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Modification of sudden onset auditory ERP by involuntary attention to visual stimuli

Serkan Oray, Zhong-Lin Lu*, Michael E. Dawson

Department of Psychology, University of Southern California, Los Angeles, CA 90089-1061, USA

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Abstract

To investigate the cross-modal nature of the exogenous attention system, we studied how involuntary attention in the visual modality affects ERPs elicited by sudden onset of events in the auditory modality. Relatively loud auditory white noise bursts were presented to subjects with random and long inter-trial intervals. The noise bursts were either presented alone, or paired with a visual stimulus with a visual to auditory onset asynchrony of 120 ms. In a third condition, the visual stimuli were shown alone. All three conditions, auditory alone, visual alone, and paired visual/auditory, were randomly inter-mixed and presented with equal probabilities. Subjects were instructed to fixate on a point in front of them without task instructions concerning either the auditory or visual stimuli. ERPs were recorded from 28 scalp sites throughout every experimental session. Compared to ERPs in the auditory alone condition, pairing the auditory noise bursts with the visual stimulus reduced the amplitude of the auditory N100 component at Cz by 40% and the auditory P200/P300 component at Cz by 25%. No significant topographical change was observed in the scalp distributions of the N100 and P200/P300. Our results suggest that involuntary attention to visual stimuli suppresses early sensory (N100) as well as late cognitive (P200/P300) processing of sudden auditory events. The activation of the exogenous attention system by sudden auditory onset can be modified by involuntary visual attention in a cross-modal, passive prepulse inhibition paradigm. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Several major functional differences have led to the distinction of two attention systems, an *exogenous* system and an *endogenous* system

(Briand and Klein, 1987; Posner, 1980; Posner and Cohen, 1984): reflexive vs. voluntary (Jonides and Yantis, 1988; Nakayama and Mackeben, 1989), large vs. small cuing effects (Jonides, 1981; Henderson, 1991), faster vs. slower action (Müller and Rabbitt, 1989; Cheal and Lyon, 1991), differences in inhibition of return (Posner and Cohen, 1984), and different mechanisms of attention (Lu and Doshier, 2000). The existence and function of the exogenous attention system is

* Corresponding author. Tel.: +1-213-740-2282; fax: +1-213-746-9082.

E-mail address: zhonglin@rcf.usc.edu (Z. Lu).

perhaps best demonstrated in the phenomenon of attention capture — abrupt onset of a stimulus improves human response to the stimulus itself or stimuli in its spatio-temporal proximity (Jonides and Yantis, 1988; Kilgard and Merzenich, 1995; McDonald and Ward, 1999; Nakayama and Mackeben, 1989; Spence and Driver, 1994, 1996; Yantis and Jonides, 1984). For example, Jonides and Yantis (1988) demonstrated that the detection of a visual target was markedly enhanced when the target was presented as an abruptly onset character embedded among other characters whose presentation was not characterized by abrupt onset, even though differences in stimulus luminance and hue did not lead to the same effect.

In event related potential (ERP) studies, attention effects have been documented in the visual modality (Van Voorhis and Hillyard, 1977; Harter and Previc, 1978; Eason, 1981; Eimer, 1993, 1994; Hopfinger and Mangun, 1998; Luck et al., 1994; Mangun and Hillyard, 1991; McDonald et al., 1999), in the auditory modality (Näätänen, 1967; Picton et al., 1971; Hillyard et al., 1973; Schröger, 1993, 1994; Schröger and Eimer, 1993, 1997), and across the two modalities (Alho et al., 1994, 1992; Eimer and Schröger, 1998; Hillyard et al., 1984; Luo and Wei, 1999; McDonald and Ward, 2000; Teder-Sälejärvi et al., 1999; Woods et al., 1992). Whereas prior cross-modal ERP studies have addressed voluntary attention orienting (Eimer and Schröger, 1998; Hillyard et al., 1984; Teder-Sälejärvi et al., 1999; Woods et al., 1992) or the effects of involuntary attention in one modality (non-predictive auditory cues) on voluntary attention in another modality (i.e. visual ERP; McDonald and Ward, 2000), we studied whether and how involuntary attention in the visual modality affects ERPs elicited by sudden onsets of events (involuntary attention) in the auditory modality.

