ELSEVIER Biological Psychology 44 (1997) 143–160

BIOLOGICAL PSYCHOLOGY

An event-related potential (ERP) study of transient and sustained visual attention to color and form

Martin Eimer*

Institut für Psychologie, Universität München, Leopoldstr. 13, 80802 München, Germany

Abstract

Event-related potential (ERP) effects of transient and sustained non-spatial visual attention were investigated in an experiment where subjects were instructed to attend to the color or form of visual stimuli in order to detect infrequently presented targets with the relevant feature. The to-be-attended feature was either varied in a trial-by-trial fashion (transient attention) or was kept constant for an entire experimental block (sustained attention). Both transient and sustained attention resulted in a larger negativity for attended as compared to unattended stimuli between 200 and 300 ms post-stimulus. This effect was more pronounced for sustained attention than for transient attention and larger for attention to color than for attention directed to stimulus form. In the sustained, but not in the transient attention condition, color attention resulted in larger positivities for attended stimuli between 150 and 200 ms and in the P3 time range. These effects are interpreted as evidence for the existence of non-spatial attentional selection processes that are more effective under sustained than under transient attention conditions and are different from processes of visual-spatial attention. Moreover, the results indicate a special status for sustained attention to stimulus color.

Keywords: Event-related potential; Perception; Attention

* E-mail: eimer@mip.paed.uni-muenchen.de.

PII S0301-0511(96)05217-9

1. Introduction

The mechanisms of selective attention are studied in experiments where subjects are instructed to attend to specific features of stimuli and to ignore stimuli without the to-be-attended features. Studies of selective attention differ with respect to the stimulus modality (visual, auditory, somatosensory), with respect to the features that are to be attended, and with respect to the dependent variables measured. Usually, behavioral parameters (response times, detection accuracy, error rates) or event-related potential (ERP) waveforms obtained for stimuli with to-be-attended features are compared with behavioral or electrophysiological measures obtained for stimuli with irrelevant features.

In studies of visual selective attention, subjects are instructed to attend to specific attributes of visual stimuli (location, color, orientation, size, or spatial frequency), and behavioral as well as electrophysiological parameters are used as dependent measures to study the mechanisms underlying the attentional selection of different stimulus features. On the basis of numerous studies, it has been concluded that stimulus location plays a specific role in visual selective attention. Responses to stimuli at attended locations are usually faster and more accurate than responses to stimuli at unattended positions, and attended-location stimuli are usually detected more efficiently than stimuli at unattended locations (see Posner et al., 1978, 1980; Bashinski and Bacharach, 1980; Jonides, 1981; Müller and Findlay, 1987; Downing, 1988; Müller and Rabbitt, 1989; Hawkins et al., 1990). Moreover, ERP studies have found that stimuli at attended locations elicit enhanced posterior P1 and N1 components when compared to stimuli at unattended locations (Eason, 1981; Mangun et al., 1986; Mangun and Hillyard, 1987; Neville and Lawson, 1987; Rugg et al., 1987). These effects start as early as 80–90 ms following stimulus onset. On the basis of these results, Mangun and Hillyard (1991) have proposed that visual-spatial attention may consist of 'sensory gating' processes that modulate sensory processing in afferent visual pathways.

In contrast to the early ERP effects found for visual-spatial attention, attending to non-spatial attributes of visual stimuli like color, orientation, contour, or spatial frequency affects ERP waveforms at a later point in time. Generally, non-spatial visual attention was found to result in a larger negativity elicited by attended stimuli that starts beyond 150 ms and may extend up to 300 ms post-stimulus (Harter and Previc, 1978; Harter and Guido, 1980; Harter et al., 1982; Previc and Harter, 1982; Aine and Harter, 1984; Wijers et al., 1989a,b,c; Kenemans et al., 1993). The fact that attending to various non-spatial attributes results in qualitatively similar ERP modulations is in line with the assumption that different non-spatial stimulus features are processed within the same visual sub-system, the so-called 'ventral pathway' (Ungerleider and Mishkin, 1982).

In addition to differences in the to-be-attended stimulus features, studies on selective attention differ in another important dimension that is nevertheless often overlooked in the literature. Selective attention may either be shifted between features on a trial-by-trial basis or may be kept focused on a specific feature for an entire experimental block. In the first case, which will be termed *transient selective* *attention*, subjects are informed by a precue at the beginning of each trial about the to-be-attended stimulus feature for this trial. Attention may thus be directed to different stimulus features in successive trials. In the second case, which will be termed *sustained selective attention*, subjects are instructed at the beginning of each experimental block to attend to a specific stimulus feature during the entire block. In this situation, attention is to be held constantly at a single feature for a longer time period. Given this difference between transient and sustained selective attention paradigms, we investigated whether different attentional mechanisms are operative in these two situations, and whether attention to different stimulus attributes is differently influenced by transient and sustained selective attention.

In the case of visual-spatial attention, most behavioral studies have employed a transient attention paradigm, while the majority of ERP studies has used a sustained attention paradigm. However, there may be important differences in the attentional processes activated during transient and during sustained spatial attention. For example, Posner (1980) has argued that visual-spatial attention should not be regarded as a passive filter, but rather as an active process that is more effective in transient attention situations, in which the attentional focus has to be constantly shifted between different locations, than under sustained attention conditions. Given these considerations, it seems problematic to explain behavioral effects obtained in a trial-by-trial cueing situation with reference to ERP data collected within the sustained attention paradigm.

