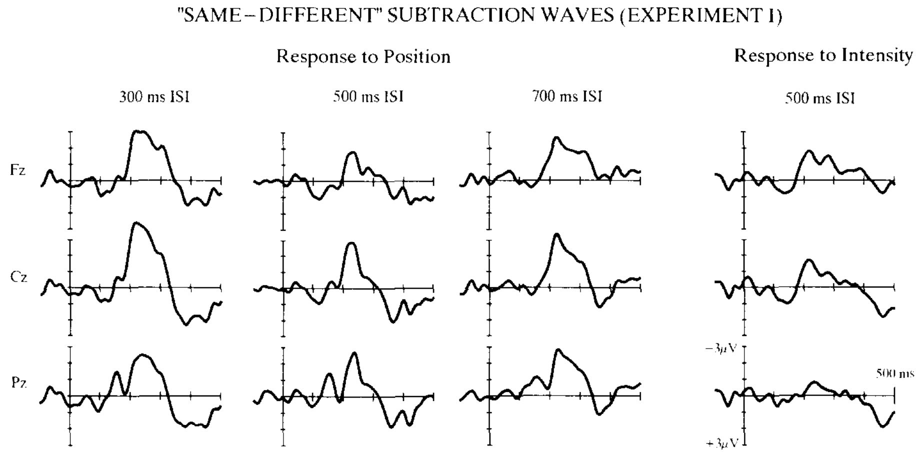

Fig. 2. Difference waves where the ERPs elicited by different position stimuli were subtracted from those elicited by same position stimuli, separately for the different ISI conditions and response requirements (Experiment I).

sensitive to spatial position are less responsive in the case of same position stimuli holds for the small N1 decrease to same position as compared with different position stimuli (Fig. 1). A slight location specificity of the N1 component and a larger location specificity of the magnetoencephalographically measured N100m have also been reported from other studies (Butler, 1972; McEvoy, Hari, Imada, & Sams, 1993; Näätänen, Sams, Alho, Paavilainen, Reinikainen, & Sokolov, 1988). The negativity in the Nd1-interval, however, cannot be explained by refractoriness since an enlarged negativity to different position stimuli would have been predicted by this hypothesis. It seems also unlikely that the Nd2 can be sufficiently explained by the refractoriness hypothesis, since (a) increasing ISIs should have led to decreasing ERP effects in the Nd2 range and (b) location specifity in the P2 range has not been reported in those studies examining location-specifity of ERP components (e.g., Näätänen et al., 1988). However, for the Nd2, the refractoriness hypothesis cannot be completely ruled out on the basis of the present data.

Alternatively, the Nd effects may be interpreted in attentional terms. Similar ERP effects have been reported from transient voluntary spatial attention experiments employing central cues: ERPs to visual or auditory stimuli presented from attended positions were found to be negatively modulated as compared with stimuli from unattended positions (Eimer, 1993, 1994b, 1995; Schröger, 1993, 1994; Schröger & Eimer, 1993). In the case of informative cues, Nd effects may be interpreted as indicating voluntary attentional selection, that is, enhanced processing of stimuli being characterized by a relevant spatial feature, or, vice versa, as indicating inhibition or impoverished processing of stimuli being presented at an irrelevant, to-be-ignored position. In the present Experiment I, it seems that the cue tunes the system to 'select' same position stimuli. There was no necessity (due to the instruction) and no benefit (due to equal probabilities of same and different position stimuli) to treat same position stimuli in a different way than different position stimuli. Yet, the Nd effects indicated that same and different position stimuli were processed differentially. Therefore, the 'selection' of same position stimuli appeared to be triggered automatically or involuntarily in the sense that it was executed without explicit instruction and intention. It seems as if the cue triggered involuntary attention switches to its position.

