

Visual evoked potentials and selective attention to points in space

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Visual evoked potentials (VEPs) were recorded to sequences of flashes delivered to the right and left visual fields while subjects responded promptly to designated stimuli in one field at a time (focused attention), in both fields at once (divided attention), or to neither field (passive). Three stimulus schedules were used: the first was a replication of a previous study (Eason, Harter, & White, 1969) where left- and right-field flashes were delivered quasi-independently, while in the other two the flashes were delivered to the two fields in random order (Bernoulli sequence). VEPs to attended-field stimuli were enhanced at both occipital (O_2) and central (C_z) recording sites under all stimulus sequences, but different components were affected at the two scalp sites. It was suggested that the VEP at O_2 may reflect modality-specific processing events, while the response at C_z , like its auditory homologue, may index more general aspects of selective attention.

The neural systems which mediate selective visual attention in man have been studied extensively by recording the visual evoked potentials (VEPs) from the scalp while a subject shifts his attention between different classes of photic stimuli (for recent reviews, see Hillyard & Picton, in press; Näätänen, 1975). In order to certify that a component of the VEP is a physiological correlate of *selective* visual processing, however, several stringent methodological criteria must be met. First, the evoked component must be preferentially associated with the "attended" stimulus class and then "switch over" to the other class when attention is shifted to those previously irrelevant stimuli. Second, the relevant and irrelevant stimuli must be delivered in a random temporal sequence to prevent the subject from anticipating which stimulus will occur next and adjusting his prior level of arousal or alertness (Karlin, 1970; Näätänen, 1967). Thirdly, the visual stimulus at the receptors must be held invariant across experimental conditions by monitoring the subject's direction of gaze, state of accommodation, and/or pupil size, whenever appropriate. Fourthly, the trials on which eyeblinks, eye movements, or other muscle artifacts occur must be rejected or compensated in the data analysis to prevent contamination of the VEP. Finally, it is desirable to obtain behavioral measures of stimulus detectability or discriminability concurrently with the VEPs, so that physiological and psychological indices of selective processing can be compared. The majority of the earlier studies reporting changes in the VEP as a function of attention have been

criticized for failure to control one or more of these factors (Hillyard & Picton, in press; Karlin, 1970; Näätänen, 1975).

A number of adequately controlled studies have established that a late positive wave (the "P₃" or "P₃₀₀" component) is differentially emitted following task-relevant visual stimuli, after a latency of 300-400 msec (Chapman, 1973; Courchesne, Hillyard, & Galambos, 1975; Donchin & Cohen, 1967; Harter & Salmon, 1972; Rohrbaugh, Donchin, & Eriksen, 1974; Ruchkin & Sutton, 1973). This P₃₀₀ wave is widely considered to be a modality nonspecific brain event which *follows* the selection of a relevant stimulus rather than a unique index of selective visual processing (Ritter, Simson, & Vaughan, 1972; Simson, Vaughan, & Ritter, 1976; N. Squires, Donchin, K. Squires, & Grossberg, in press). There has been little reliable evidence, however, that paying attention selectively can modify evoked visual activity prior to 200 msec (Hartley, 1970; Hillyard & Picton, in press). This is in marked contrast to the auditory modality, in which substantial increases of the evoked N₁ component beginning at 70-90 msec have been related to selective listening to tones or speech messages (Hillyard, Hink, Schwent, & Picton, 1973; Hink & Hillyard, 1976; Schwent & Hillyard, 1975; Schwent, Hillyard, & Galambos, 1976a, 1976b; Schwent, Snyder, & Hillyard, 1976c).

Eason, Harter, and White (1969) have reported a clear and consistent enhancement of relatively early components of the VEP to flashes at an attended locus in space, with a negative peak at 160-180 msec showing the most dramatic changes. In their study, 1° flashes were presented irregularly to the right or left of the fixation point while subjects attended and responded to those on one side at a time.

Näätänen (1975) has noted, however, that the right- and left-field flashes did not occur in a completely random, unpredictable sequence, and he suggested that the enhancement of the VEP to the attended flashes may have resulted from a differential anticipatory state rather than from selective processing. Moreover, Eason et al. (1969) did not take an objective measure of the subject's eye position to guard against his looking from the fixation point towards the attended flashes.

Since the changes in the occipital VEP reported by Eason et al. (1969) appeared to be strong and reliable, and were in certain respects analogous to the attention effects reported for the auditory N₁ component, we decided to replicate their study while controlling for visual fixation and for the degree of randomness in the stimulus sequences. In one condition of the present study, right and left field flashes were delivered according to schedules that were largely independent of one another (the same as Eason et al., 1969). In a second condition, right and left flashes were delivered in a completely random (Bernoulli) sequence at the same overall mean rate (0.4/sec). If Näätänen's (1975) hypothesis is correct, this randomization of the stimulus order should eliminate the "attention effects" on the VEP. In a third condition, flashes were again presented in a Bernoulli sequence, but at a much faster mean rate (2.2/sec), to investigate whether a higher information load might increase the selectivity of processing (Schwent et al., 1976a). To enable further comparisons between the present study and the auditory work on selective attention, VEPs were recorded from vertex as well as the occipital site, and a condition of divided attention (to both fields at once) was included to relate VEP amplitudes to the subject's allocation of his attentional capacity (Hink, Van Voorhis, Hillyard, & Smith, in press).