Only few ERP studies have so far investigated electrophysiological effects of transient visual-spatial attention. Mangun and Hillyard (1991), for instance, found enhanced P1 and N1 components for attended as compared with unattended stimuli in a trial-by-trial cueing paradigm. Because these effects were similar to the attentional enhancements of sensory-evoked components found with the sustained attention paradigm, they argued that functionally similar 'sensory gating' mechanisms may be activated in transient as well as in sustained attention. Recent studies by Eimer (1993, 1994b), in which the direction of spatial attention was also cued on a trial-by-trial basis, showed that the presence or absence of these effects may depend upon specific factors like the discrimination requirements in an experimental situation or whether or not responses are required to stimuli at uncued locations. In these studies, transient spatial attention invariably resulted in a larger negativity for attended compared to unattended stimuli at midline electrodes that peaked around 160 ms with an initial parietal maximum (Nd1), and was followed by a second, more broadly distributed peak between 220 ms and 280 ms (Nd2). Similar effects were obtained in experiments in which the to-be-attended location was indicated by a peripheral cue (Eimer, 1994a) and in which auditory stimuli were used instead of visual stimuli (Schröger, 1993, 1994; Schröger and Eimer, 1993). In a study by Eimer (1996), ERP effects of transient and sustained spatial attention where directly compared. While transient spatial attention resulted in the Nd1-Nd2 pattern reported above, the ERP modulations due to sustained spatial attention were found to be delayed (starting beyond 200 ms post-stimulus) and of much smaller amplitude. From these findings, one could assume that the selective processes underlying transient and sustained spatial attention are not identical. The fact that the attention-related negativities described above were found to be larger for transient than for sustained spatial attention may be interpreted as indicating an advantage of transient over sustained spatial attention with respect to their selective efficiency. It must be noted, however, that Eimer (1996) employed a S1-S2 paradigm not only in the transient, but also in the sustained attention condition. The stimulus presentation rate was thus considerably slower than in most other ERP studies on sustained attention, which may have attenuated the ERP effects of sustained attention.

The present experiment investigates the difference between transient and sustained attention in the selection of non-spatial attributes of visual stimuli. Virtually all ERP studies on non-spatial visual attention so far conducted (see above) have employed a sustained attention paradigm. Given the dissociations between transient and sustained *spatial* attention discussed above, one may ask whether different mechanisms are operative under transient and under sustained *non-spatial* attention. In order to find this out, the present study compared ERP waveforms elicited by stimuli with to-be-attended non-spatial attributes with ERPs elicited by stimuli with irrelevant non-spatial attributes, and these comparisons were done both for a transient and for a sustained attention condition. Subjects were instructed to attend to a specific color (red vs. blue) or to a specific form (circle vs. square) of a visual stimulus in order to detect infrequent targets (stimuli possessing the relevant attribute together with a small white central dot). The to-be-attended stimulus attribute was specified in two different ways. In the transient attention conditions, a letter precue informed the subject at the beginning of each trial about the relevant stimulus attribute for the forthcoming trial. In the sustained attention condition, the to-be-attended attribute was specified at the beginning of each block, and subjects were instructed to keep their attention focused on that attribute for the entire block. Instead of an informative precue, a warning stimulus (the letter X) was presented at the beginning of each trial in the sustained attention conditions.

The present study thus investigated the influence of two experimental factors on attentional modulations of ERP waveforms: the dynamics of attentional focusing (transient vs. sustained), and the stimulus dimension (color vs. form) relevant for attentional selection. Both factors were varied independently, resulting in a total of four experimental conditions (transient-color, sustained-color, transient-form, sustained-form). If there was a difference in attentional selection efficiency between transient and sustained non-spatial attention, one would expect to find differential effects of these two attentional focusing conditions on the attended-unattended difference ERP waveforms. If transient non-spatial attention was more efficient than sustained non-spatial attention (as it presumably is for visual-spatial attention), one would expect to find earlier, and probably also larger attentional effects on the ERP waveforms in the transient than in the sustained attention conditions.

2. Methods

2.1. Subjects

Twelve paid volunteers, aged 21–37 years (mean age: 28.8 years) participated in the experiment. All subjects were right-handed and had normal or corrected-to-normal vision.

2.2. Stimuli and apparatus

Subjects were seated in a dimly lit, electrically shielded and sound-attenuated cabin, with response buttons under their left and right hands. A computer screen was placed 100 cm in front of the subject and carefully positioned so that the stimuli appeared on the subject's straight-ahead line of sight. All stimuli were presented in the center of the screen and subtended a visual angle of approximately $1° \times 1°$. Each trial began with a 200 ms presentation of a white cue letter stimulus. In the transient-color condition, the letters B and R were used as cues, signalling blue or red as relevant color. In the transient-form condition, the letter R (for 'rund', the German word for 'round') specified that roundness was the relevant attribute, and the letter V (for 'viereckig', the German word for 'rectangular') specified that squareness was relevant. In the sustained attention conditions, the letter X was used as a warning stimulus in place of the cue letter. Seven hundred milliseconds after the offset of the cue, an imperative stimulus was presented for 100 ms. In the transient- and sustained-color conditions, blue or red squares served as imperative stimuli. In the transient- and sustained-form conditions, blue squares or blue circles were presented as imperative stimuli. On occasional trials, a small white dot (subtending a visual angle of about $0.1° \times 0.1°$) was present in the center of the imperative stimuli. The intertrial interval between target offset and onset of the next cue was 1.5 s.

2.3. Procedure

Twenty-four experimental blocks were run. Each block consisted of 60 trials and had a duration of approximately 2.5 min. For each attention condition (transient-color, sustained-color, transient-form, sustained-form), a total of six successive blocks was delivered. Subjects were instructed to attend to a specific attribute of the imperative stimuli (the color red or blue in the color attention conditions, and squareness or roundness in the form attention condition), and to respond with a left-hand or right-hand button press whenever a target stimulus (that is, a stimulus with a white dot inside) was presented that possessed the relevant attribute. In the color attention conditions, relevant red targets required a left-hand button press, and relevant blue targets required a right-hand button press. In the form attention conditions, relevant square targets required a left-hand button press, and relevant round targets required a right-hand button press.

