

Steady-State VEP and Attentional Visual Processing

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INTRODUCTION

The vast majority of studies that investigated attentional modulation of the visual evoked potential (VEP) have been confined to the transient responses evoked by isolated stimuli. This class of potentials is evoked by stimuli having an asynchronous and low repetition rate (not faster than 2 stimuli per second). These potentials are called "transient" because the slow rate of stimulation allows the sensory pathways to recover or "reset" before the next stimulus appears. When visual stimuli are presented

at a constant rate that is rapid enough to prevent the evoked neural activity from returning to base line state, the elicited response becomes continuous and is called the steady-state visual evoked potential (SSVEP). With steady-state stimulation the typical VEP wave form is markedly changed. For instance, the transient VEP includes three major early components: the C1 at 60–80 msec, the P1 at 80–120 msec, and the N1 at 120–180 msec. (see Fig. 1). At more rapid stimulation rates, the brain response to the same stimulus becomes sinusoidal and is typically modulated at

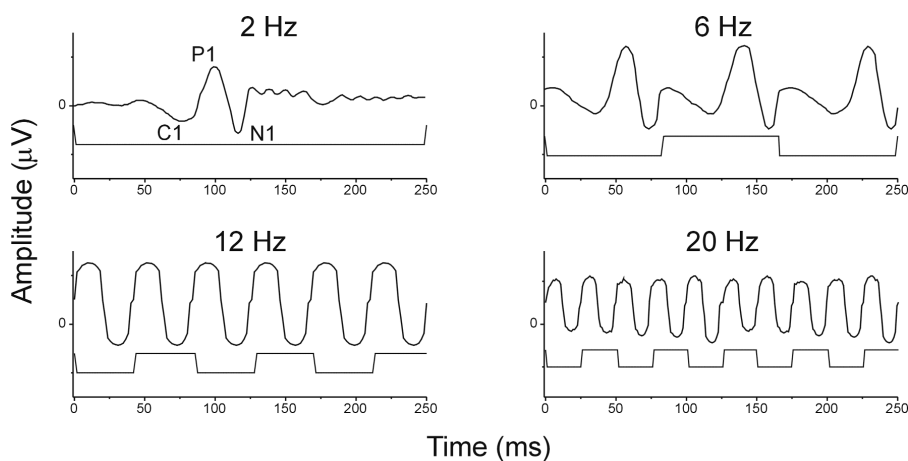


FIGURE 1 Pattern-reversal VEP wave form as a function of stimulation frequency. Note that the wave form is basically modulated at the second harmonic of the stimulus frequency. At the slowest rate (2 Hz) the components of the transient VEP can be seen.

the fundamental stimulus frequency in the case of an unstructured stimulus (e.g. flash) or at the second harmonic (double the stimulation frequency) if the stimulus is a pattern-reversal (Regan, 1989).

Like any sinusoidal wave form, the SSVEP can be measured in terms of its amplitude and phase. The phase is a joint function of the stimulus frequency and the time delay between stimulus and brain response. The amplitude indicates the relative magnitude of a given harmonic of the response and, as for transient evoked potentials, is measured in microvolts. The amplitude and phase of the SSVEP vary as function of the temporal frequency, spatial frequency, contrast, luminance, and hue of the driving stimulus (Regan, 1989).

SSVEP AND COGNITIVE PROCESSES

The SSVEP offers certain advantages over the transient VEP for the study of sensory and cognitive processes in that its signal is easily recorded and quantified and can be rapidly extracted from background noise (Regan, 1989). It is somewhat surprising, therefore, that only a few studies have attempted to relate SSVEP parameters to cognitive processes. One of the first such studies was by Wilson and O'Donnell (1986), who found that individual differences in reaction time in mental rotation and memory matching tasks were correlated with the conduction speed ("apparent latency") of the SSVEP recorded in a separate session. These investigators did not find any reliable relationships between SSVEP latency and mental workload, however (Wilson and O'Donnell, 1986).

In a visual vigilance task, Silberstein *et al.* (1990) found that the SSVEP amplitude to an irrelevant flicker was reduced during a period when the subject was actively searching for a target shape as compared to when no target was expected.

This effect was interpreted in line with the authors' hypothesis that the SSVEP to such an irrelevant probe would be reduced in brain areas as a function of how actively engaged those brain areas were in performing the ongoing task. Accordingly, they concluded that during the period of active vigilance there was increased brain activity in parietooccipital regions, leaving fewer neurons available to respond to the irrelevant background 13-Hz flicker.

The use of the SSVEP as a probe of cognitive function was extended by Silberstein *et al.* (1995) in a study of the Wisconsin Card Sorting Task. They found that the SSVEP amplitude to a continuous irrelevant background flicker was attenuated over prefrontal, central, and right parietotemporal regions in the interval following a cue to change the card-sort criterion. These SSVEP reductions were interpreted as reflecting an increase in task-related cortical activity in those brain regions during task performance.

SSVEP AND SPATIAL ATTENTION

The neural mechanisms of visual-spatial attention have been studied extensively by means of transient VEPs (reviewed in Hillyard and Anllo-Vento, 1998; Martinez *et al.*, 2001). The general finding has been that paying attention to a specific region of the visual field is associated with increased amplitudes of the early components of VEPs to stimuli flashed at the attended location. This attentional modulation of the transient VEP includes amplitude enhancements of the sensory-evoked P1 (80–120 msec) and N1 (140–200 msec) components, which have been localized by dipole modeling techniques to specific zones of extrastriate visual cortex (Martinez *et al.*, 2001). It has been proposed that these P1 and N1 modulations reflect a sensory gain control mechanism, whereby visual information falling within the spotlight of spatial attention is facilitated and passed along to