METHOD

Subjects

The subjects were 12 young adults, 6 male and 6 female, who were paid for participating in the experiment.

Stimuli

The stimulus arrangement consisted of a translucent white screen with a luminance of 0.64 cd/m², measuring 35 × 43 cm, and positioned 40 cm from the subject's eyes. In the center of the screen was a 1° black dot designated as the fixation point. Circular flashes subtending 1° of visual angle were presented through the translucent screen from two Grass photo stimulators, positioned 20° to the left and right of the fixation point, respectively. All flashes were presented at a luminance of one log unit above the subject's threshold. The subjects viewed the stimuli binocularly and wore earphones which delivered continuous white noise at 60 dB SL to mask extraneous sounds and photostimulator discharge.

Design

Stimuli were presented according to three different schedules

which were generated by a PDP-11/45 computer and recorded on audio tape.

In the first schedule (a replication of Eason et al., 1969), the right and left field flashes were presented in accordance with two independent, concurrently running sequences. Each sequence delivered flashes at random intervals between 2 and 8 sec (rectangular distribution), with the additional proviso that the minimum cross-channel interstimulus interval (ISI) was 1.0 sec. In the second schedule (slow, random), left and right flashes occurred in random order with equal probability following a single Bernoulli distribution, with ISIs ranging from 1.0 to 4.0 sec (rectangular distribution). The third schedule (fast random) also consisted of a Bernoulli sequence of equiprobable left and right field flashes, but the ISIs ranged from 300 to 600 msec (rectangular distribution). In addition, 10% of these flashes were "targets" (doublets separated by 70 msec) randomly distributed throughout the sequence, to which the subjects were required to respond in some conditions.

For each of the three stimulus schedules, the subjects were required to perform under four conditions of attention: passive, attend-left field, attend-right field, and attend-both fields. In the passive condition, the subjects were told to fixate the black dots and make no overt behavioral responses. In the three active-attention conditions using the replication and slow random schedules, the subject responded to each flash in the attended visual field(s) by pressing a button as fast as possible with the right thumb. In the three active-attention conditions with the fast random schedule, however, he pressed the button only after detecting a doublet flash (target) in the appropriate visual field(s).

Each subject was run in two sessions, 1 week apart. The second session was a complete replication of the first, with the experimental conditions administered in reverse order. In each session, the subjects were run through all 12 experimental conditions (three stimulus sequences by four attention conditions). One block of 150 total stimuli was given for the replication and slow random schedules in each attention condition, while two blocks of the fast random schedule (a total of 300 stimuli) were given under each attention condition. The order of presentation of attention conditions and stimulus schedules was counter-balanced across subjects.

Procedure

At the start of each session, the subject's threshold was determined for the stimuli in each visual field by the method of descending limits, using interposed neutral density filters. A short practice session was given under each experimental condition to ensure that the subject could properly identify the appropriate stimuli. He was not told of the difference between the slow random and replication schedules.

Recording electrodes were placed at C_z and O_z sites (International 10-20 system) and below the right eye, all referenced to the right mastoid. The left mastoid was grounded. These channels were amplified with Grass 7P5 preamplifiers (bandpass 0.15 to 500 Hz). In addition, horizontal eye position was monitored via a bipolar dc recording of the electrooculogram (EOG) between the left and right lateral canthi using Beckman silver/silver-chloride electrodes and a Grass 7P1 preamplifier with polygraph writeout. In order to minimize dc drift in these recordings, the electrodes were stored in conductive media with the ends shorted together, and the interelectrode impedance during the recording was maintained below 5K ohms. This method measures shifts in eye position with a resolution of better than 2° (Trevarthan & Tursky, 1969).¹

Before the start of each block of trials, the subject was instructed to fixate successively the black dot, left stimulus location, right stimulus location, and black dot again in order to calibrate the dc horizontal eye position channel. Then, while he was fixating the central dot, the subject was told which visual field (left, right, both, or neither) would be attended in the upcoming block. He was reminded to keep the black dot fixated and to avoid blinking.

The block was then begun. Failure of the subject to fixate the black dot resulted in halting the experiment and restarting that block from the beginning. In this way, it was not possible for the subject to bias his fixation systematically towards the attended stimulus location.