The relevant stimulus attribute was specified differently in the transient and sustained attention conditions. In the transient attention conditions, the to-be-attended attribute was varied between trials, with the cue letter informing subjects about the relevant attribute of the forthcoming imperative stimulus (see Section 2.2). In the sustained attention conditions, the to-be-attended attribute remained constant for an entire experimental block and was specified by verbal instruction in advance of each block. Blocks in which one attribute (e.g. red or roundness) was relevant were followed by blocks in which the other attribute (e.g. blue or squareness) was relevant, and vice versa. Preceding each imperative stimulus, a non-informative cue stimulus (the letter X) was presented in the sustained attention conditions.

On 44 out of the 60 trials per block, non-target stimuli were presented; 22 of these non-target stimuli possessed the to-be-attended attribute, while the remaining 22 non-target stimuli possessed the other, irrelevant attribute. Target stimuli were presented in the remaining 16 trials. On the average, eight target stimuli per block possessed the to-be-attended attribute and thus required a response, while the other eight targets possessed the irrelevant attribute and required no response. The ratio of attended and unattended target stimuli was randomly varied between blocks, so that the number of attended targets per block varied between 5 and 11. Attended and unattended non-target and target stimuli were delivered in random sequence. The order in which the four attention conditions (transient-color, sustained-color, transient-form, and sustained-form), each consisting of six successive blocks were delivered was balanced across subjects. Subjects were instructed to respond as quickly and accurately as possible and to withhold responding to non-targets and unattended targets while maintaining fixation throughout the trial. To make subjects familiar with these specific task requirements, one or two training blocks were run prior to the start of the first experimental block of each attention condition.

2.4. Recording and data analysis

The EEG was recorded with Ag-AgCl electrodes from Fz, Cz, and Pz (according to the 10–20 system), from C_3' and C_4' (1 cm in front of C_3 and C_4), from PL and PR (located halfway between Pz and each ear canal), and from OL and OR (located halfway between O_1 and T_5, and O_2 and T_6, respectively). All electrodes were referenced to the right earlobe. The horizontal EOG was recorded bipolarly from electrodes at the outer canthi of both eyes, and the vertical EOG was recorded bipolarly from electrodes above and below the right eye. Electrode impedance was kept below 5 kΩ. The amplifier bandpass was 0.10–40 Hz. EEG and EOG were sampled with a digitization rate of 200 Hz, and stored on disk. Reaction times were recorded for each response.

EEG and EOG were sampled off-line into epochs of 800 ms, starting 100 ms prior to the onset of the imperative stimulus, and ending 700 ms after the onset of the imperative stimulus. Trials with eyeblinks, horizontal eye movements, artifacts resulting from bodily movements, response errors, or overt responses to non-targets and to unattended targets were excluded from analysis. Only the EEG data obtained in non-target trials were further analysed. EEG epochs obtained in non-target trials were averaged separately for the transient-color, the sustained-color, the transient-form and the sustained-form attention conditions for all four combinations of stimulus conditions (attention: attended vs. unattended, and stimulus feature: red vs. blue, and round vs. squared, respectively), resulting in a total of 16 average waveforms for each subject and electrode site. All ERP amplitude measures were taken relative to the mean voltage of the 100 ms interval preceding the onset of the imperative stimulus.

Mean ERP amplitudes were determined within four consecutive post-stimulus time windows: 150–200 ms (termed N1 time window), 200–260 ms (P2 time window), 260–320 ms (N2 time window), and 320–500 ms (P3 time window). The mean ERP amplitudes obtained within each time window were submitted to repeated measures analyses of variance. Separate ANOVAs were conducted for lateral recording sites (C3′, C4′, PL, PR, OL, and OR) and for midline recording sites (Fz, Cz, and Pz) for the variables attention (attended vs. unattended stimulus), attentional focusing dynamics (transient vs. sustained), attended dimension (color vs. form), stimulus feature (red vs. blue and round vs. squared, respectively; since these stimulus features determined the side of the response required by target stimuli, the 'stimulus feature' factor may have also been termed 'response hand' factor), and electrode location (frontal vs. central vs. parietal for midline sites; central vs. parietal vs. occipital for lateral sites). For the lateral electrode pairs, electrode side (left vs. right) was included as an additional factor. On the basis of the results of these omnibus ANOVAs, separate follow-up ANOVAs were conducted on the ERPs obtained at different electrode locations in the sustained and in the transient attention conditions. For the RT data, a repeated measures analysis of variance was run for the factors attentional focusing dynamics (transient vs. sustained), attended dimension (color vs. form), and response side (left vs. right).

3. Results

3.1. Behavioral performance

Response times (RTs) were influenced both by the attended dimension ($F(1,11) = 18.66$, $P < 0.001$) and by the difference between transient and sustained attention ($F(1,11) = 5.27$, $P < 0.042$). Faster RTs were found in the color than in the form attention conditions (389 ms vs. 421 ms, collapsed over transient and sustained attention). In addition, RTs were faster in the sustained as compared to the transient attention condition (393 ms vs. 417 ms, collapsed over color and form attention). As evidenced by paired t-tests, RTs were significantly faster in the color than in the form attention condition both for sustained as well as for transient attention ($t(11) = 4.85$ and 2.41, $P < 0.001$ and $P < 0.034$, respectively). The RT advantage for sustained as compared to transient attention was found to be significant for attention directed to color ($t(11) = 2.22$, $P < 0.05$), but only approached significance for attention directed to form ($t(11) = 1.79$, $P < 0.102$).