Although results from previous behavior studies suggest that visual warning (involuntary attention) does not facilitate auditory task performance (Posner et al., 1978; Spence and Driver, 1994, 1997; but see Ward, 1994), ERPs may provide a more sensitive measure of the effect(s) of involuntary visual attention on auditory processing. To maximally engage the exogenous attention

system to auditory stimuli, we adopted procedures from the studies of prepulse inhibition of the acoustic startle eyeblink (see reviews in Dawson et al., 1999; Filion et al., 1998). Relatively loud and short auditory white noise bursts were presented to subjects at random with long inter-trial intervals. Each noise burst was either presented alone, or preceded by the sudden onset of a visual stimulus. In a third condition, the visual stimuli were presented alone. All three conditions, auditory alone, visual alone, and paired auditory and visual, were randomly inter-mixed and occurred with equal probabilities. We compared the amplitudes and topographies of the N100 and P200/P300 ERP components elicited by the noise bursts in the auditory alone condition with those in the paired visual/auditory condition. If attention to the auditory modality could be distracted by the sudden onset of visual events, the auditory ERP generated by the noise bursts may be changed in three different ways in the paired visual/auditory condition when compared with the auditory alone condition: (1) The auditory noise burst, when paired with the visual stimulus, may excite different neuronal populations, thereby causing changes in the auditory ERP spatial topography. (2) A global reduction of auditory ERP amplitude — i.e. when the auditory stimulus is paired with the visual stimulus, auditory ERP amplitude is decreased uniformly. (3) A combination of global amplitude reduction and a shift in spatial topography. The current experiment tested all these possibilities.

2. Method

2.1. Participants

Subjects were graduate students at the University of Southern California and were compensated for their participation in the experiment. Written informed consent was obtained from all ten subjects. Data from three subjects were eliminated due to equipment problems during data collection. Data from seven subjects, five male and two female, average age 23.6 (range 22–27), were included in all analyses.

2.2. Experimental stimuli

The auditory stimulus consisted of a 104 dB white noise pulse, 40 ms in duration, gated to near instantaneous rise/fall time and generated by a Grason-Stadler 901B noise generator. The stimulus was presented binaurally through Telephonics TDH-49P headphones and controlled by a 386 computer with a Metrabyte DA-16 Analog/Digital board and running a custom program written in C.

At a viewing distance of 140 cm, the visual stimulus was a $22.2^\circ \times 15.1^\circ$ neutral slide of black vertical bars on a white background. It was presented for one second by a Kodak Ektapro 7000 slide projector, housed in a sound-proof chamber and controlled by the same computer and program mentioned above. The noise from the operation of the slide projector was inaudible to the subject.

In the paired presentation condition, the onset asynchrony of the visual and auditory stimuli was 120 ms. The particular SOA was selected to maximally engage the exogenous attention system to the sudden onset of the visual stimulus when the auditory stimulus occurs (Cheal and Lyon, 1992). The cross-modal design was chosen because it minimizes confounding effects of within-modality cortical cross-talks and refractory processes.

2.3. Procedure

Each experimental session consisted of 150 trials, 50 for each of three conditions: (1) auditory alone (A); (2) visual alone (V); and (3) paired visual/auditory (VA). Stimuli were presented in pseudorandom order in 25 blocks of six trials such that each condition was presented twice in each block. The inter-trial interval of 12, 15 or 18 s was also randomized such that each inter-trial interval appeared twice in each block. Stimuli were presented at long inter-trial intervals so as to allow complete recovery of the ERPs between trials and to maximally engage the exogenous attention system. Subjects fixated on a point 1.4 m in front of them in order to restrict unnecessary eye movements and minimize EEG artifacts. They were instructed to sit quietly while visual slides

and noise bursts were presented. They were not required to perform any task.

EEG was recorded from 28 electrodes using a linked-ear reference and placed according to the 10–20 international system and standardized by the use of an electrode cap (Electro-Cap International). EOG was recorded from two miniature electrodes (4 mm in diameter) placed above and below the right eye. The EOG electrodes were connected to a supplemental bipolar input of the EEG electrode array and were subsequently treated in the same manner as the EEG signals.

The EEG and EOG signals were amplified by a Neuroscan 32 channel amplifier and were then digitized at a rate of 256 Hz by a Labmaster AD analog/digital card, controlled by a 486 computer running proprietary EEGSYS electroencephalogram recording and analysis software (Hartwell, 1993). The EOG and EEG signals were then converted to μV units and exported from EEGSYS. The data were then reduced into 150 separate 2000 ms epochs in MATLAB (Mathworks) each corresponding to a single trial of the experiment. The epochs began 500 ms before the onset of the first stimulus of each trial.

Eyeblink was also measured as electromyographic activity (EMG) of the orbicularis oculi muscle following standard procedures (Berg and Balaban, 1999).

2.4. Data analyses

The EOG and EEG records were analyzed as suggested by Gratton et al. (1983) for off-line removal of ocular artifact. After implementation of this algorithm, the ERPs were band-pass filtered forwards and backwards to eliminate phase lag with a four pole Butterworth band-pass filter (pass-band 1–30 Hz). Baseline activity was removed from each ERP by subtracting the mean activity in the 500-ms window immediately prior to stimulus onset. Overlapping ERP components in the paired stimulus (VA) condition were separated by subtracting the response to the visual stimulus alone (V) from the record of the paired stimuli. If visual and auditory ERPs in the VA condition were generated by spatially or temporally separated sources, this new record would