The present ERP effects in the auditory modality are consistent with ERP effects of lateralized visual stimuli reported by Eimer (1994a). In this experiment, which employed a constant ISI of 700 ms, subjects had to respond to target identity in one condition and to target position in another. With uninformative spatial visual cues, no RT differences between same and different position stimuli were obtained whereas there were distinct ERP effects in both conditions. The Nd2 effects obtained in the visual and auditory experiments were of comparable latencies and amplitudes. Furthermore, the Nd1 effects had peak latencies of about 150 ms in both cases although their amplitudes were larger in the visual experiment. Thus, the present data are consistent with the hypothesis of several authors (e.g., Mondor & Bryden, 1992a, 1992b; Shimojo, Miyauchi, & Hikosada, 1992; Spence & Driver, 1994) that lateralized auditory stimuli may pull attention to the cued position. It may be argued that the lateralized cue affected target processing since position was relevant for performing the task. This, however, would not explain the Nd2 effects occurring in the control condition where any low-intensity target had to be counted, irrespective of the position where it was presented. This finding suggests that the differential processing of same and different position stimuli does not necessarily depend (a) on overt responses and (b) on the task-relevance of spatial position. It should be noted that the differential processing of same and different position stimuli as indicated by ERPs was not reflected in RTs. This divergence of ERP and RT results could be due to an uncoupling of the processes responsible for the ERPs and RTs or to a ceiling effect preventing RT effects to occur (see Section 5, General discussion).

3. Experiment II

In order to study whether a lateralized cue still affects the processing of a subsequent lateralized stimulus even when the cue predicts with high validity a different position stimulus, a second experiment was performed. In Experiment II, everything was kept identical to Experiment I, except that the cue was followed by a different position target in most trials. Since the cue was informative about target position in this case, an expectancy of different position stimuli or different position reactions should occur (e.g., Mondor & Zatorre, 1995; Spence & Driver, 1994), resulting in RT benefits of different position as compared with same position stimuli. On the contrary, the ERPs might reveal enhanced negativities to same position stimuli if the lateralized cue involuntarily captures attention.

3.1. Methods

3.1.1. Subjects

Nine paid subjects were employed (5 males; mean age 25.3 years). None of these subjects (except one) participated in Experiment I.

3.1.2. Stimuli, apparatus, recording and data analysis

Stimuli, apparatus, recording and data analysis were identical to Experiment I.

3.1.3. Procedure

Twenty-five percent of the S2 were same position stimuli, that is, they were preceded by an ipsilateral S1, and 75% of the stimuli were different position stimuli, that is, they were preceded by a contralateral S1. During the first 10 experimental blocks (120 trials each), S2 required a button-press response with the right index finger when it was delivered from the right loudspeaker, and a button-press response with the left index finger when it was delivered from the left. At the end of the experiment, two additional blocks (each containing 180 sound pairs) were run, where the subjects were asked to count any (infrequently occurring) S2 which was reduced in intensity ($p = 0.10$). In these blocks, the ISI was 300 ms. Everything else, for example the proportion of same and different position stimuli, was kept identical to the first experiment.

3.2. Results of Experiment II

3.2.1. RT data

Table 2 contains the mean RTs of Experiment II for the factors Position and ISI. RTs were longer to same than to different position stimuli (main effect Position: $F(1,8) = 22.52, p < 0.001$). There was a Position × ISI interaction ($F(2,16) = 6.93, p < 0.008, \epsilon = 0.94$) indicating smallest effects of position with the 700-ms ISI as compared with the 500- and 300-ms ISIs (58 ms vs. 77 and 74 ms, respectively; Scheffé's critical distance = 15 ms). There was an additional main effect of ISI ($F(2,16) = 5.58, p < 0.021, \epsilon = 0.83$). The RTs were slower with the 300-ms ISI as compared with the 500-ms and 700-ms ISIs (359 ms vs. 346 and 350 ms). However, Scheffé's test did not yield significant differences between these values (critical distance = 22 ms).