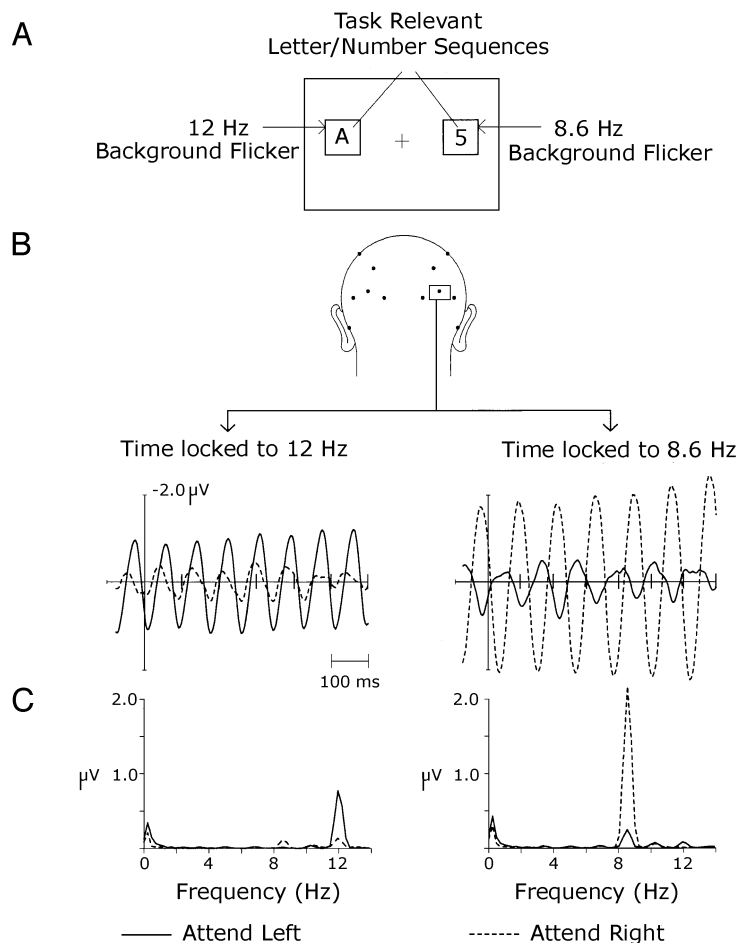


FIGURE 2 Overview of experimental design and results from the study of Morgan *et al.* (1996). (A) Subjects monitored the character sequence in one visual field while ignoring the contralateral sequence. (B) Time domain averages of SSVEP responses to flickering squares in the left (12 Hz) or right (8.6 Hz) visual field recorded from the right occipitotemporal scalp (site PO8) in a typical subject. Wave forms shown were obtained by averaging the responses to successive flashes over the first 6 sec of the flickering sequence, time locked to either the 12- or the 8.6-Hz flashes, and then averaging across all the trials of that type. Dashed wave forms correspond to the attend-left condition and solid waveforms to the attend-right condition. (C) Frequency domain analysis of the SSVEPs illustrated in B. Amplitude values were derived from fast Fourier transforms. Reprinted from Morgan, Hansen & Hillyard; *Proc. Nat. Acad. Sci. USA* **93**, 4770–4774. Copyright 1996 National Academy of Sciences, USA.

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higher levels of processing (Hillyard and Anllo-Vento, 1998).

The effects of spatial attention on the SSVEP in response to flickering stimuli was studied by Morgan *et al.* (1996) in a task in which subjects were cued to attend to a letter/number sequence in one visual field and to ignore a similar, concurrent sequence in the opposite field (Fig. 2A). The letter/number sequences in the two

fields were superimposed on small background squares flickering at 8.6 Hz in one field and 12 Hz in the other. Representative SSVEP waveforms (averaged in the time domain) from one subject are shown in Fig. 2B for the condition in which the 12-Hz background flicker was presented in the left visual field and the 8.6-Hz flicker was presented in the right visual field. Recordings shown are from

the right occipital scalp, where consistent attention-related enhancement was observed for SSVEPs at both frequencies. The amplitude of the SSVEP elicited by the 12-Hz flicker was much larger when attention was directed to the left stimulus sequence rather than the right, whereas the SSVEP in response to the concurrently presented 8.6-Hz flicker showed the reverse. This amplitude enhancement of the SSVEP in response to the irrelevant background flashes at the attended location was also evident in the frequency domain (fast Fourier) analysis of these wave forms (Fig. 2C). These findings indicate that the relative amplitudes of the frequency-specific SSVEPs elicited by each stimulus may index the allocation of attention among the flickering stimulus locations.

To gain information about the cortical regions responsible for generating the enhanced SSVEP to attended stimuli, a further study used functional magnetic resonance imaging (fMRI) to localize active brain regions while subjects performed the same task shown in Fig. 2 (Hillyard *et al.*, 1997). Two specific zones of extrastriate visual cortex were found to be activated during attention to the lateralized flickering stimuli, one in the fusiform gyrus/inferior occipital area and the other in more lateral occipitotemporal cortex. Dipole modeling of the grand-average SSVEP that was recorded in the same subjects revealed dipolar sources in occipitotemporal cortex just medial to the fMRI activations.

These findings of increased SSVEP amplitudes to irrelevant flicker at attended versus unattended locations might at first appear to conflict with the finding of Silberstein *et al.* (1990), that the SSVEP to irrelevant flicker was decreased during a period of active vigilance. This difference in outcome can be explained, however, by differences in the size and location of the irrelevant flickering stimuli between the two studies. Whereas the flickering backgrounds in the study of Morgan *et al.* (1996) were discrete and superimposed on the

task-relevant stimulus locations, the flickering background in the Silberstein *et al.* study was large and diffuse, subtending 30° by 80° of visual angle. Thus, focusing attention on the relevant stimulus sequence in the design of Morgan *et al.* would result in enhanced processing of the discrete flicker because it fell within the attentional spotlight, whereas in the Silberstein *et al.* study very little of the diffuse flicker would be included in the attentional spotlight. Indeed, if the attentional spotlight was narrowly focused on the relevant stimuli, the SSVEP response to the diffuse surrounding flicker may actually have been suppressed.

The SSVEP was also found to be a sensitive index of spatial attention to stimuli flickering in the range of 20–28 Hz (Müller *et al.*, 1998a). In this experiment, subjects were asked to attend to a flickering light-emitting diodes (LED) display in one visual field while ignoring a similar display flickering at a different frequency in the other visual field. For example, when subjects attended to an array of LEDs flickering at 27.8 Hz in one visual field and ignored an array flickering at 20.8 Hz in the opposite field, the SSVEP at the attended frequency was more than doubled in amplitude (Fig. 3). Modeling of the neural generators of the higher frequency SSVEP using a current estimation technique indicated focal sources in dorsal occipital cortex in the hemisphere contralateral to the stimulus position.