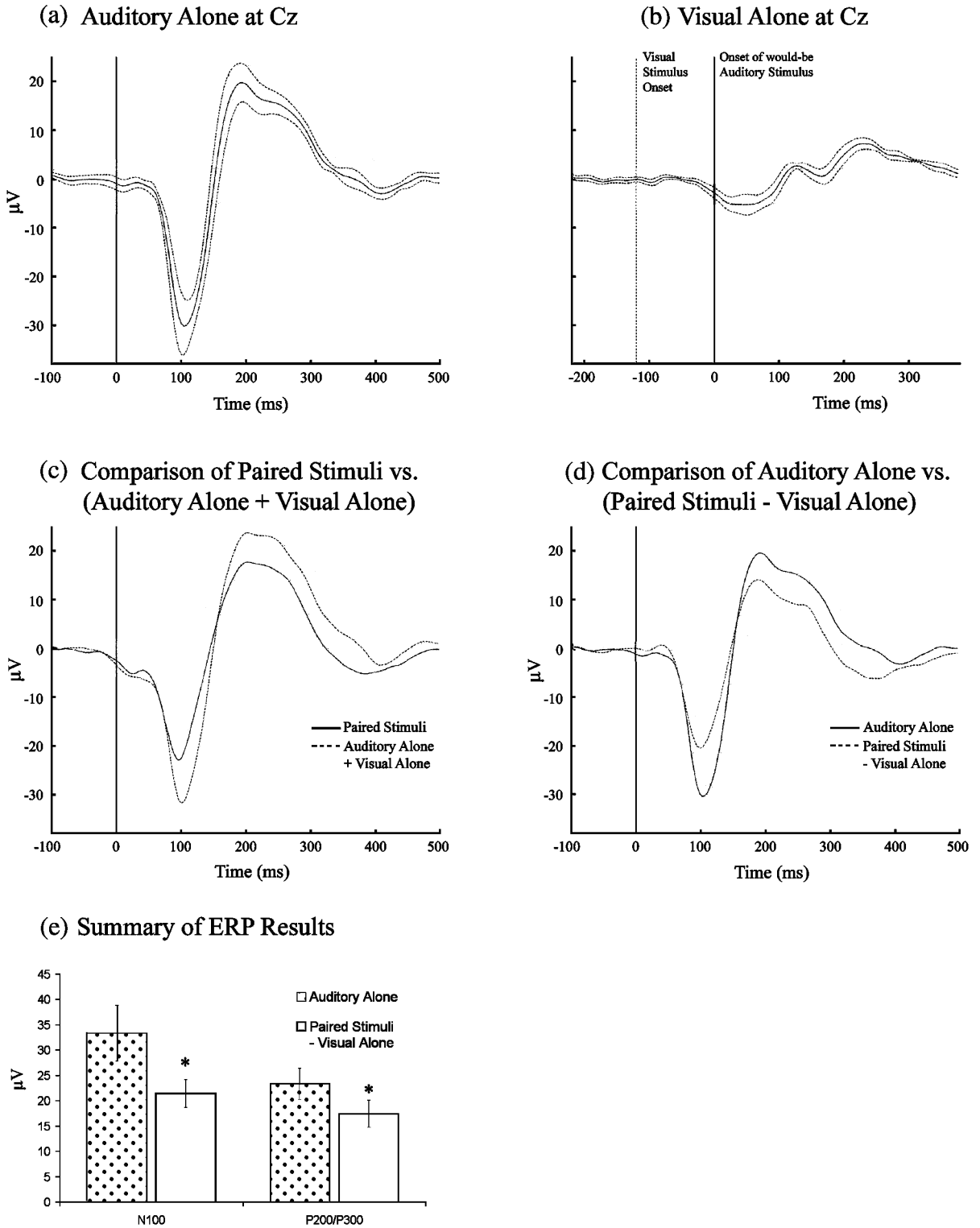


Fig. 1.

represent only the modified response to the stimulus characteristics of the acoustic stimulus in the paired stimulus condition.

The latencies of two ERP components, the N100 and the P200/P300 complex, were determined from the ERP record for the auditory alone condition and the (computed VA-V) ERP record in the paired stimuli condition at the vertex (Cz). The N100 was defined as the largest negative deviation from baseline in a window 80–160 ms following the presentation of the auditory stimulus. Though it was easy to discern in the averaged waveform across subjects, it was difficult to separate the P200 and P300 components of the ERP for individual subjects because of the merge of the two components for some subjects (Putnam and Roth, 1990). Therefore, the two were defined together as the largest positive deviation from baseline between N100 and 450 ms following stimulus onset. The peak values for the N100 and P200/P300 at Cz were compared statistically between the auditory alone and paired stimulus (after subtracting the waveform obtained for visual alone) conditions. Cz was chosen because (1) it had the best signal to noise ratio for both the N100 and P200/P300 and (2) it was least likely to be contaminated by any residual eye-blink artifacts due to its relative large distance to the eyes.

Although it was expected that the P50 waveform would also be elicited with these stimulus parameters, it was not discernible from the background noise level in individual subjects. Since only 50 trials were used to generate the event related potentials in this experiment, it is possible that the signal to noise ratio was too small to clearly elucidate the P50 waveform.