3.2.2. ERP data

Figure 3 shows the ERPs to same and different stimuli, separately across the different ISIs. Figure 4 shows the corresponding 'same-different' subtraction waves at central electrode sites, separately for the 300-, 500- and 700-ms ISIs. In the Nd2-

Table 2
Mean reaction times (ms) and corresponding standard errors to same and different position stimuli for the different ISIs (Experiment II)

	ISI (ms)					
	300		500		700	
	Mean	(S.E.)	Mean	(S.E.)	Mean	(S.E.)
Same position	397	(26)	383	(25)	379	(25)
Different position	320	(14)	308	(14)	321	(14)

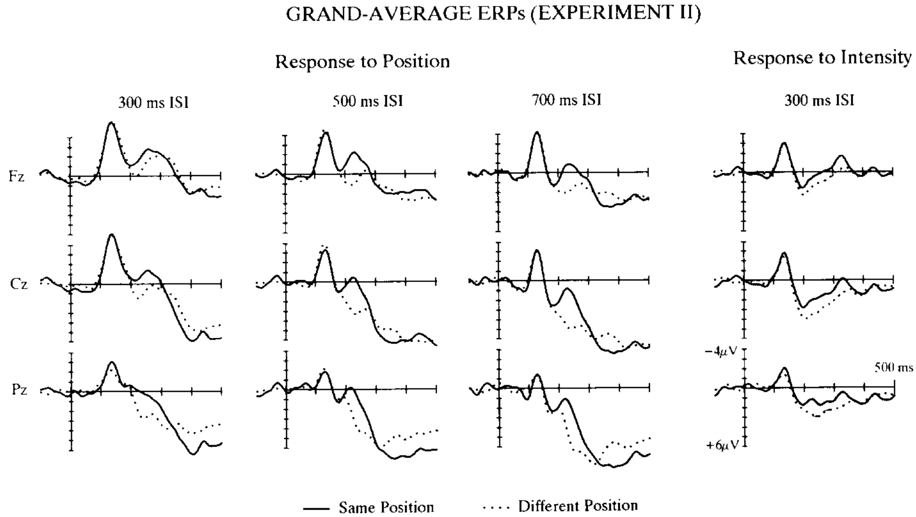

Fig. 3. Grand-average ERPs elicited by same and different position stimuli, separately for the different ISI conditions and response requirements (Experiment II).

intervals of both conditions, the ERPs to same position stimuli were negatively modulated as compared with the ERPs elicited by different position stimuli. No distinct Nd1 can be identified.

3.2.3. Response to position

In the Nd1-interval, the differences in mean amplitudes at Pz between same and

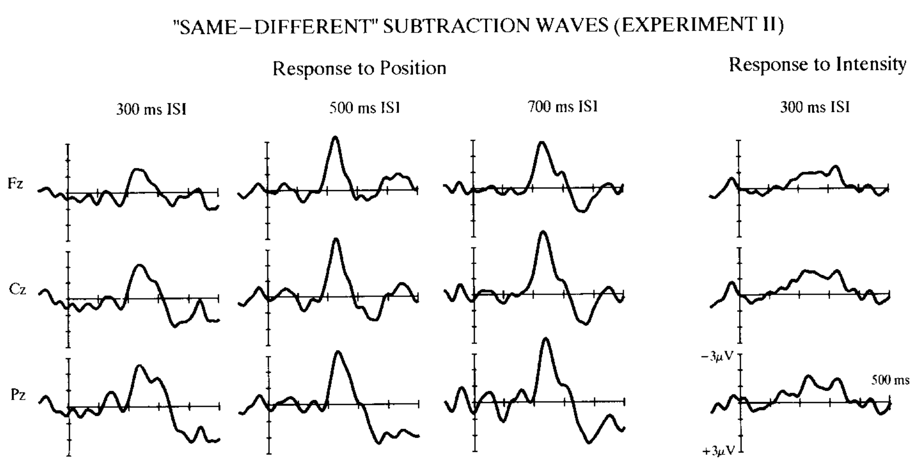

Fig. 4. Difference waves where the ERPs elicited by different position stimuli were subtracted from those elicited by same position stimuli, separately for the different ISIs (Experiment II).

different position stimuli were not statistically significant (300-, 500- and 700-ms ISIs: −0.60, 0.03, −0.43 μV). However, the ANOVA yielded a Position × Electrode Site interaction ($F(2,16) = 6.12$, $p < 0.023$, $\epsilon = 0.70$; Scheffé's critical distance = 0.58 μV). This interaction results from the fact that the same-different position differences were more negative at Pz (−0.33 μV) compared with Fz, where they were positive (0.24 μV).