In further studies, the SSVEP response to these high-frequency flickers was used to provide an electrophysiological index of the speed of attention switching (Müller *et al.*, 1998b). In this study, each trial began with concurrent flickering of LED displays in the left (at 20.8 Hz) and right (at 27.8 Hz) visual fields. A central cue then appeared adjacent to the fixation point to indicate whether the left or right display was to be attended on that trial. It was found that the SSVEP amplitude at the attended frequency (measured by moving-window

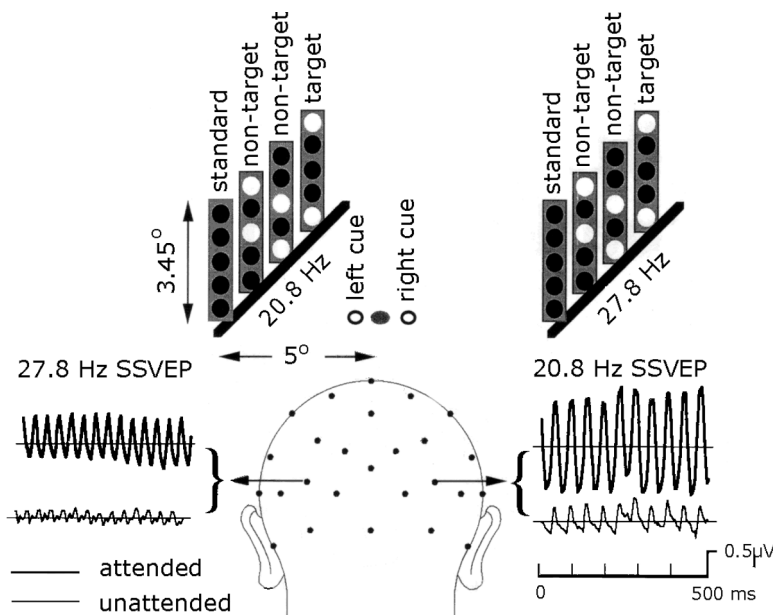


FIGURE 3 Schematic diagram of stimulus array and SSVEP wave forms from one subject shown for the attended (bold line) and unattended (thin line) conditions recorded from occipitotemporal sites (TO2 and TO1) contralateral to the flickering stimulus. The flicker rates were 20.8 Hz for the left row and 27.8 Hz for the right row of LEDs. The four possible color configurations are shown for each row, with all five LEDs being red in the standard configuration. Target and nontarget color changes (two LEDs changed to green) occurred in random order on both sides with a stimulus-onset asynchrony of 400 to 700 msec (onset to onset). Gray oval is the fixation point. The SSVEPs were obtained by a sliding-average technique in the time domain and were time-locked to either the left or the right flickering stimulus. From Müller *et al.* (1998b). Reprinted from Müller, Teder-Sälejärvi, & Hillyard; *Nature Neuroscience* 1, 631–634, 1998.

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Fourier analysis) increased abruptly after the cue (Fig. 4); it was calculated that steady-state cortical activity evoked by the attended-side stimulus was facilitated by about 500 msec after the onset of the cue to shift attention. This estimate of attention switching time corresponded with the time at which behavioral target detection within the attended display was reaching its maximum. Moreover, the SSVEP rise times were substantially faster in those subjects who switched attention more rapidly, as indicated by their earlier target detections. Also of interest was the finding that the attention effect on the SSVEP was purely facilitatory; that is, the SSVEP elicited by the attended flicker was enhanced following the attention-directing cue, but the SSVEP to the unattended-location flicker in the opposite visual field was not attenu-

ated. Müller *et al.* (1998b) proposed that this facilitation reflects the operation of a gain-control mechanism that boosts the discriminability of attended-location stimuli by enhancing their signal-to-noise ratio. They concluded that the SSVEP provides a continuous measure of the time course of attention switching and the facilitation of the cortical processing of the newly attended stimulus.

A further study investigated the effects of spatial attention on concurrently recorded transient and steady-state visual ERP responses to the flickering arrays (Müller and Hillyard, 2000). Consistent with previous findings, SSVEP amplitude was enlarged for attended flicker stimuli at posterior electrode sites contralateral to the attended visual hemifield. Significant correlations were found between the N1 and

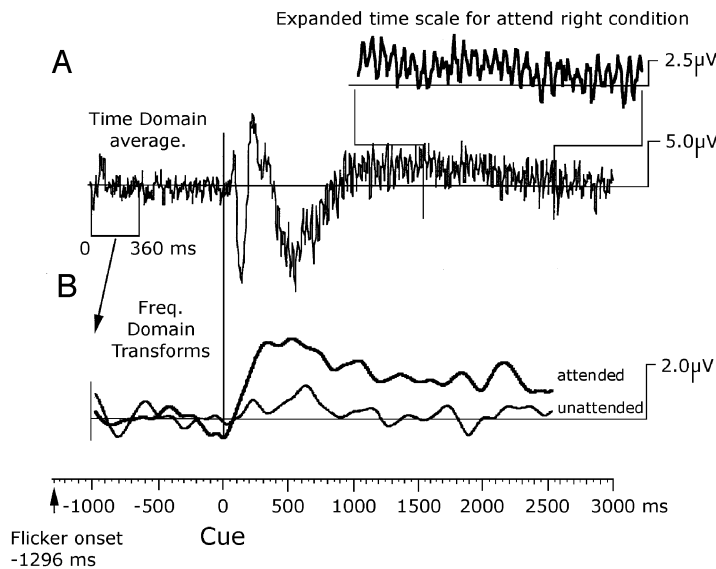


FIGURE 4 Representative time- and frequency-domain wave forms from a single subject in the study of Müller *et al.* (1998b). (a) Averaged time-domain wave form following the cue to attend right, time-locked to the right flickering stimulus. SSVEP activity to this attended flicker can be seen at the expanded time scale. (b) Time course of SSVEP amplitude in the frequency domain obtained from the wave form shown in (a) by a moving-window fast Fourier transform at the stimulus frequency; successive window steps were 4 msec. Thin horizontal line is drawn through precue base line. Bold tracing is attended wave form; thin tracing shows unattended wave form elicited by the same flickering stimulus when the cue directed the attention to the left. Note that the last 500 msec were not analyzed because the moving window reached the end of the epoch. Reprinted from Müller, Teder-Sälejärvi & Hillyard; *Nature Neuroscience* 1, 631–634, 1998.

N2 components of the transient ERP response to color-change target stimuli and the SSVEP attention effects, suggesting that the SSVEP and transient ERP reflect partially overlapping attentional mechanisms that facilitate the discriminative processing of stimuli at attended locations.