Subjects missed less than 0.5% of the attended targets, and these misses were observed exclusively in the transient attention conditions. Responses to unattended targets were executed on 2.2% of all unattended target trials. Significantly more responses to unattended targets (3.4% vs. 1%) were observed under transient than under sustained attention conditions ($P < 0.008$, Wilcoxon Matched-Pairs Signed-Ranks Test). Responses to non-target stimuli were virtually absent.

3.2. Effects of attention on ERP waveforms

Fig. 1 shows the grand averaged ERP waveforms elicited by attended and unattended non-target stimuli at Cz and at occipital sites (collapsed over OL and OR) for sustained attention (left side) and transient attention (right side), displayed separately for attention directed to stimulus color and to stimulus form. As can be seen from this figure, the ERPs elicited by attended stimuli tended to be more negative than the ERPs elicited to unattended stimuli beyond 200 ms post-stimulus. In some conditions, however, this effect tended to reverse at longer latencies, giving rise to an larger positivity for attended stimuli beyond 300 ms post-stimulus. These observations become clearer on the basis of the attended-unattended difference waveforms obtained for transient and sustained attention to color and form that are displayed in Fig. 2 for midline electrode sites and in Fig. 3 for lateral electrode pairs. On the left sides of these figures, one finds the effects of sustained attention to color and form, on the right sides the effects of transient attention to color and form. As becomes immediately clear, the effects of sustained non-spatial attention were larger in amplitude than the effects of transient non-spatial attention. This can also be seen from Fig. 4, where the overall effects of transient and sustained attention are compared, collapsed over attention directed to stimulus color and

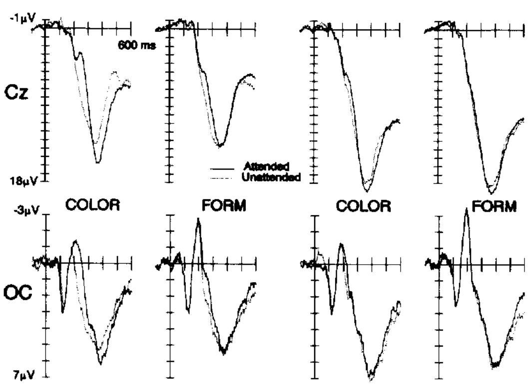

Fig. 1. Grand-average ERPs at Cz (top row) and at lateral occipital electrodes (OC, bottom row, collapsed over OL and OR) for attended and unattended stimuli under sustained attention conditions (left side) and transient attention conditions (right side). Waveforms for attention directed to stimulus color and stimulus form are displayed separately. Numbers of trials (attended/unattended) contributing to each grand average ERP waveform: 1252/1244 (sustained color), 1286/1296 (sustained form), 1094/1098 (transient color), 1195/1175 (transient form).

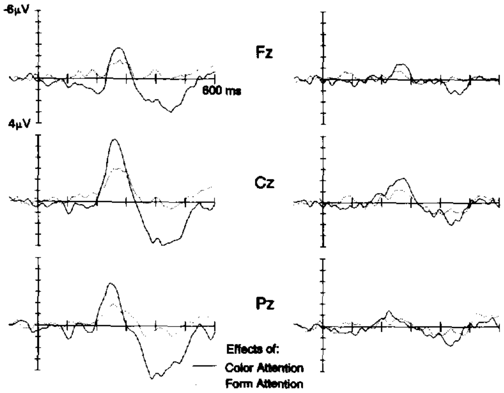

Fig. 2. Difference waveforms reflecting effects of selective attention at midline electrodes, obtained by subtracting ERPs elicited by unattended stimuli from ERPs elicited by attended stimuli for attention directed to color (solid lines) and attention directed to form (dashed lines). Left side: sustained attention conditions. Right side: transient attention conditions.

attention directed to stimulus form. Moreover, it seems that attending to stimulus color yielded larger ERP effects than did attending to the form of the stimulus. These informal observations were in turn substantiated with the help of statistical analyses.

Table 1 shows the results from the omnibus ANOVAs on the ERP mean amplitudes recorded at lateral and midline sides for the different measurement windows. Main effects of attention were found in the P2 and N2 measurement windows for lateral as well as for midline sites, reflecting the fact that attended stimuli elicited a larger negativity as compared to unattended stimuli within this time range. In the P3 time range, another significant main effect of attention was

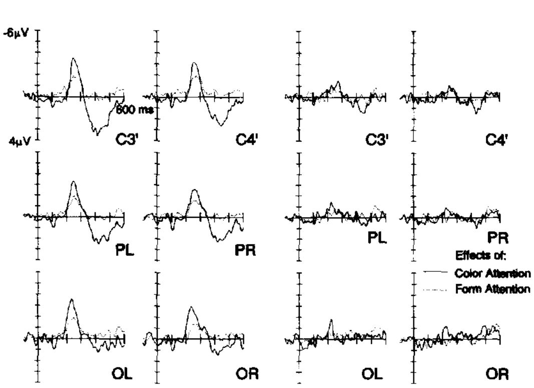

Fig. 3. Difference waveforms reflecting effects of selective attention at lateral central, parietal, and occipital electrodes, obtained by subtracting ERPs elicited by unattended stimuli from ERPs elicited by attended stimuli for attention directed to color (solid lines) and attention directed to form (dashed lines). Left side: sustained attention conditions. Right side: transient attention conditions.