In the Nd2-interval, the Cz ERPs to same position stimuli were negatively modulated compared to ERPs to different position stimuli with each ISI (300-, 500- and 700-ms ISIs: −1.52, −1.82 and −2.38 μV; t-values = 2.81, 1.87 and 4.57, p-values < 0.05). The ANOVA yielded a main effect of position ($F(1,8) = 28.34$, $p < 0.001$) (Figs. 3 and 4). There was no interaction involving the Position factor.

3.2.4. Response to intensity (control condition)

In the Nd2-interval, the Cz comparison between the ERPs to same and different position was −1.10 μV ($t(8) = 2.33$, $p < 0.024$). The ANOVA yielded a significant main effect of Position ($F(1,8) = 6.94$, $p < 0.030$; Figs. 3 and 4).

3.3. Discussion of Experiment II

3.3.1. RT data

First, the ISI main effect obtained in Experiment I was replicated in Experiment II. Similar to Experiment I, RTs were longest with the 300-ms ISI, presumably due to highest uncertainty of stimulus presentation or to an alerting effect that is increasing with ISI. Second, the predicted RT difference between different compared to same position stimuli indicates that the subjects made use of the information that the first sound of the pair is highly validly followed by a contralateral second sound. These results are consistent with results from trial-by-trial experiments in the visual and auditory modality when informative cues were employed to direct spatial attention (e.g., Eimer, 1993; Mondor & Zatorre, 1995; Robin & Rizzo, 1992; Schröger, 1993; Spence & Driver, 1994).

3.3.2. ERP data

In contrast to Experiment I, no clear (significant) Nd1 could be identified in Experiment II. This seems to indicate that part of the effects of cue position on the processing of the target stimulus are absent or reduced when stimulus contingencies suggest an expectancy for a different position stimulus. Nevertheless, the Nd effects observed in the Nd2-interval (Figs. 3 and 4) still reveal differential processing of same as compared with different position stimuli. These effects cannot be fully accounted for by movement-related processes since there was also an Nd effect in the counting condition. Provided that they cannot completely be explained by the refractoriness hypothesis, the Nd effect either results from the lower probability of same compared with different position stimuli or from some kind of attentional selection. The finding that low-probability auditory stimuli usually elicit negative ERP modulations, namely, the MMN and the N2b components (e.g., Ritter, Paavilainen, Lavikainen, Reinikainen, Alho, Sams, & Näätänen, 1992; for review, see Näätänen, 1990, 1992), is consistent with the first hypothesis. Furthermore, the morphology of the ERP waveforms show a clear frontally maximal peak in the 200–300-ms range, which could reflect an N2b. Nevertheless, there are two differences between experiments studying MMN or N2b components and the present Experiment II. First, low-probability stimuli eliciting the MMN and N2b (usually) deviate in some physical feature from high-probability standard stimuli, such as being of lower intensity or of higher frequency. However, MMN-like effects have also been obtained with deviations from abstract stimulus features (Saarinen, Paavilainen, Schröger, Tervaniemi, & Näätänen, 1992; Tervaniemi, Maury, & Näätänen, 1994). In the present experiment, there was no physical difference between same and different position stimuli. They only differed with respect to the position relative to the preceding S1. Thus, it is not a physical difference per se but a higher-level difference that distinguishes low-probability from high-probability stimuli. Therefore, if the Nd really results from differential probabilities, it might be regarded as indicating the violation of a particular rule about the positions of the sounds as they succeed in time. Second, the MMN and N2b usually reveal a frontocentral distribution with rather small effects on Pz. In Experiment II, the Nd effect at Pz is of comparable amplitude than the one at Fz. This suggests that the Nd effect is not (only) reflecting an MMN-N2b and is therefore not completely due to a difference in probability.