ATTENTION EFFECTS ON SSVEP PHASE

The aforementioned studies found that spatial attention strongly increased the amplitude of the SSVEP, but attention effects on response phase were not analyzed in detail. Morgan and colleagues (1996), using 8.6- and 12-Hz flickering stimuli, observed substantial phase shifts between attended and unattended wave forms in some subjects (e.g., Fig. 2), but

these shifts were inconsistent across subjects and electrode sites. In the studies of Müller and colleagues (1998a,b) that used stimulus frequencies of 20.8 and 27.8 Hz, phase shifts were observed at many scalp sites between the attended and unattended wave forms. Statistical analysis, however, failed to demonstrate any consistent phase shifts across subjects as a function of attention

The phase of the SSVEP depends in part on the transmission time between the stimulus and the evoked brain activity but does not give a direct measure of this transmission time. The steady-state phase can be expressed in terms of the ratio of the sine/cosine components of the Fourier analysis (see Regan, 1989; Porciatti *et al.*, 1992), but this solution is not unique and includes a group of phase values separated by multiples of 2π radians. For instance, a

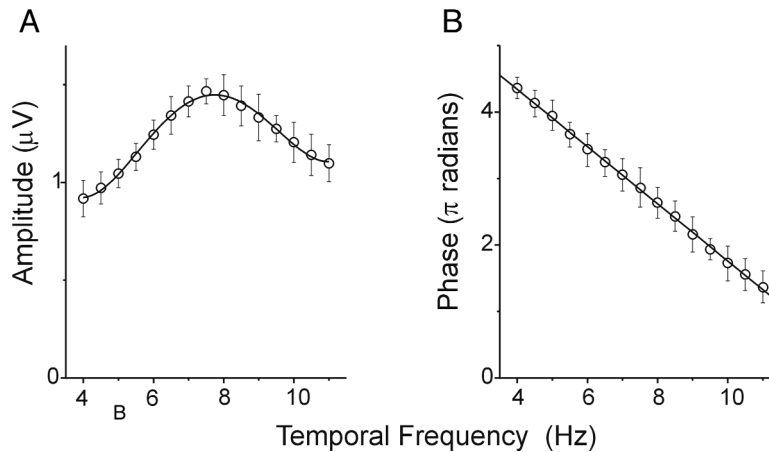


FIGURE 5 The dynamics of the SSVEP can be described by two graphs, one (a) representing the amplitude of the harmonic component analyzed as function of the stimulation frequency, and another (b) representing the phase as function of the stimulation frequency. In this example the graphs describe the second harmonic amplitude and phase as a function of the stimulation frequency (from 4 to 11 Hz) in response to a sinusoidal pattern-reversal grating having a spatial frequency of 0.6 cycle/degree (unpublished data).

45° phase shift with respect to stimulus onset for the first harmonic of a 20-Hz SSVEP corresponds to a time shift of 12.5 msec, but it is impossible to know whether the response is delayed by additional whole cycles. Thus, in this example the response latency could be 12.5, 62.5 or 102.5 msec, etc., depending on how many cycles may have occurred.

The true latency of the SSVEP cannot usually be determined unequivocally, but its "apparent latency" can be estimated as the slope of the function relating phase change to the stimulation frequency (Regan, 1989). In other words, if the SSVEP is recorded over a range of several different stimulation frequencies (for example, from 4 to 11 Hz with 0.5-Hz steps), the phase value will linearly decrease as function of the frequency (see Fig. 5b). The VEP latency for that frequency range can then be estimated in terms of the slope of the phase-frequency function. As demonstrated in numerous studies (e.g., Spekreijse *et al.*, 1977; Riemsdag *et al.*, 1982; Spinelli *et al.*, 1994; Spinelli and Di Russo, 1996; Di Russo and Spinelli, 1999a,b), the apparent SSVEP latency estimated in this way is around 100–150 msec, which cor-

responds with the latency of the P100 component of the transient VEP.

The first study to systematically analyze the SSVEP phase and apparent latency in a visuo spatial attention experiment was by Di Russo and Spinelli (1999a). In this study the SSVEP was recorded in response to a task-irrelevant grating that was phase-reversed at nine temporal frequencies ranging from 5 to 9 Hz with 0.5-Hz steps. This background grating (11° wide by 18° high) was continuously displayed in the left visual field with its medial edge 1.5° from fixation. A target (a light changing color) was presented either in the left or in the right visual field (eccentricity 7°). The task was to count the number of target color changes, without moving the eyes from the central fixation point. Thus, attention was directed either to the left or to the right visual field. The results in a single subject (Fig. 6) and averaged over all subjects (Fig. 7) confirmed that the amplitude of the early sensory activity was modulated by spatial attention. Moreover, they showed that the speed of stimulus processing in an attended region of the visual field was facilitated; i.e., the SSVEPs in the attended condition had a shorter apparent