The ERP data were further analyzed by generating topographic maps for N100 and P200/P300

activity. A temporal ‘slice’ was taken across all electrodes for the time point at which the N100 and P200/P300 waveforms peaked at Cz, as defined in the component calculations above. Two-dimensional maps of scalp voltage were then calculated by spline interpolation and pseudo-color plots of electrical activity were generated.

Additional statistical analysis of ERP topography was conducted with cross-correlation. A two-dimensional cross-correlation calculates the correlation between two surfaces, then shifts the surfaces in a two-dimensional plane in relation to one another and recalculates the correlation. After several iterations, the maximal correlation can be seen at a spatial ‘lag’ when the two matrices being compared are aligned so that they are shaped as similarly as possible. This calculation was used to detect the presence of a shift in ERP topography from the auditory alone to the paired stimulus condition. A shift in topography would be indicated by a non-zero lag in the maximal point.

3. Results

Fig. 1a,b shows the grand average auditory/visual event related potential record at Cz from all subjects for the auditory and visual alone conditions. The dotted curves in Fig. 1a,b indicate the confidence interval at ± 1 S.E. from the mean ERP. The onset of the stimulus is at zero ms as denoted by the vertical line in Fig. 1a,b.

In Fig. 1c, the solid curve plots the grand average ERP record at Cz from all subjects for the paired visual/auditory condition with zero ms aligned with the onset of the auditory stimuli; the dotted curve is ‘generated’ by summing the grand average ERP in the auditory and visual alone conditions (sum of the solid curves in Fig. 1a,b with the curve in Fig. 1b shifted leftward 120 ms). (d) A comparison of the grand average ERP in the auditory alone condition (the solid curve) with that of the difference between the paired visual/auditory condition and the visual alone condition, computed by subtracting the solid curve in Fig. 1b (shifted leftward 120 ms first) from the solid curve in Fig. 1c. (e) Summary of ERP amplitude reduction. Error bars denote standard errors of the mean. Significant differences are marked by an asterisk and values are given in μV .

Fig. 1. (a) and (b) grand average auditory/visual event related potential record at Cz from all subjects for the auditory and visual alone conditions. The dotted curves indicate the confidence interval at ± 1 S.E. from the mean ERP. The onset of the stimulus is at zero ms as denoted by the vertical line. (c) The solid curve plots the grand average ERP record at Cz from all subjects for the paired visual/auditory condition with zero ms aligned with the onset of the auditory stimuli; the dotted curve is ‘generated’ by summing the grand average ERP in the auditory and visual alone conditions (sum of the solid curves in Fig. 1a,b with the curve in Fig. 1b shifted leftward 120 ms). (d) A comparison of the grand average ERP in the auditory alone condition (the solid curve) with that of the difference between the paired visual/auditory condition and the visual alone condition, computed by subtracting the solid curve in Fig. 1b (shifted leftward 120 ms first) from the solid curve in Fig. 1c. (e) Summary of ERP amplitude reduction. Error bars denote standard errors of the mean. Significant differences are marked by an asterisk and values are given in μV .

average ERP in the auditory and visual alone conditions (sum of the solid curves in Fig. 1a,b with the curve in Fig. 1b shifted leftward 120 ms). It is clear that the ERP in the paired visual/auditory condition is rather different from the computed summation of ERPs in the visual and auditory alone conditions. The generated N100 peak is 39.2% larger (paired *t*-test, $P < 0.005$) and the P200/P300 peak is 33.9% larger (paired *t*-test, $P < 0.007$) than the corresponding peaks in the paired visual/auditory condition.

Fig. 1d illustrates one of the most important results in this study: a comparison of the grand average ERP in the auditory alone condition (the solid curve) with that of the difference between the paired visual/auditory condition and the visual alone condition, computed by subtracting the solid curve in Fig. 1b (shifted leftward 120 ms first) from the solid curve in Fig. 1c. The amplitude of the entire ERP waveform is reduced in the paired condition (after subtracting the contribution from the visual ERP).

The amplitudes of the N100 and P200/P300 components in the auditory alone condition and the paired visual/auditory condition (after subtracting the ERP from the visual alone condition) for individual subjects are listed in Table 1. On average, subjects showed a significant 39.4% (paired *t*-test, $P < 0.002$) reduction of the amplitude of the N100 component in the paired stimuli condition as compared to the auditory noise alone condition (Fig. 1d). As can be seen in Table 1,

this reduction of the N100 amplitude occurred in every subject tested. Habituation assessment over five blocks with a one-way analysis of variance did not detect a significant difference between blocks for the comparison of auditory N100 amplitude in the alone and paired condition ($P = 0.311$) or peak N100 activity in the auditory alone ($P = 0.350$) or paired stimulus conditions ($P = 0.995$). These results suggest that the auditory N100 amplitude was reduced in the paired stimulus condition and neither this reduction nor peak activity in the two stimulus conditions habituated over the course of the experiment.