According to the second hypothesis, the Nd effects reflect a selection of the target according to their position in respect to the position of the preceding cue. This hypothesis is in line with the explanation of ERP modulations observed in Experiment I. The similarities in results between Experiments I and II, regarding Nd2 amplitudes and latencies (cf. Figs. 1–4), support this hypothesis. Nevertheless, on the basis of the present data the hypothesis of the violation of an implicit rule about the relative positions of two succeeding events and the hypothesis of an attentional tuning to the position of the preceding lateralized cue might both be true.

While the ERP data seem to indicate a selection of same position stimuli (possibly due to an involuntary attention switch to the physically cued position), the RT data seem to indicate a selection of different position stimuli (possibly due to a voluntary attention switch to the symbolically cued position). This inconsistency can be resolved by assuming two uncoupled processes, a tuning for the selection of same position stimuli and a bias to respond to different position stimuli. Thus, the RT effect does not reflect a selection of different position stimuli but some other attentional process, for example, a selection of a different position response.

4. Experiment III

Experiments I and II revealed processing differences (indexed by the Nd) between stimuli preceded by a same and by a different position cue. In principle, these Nd effects can be attributed to a simple refractoriness mechanism of exogeneous ERP components or to some kind of attentional selection, that is, for example, increased processing of same position stimuli or reduced processing of different position stimuli. Although it does not seem to be likely that these effects only reflect differential refractory times of location-specific exogeneous ERP components (see above), this alternative cannot completely be ruled out with the present data. To determine the influence of location-specifity of exogeneous ERP components on the Nd effects, a control experiment was performed in which series of S1-S2 trials were delivered in attend and in ignore condition. The refractoriness hypothesis has to predict similar Nd effects in both experimental conditions, whereas the involuntary attentional selection hypothesis would expect Nd effects to be smaller (or even absent) when stimuli are not sufficiently processed (as in the case of the ignore condition).

4.1. Methods

4.1.1. Subjects

Eight new subjects (2 males; mean age 37 years), students of a seminar in cognitive psychophysiology, participated in the experiment. Subjects were naive about the experimental hypothesis.

4.1.2. Stimuli

Pairs of tones were delivered via headphones to the left and right ear of the subject. S1 (1000 Hz, 50 ms, 70 dB SPL, 5-ms rise and fall times) were followed by S2 (500 Hz, 50 ms, 70 dB SPL, 5-ms rise and fall times) at the same or at the different ear. The inter-trial interval (offset of S1 to onset of S2) was 700 ms. Subjects were seated in a reclining chair in an electrically and acoustically shielded cabin.

4.1.3. Procedure

Two blocks each consisting of 200 trials were run. In one block (attend condition), S2 required a button-press-response with the left index finger when it was delivered to the left ear, and a button-press response with the right index finger when it was delivered to the right ear. The probability that the two tones within a pair were presented to the same ear was 0.5. In the other block (ignore condition), subjects were instructed to read a book and to ignore the auditory stimuli. The order of the attend and ignore conditions was counterbalanced across subjects.

4.1.4. Recording

The EEG was recorded from 5 channels with Ag-AgCl electrodes. Recordings were made from electrode sites Fpz, Fz, Cz, Pz, and at the outer canthus of the left eye. All channels were referenced to the nose. Horizontal and vertical eye movements were monitored with the recordings from the electrodes placed at the outer canthus of the left eye and Fpz, respectively. The EEG was amplified with a filter-bandwidth of 0.10–40 Hz and stored on a computer disc (sampling rate was 200 Hz). The recordings were epoched off-line into periods of 1500 ms, starting 100 ms before the onset of S1. Baseline was set to the 100-ms interval preceding S2. Trials exceeding $\pm$ 50 μV relative to the baseline were rejected from further analysis to avoid artifacts resulting from eye blinks or movements.

4.1.5. Data analysis

Averaging was conducted for same and for different position stimuli, separately for the attend and ignore conditions. Frequencies higher than 30 Hz were digitally filtered out from the individual ERPs (24 dB/octave). Measurement and statistical analyses of the Nd1 and Nd2 amplitudes were identical to Experiments I and II.