Table 1

Results of the omnibus ANOVAs conducted separately on ERP mean amplitudes at lateral and midline recording sites within the different measurement windows (latency bands are given underneath the name of the measurement window). The table contains the *F*-values and the respective *P*-values for the main effects of attention (ATT) and interactions of attention with attentional focussing dynamics (AFD), attended dimension (DIM), and electrode location (LOC). When necessary, the correspondig Greenhouse-Geisser ϵ-values are given. Unless otherwise specified, degrees of freedom for the *F*-values are (1,11)

	N1 lateral 150–200 ms	N1 midline 150–200 ms	P2 lateral 200–260 ms	P2 midline 200–260 ms	N2 lateral 260–320 ms	N2 midline 260–320 ms	P3 lateral 320–500 ms	P3 midline 320–500 ms
ATT			60.04; 0.000	36.12; 0.000	21.67; 0.001	13.51; 0.004	6.55; 0.027	13.81; 0.003
ATT × AFD			7.88; 0.017	5.04; 0.036	11.79; 0.006	10.14; 0.009		
ATT × DIM			12.57; 0.005	6.08; 0.031			6.94; 0.023	6.41; 0.028
ATT × AFD × DIM		7.14; 0.022					21.06; 0.001	29.45; 0.001
LOC × ATT $F(2,22)$				10.99; 0.004 $\epsilon = 0.587$		10.16; 0.001 $\epsilon = 0.972$	6.22; 0.028 $\epsilon = 0.526$	
LOC × ATT × AFD $F(2,22)$	4.18; 0.041 $\epsilon = 0.781$		4.59; 0.036 $\epsilon = 0.724$	8.85; 0.006 $\epsilon = 0.680$		6.41; 0.016 $\epsilon = 0.696$		
LOC × ATT × DIM $F(2,22)$			5.28; 0.040 $\epsilon = 0.518$	7.78; 0.010 $\epsilon = 0.660$		4.36; 0.034 $\epsilon = 0.826$	7.95; 0.014 $\epsilon = 0.545$	

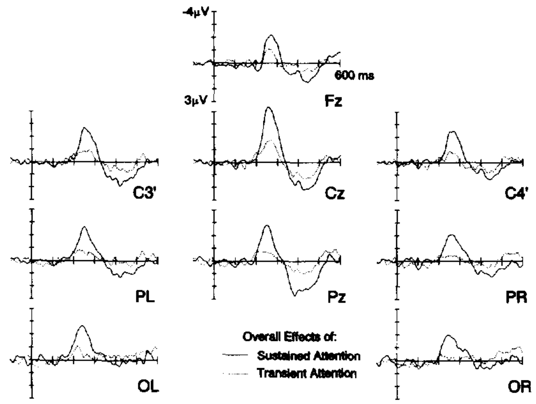

Fig. 4. Difference waveforms reflecting overall effects of transient and sustained selective attention. Solid lines: difference waveforms obtained by subtracting ERPs elicited by unattended stimuli from ERPs elicited by attended stimuli under sustained attention (collapsed over attention directed to color and attention directed to form). Dashed lines: difference waveforms obtained by subtracting ERPs elicited by unattended stimuli from ERPs elicited by attended stimuli under transient attention (collapsed over attention directed to color and attention directed to form).

observed, which will be discussed in detail below. No main effect of attention was present in the N1 time range.

In the N1 time range, three-way interactions were present at midline electrodes (attention × attended dimension × attentional focusing dynamics) and at lateral electrodes (electrode location × attention × attentional focusing dynamics). These were further analysed by follow-up ANOVAs conducted separately for the transient and sustained attention conditions and different electrode sites. For sustained attention, significant interactions between attention and attended dimension were present at Fz and Cz as well as at lateral central sites ($F(1,11) = 25.76$, $P < 0.001$, $F(1,11) = 5.5$, $P < 0.039$, $F(1,11) = 5.7$, $P < 0.036$, respectively). These findings reflect the observation that in the N1 time range, ERPs elicited by attended stimuli were more positive than ERPs elicited by unattended stimuli at frontocentral sites under sustained attention instructions when stimulus color was the relevant attribute (see Figs. 2 and 3).

In the P2 measurement window, interactions were obtained between attention and attentional focusing dynamics both at lateral and midline sites (see Table 1), thus validating the observation from Fig. 4 that attentional effects were generally more pronounced in the sustained than in the transient attention conditions. Three-way interactions (electrode location × attention × attentional focusing dynamics) indicated that these differential attention effects were also influenced by the recording site. In addition, interactions between attention and attended dimension substantiated the observation from Figs. 2 and 3 that attentional effects were larger when color was the relevant stimulus feature. Again, three-way interactions with electrode location indicated that this pattern of results differed between recording sites. To further investigate these findings, follow-up ANOVAs were conducted on the ERP mean amplitudes obtained in the P2 time range for different recording sites and both attention conditions. Main effects of attention were obtained at lateral as well as at midline sites both for transient and for sustained attention (all $F(1,11) > 10.13$, all $P < 0.009$). A notable exception was Fz, where no effects of transient or sustained attention could be found at all. This was reflected by an interaction between electrode location and attention obtained at midline electrodes (see Table 1). Significant interactions between attention and attended dimension were found at lateral occipital sites and at Pz ($F(1,11) = 10.3$, $P < 0.008$, $F(1,11) = 8.12$, $P < 0.016$, respectively) under sustained attention conditions, indicating larger effects of sustained attention directed to color as compared with sustained attention directed to form. The presence of differential effects of color and form attention in the P2 measurement window under sustained and transient attention conditions was also indicated by four-way-interactions (electrode location × attention × attended dimension × attentional focusing dynamics) in the omnibus ANOVAs that were significant for lateral sites and almost significant at midline sites ($F(2,22) = 5.19$, $P < 0.022$, $\epsilon = 0.800$, $F(2,22) = 3.67$, $P < 0.067$, $\epsilon = 0.624$, respectively).