On average, subjects also showed significant amplitude reduction of the P200/P300 complex (25.2%, paired *t*-test $P < 0.001$). All subjects, save one, showed P200/P300 amplitude reduction while one subject showed an increase of 8.5%. As with the N100, a one-way analysis of variance over five blocks did not detect significant differences for amplitude reduction of the P200/P300 complex ($P = 0.615$) or for peak P200/P300 activity in the auditory alone ($P = 0.800$) or paired stimulus ($P = 0.961$) conditions. These results suggest that the amplitude of the P200/P300 complex was reduced in the paired stimulus condition and neither this reduction nor peak activity in the two stimulus conditions habituated over the course of the experiment.

Analysis of the EMG data showed no significant prepulse inhibition of the eyeblink response

Table 1

Amplitudes (in μV) of the N100 and P200/P300 components in the auditory alone condition and the paired visual/auditory condition (after subtracting the ERP from the visual alone condition)

Subject	N100 Auditory alone	N100 Paired	% Change	P200/P300 Auditory alone	P200/P300 Paired	% Change
1	-40.70	-19.99	-50.8%	26.17	16.79	-35.8%
2	-30.55	-18.74	-38.6%	14.36	7.49	-47.8%
3	-63.65	-49.80	-21.7%	41.48	36.00	-13.2%
4	-34.77	-26.58	-23.5%	17.97	19.51	8.5%
5	-13.07	-4.85	-62.9%	30.23	18.67	-38.2%
6	-18.42	-11.73	-36.3%	12.10	10.52	-13.1%
7	-32.68	-18.86	-42.2%	21.15	13.29	-37.1%
Mean	-33.41	-21.51	-39.4%	23.35	17.47	-25.2%
S.E.M.	6.20	5.38	5.4%	3.86	3.50	7.5%

when the auditory noise was preceded by the visual stimulus.

Two-dimensional pseudo-color plots of scalp

electrical activity were generated for both the N100 waveform (Fig. 2A,B) and the P200/P300 complex (Fig. 2C,D). By visual inspection, the