4.2. Results of Experiment III

4.2.1. RT data

No significant difference in the mean RTs for same and different position S2 stimuli was obtained (444 ms vs. 436 ms). Right-hand responses to S2 stimuli were slightly faster (429 ms) than were left-hand responses (451 ms). However, this difference also failed to reach statistical significance.

4.2.2. ERP data

Figure 5 shows the ERPs elicited by same and different position stimuli as well as the corresponding subtraction waves, separately for the attend and ignore conditions. In the attend condition, the ERPs elicited by same position stimuli showed a negative modulation as compared to the ERPs elicited by different position stimuli which was again largest between 200 and 300 ms post-stimulus. In contrast, no such effect was present for the ignore condition.

These informal observations were further investigated by statistical analyses. No effect of cue position could be obtained in the Nd1-interval. For the Nd2-interval, however, the same-different position comparison at Cz revealed a significant difference of $-2.15\ \mu V$ ($t(7) = 3.40, p < 0.01$) in the attend condition but not in the ignore

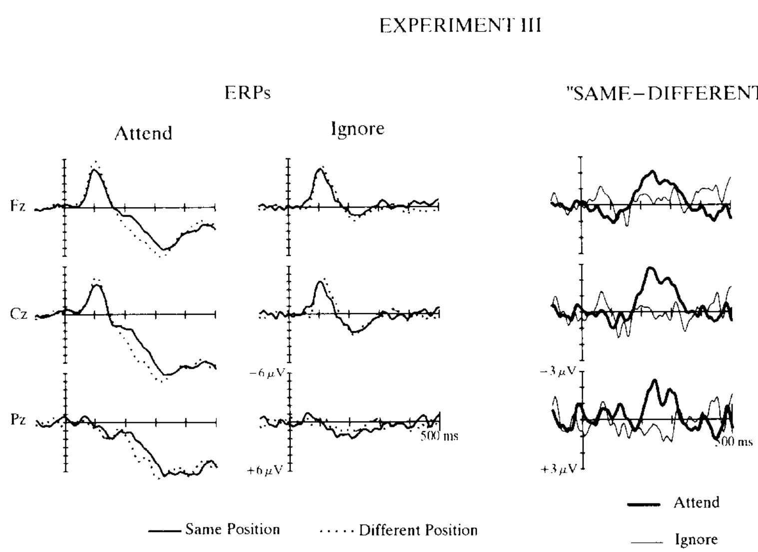

Fig. 5. Left: Grand-average ERPs elicited by same and different position stimuli in attend and in ignore condition (Experiment III). Right: Corresponding difference waves where the ERPs elicited by different position stimuli were subtracted from those elicited by same position stimuli.

condition in which the difference was 0.08 μV ($t(7) = 0.13$, $p = 0.90$). The ANOVA yielded a significant Position main effect in the attend condition ($F(1,7) = 10.27$, $p < 0.015$), whereas there was no effect of cue position in the ignore condition ($F(1,7) = 0.09$, $p > 0.77$). The difference between the attend and ignore conditions was reflected in a marginally significant Experimental Condition × Position interaction ($F(1,7) = 4.42$, $p < 0.074$) and a significant Experimental Condition × Position × Electrode Site interaction ($F(2, 14) = 5.55$, $p < 0.025$; $\epsilon = 0.82$).

4.3. Discussion of Experiment III

4.3.1. RT data

Similar to previous studies (Experiment I; Eimer, 1994a; Simon et al., 1975) in which the cue was not informative about the position of the forthcoming target, there was no RT effect of the cue position in Experiment III. Since Spence and Driver (1994) convincingly demonstrated effects of cue position on target processing when subjects had to perform a location discrimination (but not when they performed a frequency discrimination), the effectiveness of the position of uninformative precues seems to be highly sensitive to the nature of the task.