Data Analysis

Coded stimulus triggers, reaction time (RT) markers, EEG, and eye-movement channels were tape-recorded (Vetter FM-5, band-pass 0-300 Hz) for off-line analysis, using a Nicolet 1072 signal averager. Trials containing eye blinks or phasic eye movements were marked and excluded from further analysis. For each of the two sessions, VEPs were averaged separately for right- and left-field flashes, over 64 stimuli for the replication and slow random schedules and over 128 of the nontarget stimuli for the fast random schedule, under each of the four attention conditions. Peak amplitudes of the different components were measured with reference to a 50-msec prestimulus baseline according to the following criteria: P_1 was defined as the largest positive deflection between 65 and 140 msec poststimulus, N_1 as the most negative deflection between 120-200 msec, P_2 as the most positive deflection between 180-240 msec, and P_3 as the most positive deflection between 320 and 500 msec.

For the replication and slow random schedules, the median of the RT distribution for each condition was determined. For the fast random schedule, buttonpresses made within a 200-1,000-msec posttarget window were considered as hits, and all other responses as false alarms. The obtained hit and false-alarm probabilities were used to calculate the signal detection parameters d' and β .²

Since there were no significant differences in any of the VEP measures between sessions, the data was collapsed over both sessions for purposes of quantitative analysis. Unless otherwise noted, statistical comparisons were done by repeated measures analyses of variance.

RESULTS

Evoked Potentials

Typical VEP waveforms are illustrated in Figure 1, which shows the responses of one subject to right- and left-field flashes presented at the two slower rates (replication and slow random schedules). The major components, P_1 , N_1 , P_2 , and P_3 , were observed at both C_z and O_2 electrode sites in nearly every subject and condition. As is evident in Figure 1, some components did not always occur at exactly the same latency at the C_z and O_2 electrodes. Both the P_1 and N_1 waves peaked significantly later (see Table 1) at the O_2 site than at C_z ($p < .01$ for both waves), suggesting that these waves may reflect contributions from separate neural generators at the two sites. The P_2 and P_3 waves, however, could not be so subdivided on the basis of latency evidence. In several subjects, there was an asymmetry between the VEP amplitudes to ipsilateral (right field) and contralateral (left field) flashes at the O_2 site (Figure 1), but it failed to reach overall statistical significance.

Attention effects. The direction of attention had significant differential effects upon the amplitudes of VEPs to left- and right-field stimuli for all three stimulus sequences (Figures 1 and 2). Since the effects of attention did not differ significantly for right- and left-field flashes, the VEP amplitudes in

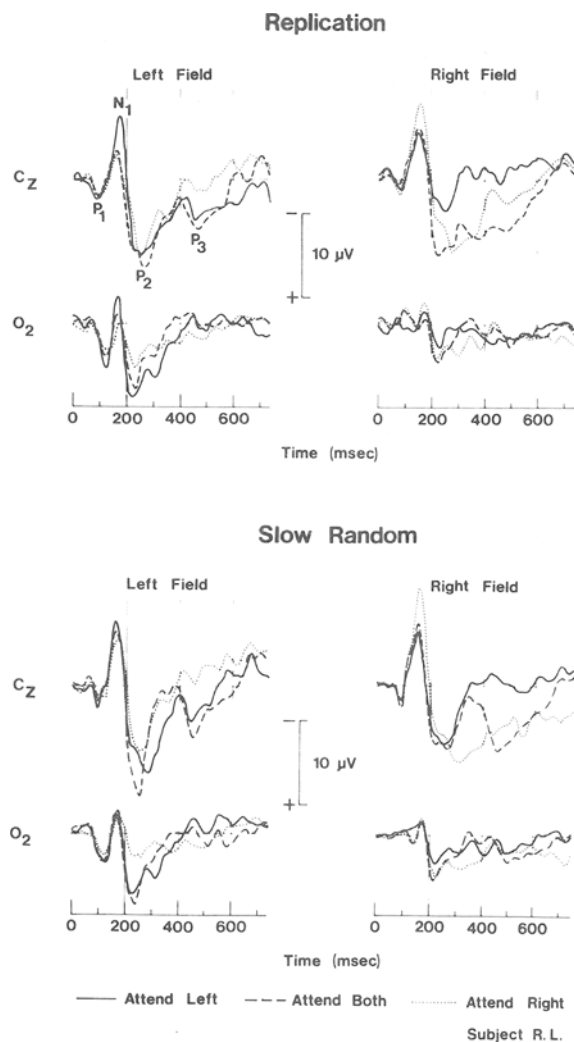


Figure 1. Vertex and occipital responses from one subject evoked by left and right field flashes under three conditions of attention for both the replication and slow random schedules. Each tracing is an average of 128 responses.

Table 2 are averaged across both fields (e.g., to obtain the "focused-attended" amplitudes, the left-field response during the attend-left condition was averaged with the right-field response during the attend-right condition, etc). In general, VEPs were largest to flashes in a given field when they received unilateral or focused attention, smallest when attention was focused on the opposite field, and intermediate in amplitude when attention was divided between both fields (Table 2). These effects of attention were most prominent and consistent for the N_1 component at C_z , and for the P_1 and P_2 components at O_2 . The P_3 wave was also greatly enlarged at both electrode sites to attended-field flashes.