In the N2 measurement window, main effects of attention were accompanied by interactions between attention and attentional focusing dynamics (see Table 1), again indicating larger attention effects under sustained attention. In addition, as evidenced by three-way interactions, these effects were influenced by electrode location at midline electrodes. These latter effects were further investigated by conducting separate ANOVAs for ERP mean amplitudes obtained in the N2 measurement window at midline sites under transient and sustained attention. For the sustained attention conditions, significant effects of attention were found for all midline electrodes (all $F(1,11) > 7.54$, all $P < 0.009$), while for the transient attention conditions, effects of attention only approached significance at Cz ($F(1,11) = 4.41$, $P < 0.060$), but were absent at Fz and Pz.

In the P3 time range, main effects of attention were accompanied by interactions between attention and attended dimension and, most notably, by three-way interactions between attention, attended dimension and attentional focusing dynamics (see Table 1). As can be seen from Fig. 1 and also from the difference waveforms in Figs. 2 and 3, these effects were presumably due to the fact that a larger positivity was elicited in the P3 time range by attended stimuli as compared to unattended stimuli under sustained attention instructions, but only when attention was directed to stimulus color. This was investigated by conducting additional ANOVAs separately for the transient and sustained attention conditions. Under sustained attention conditions, interactions between attention and attended dimension were obtained at all lateral electrode pairs (all $F(1,11) > 7.26$, all $P < 0.021$), reflecting larger positivities elicited by attended stimuli. No such effect was present under transient attention conditions. Similar results were obtained for midline sites. Significant interactions between attention and attended dimension were present under sustained attention conditions at all electrodes (all $F(1,11) > 14.88$, all $P < 0.003$), but no effects were observed during transient attention.

4. Discussion

The present experiment was conducted to investigate ERP effects of transient and sustained attention to the color or form of visual stimuli in order to find evidence for functional differences between the mechanisms of transient and sustained attention to different non-spatial attributes in the visual domain.

4.1. ERP effects of sustained attention

Sustained selective attention to stimulus color was found to have profound effects on the ERP waveforms at early as well as later time windows. The first effect of sustained color attention was a larger positivity to attended as compared to unattended stimuli at frontocentral electrodes between 150 and 200 ms. This effect is similar to early effects of sustained attention to color reported by Wijers et al. (1989c). These authors found an enhanced positivity to attended-color stimuli between 120 and 230 ms post-stimulus at Fz, Cz, and Pz. Similar findings have been reported by Harter and Aine (1984) and Aine and Harter (1986). The fact that this early ERP effect of sustained attention to color has a frontocentral distribution may be interpreted as evidence for a special role of the frontal cortex in the regulation of non-spatial selective attention (see Posner and Presti, 1987; Rugg et al., 1987). When sustained attention was directed to stimulus form, no early positivity for attended stimuli was observed. This dissociation between color attention and form attention may indicate functional differences in the mechanisms that underlie the attentional selection of different non-spatial features under sustained attention conditions.

Following the early positivity elicited by attended-color stimuli, sustained attention to color resulted in a larger negativity for attended stimuli in the P2 and N2 measurement windows (between 200 and 320 ms post-stimulus). The existence of attention-related negativities around 200 ms post-stimulus is a common finding of most ERP studies on non-spatial visual attention and is usually interpreted as reflecting the covert orienting of attention toward relevant stimulus features (see Näätänen and Gaillard, 1983). When sustained attention was directed to stimulus form, similar ERP effects could be observed. Attended-form stimuli elicited a larger negativity as compared to unattended-form stimuli starting around 200 ms post-stimulus. However, this effect was smaller than in the case of attention directed to stimulus color. This difference could be partially due the fact that the discrimination of the two colors in the color attention task may have been somewhat easier than the discrimination of the two stimulus forms. Evidence for this comes from the fact that the RTs in the color attention conditions were about 30 ms faster than the RTs measured in the form attention conditions.

In the P3 time range, attended-color stimuli elicited a larger positivity as compared to unattended-color stimuli. No such effect was present for sustained attention directed to form. As the effect of sustained attention to color was observed beyond 300 ms post-stimulus, it is unlikely to reflect an influence of attention on perceptual processing, but may rather indicate attentional effects on processes that follow stimulus identification. The absence of this effect when sustained attention was directed to form cannot be due to differences in the stimulus discriminability between the color and form conditions, since no larger positivity for attended-color stimuli was elicited under transient attention conditions (see below). Therefore, the effect of color attention in the P3 time range suggests that the mechanisms underlying sustained attention to color differ from the mechanisms responsible for the attentional selection of other non-spatial attributes like the form of a stimulus.

4.2. ERP effects of transient attention

Transient attention to color or form was reflected in a larger negativity for attended stimuli beyond 200 ms. Similar to the sustained attention conditions, this effect was more pronounced for attention directed to stimulus color than for attention directed to form. This again suggests that attentional selectivity was less effective in the form as compared to the color attention conditions, possibly reflecting differences in the between-stimulus discriminability in these two conditions.

The ERP effects to transient attention to color observed in the present experiment were similar to the results found in a study by Eimer (1995), where subjects had to attend to specific color-location conjunctions, and the relevant features were indicated by a single cue stimulus on a trial-by-trial basis. Larger negativities to attended-color stimuli were found at midline as well as at lateral posterior electrodes between 220 and 300 ms post-stimulus. With the exception of this study, ERP effects of transient non-spatial attention have not yet been investigated systematically. Nevertheless, the present data show that the ERP effects elicited by transient non-spatial attention differ markedly from the ERP effects of transient spatial attention. As described in the Introduction, transient spatial attention sometimes affects posterior P1 and N1 amplitudes and invariably results in larger negativities (Nd1, Nd2) for attended as compared to unattended locations. The ERP effects of transient non-spatial attention observed in the present study showed a considerably longer latency as well as a much smaller amplitude than the effects reported previously for transient spatial attention. In the latter case, a parietally maximal negative peak (Nd1) was present in the attended-unattended difference waveforms between 160 and 200 ms post-stimulus. This effect was completely absent in the difference waveforms obtained in the present study showing the effect transient non-spatial attention (see Fig. 4). This difference again suggest that in the visual domain, transient attention based on the spatial location of visual stimuli operates along rather different functional principles than transient non-spatial selection processes.