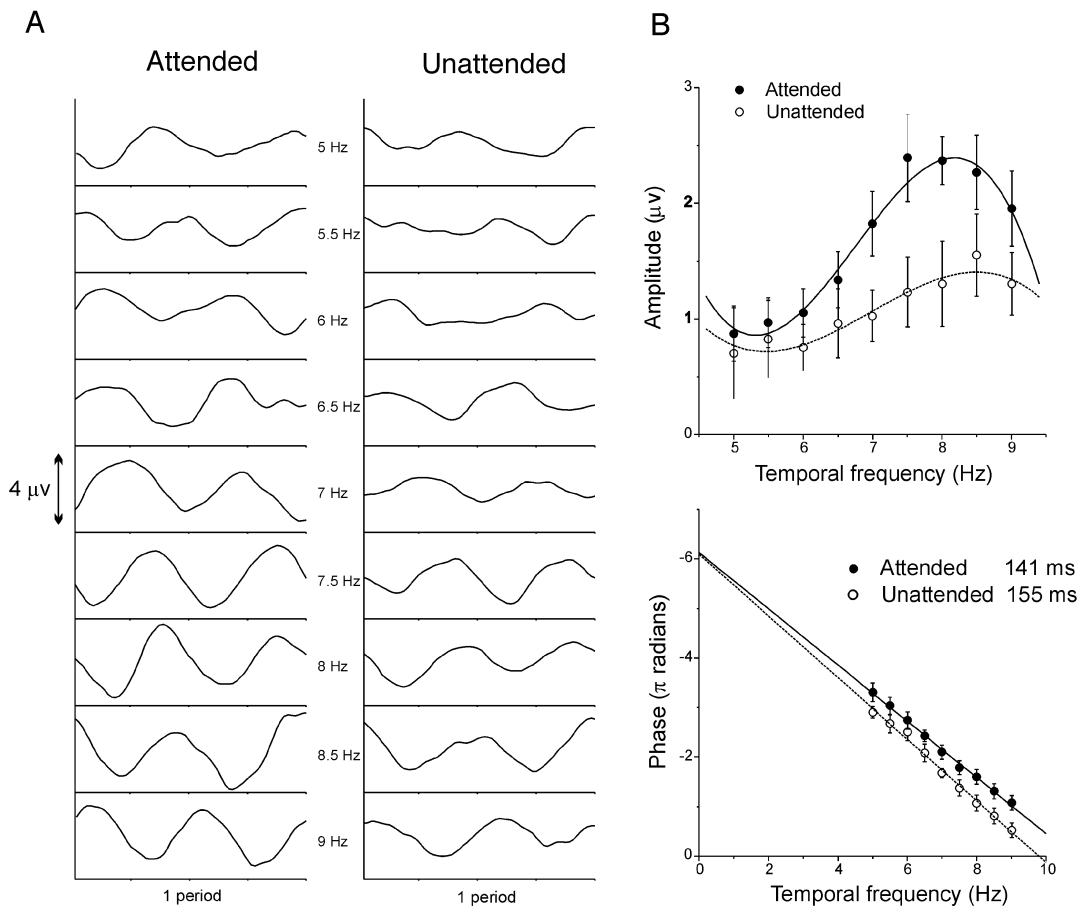


FIGURE 6 (a) SSVEP phase and amplitude variation as a function of stimulation frequency can be observed in recordings obtained from a typical subject in the attended and unattended conditions in the study of Di Russo and Spinelli (1999a). Stimuli were contrast-reversed at increasing frequencies (5–9 Hz) and SSVEPs were recorded over corresponding time epochs. (b) The resulting apparent latencies estimated from the slope of the phase-frequency function are shown below and the SSVEP amplitude-frequency function is shown above. Bars represent the standard deviations of the amplitudes and phases.

latency than SSVEPs in the unattended condition. The difference in latency produced by attention ranged from 5 to 20 msec. Similar results were obtained in this study with transient VEPs; stimuli at the attended location elicited VEPs with shorter latencies for the N60, P100, and N140 components and larger amplitudes for the P100 and N140

As mentioned before, the apparent latency of the SSVEP was calculated from

the slope of the function relating phase to stimulation frequency. In control experiments, the effect of varying stimulus eccentricity on SSVEP amplitude and latency was measured (Fig. 8). It was found that the amplitude was dramatically increased when the eccentricity was reduced, but the latency was little affected. This ruled out the possibility that the attention effect on SSVEP latency was an artifact of the subjects' shifting their gaze toward the stimulus.

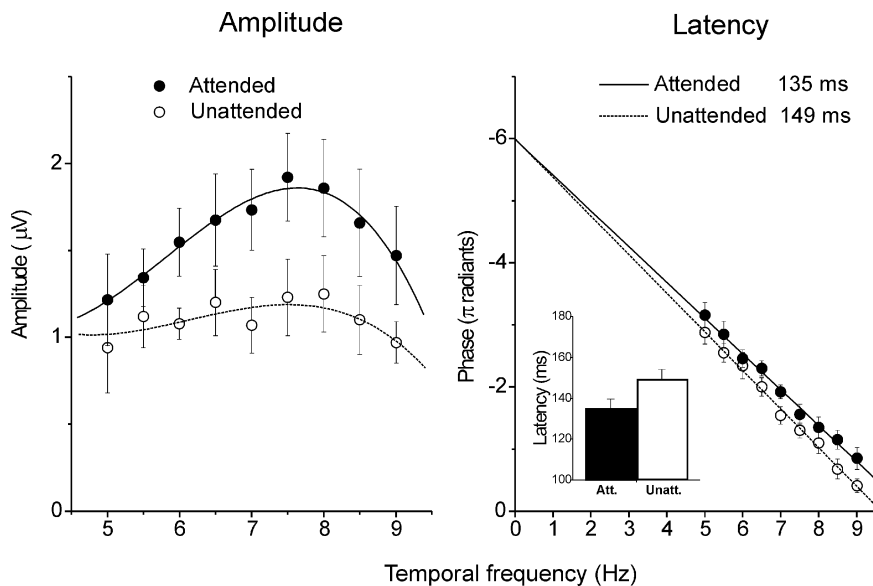


FIGURE 7 SSVEP data averaged across subjects under attended and unattended conditions in the study of Di Russo and Spinelli (1999a). Left: Mean amplitudes (and standard errors) are plotted as a function of stimulation frequency. Right: Mean phase values in radians are plotted as a function of stimulus frequency. Note the difference in phases between the two conditions. Apparent latencies are derived from the slopes of the regression lines. Mean latencies (and standard errors) across subjects are shown in the bar graph. Reprinted from *Vision Research* 39; F. Di Russo and D. Spinelli; Electrophysiological evidence for an early attentional mechanism in visual processing in humans, pp. 2975–2985. Copyright 1999, with permission from Elsevier Science.

EFFECT OF ATTENTION ON THE MAGNO CELLULAR AND PARVOCELLULAR VISUAL PATHWAYS

A subsequent experiment (Di Russo and Spinelli, 1999b) examined the effect of spatial attention on the magno- and parvocellular components of the visual pathways. The so-called p (parvo) pathway originates predominately in the foveal region of the retina from ganglion cells that are characterized by low conduction velocity, small receptive fields, strong center surround inhibition, high-contrast sensitivity, and a tendency to adapt slowly to stationary stimuli. The optimal visual stimulus for this system is a sinusoidally modulated pattern having a low temporal frequency (1–5 Hz) and high spatial frequency. Another important feature of the p system

is its processing of color information (Eskin and Merigan, 1986). The second m (magno) pathway is so labeled because its ganglion cells are larger than the parvo cells. The magno ganglion cells are widely distributed throughout the retina and are characterized by high conduction velocity, large receptive fields, low contrast sensitivity, and rapid adaptation to stationary stimuli. This system responds over a wide range of temporal frequencies (5–40 Hz), but the optimal stimulus is a sinusoidal luminance modulation with high temporal frequency (6–10 Hz) and low spatial frequency (e.g., Bodis-Wollner, 1992; Spinelli *et al.*, 1994).