The percentages by which the various VEP components were incremented by shifting attention between the fields are shown in Table 3.³ At the

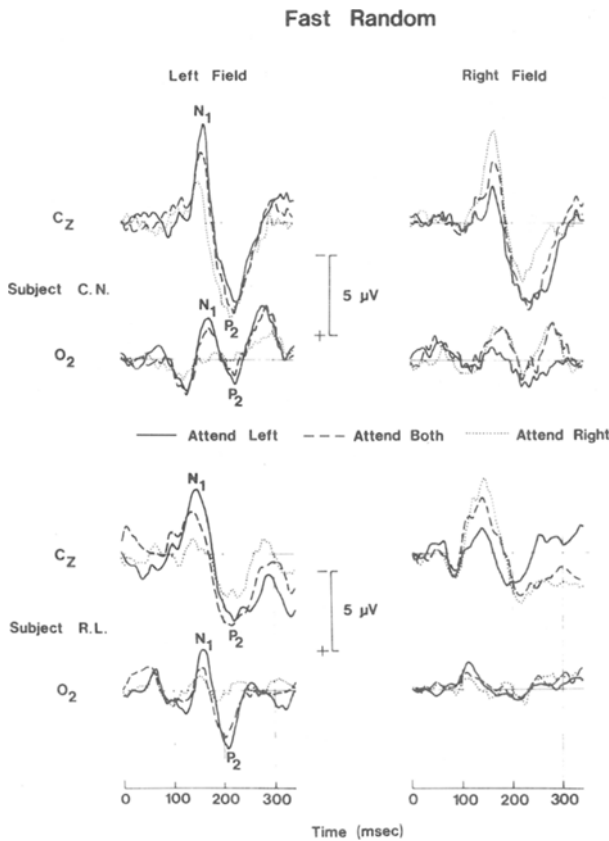


Figure 2. Vertex and occipital responses evoked by left and right field flashes under three conditions of attention for the fast random schedule. Each tracing is an average of 256 responses. Two subjects.

vertex, the N_1 wave and, less consistently, the P_1 wave were enhanced to attended-field stimuli under all schedules, making the P_1-N_1 measure the strongest electrophysiological sign of selective attention. Although the effect of attention on P_1-N_1 and on most other components was largest with the fast random schedule, there were no statistically significant differences among the three schedules in the magnitude of attention effects at C_z .

A more detailed picture of the changes in the vertex-recorded P_1-N_1 as a function of attention is shown in Figure 3. Note the reciprocal and symmetrical amplitude changes as attention was shifted between the two visual fields, an effect seen in 12/12

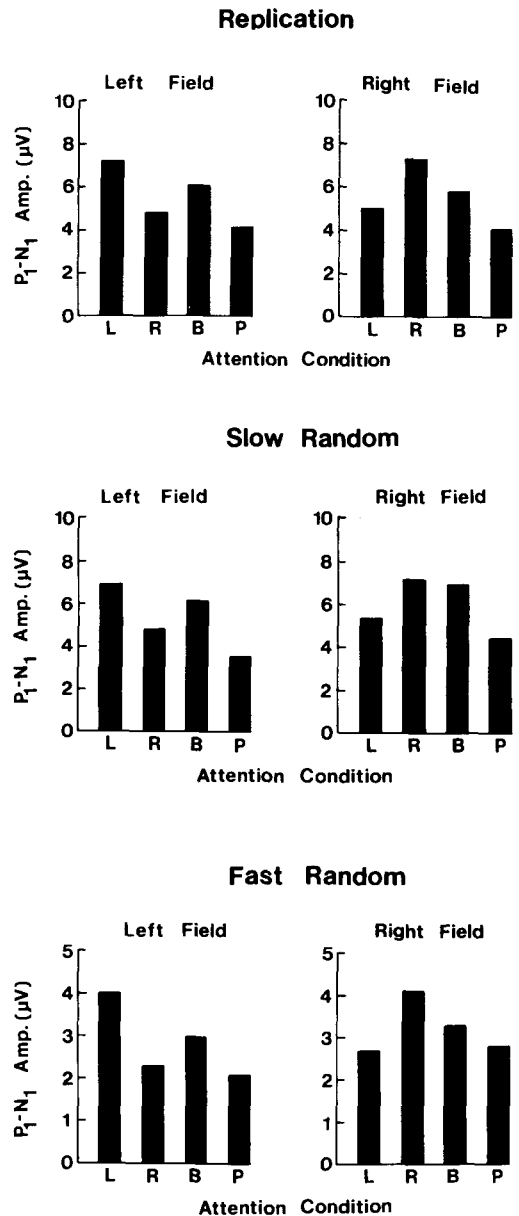


Figure 3. Mean amplitudes of the P_1-N_1 measure at the vertex across all subjects under the three different stimulus schedules and four attention conditions (L = attend left, R = attend right, B = attend both, P = passive).