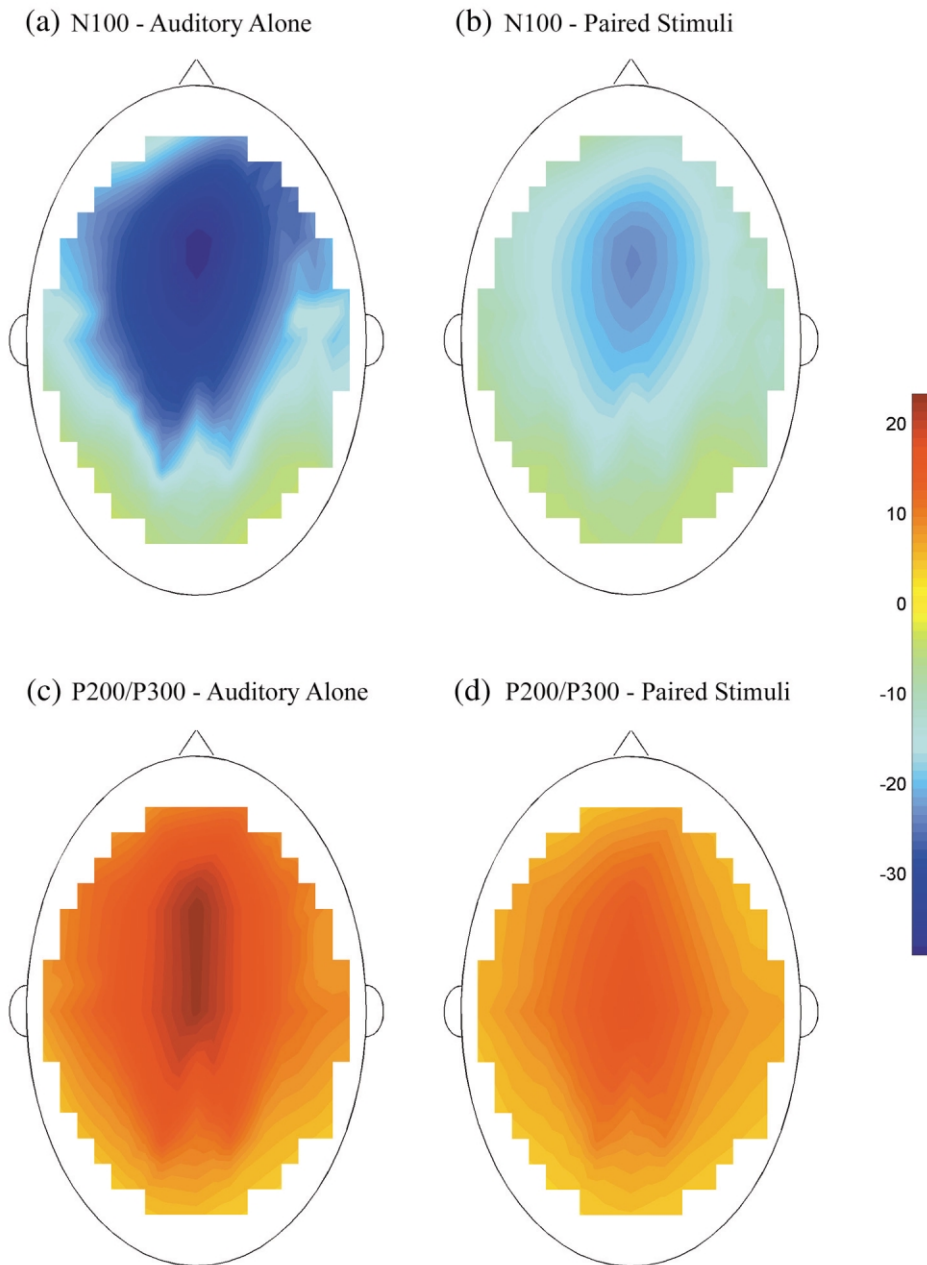


Fig. 2. Grand average N100 and P200/P300 ERP topography. (A) Auditory alone and (B) paired stimulus topography for the N100 waveform. (C) Auditory alone and (D) paired stimulus topography for the P200/P300 complex. In both pairs of figures, the contours of the topography remain the same while the absolute magnitude of the activity is reduced in the paired stimulus condition. The scale bar denotes values in μV .