4.3.2. ERP data

In the attend condition, Experiment III yielded a distinct modulation of the ERPs to target stimuli in the Nd2 range depending on whether it was a same or a different position stimulus. In the ignore condition, however, no Nd effects occurred. The absence of an Nd in the ignore condition argues against the simple refractoriness hypothesis according to which the Nd2 results from differential P2 refractoriness between same and different position stimuli. This suggests that the Nd2 obtained in Experiments I and II cannot be explained by refractoriness effects due to location-specifity of exogeneous ERP components in the 200–300-ms range. That is, the Nd2 reflects some other processing difference between same and different position stimuli, probably some form of attentional selection triggered by the spatial position of the cue[1]. The absence of an Nd effect in the ignore condition suggests that the form of attentional selection reflected in the Nd2 is not strongly automatic in the sense that it is elicited even when the auditory stimuli are not attended.

5. General discussion

5.1. Attentional interpretation of the Nd

The present ERP results revealed differential processing of target stimuli caused by task-irrelevant positional information of a preceding lateralized cue even when

[1] There is some debate about whether the P2 is modulated by attention (Goodin, Squires, Henderson, & Starr, 1978; Goodin, Squires, & Starr, 1983). If there exists an attention-dependent P2-subcomponent it cannot be ruled out that it may be prone to refractoriness. However, even then the Nd effect may be regarded as not reflecting a simple refractoriness mechanism but some form of selection due to attentional processes.

cue position was not informative about the position of the target (Experiment I and III) or when cue position highly validly predicted a different position target (Experiment II). Experiment I yielded almost identical results to the very similar visual study of Eimer (1994a): in both the visual and the auditory experiments, there were no RT effects of cue position but distinct ERP modulations in the Nd1- and Nd2-intervals. This suggests that the differential processing of same and different position stimuli is not modality-specific. In addition, the absence of any effect of cue position for the S2 ERPs in the ignore condition of Experiment III strongly argues against a simple refractoriness explanation of the Nd effects according to which exogeneous ERP components to same position stimuli are (due to location-specifity) more refractory than those to different position stimuli. Therefore, similar to several visual, auditory and auditory-visual behavioral experiments demonstrating effects of uninformative cues on the processing of subsequent targets (e.g., Nakayama & Mackeben, 1989; Shimojo et al., 1992; Spence & Driver, 1994), the present data support theories asserting that lateralized stimuli may affect processing of subsequent stimuli due to attentional capture triggered by the task-irrelevant positional information of these 'cues' (e.g., Eimer et al., 1996; Näätänen, 1990, 1992; Theeuwes, 1991).

In sum, this differential processing seems to be initiated automatically or involuntarily in the sense that there was no instruction, no intention, and no advantage to perform it. Furthermore, this differential processing does not rely on the fact that the spatial position is relevant for performing the task. This is shown by the presence of Nd effects in the control conditions of Experiments I and II where any low-intensity stimulus has to be counted (irrespective of which position it was presented on). Nevertheless, the findings that the Nd1 effects were absent in these control conditions as well as in the attend condition of Experiment III and that the Nd2 tended to be smaller when position was not relevant for performing the task suggest that effects of cue position may be modulated by the task relevance of positional features. In addition, the absence of an ERP effect of cue position on the processing of the subsequent target in the ignore condition of Experiment III suggests that cue position is effective only when the cue is sufficiently processed.

5.2. Comparison of the present Nd effects with other Nd effects

The present Nd effects are similar to those observed in the case of transient voluntary auditory spatial attention studies in which attention was oriented on a trial-by-trial basis by means of centrally presented symbolic cues (Schröger, 1993, 1994; Schröger & Eimer, 1993) or by means of lateralized cues (Schröger, Wolff, Tschakert, & Schubö, in press). The present S1-S2 experiment may also be regarded as a transient attention situation, since position appeared to be 'cued' anew by S1 at each trial. Latency and distribution of the Nd1 observed in Experiment I is very similar to that observed in auditory and visual voluntary attention studies. It also seems to reflect some kind of initial selection according to spatial criteria in transient attention situation. The Nd2, which was present in each condition of Experiments I and II as well as in the attend condition of Experiment III, reflects some kind of selective stimulus processing but it is unclear whether this selection is due to (a) benefits in the processing of same position stimuli, (b) costs in the processing of different position stimuli, or (c) some other mechanisms, for example, a re-orienting to initially unattended different position stimuli. Recent experiments on the auditory and visual Nd2 in voluntary attention situation, in which ERPs to attended and to unattended stimuli were compared with ERPs obtained in a neutral condition, show that the Nd2 seems to reflect costs as well as benefits (Eimer, 1996; Schröger & Eimer, 1995). If the Nd2 reflects a modulation of the ERPs to different position stimuli, the Nd2 may in fact be regarded as (partly) resulting from increased positivity to different position stimuli. This is consistent with positivities to to-be-ignored stimuli obtained in sustained auditory spatial attention studies which were interpreted as indexing inhibition of processing (Alho, Töttölä, Reinikeinen, Sams, & Näätänen, 1987; Michie, Bearpark, Crawford, & Glue, 1990).