Table 1
Component Latencies (Mean ± Standard Error)

	C_z				O_2			
	P_1	N_1	P_2	P_3	P_1	N_1	P_2	P_3
Replication	96 ± 3	157 ± 3	219 ± 4	396 ± 7	104 ± 4	164 ± 4	222 ± 4	388 ± 6
Slow Random	95 ± 3	159 ± 4	221 ± 5	393 ± 8	105 ± 4	168 ± 3	223 ± 4	381 ± 6
Fast Random	93 ± 3	150 ± 3	214 ± 3		107 ± 4	168 ± 4	221 ± 3	
Mean	95	155	218	395	105	167	222	385

Table 2
Mean Amplitudes (μV) of VEP Components From All Experimental Conditions, Averaged Across Right and Left Visual Fields

	C_z						O_2					
	P_1	N_1	P_2	P_1-N_1	N_1-P_2	P_3	P_1	N_1	P_2	P_1-N_1	N_1-P_2	P_3
Replication												
Focused-Attended	1.8	5.4	4.6	7.2	10.0	5.8	2.1	1.9	3.7	4.0	5.6	3.9
Divided Attention	1.5	4.4	5.0	5.9	9.4	5.7	1.8	1.5	4.2	3.4	5.7	2.7
Focused-Unattended	1.0	3.8	4.2	4.8	8.0	2.3	1.0	1.9	1.5	2.9	3.4	1.6
Passive	1.3	2.8	4.5	4.1	7.3	1.6	1.3	1.6	1.8	2.9	3.4	1.7
Slow Random												
Focused-Attended	1.7	5.3	4.4	7.0	9.7	6.5	1.6	2.0	3.4	3.6	5.4	4.3
Divided Attention	1.9	4.5	4.8	6.4	9.3	6.5	1.8	2.4	4.1	4.2	6.5	3.1
Focused-Unattended	1.3	3.7	3.7	5.0	7.4	2.1	1.0	2.0	1.8	3.0	3.8	1.6
Passive	1.2	2.7	4.7	3.9	7.4	2.8	1.2	1.6	2.0	2.8	3.6	1.6
Fast Random												
Focused-Attended	1.3	2.8	3.3	4.1	6.1		1.2	1.9	1.8	3.1	3.7	
Divided Attention	.6	2.5	2.9	3.1	5.4		1.1	1.8	1.6	2.9	3.4	
Focused-Unattended	.7	1.7	2.4	2.4	4.1		.8	1.3	1.1	2.1	2.4	
Passive	.7	1.7	2.3	2.4	4.0		.9	1.3	1.2	2.2	2.5	

Table 3
Percentage Increments of VEP Components, Comparing Attended vs. Unattended Visual Field

	C_z						O_2					
	P_1	N_1	P_2	P_1-N_1	N_1-P_2	P_3	P_1	N_1	P_2	P_1-N_1	N_1-P_2	P_3
Replication	80	42*	10	50†	25**	152†	110†	0	146†	38*	65**	144†
Slow Random	31	43*	19	40**	31**	210†	60	0	89*	20	42	169†
Fast Random	43	65*	38**	71†	49†		50	46*	64*	48†	54**	

Note—One-tailed *t* test on μV differences; significance levels = *.025, **.01, †.001.

subjects with the replication, in 10/12 with the slow random and in 11/12 with the fast random schedule. The mean P_1-N_1 averaged across both fields during divided attention was intermediate in amplitude between those evoked by attended and unattended flashes during focused attention. The amplitude of P_1-N_1 in the passive condition was typically about the same as that elicited by stimuli in the unattended field.

At the O_2 site, however, the N_1 was the component least sensitive to shifts in the direction of attention, while P_1 and P_2 were more consistently enhanced with attention under all schedules. The P_1 showed significantly greater attention-related enhancement under the replication schedule as compared with both the slow random ($p < .05$) and fast random ($p < .01$) schedules. The P_2 demonstrated significantly less additional enhancement under the fast random as compared with either of the two slower schedules (vs. replication, $p < .01$; vs. slow random, $p < .05$). This is in contrast to the situation at C_z , where the largest effects of attention were generally observed under the fast random schedule.

Further dissociations were observed between the effects of attention on C_z and O_2 components. An example is shown in Figure 2 (subject R.L.); paying attention to left-field flashes increased N_1-P_2 to those stimuli at both C_z and O_2 sites, whereas attending

to the opposite field markedly enhanced N_1 at the vertex to right-field flashes without any augmentation of the N_1 at O_2 . Such dissociations offer further evidence that N_1 and P_2 can each be subdivided into distinctive central and occipital subcomponents.

For most VEP components, the summed amplitude over both visual fields during the divided attention condition did not differ significantly from the summed amplitude over attended and inattended stimuli in the focused conditions having the same schedule (Tables 2 and 4). Exceptions to this occurred for the P_2 wave at O_2 and the P_3 wave at C_z , both of which had larger summed amplitudes during divided than during focused attention conditions at the slower rates (Table 4). There were no significant differences between VEPs to unattended stimuli and those evoked passively under any schedule.