As in the previous study, attention was directed to the left or to the right of the fixation point, but this time the stimulus gratings were modulated either in luminance or color contrast. Different temporal frequencies (from 2 to 6 Hz for color and 5

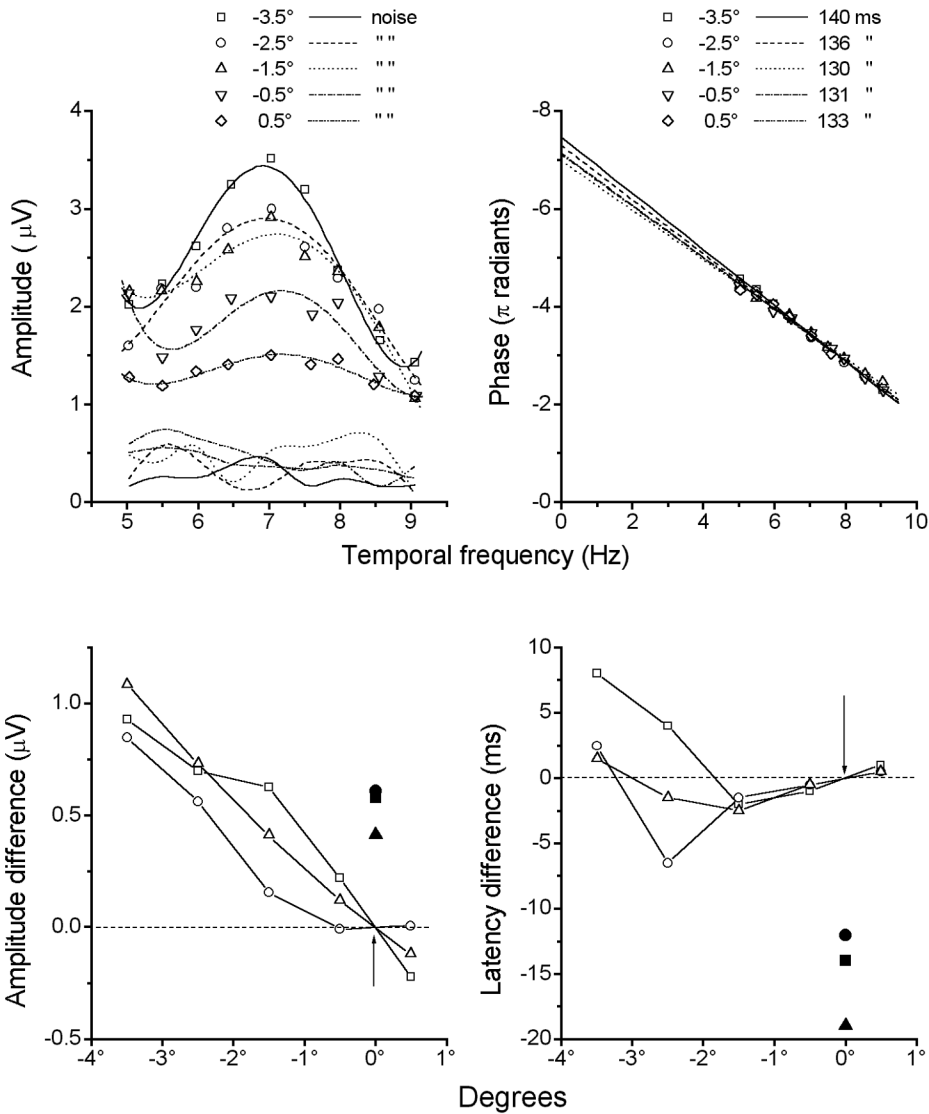


FIGURE 8 Effect of stimulus eccentricity on the SSVEP. Top graphs show the amplitude and latency data for one subject at various eccentricities. Increasing negative degree values (in the upper labels) indicate fixation points closer to the stimulus. Note the systematic increment of amplitude (top left graph) and the small variation of latency (top right graph) with decreasing eccentricity. Data from three subjects are reported with different symbols in the lower graphs. The positions of the different fixation points are shown on the abscissa. The arrow indicates the location of the fixation point used in the attention experiment. At -1.5° , the fixation point was on the edge of the grating. The SSVEP amplitudes recorded at the nine temporal frequencies were averaged to obtain a mean value for each eccentricity for each subject. The differences of the mean amplitude (bottom left graph) or the latency (bottom right graph) with respect to the reference values of each subject are showed on the ordinate. The reference values were the amplitude and the latency recorded when the fixation point was in the same position used in the attention experiment, i.e., 0° on the abscissa. For comparison, filled symbols show the increase in amplitude and the shortening of the latency observed in the same subjects when attention was manipulated. Reprinted from *Vision Research*, 39, F. Di Russo and D. Spinelli; Electrophysiological evidence for an early attentional mechanism in visual processing in humans, pp. 2975–2985. Copyright 1999, with permission from Elsevier Science.

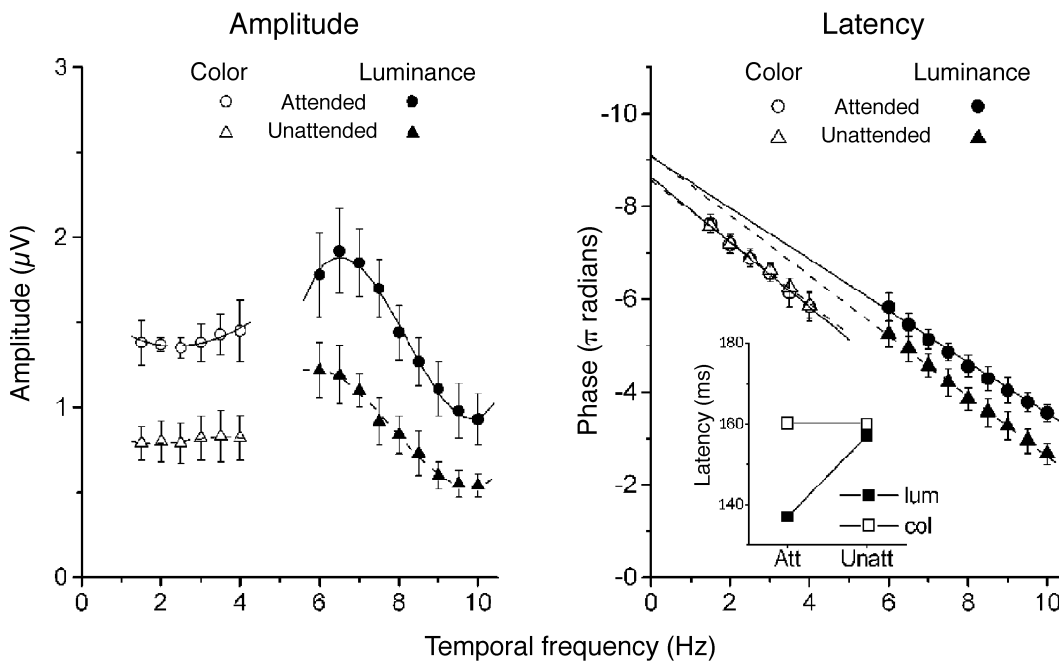


FIGURE 9 The effect of attention on SSVEPs to time-varying luminance and chromatic modulations in the study of Di Russo and Spinelli (1999b). Left: SSVEP amplitudes (and standard errors) are plotted as a function of modulation frequency. Filled symbols denote luminance gratings; open symbols denote isoluminant chromatic gratings. Attended values are shown as circles, unattended values as triangles. Right: SSVEP phases (in radians) are plotted as a function of modulation frequency. Note the differences in phase (and in apparent latency) between the attended and unattended SSVEPs for luminance gratings and the absence of such differences for chromatic gratings.

to 10 Hz for luminance) were used in order to maximize the activation of parvocellular or magnocellular pathways, respectively. SSVEPs recorded in attended and unattended conditions were again compared. As shown in Fig. 9, both the latency and amplitude of SSVEPs to the luminance-modulated stimuli were modified by attention. For the chromatically modulated stimuli, however, attention affected only the amplitude and not the latency of the SSVEPs.