It is conceivable, however, that the ERP differences between transient spatial and non-spatial attention discussed above may at least partially be due to the different types of cues used in these two experimental situations. In typical experiments on transient visual-spatial attention, centrally presented arrows indicate the to-be-attended location, whereas in the present experiment, relevant non-spatial stimulus features were indicated by letters, that is, in a purely symbolic way. Although arrows are also considered to be symbolic cues, it is clear that they signal relevant locations more directly than relevant colors are signalled by letter stimuli. Smaller attentional effects for transient non-spatial attention may thus be related to the difficulty of translating a purely symbolic cue into a proper attentional set (this possibility was suggested by one of the reviewers). However, it should be noted that the cue-target SOA was 900 ms in the present experiment, which should be sufficiently long for such a symbolic translation process to be completed. It is therefore unlikely that differences between arrow and letter cues are solely responsible for the ERP differences observed between transient spatial and non-spatial attention.

4.3. *Differential effects of transient and sustained non-spatial attention*

When the ERP effects obtained during transient and sustained attention were directly compared, two main differences could be found. First, the enhanced negativities elicited by attended stimuli beyond 200 ms were considerably larger for the sustained as compared to the transient attention conditions (see Fig. 4). Although the onset latency of the attention-related negativities was similar in both conditions, sustained attention resulted in longer-lasting effects with larger amplitudes than transient attention. If the larger negativities elicited by attended stimuli are to be regarded as an electrophysiological indicator of attentional orienting towards relevant stimulus attributes, it could be concluded from the present findings that attentional selectivity with respect to non-spatial features like color and form is more effective under sustained than under transient attention conditions. Evidence for such an advantage for sustained attention can also be found in the RT data, where the RTs measured under sustained attention were about 25 ms faster than under transient attention.

The observation that the attention-related negativities in the ERP were larger for sustained than for transient non-spatial attention differs from results obtained for visual-spatial attention. Attentional modulations of the P1 and N1 components were observed to be similar under transient and sustained attention (see Mangun and Hillyard, 1991), and the negative ERP modulations elicited by transient spatial attention at midline electrodes beyond 150 ms post-stimulus were found to be of shorter latency as well as of much larger amplitude as compared to the effects of sustained spatial attention (see Eimer, 1996). This difference once again points to the special selective role of spatial attention and is further evidence for the assumption that distinct processes are operative in spatial and non-spatial visual attention. For attention directed to stimulus location, transient shifts of attention seem to be beneficial for attentional selection, while for non-spatial attention, keeping attention focused at a specific stimulus attribute for a longer period of time seems to be the more effective selection strategy.

A second difference between transient and sustained attention found in the present study was the differential influence of attentional allocation dynamics on the ERP effects of color attention. In the sustained attention condition, stimuli with the to-be-attended color elicited an larger positivity at frontocentral electrodes in the N1 time range and another enlarged positivity in the P3 time range. These effects were virtually absent when attention was directed to stimulus color in a trial-by-trial fashion (and also when stimulus form was the relevant dimension). The differential ERP effects of sustained and transient attention to color in the P3 time range cannot be explained by differences in stimulus relevance or probabilities, since these were held constant in all experimental conditions. Because these effects were absent in the transient attention conditions, they can also not be accounted for by differences in stimulus discriminability in the color and form conditions. Therefore, these results suggest that for non-spatial selective attention, sustained attention to stimulus color may have a special status that is reflected in distinct ERP effects.

In summary, the present study has provided electrophysiological evidence for the hypothesis that in contrast to visual-spatial attention, the attentional selection of non-spatial visual attributes is more effective under sustained than under transient attention conditions. This was the case for attention directed to color as well as for attention directed to form, with more pronounced ERP differences between transient and sustained attention to be found in the color attention conditions.

Acknowledgements

This research was supported by the Max-Planck-Institute for Psychological Research and by a grant from the Deutsche Forschungsgemeinschaft (No. Ei 266/2-2). The author wants to thank Dr. Erich Schröger and two anonymous reviewers for helpful comments on earlier drafts of this article, and Renate Tschakert, Desiree Schön, and Andreas Widmann for their help in conducting the experiment.

References

Aine, C.J., & Harter, M.R. (1984). Event-related potentials to stroop stimuli: Color and word processing. In R. Karrer, J. Cohen, & P. Tueting (Eds.), *Brain and information: Event-related potentials.* (Vol. 425, pp. 154–156). Annals of the New York Academy of Sciences.

Aine, C.J., & Harter, M.R. (1986). Visual event-related potentials to colored patterns and color names: Attention to features and dimension. *Electroencephalography and clinical Neurophysiology, 64,* 228–245.

Bashinski, H.S., & Bacharach, V.R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. *Perception and Psychophysics, 28,* 241–248.

Downing, C.J. (1988). Expectancy and visual-spatial attention: Effects on perceptual quality. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 188–202.

Eason, R.G. (1981). Visual evoked potential correlates of early neural filtering during selective attention. *Bulletin of the Psychonomic Society, 18,* 203–206.