Rate effects. It is clear from Table 2 that all VEP components decline in amplitude at the more rapid rate of stimulus delivery. This rate-dependent depression was significantly greater for responses measured at the vertex than at O_2 for components N_1 , P_1-N_1 , and N_1-P_2 , over all conditions of attention (each $p < .01$). In the passive condition, however, only the P_2 and N_1-P_2 were significantly more refractory at the vertex than at O_2 (both $p < .01$). In no case did any component show greater rate-

Table 4
Percentage Increments of VEP Components, Comparing Divided vs. Focused and Passive vs. Focused-Unattended Conditions

	C _Z						O ₂					
	P ₁	N ₁	P ₂	P ₁ -N ₁	N ₁ -P ₂	P ₃	P ₁	N ₁	P ₂	P ₁ -N ₁	N ₁ -P ₂	P ₃
	Replication											
Divided vs. Mean of Attend and Unattend	7	-14	2	2	4	41*	16	-21	62*	-2	27	-2
Unattend vs. Passive	-23	36	-7	17	10	44	-23	19	-17	0	0	16
	Slow Random											
Divided vs. Mean of Attend and Unattend	27	0	19	7	9	51*	38	20	58*	27	41	5
Unattend vs. Passive	8	37	-21	28	0	-25	-17	25	-10	7	6	0
	Fast Random											
Divided vs. Mean of Attend and Unattend	-40	11	2	-5	6		10	13	10	38	11	
Unattend vs. Passive	0	0	4	0	3		-11	0	-8	-5	-4	

Note—Two-tailed *t* test on μV differences; significance levels = *.01.

dependent depression at the O₂ site. Paralleling these amplitude changes, the latency of the N₁ wave at C_Z was significantly shorter (by 8 msec, Table 1) during the fast random schedule than at the slower rates, while the N₁ latency at O₂ was unchanged as a function of stimulus schedule ($p < .01$ for Electrode Site by Schedule interaction for N₁).

Behavioral Measures

The mean RT was significantly faster (by 11 msec) under the replication schedule than under the slow random schedule ($p < .025$) and averaged 27 msec faster ($p < .001$) when the subjects responded to both visual fields (divided attention) rather than to a single field (focused attention) (Table 5). These RT effects were not paralleled by significant changes in the latency of the P₃ component across conditions.

The detectability of target flashes in the fast random schedule was significantly lower ($p < .025$) in the attend-both condition ($d' = 1.26 \pm 0.15$) than in the focused attention conditions ($d' = 1.71 \pm 0.18$ and 1.61 ± 0.18 for left- and right-field flashes, respectively). The decision criteria (β values) did not differ significantly between focused and divided attention conditions, averaging 2.91 for attend-left, 2.65 for attend-right, and 2.00 for attend-both conditions.

DISCUSSION

Shifts of attention between right and left spatial locations were found to produce strong and consistent modifications of specific components of the VEP under all experimental conditions. These attention-related changes observed using the random schedules fulfill the criteria for bona fide physiological signs of selective attention stated at the outset,

namely: (1) specific VEP components showed reciprocal increases and decreases in amplitude to flashes in either field when attention was switched between them, (2) the order of stimulus delivery could not be anticipated by the subject, (3) lateral shifts of gaze and eye-movement artifacts were under control, and (4) behavioral evidence of selective processing was concurrently obtained. Moreover, the attention-related changes in the P₁, N₁, and P₂ components cannot be explained as consequences of selective motor responding, since they were present to the nontarget stimuli in the fast random condition, to which no motor responses were made. These results thus provide unequivocal evidence that selective attention to spatial location can be associated with distinct modifications of neurophysiological processing as reflected in the VEP.

The effects of attention on the N₁ and P₂ waves were not diminished in the slow random condition in comparison with the replication condition. This suggests that differential preparatory states of alertness or arousal (Näätänen, 1967; Karlin, 1970) did not contribute substantially to the experimental modifications of these components. The P₁ wave, however, did show less enhancement during the slow random schedule than during the replication, at both C_Z and O₂ sites. This result tends to support

Table 5
Mean Reaction Times (\pm SD) in the Different Conditions

	Configuration		
	Replication	Slow Random	Mean
Attend Left	361 \pm 34	376 \pm 36	369
Attend Right	364 \pm 35	366 \pm 33	365
Attend Both	334 \pm 38	346 \pm 40	340
Mean	348	359	

Näätänen's hypothesis that modulation of the subject's prior arousal, governed by his expectancy of stimulus delivery, can in some cases confound the effects of selective attention on EP amplitude. Näätänen's (1975) critique of the stimulus schedules used by Eason et al. (1969) receives further support from the present behavioral findings. Discriminative RTs were significantly faster with the replication than with the slow random schedule, suggesting that subjects can indeed predict the timing and order of stimuli with greater than chance accuracy when the two fields are governed by independent schedules. Thus, it is essential, in electrophysiological studies of selective attention, to prevent the possibility of differential stimulus expectancy and prior arousal by appropriate stimulus randomization.