Di Russo and Spinelli (1999b) concluded that spatial attention uses different mechanisms to affect sensory transmission in the magno and parvo systems. Attention produced a decrease in latency only for evoked activity in the fast, magnocellular pathway. It was proposed that attention uses the faster signals of the magnocellular

pathways to give priority to stimuli at attended locations and to direct resource allocation and enhancement of activity of the parvosystem.

The effects of attention on SSVEP amplitude and latency suggest that attention may play a role in regulating gain control mechanisms operating in human cortex. Automatic gain control mechanisms for contrast are present at several levels in the visual system, from the retina to the visual cortex (Shapley and Victor, 1981; Bernadette *et al.*, 1992; Reid *et al.*, 1992). This control, specific for m but not for p pathways, is mediated by feedback loops that cause a nonlinear increment of the response amplitude and phase advance with increasing luminance contrast (Shapley and Victor, 1981; Lee *et al.*, 1994; Bernadette and Kaplan, 1999).

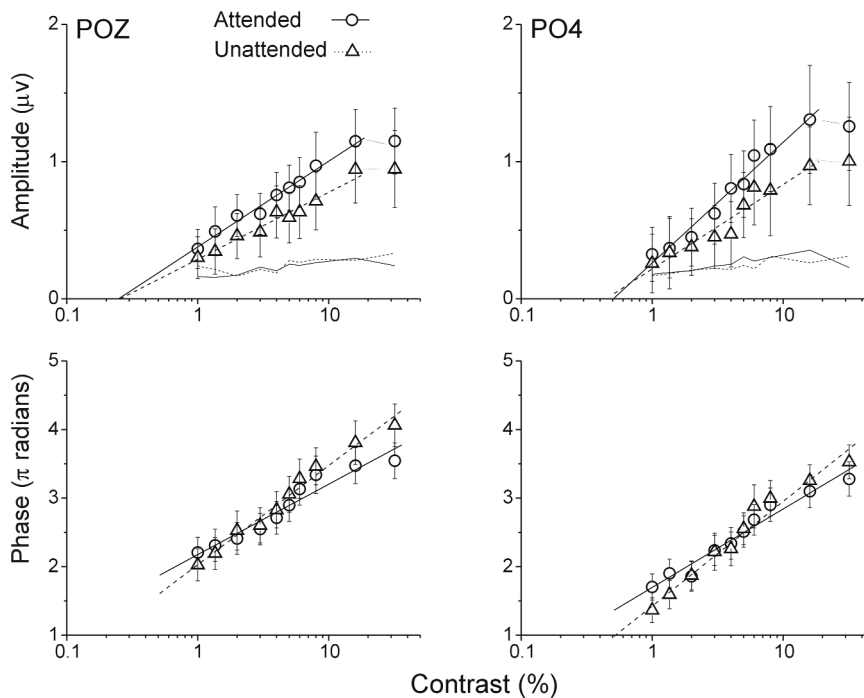


FIGURE 10 The effect of attention on SSVEP contrast-response curves for luminance gratings. Averaged data ($N = 11$) from the study of Di Russo *et al.* (2001). Top: SSVEP amplitudes (and standard deviations) as a function of luminance contrast recorded at two electrode sites (POz and PO4) in the attended (circles) and unattended (triangles) conditions. Noise levels recorded in the two conditions are shown as continuous (attended) and dashed (unattended) lines. Slopes of the regression lines were 0.66 (attended) vs. 0.49 (unattended) at POz, and 0.88 (attended) vs. 0.62 (unattended) at PO4. Regression lines intercepted the abscissa at 0.24% (attended) vs. 0.23% (unattended) at POz, and 0.54% (attended) vs. 0.46% (unattended) at PO4. Bottom: SSVEP phases (and standard deviations) in radians as a function of luminance contrast. The slopes of the curves were 1.09 (attended) vs. 1.42 (unattended) radians/log unit of contrast at POz, and 1.13 (attended) vs. 1.51 (unattended) radians/log unit of contrast at PO4. In other words, the phase advance with contrast was reduced in the attended condition. Reprinted from *Vision Research* 41, F. Di Russo, D. Spinelli, and M. C. Morrone; Automatic gain control contrast mechanisms are modulated by attention in humans: Evidence from visual evoked potentials, pp. 2435–2447. Copyright 2001, with permission from Elsevier Science.

This attentional modulation of SSVEP latency is consistent with findings in patients having an attentional deficit for contralesional space (hemineglect) consequent to brain lesions. The VEPs responses to stimuli located in the contralesional, neglected hemifield have latencies longer than do those to ipsilesional, nonneglected stimuli (Spinelli *et al.*, 1994; Angelelli *et al.*, 1996; Spinelli and Di Russo, 1996); this delay was observed only for luminance-modulated stimuli, not for chromatic-modulated stimuli (Spinelli *et al.*, 1996).

ATTENTION EFFECT ON SSVEP CONTRAST RESPONSE

The effect of attention on the SSVEP response to stimuli at varying contrast levels was investigated by Di Russo *et al.*, (2001). The purpose of this study was to use SSVEPs to examine how attention may affect the cortical mechanisms that control contrast gain. Both luminance-modulated and chromatically modulated stimuli were used in order to investigate possible differ-