Eimer, M. (1993). Spatial cueing, sensory gating and selective response preparation: an ERP study on visuo-spatial orienting. *Electroencephalography and clinical Neurophysiology, 88,* 408–420.

Eimer, M. (1994a). An ERP study on visual-spatial priming with peripheral onsets. *Psychophysiology, 31*, 154–163.
Eimer, M. (1994b). 'Sensory gating' as a mechanism for visual-spatial orienting: Electrophysiological evidence from trial-by-trial cueing experiments. *Perception and Psychophysics, 55*, 667–675.
Eimer, M. (1995). Event-related potential correlates of transient attention shifts to color and location. *Biological Psychology, 41*, 167–182.
Eimer, M. (1996). ERP modulations indicate the selective processing of visual stimuli as a result of transient and sustained spatial attention. *Psychophysiology, 33*, 13–21.
Harter, M.R., & Aine, C.J. (1984). Brain mechanisms of visual selective attention. In R. Parasuraman, & D.R. Davies (Eds.), *Varieties of Attention* (pp. 293–321). London: Academic Press.
Harter, M. R., Aine, C., & Schroeder, C. (1982). Hemispheric differences in the neural processing of stimulus location and type: Effects of selective attention on visual evoked potentials. *Neuropsychologia, 20*, 421–438.
Harter, M.R., & Guido, W. (1980). Attention to pattern orientation: Negative cortical potentials, reaction time, and the selection process. *Electroencephalography and clinical Neurophysiology, 49*, 461–475.
Harter, M.R., & Previc, F.H. (1978). Size-specific information channels and selective attention: Visual evoked potential and behavioral measures. *Electroencephalography and Clinical Neurophysiology, 45*, 628–640.
Hawkins, H.L., Hillyard, S.A., Luck, S.J., Mouloua, M., Downing, C.J., & Woodward, D.P. (1990). Visual attention modulates signal detectability. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 802–811.
Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J.B. Long, & A.D. Baddeley (Eds.), *Attention and Performance* (Vol. IX, pp. 187–203). Hillsdale: Erlbaum.
Kenemans, J.L., Kok, A., & Smulders, F.T. (1993). Event-related potentials to conjunctions of spatial frequency and orientation as a function of stimulus parameters and response requirements. *Electroencephalography and clinical Neurophysiology, 88*, 51–63.
Mangun, G.R., Hansen, J.C., & Hillyard, S.A. (1986). Electroretinograms reveal no evidence for centrifugal modulation of retinal inputs during selective attention in man. *Psychophysiology, 23*, 156–165.
Mangun, G.R., & Hillyard, S.A. (1987). The spatial allocation of visual attention as indexed by event-related brain potentials. *Human Factors, 29*, 195–211.
Mangun, G.R., & Hillyard, S.A. (1991). Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 1057–1074.
Müller, H.J., & Findlay, J.M. (1987). Sensitivity and criterion effects in the spatial cueing of visual attention. *Perception and Psychophysics, 42*, 383–399.
Müller, H.J., & Rabbitt, P.M.A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 315–330.
Näätänen, R., & Gaillard, A.W.K. (1983). The orienting reflex and the N2 deflection of the event-related potential (ERP). In A.W.K. Gaillard, & W. Ritter (Eds.), *Tutorials in ERP Research: Endogenous Components* (pp. 119–141). North-Holland Publishing Company.
Neville, H.J., & Lawson, D. (1987). Attention to central and peripheral visual space in a movement detection task: An event-related potential and behavioral study. I. Normal hearing adults. *Brain Research, 405*, 253–267.
Posner, M.I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.
Posner, M.I., & Presti, D.E. (1987). Selective attention and cognitive control. *Trends in Neuroscience, 10*, 13–17.
Posner, M.I., Nissen, M.J., & Ogden, W.C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H.L. Pick, & E.J. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137–157). Hillsdale, NJ: Erlbaum.
Posner, M.I., Snyder, C.R.R., & Davidson, B.J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109*, 160–174.

Previc, F.H., & Harter, M.F. (1982). Electrophysiological and behavioral indicants of selective attention to multifeature gratings. *Perception and Psychophysics*, *32*, 465–472.

Rugg, M.D., Milner, A.D., Lines, C.R., & Phalp, R. (1987). Modulation of visual event-related potentials by spatial and non-spatial visual selective attention. *Neuropsychologia*, *25*, 85–96.

Schröger, E. (1993). Event-related potentials to auditory stimuli following transient shifts of spatial attention in a Go/Nogo task. *Biological Psychology*, *36*, 183–207.

Schröger, E. (1994). Human brain potential signs of selection by location and frequency in an auditory transient attention situation. *Neuroscience Letters*, *173*, 163–166.

Schröger, E., & Eimer, M. (1993). Effects of transient spatial attention on auditory event-related potentials. *Neuroreport*, *4*, 588–590.

Ungerleider, L.G., & Mishkin, M. (1982). Two cortical visual systems. In D.J. Ingle, M.A. Goodale, & R.J.W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549–586). Cambridge: MIT Press.

Wijers, A.A., Lamain, W., Slopsema, J.S., & Mulder, G. (1989a). An electrophysiological investigation of the spatial distribution of attention to colored stimuli in focused and divided attention conditions. *Biological Psychology*, *29*, 213–245.

Wijers, A.A., Mulder, G., Okita, T., & Mulder, L.J.M. (1989b). An ERP-study of memory search and selective attention to lettersize and conjunctions of lettersize and color. *Psychophysiology*, *26*, 529–547.

Wijers, A.A., Mulder, G., Okita, T., Mulder, L.J., & Scheffers, M.K. (1989c). Attention to color: An analysis of selection, controlled search, and motor activation, using event-related potentials. *Psychophysiology*, *26*, 89–109.