In our replication of Eason et al.'s (1969) design, the predominant effects observed were on different VEP components than in the original study. The figures of Eason et al. depict a negative wave at O₂, peaking at 160-180 msec (corresponding to our N₁), which was at least twice as large, on the average, to attended-field flashes, but we observed no attention-related changes in this occipital component in the replication. We did, however, confirm Eason et al.'s observation that the subsequent positive peak at 200-220 msec (P₂), and hence the N₁-P₂ measure, was substantially increased with the lateralized focusing of attention. The P₁ component (ca. 100-120 msec) was less evident in their tracings, but appeared to increase with attention in several subjects in accordance with our findings. The discrepancy between our results and those of Eason et al., regarding the occipital N₁ wave might possibly be attributed to higher motivation levels in their subjects (all were professional laboratory personnel whose RTs averaged some 100 msec faster than these of the present inexperienced subjects) or, perhaps, to uncontrolled changes in their subject's visual fixation.

At the vertex recording site, on the other hand, the N₁ component (ca. 155 msec) did show strong and consistent attention effects at all ISIs. Further distinctions between the occipital and central N₁ waves were observed in their latencies and relative refractory periods, with the vertex component being attenuated to a greater extent at the shorter ISIs. Lehtonen (1973) has similarly reported that the visually evoked N₁-P₂ components recorded centrally and occipitally can be dissociated from one another on the basis of differing latencies, refractory periods, and sensitivity to spatial structure in the stimulus. Lehtonen concluded that these "apparently similar late VEP deflections . . . represent different neurophysiological phenomenon." He suggested that the occipital N₁ reflects "the function of the modality-specific cortical area" while the vertex N₁

is associated with "the function of a modality non-specific area." This concept of parallel anterior and posterior foci for the late waves of the VEP might also help to explain discordant results of topographical mapping studies. Some investigators have reported a narrow, preoccipital focus for N₁ and a parieto-occipital distribution for P₂ (Simson et al., 1976), while others have found more anterior distributions for both of these waves (Allison, Goff, Williamson, & VanGilder, in press; Goff, Matsumiya, Allison, & Goff, 1969). It may be that differences in stimulus parameters or attentional requirements between studies bring one or the other of these parallel late waves into prominence.

It is perhaps not a coincidence that paying attention to one source or channel of auditory information (e.g., one ear) while ignoring a second source is also reflected most faithfully by changes in a vertex-centered "N₁" component of the auditory evoked potential (peaking at 90-120 msec). Like the vertex-recorded N₁ of the VEP, the auditory-evoked N₁ is preferentially enlarged to all attended-channel stimuli in relation to stimuli in an irrelevant channel (Hillyard et al., 1973; Hink, 1975; Schwent and Hillyard, 1975; Schwent et al., 1976a, 1976b, 1976c). Moreover, Hink et al. (in press) have found that the summed amplitude of the auditory N₁ waves across both input channels (the two ears) remained relatively constant between conditions of focused and divided attention, as was shown here for the N₁ of the VEP. These cross-modality similarities make it tempting to speculate that the attention-sensitive portion of this vertex-negative wave between 90 and 160 msec is a sign of nonspecific selective processing which operates with a limited overall capacity (at least in its physiological aspect). Hillyard et al., 1973, have suggested that the N₁ amplitude may be a general physiological sign of a "stimulus set" mode of selective attention which operates early in sensory processing to reject irrelevant stimuli "at the time of arrival, after analyzing as little information from them as possible" (Broadbent, 1970). Operating in parallel with this hypothesized general selection system, the attention-sensitive components of the occipital VEP might reflect modality-specific aspects of attention, a distinction analogous to that made by Lehtonen.

There are certain apparent discrepancies between the behavior of the auditory and visual "vertex potentials," however, which should be noted. In the auditory modality, the N₁ wave was clearly differentiated between attended and irrelevant channels only when a fairly high information load was placed on the subject (mean ISI shorter than 0.5 sec) and moderate-to-low-intensity stimuli were used (Schwent et al., 1976a, 1976b). In the present study, however, we found clear evidence of attention effects on the vertex N₁ of the VEP (and other components

as well) at much longer ISIs. This sensitivity of the VEP to manipulations of attention at slow rates of stimulation may reflect a difference between the two modalities in their underlying selection mechanisms. Alternatively, the requirement for rapid motor responses or the low intensity levels of the stimuli used may have augmented the attention effects. It should be emphasized, however, that the attention-related changes in sharp peaks such as P_1 and N_1 at the longer ISIs could not be caused by the addition of "motor potential" components (Gilden, Vaughan, & Costa, 1966), since the RTs were too long and too poorly time-locked to the stimulus for this to occur. However, the later positive waves (P_2 and P_3) could, in principle, be partially contaminated by motor potential components or by the termination of CNV waves which might have been present.