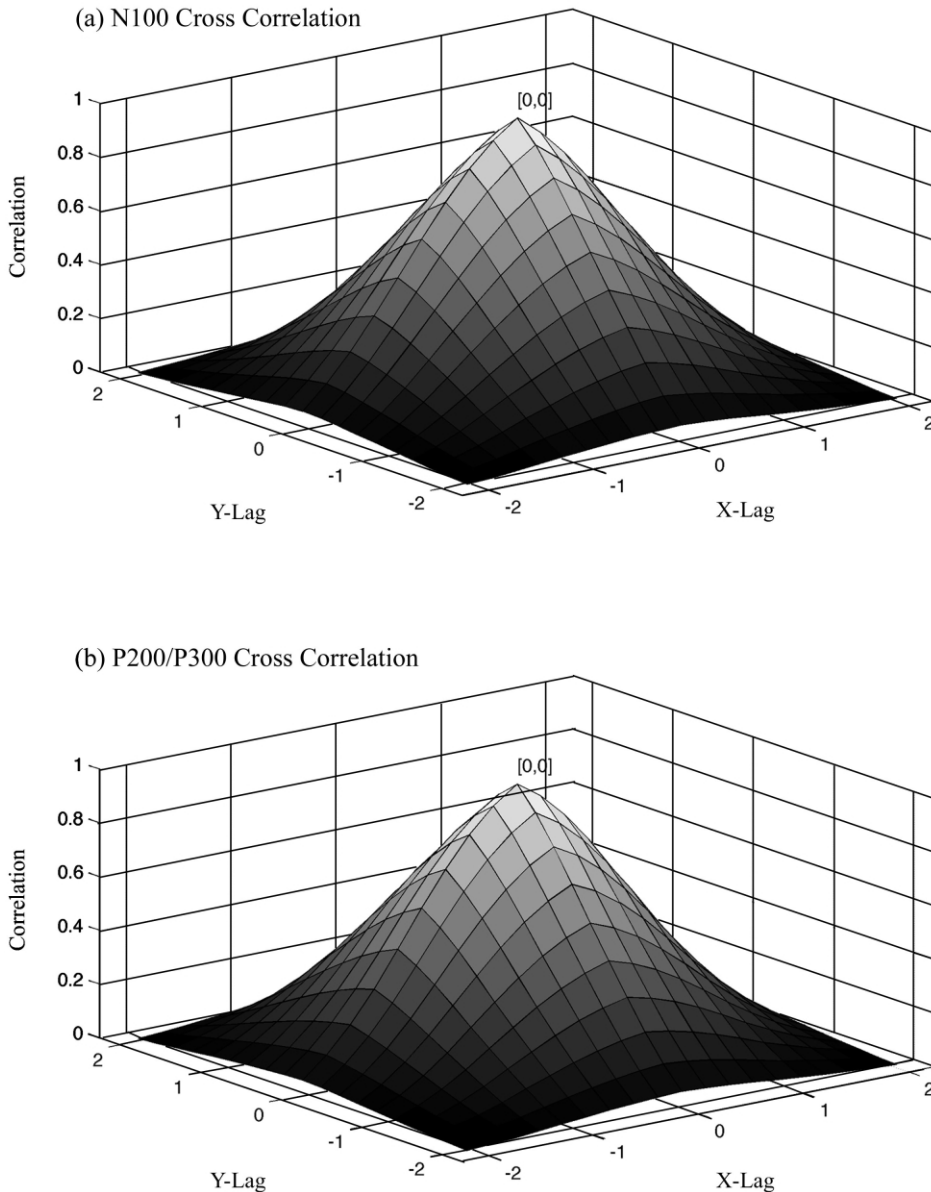


Fig. 3. Grand average cross-correlation results. (a) Cross-correlation of the N100 auditory alone and paired stimuli and (b) cross-correlation of the P200/P300 auditory alone and paired stimuli. A peak in the three dimensional structure of the cross-correlation indicates the point at which two matrices (auditory alone topography and paired stimuli topography) are most closely correlated when they are shifted in relation to one another in a two-dimensional plane. The 'x' and 'y' axes represent spatial lag values: the degree to which the two matrices have been shifted in a particular direction. Each spatial lag unit in the figure corresponds to the approximated two dimensional distance between electrode locations Cz and Fz. A lag of zero in both the 'x' and 'y' axes for the N100 and P300 indicates that the three-dimensional structures of the two stimulus conditions did not shift in relation to one another.

contours of N100 activity appear nearly identical for both the auditory alone and paired stimulus conditions, with a global (negative) maximum amplitude at Fz. Cross-correlation analysis confirmed that the maximal correlation in a two-dimensional plane occurred at a lag of zero in all seven subjects (Fig. 3a) indicating that no shift in the spatial distribution of activity had occurred. However, Fig. 2A,B differ with respect to their dynamic ranges, with the auditory alone stimulus in Fig. 2A varying between -38 and -4 μV , and the paired stimuli in Fig. 2B varying between -23 and -5 μV . It can be seen from these plots that, while the general shape has been conserved, absolute activity is reduced in the paired stimulus condition. This global reduction of activity was observed in every subject.

Similarly, visual comparison of Fig. 2C,D for the positive P200/P300 complex activity suggests that the contours of the paired stimuli are virtually identical to those of the auditory alone, with a global maximum near Cz. Cross-correlation analysis confirmed that the maximal correlation in a two-dimensional plane occurred at a lag of zero in all seven subjects (Fig. 3b) once again indicating that no shift in activity had occurred. Fig. 2C,D differ with respect to their dynamic ranges, with the auditory alone in Fig. 2C varying between 3 and 23 μV , and the paired stimuli in Fig. 2D varying between 3 and 17 μV . This global reduction of activity was seen in all subjects and, as with the N100, while the general shape of the contours in Fig. 2C,D are similar, absolute activity is reduced in the paired stimulus condition.

4. Discussion

In this study, we showed that involuntary attention to visual stimuli reduced the amplitude of auditory ERPs. Specifically, at Cz, the amplitude of the N100 component was reduced by 39.4% and the P200/P300 complex was reduced by 25.2%. We further documented that the amplitude reduction is uniform across all the recording sites — there is no significant change in the topographic distribution of the N100 and P200/P300 on the scalp. In addition, both the

N100 component and the P200/P300 complex showed no significant habituation in all the experimental conditions during the course of the experiment.

Our observation of N100 and P200/P300 amplitude reduction is consistent with several other studies in the literature. Most notably, Perlstein et al. (1993) found that the amplitudes of N100 and P200 components of auditory ERP were reduced when the auditory noise burst was paired with another auditory stimulus that occurred 120 ms before it. Simons and Perlstein (1997) also found similar effects when the auditory noise burst was paired with a cross-modal tactile stimulus that occurred either 60 ms or 360 ms before it. The current study investigated the interaction between visual and auditory involuntary attention and extends the previous results to include the spatial topography of the ERPs.

The lack of significant prepulse inhibition of the startle eyeblink with visual prepulses and 120 ms lead interval has also been noted by other investigators (Bohmelt et al., 1999; Graham, 1980). The absence of eyeblink prepulse inhibition coupled with the concurrent reduction in ERP amplitudes suggests that inhibition in these responses might occur in separate pathways (Ford and Roth, 1999). This hypothesis may deserve further investigation.

The discovery that the reduction of the ERP components follows a global pattern without significant change in spatial topography places strong constraints on the brain mechanism associated with cross-modal interaction between visual and auditory involuntary, exogenous attention system. Näätänen and Picton (1987) identified six separate cortical sources that can contribute to the N100, the first of which is affected by stimulus intensity and is probably generated in the primary auditory cortex. Corroborating evidence has been reported from magnetoencephalogram (MEG) source localizations that have placed the N100 generator in temporal regions involving the primary auditory cortex (Romani et al., 1982) and secondary auditory cortex (Lu et al., 1992). This is of particular interest since sounds of different intensities and frequencies have different source localizations within the auditory cortex itself

(Romani et al., 1982; Pantev et al., 1988; Pantev, et al., 1989, 1991). A global reduction of N100 amplitude without topographical change is indicative of reduced electrical activity at the source of the evoked response (e.g. reduced activity in the primary auditory cortex in the case of N100), suggesting that the influence of involuntary visual attention had more or less equal effects on all the cortical generators of the auditory ERPs. We speculate that such influence might occur prior to the primary auditory cortex to gate the input to the primary auditory cortex. Our conclusions about ERP topography are, of course, limited by the number of scalp electrodes available with the particular EEG system. Nonetheless, the current result could motivate more detailed studies using higher density EEG systems and MEG systems.