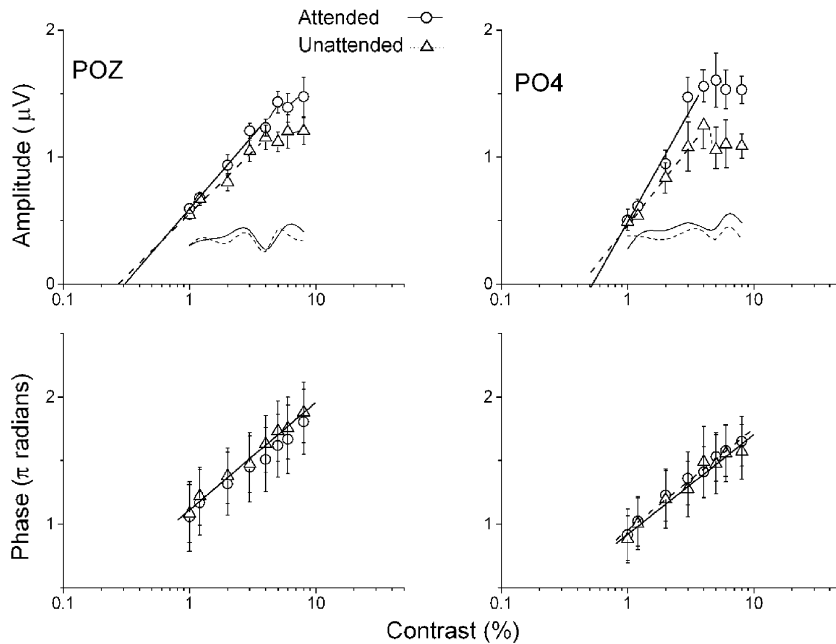


FIGURE 11 The effect of attention on SSVEP contrast-response functions for chromatic gratings. Averaged data ($N = 11$) from the study of Di Russo *et al.* (2001). Top: Averaged SSVEP amplitudes (and standard deviations) as a function of chromatic contrast. Slopes of the regression lines were 1.15 (attended) vs. 0.98 (unattended) at POz, and 1.77 (attended) and 1.26 (unattended) at PO4. Regression lines intercepted the abscissa at 0.29% (attended) vs. 0.25% (unattended) at POz, and 0.56% (attended) vs. 0.44% (unattended) at PO4. Bottom: Averaged VEP phases (and standard deviation) in radians as a function of chromatic contrast. The slopes of the curves were 0.79 (attended) vs. 0.86 (unattended) radians/ log unit of contrast at POz, and 0.81 (attended) vs. 0.80 (unattended) radians/log unit of contrast at PO4. In other words, the phase advance with contrast was not significantly changed by attention. Reprinted from *Vision Research* 41; F. Di Russo, D. Spinelli, and M. C. Morrone; Automatic gain control contrast mechanisms are modulated by attention in humans: Evidence from visual evoked potentials, pp. 2435–2447. Copyright 2001, with permission from Elsevier Science.

ences between the magnocellular and parvocellular pathways in their control of contrast gain (Derrington and Lennie, 1984; Merigan, 1989; Lee *et al.*, 1990).

The SSVEP was recorded in response to counterphased sinusoidal gratings modulated over a range of contrasts. The 1 cycle/degree gratings were modulated either in luminance or chromatic (red-green) contrast and were phase reversed at 9 and 2.5 Hz, respectively, to selectively activate the magno- and parvocellular systems. Attention was directed toward the gratings (displayed in the left visual field) by requiring subjects to detect and respond to randomly occurring changes in contrast. In a control condition, attention toward the

grating was minimized by requiring subjects to detect a target letter among distracters briefly flashed in the contralateral visual field. As shown in Figs. 10 and 11, attention increased SSVEP amplitudes for both luminance and chromatic stimuli, moreso at high than at low contrast levels, as reflected in steeper slopes of the contrast amplitude curves (over the nonsaturating range of contrasts).

The estimates of contrast threshold obtained by extrapolation of amplitudes to the abscissa were unaffected by attention. Attention also affected the SSVEP phases, but only for luminance gratings (Fig. 10), where it acted to reduce the magnitude of phase advance with contrast. Attention

had no effect on the contrast-phase functions for chromatic gratings (Fig. 11). These results are consistent with the hypothesis that attention acts on cortical gain control mechanisms, which are known to be different for the magno- and parvocellular systems.

The contrast gain mechanism acting through a feedback loop seems to occur exclusively in the magnocellular pathway (Lee *et al.*, 1994; Bernardete and Kaplan, 1999). Only cells of this pathway are reported to change their latency and temporal tuning with contrast, whereas parvocellular latency and temporal tuning remain constant both in response to isoluminant and luminance-modulated stimuli (Bernardete *et al.*, 1992; Lee *et al.* 1994). Unfortunately, no single-cell recordings have been made to assess the cortical response to equiluminant chromatic modulations. The findings of Di Russo *et al.* (2001), consistent with previous results, indicate that the human SSVEP responses to chromatic modulations are subject to contrast gain control but probably only at the cortical level, although other interpretations are possible. For instance, different sources with different integration times may contribute to the overall VEP wave form, and their relative contributions may vary with contrast. However, whatever the explanation of the phase advance for isoluminant chromatically modulated gratings, attention did not affect it systematically. This result points to a possible difference between the attentional control mechanisms for the color and luminance cortical pathways.

It is interesting to compare the present luminance data with those obtained in masking experiments, where SSVEP contrast-response curves were measured in the presence of parallel or orthogonal luminance-modulated stimuli (Burr and Morrone, 1987; Morrone *et al.*, 1987). A superimposed mask grating that was oriented orthogonally to the test grating was found to attenuate SSVEP amplitudes mul-

tiplicatively (so-called cross-orientation inhibition) and to increase the phase advance. That is, the effect of the mask mimicked the effect of engaging attention on another task, both for SSVEP amplitude and phase. It has been proposed (Burr and Morrone, 1987) that orthogonal masking effects on the SSVEP are mediated by the automatic contrast gain control mechanisms previously described. Accordingly, attention may use the same inhibitory circuitry already in place for contrast regulation to increase the processing speed and stimulus discriminability. Such a mechanism would have the advantage of improving vision without requiring any additional circuitry that was specifically dedicated to attentional processes.

CONCLUSIONS

The evidence indicates that the SSVEP provides a sensitive measure of spatial attention processes and offers certain advantages over the transient VEP. In particular, because of the high rate of stimulus presentation (4–20 times faster than for transient VEPs), it is possible to obtain reliable wave forms more rapidly. Second, with SSVEPs it is possible to study attention to stimuli that are continuously present (flickering) rather than only flashed occasionally, thereby yielding a continuous measure of attentional focusing and switching processes. Third, SSVEP measurements can reveal how attention is allocated within a complex, multielement stimulus array, because the visual response to each element can be measured individually by examining the SSVEP at its specific flicker frequency. Fourth, because the SSVEP can be elicited by an irrelevant background flicker, it can be used to study spatial attention to any type of superimposed stimulus, whether it be a rapid sequence of visual events or a stimulus that does not change over time. Finally, because of the different temporal response

characteristics of the magno- and parvocellular visual pathways, the SSVEP provides a means of studying the mechanisms of attentional modulation of these pathways in relative isolation from one another.

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