The late positive P_3 (or P_{300}) component was larger to the attended visual stimuli, which commanded a prompt motor response, in agreement with previous reports (Donchin & Cohen, 1967; Eason et al., 1969; Harter & Salmon, 1972). Parallel findings have been made using auditory and somatosensory cues, indicating that the P_3 wave is truly a modality nonspecific brain event (Ford, Roth, Dirks, & Kopell, 1973; Smith, Donchin, Cohen, & Starr, 1970; Velasco, Velasco, Machado, & Olvera, 1973). Moreover, attention-related enhancement of P_3 has been dissociated from changes in the earlier evoked N_1 and P_2 components, in both auditory and visual modalities (e.g., Courchesne et al., 1975; Ford et al., 1973; Harter & Salmon, 1972; Hillyard et al., 1973; Smith et al., 1970; present study). Hillyard et al. (1973) have suggested that the P_3 wave reflects a different mode of attention from the earlier N_1 component, perhaps akin to Broadbent's (1971) "response set" selection. The present study revealed yet another distinction between the N_1 and P_3 waves during attention tasks. While the total N_1 amplitude output remained constant when responses were directed to both channels (divided attention), the total P_3 output at the vertex was augmented by this demand for an increased rate of responding. This suggests that the capacity for response selection or decision making that is indexed by P_3 was not fully utilized in the focused attention condition.

In the recent behavioral literature on visual attention, divergent views have been expressed about the ability of human observers to attend selectively to a specific locus in space. The question being debated is whether or not focusing attention on one source results in preferential processing of those stimuli in relation to those from unattended sources. Posner, Nissen, and Ogden (in press) reported that advance cueing of the position of a flash facilitated the simple RT to correctly cued flashes and retarded the RT to falsely cued flashes. They interpreted this effect as "a change in an input pathway and/or attentional

mechanisms as a function of expectancy." On the other hand, Shiffrin, McKay, and Shaffer (1976) reported that the detectability of flashes is not improved when their spatial location is known in advance and that many spatial loci (up to 49) can be attended at once "without essential loss of processing quality." This conclusion was based on their finding that flash detectability at central loci remained constant whether subjects focused attention on those positions or divided their attention between the central position(s) and a peripheral set of positions. In the present fast random condition, which involved a difficult brightness discrimination, however, subjects could not attend to two spatial locations at once without a decrement in target detectability. Moreover, the VEP results indicate that information from attended and unattended visual loci was, in fact, being processed differentially by at least 100 msec poststimulus, and perhaps earlier. This behavioral and electrophysiological evidence converges on the conclusion that the human visual system does have a mechanism for selectively processing information from attended spatial positions.

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NOTES

1. In some subjects, a small amount of dc drift persisted in the EOG recording, but these steady (nearly linear) and unidirectional dc shifts could easily be distinguished from the more rapid deflections resulting from saccadic eye movements. Moreover, the direction of the dc drift throughout a block was independent of the field to which the subject directed his attention (as assessed by a chi-square test over all runs). Thus, there was no overall tendency for the subject's eyes to "wander" towards the direction of the attended flashes.

2. In a detection experiment of this type, where each stimulus is not associated with a clearly defined response interval, a hit can be defined as a response which falls within a specified post-target latency window. In these circumstances, the theoretical values of P(Hit) and P(F.A.) for a random responder are strictly dependent upon the relative durations of the appropriate response windows, not the probabilities of target and nontarget stimulus presentation. It is, therefore, necessary to define the experimentally obtained P(Hit) and P(F.A.) in terms of the appropriate response window durations.

In this experiment, we defined the response interval for a hit as an 800-msec window beginning 200 msec posttarget, since pilot data had indicated that the vast majority of correct responses would fall within this latency range. The first response within this range terminated the window, precluding the possibility of recording more than one hit per target presentation. The ratio of the number of responses recorded within the hit response windows to the number of hit response windows defined P(Hit). The total duration of the trial block minus the summed duration of the hit response windows was then divided by 800 msec to obtain the number of false-alarm windows. The P(F.A.) was defined as the ratio of the number of responses outside the hit response windows to the number of false alarm intervals. This procedure has the advantage of generating the appropriate ROC curve [$P(\text{Hit}) = P(\text{F.A.})$ and $d' = 0$] for a random responder receiving no sensory information. For a further discussion of signal detection with undefined observation intervals, see Swets and Kristofferson (1970).

3. These percent values were obtained by subtracting the amplitudes of the unattended field response from those of the attended field, dividing by the former, and then multiplying by 100. The t tests of dependent means ($df = 11$) reported in Tables 3 and 4 were calculated from the μV difference scores (one for each subject) between responses to attended vs. unattended stimuli.

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