The present results may also be related to Nd effects in 'traditional' sustained attention experiments (where attention is kept constant to a particular stimulus feature for a series of stimuli) which usually yielded a frontocentrally peaking early Nd and a frontally peaking late Nd (see Section 1, Introduction). The difference in scalp distribution between the Nd effects obtained in transient and sustained attention situations is probably due to a difference in the dynamic aspect of the attentional mechanisms involved. The parietally peaking Nd1 elicited in the transient attention situation is consistent with contribution of activity of the parietal cortex, which is known from human patient and animal studies to play an important role in spatial attention (Bushnell, Goldberg, & Robinson, 1981; Posner, Cohen, & Rafal, 1982; Posner & Petersen, 1990; Posner, Petersen, Fox, & Raichle, 1988). Nevertheless, the early Nd from sustained attention studies and the Nd1 from transient attention studies may both reflect initial selection of the 'relevant' (or inhibition of the 'irrelevant') stimulus feature, while the late Nd and the Nd2 may both be due to processes being concerned with further processing of stimuli that have already been selected.

5.3. Divergence between ERP and RT data

Finally, the present experiments yielded a dissociation between ERP and RT data: the finding of enhanced negativities of ERPs to same as compared with ERPs to different position stimuli had either no corresponding RT effects at all (Experiments I and III) or even a 'reverse' RT effect (Experiment II). The ERP data suggest that there was an attentional switch to the position of S1, whereas the RT data suggest that there was no attentional orienting (Experiments I and III) or that there was an attentional orienting to the position contralateral to the cue position (Experiment II). As noted in Section 1, Introduction, the absence of RT effects with uninformative auditory cues was predicted on the basis of results from visual (Eimer, 1994a) and auditory (Simon et al., 1975) studies employing similar paradigms, while the presence of ERP effects was predicted on the basis of previous ERP data (e.g., Eimer, 1994a) and on the basis of theories claiming that lateralized stimuli may cause attention switching (e.g., Näätänen, 1992). This puzzling dissociation between ERP and RT data may be resolved by assuming an uncoupling of the underlying processes. That is, the processing differences visible in the ERPs are not necessarily reflected in differences in overt behavior. The assumption of an uncoupling of the underlying processes has also to be made within different behavioral tasks, since some experiments (Spence & Driver, 1994) yielded RT effects of uninformative spatial cues while others did not (present Experiments I and III; Eimer, 1994a; Simon et al., 1975; Spence & Driver, 1994). This implies that it is not the ERP-RT difference per se that is responsible for the divergence between ERP and RT results but that these different measures are differently sensitive in revealing differences in information processing.

The present study showed that uninformative lateralized cues may lead to differences in auditory information processing stimuli which are not necessarily 'visible' with RTs measured in a particular type of task although another task (cf. Spence & Driver, 1994) would possibly have revealed behavioral consequences of this differential processing.

Acknowledgements

This research was supported by a grant from the Deutsche Forschungsgemeinschaft (No. Ei 266/2-1) and by the Max-Planck-Institute for Psychological Research. The authors want to thank Patricia Michie, Todd Mondor and two anonymous reviewers for valuable comments on an earlier draft of this paper as well as Anna Ruppl, Friederike Schlaghecken, Renate Tschakert, Angela Kallo, and Christian Wolff for their help in conducting the experiments.

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