All in all, cross-modal, passive prepulse inhibition procedures result in reduced N100 and P200/P300 ERPs without a measurable shift in ERP topography. We conclude that activation of the exogenous auditory attention system by sudden onset of rare auditory events can be modified by involuntary visual attention. Involuntary attention to the visual modality appears to affect the exogenous attention system at early levels of sensory processing of auditory information.

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References

Alho, K., Woods, D.L., Algazi, A., Näätänen, R., 1992. Inter-model selective attention: II. Effects of attentional load on

- processing auditory and visual stimuli in central space. *Electroencephalogr. Clin. Neurophysiol.* 82, 356–368.
- Alho, K., Woods, D.L., Algazi, A., 1994. Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials. *Psychophysiology* 31, 469–479.
- Berg, W.K., Balaban, M.T., 1999. Startle elicitation: stimulus parameters, recording techniques, and quantification. In: Dawson, M.E., Schell, A.M., Böhmelt, A.H. (Eds.), *Startle Modification: Implications for Neuroscience, Cognitive Science, and Clinical Science*. Cambridge University Press, Cambridge, pp. 21–50.
- Böhmelt, A.H., Schell, A.M., Dawson, M.E., 1999. Attentional modulation of short- and long-lead-interval modifications of the acoustic startle eyeblink response: comparing auditory and visual prestimuli. *Int. J. Psychophysiol.* 32, 239–250.
- Briand, K.A., Klein, R.M., 1987. Is Posner's 'beam' the same as Treisman's 'glue'? On the relation between visual orienting and feature integration theory. *J. Exp. Psychol.: Hum. Percept. Perform.* 13, 228–241.
- Cheal, M.L., Lyon, D.R., 1991. Central and peripheral precuing of forced-choice discrimination. *Q. J. Exp. Psychol.: Hum. Exp. Psychol.* 43A, 859–880.
- Cheal, M.L., Lyon, D.R., 1992. Benefits from attention depend on the target type in location-precued discrimination. *Acta Psychol.* 81, 243–267.
- Dawson, M.E., Schell, A.M., Böhmelt, A.H. (Eds.), 1999. *Startle Modification: Implications for Neuroscience, Cognitive Science, and Clinical Science*. Cambridge University Press, Cambridge.
- Eason, R.G., 1981. Visual evoked potential correlates of early neural filtering during selective attention. *Bull. Psychonomic Soc.* 18, 203–206.
- Eimer, M., 1993. Spatial cueing, sensory gating and selective response preparation: an ERP study on visuo-spatial orienting. *Electroencephalogr. Clin. Neurophysiol.* 88, 408–420.
- Eimer, M., 1994. 'Sensory gating' as a mechanism for visual-spatial orienting: electrophysiological evidence from trial-by-trial cueing experiments. *Percept. Psychophys.* 55, 667–675.
- Eimer, M., Schröger, E., 1998. Effects of intermodal attention and cross-modal links in spatial attention. *Psychophysiology* 35, 313–327.
- Filion, D.L., Dawson, M.E., Schell, A.M., 1998. The psychological significance of human startle eye-blink modification: a review. *Biol. Psychol.* 47, 1–43.
- Ford, J.M., Roth, W.T., 1999. Event-related potential components and startle. In: Dawson, M.E., Schell, A.M., Böhmelt, A.H. (Eds.), *Startle Modification: Implications for Neuroscience, Cognitive Science, and Clinical Science*. Cambridge University Press, Cambridge, pp. 284–299.
- Graham, F.K., 1980. Control of reflex blink excitability. In: Thompson, R.F., Hicks, L.H., Shryrkov, V.B. (Eds.), *Neural Mechanisms of Goal Directed Behavioral and Learning*. Academic Press, New York, pp. 511–519.

- Gratton, G., Coles, M.G.H., Donchin, E., 1983. A new method for off-line removal of ocular artifact. *Electroencephalogr. Clin. Neurophysiol.* 55, 468–484.
- Harter, M.R., Previc, F.H., 1978. Size-specific information channels and selective attention: visual evoked potential and behavioral measures. *Electroencephalogr. Clin. Neurophysiol.* 45, 628–640.
- Hartwell, J.W., 1993. EEGSYS (Version 5.3). Baltimore, MD.
- Henderson, J.M., 1991. Stimulus discrimination following covert attentional orienting to an exogenous cue. *J. Exp. Psychol.: Hum. Percept. Perform.* 17, 91–106.
- Hillyard, S.A., Hink, R.F., Schwent, V.L., Picton, T.W., 1973. Electrical signs of selective attention in the human brain. *Science* 182, 177–179.
- Hillyard, S.A., Simpson, G.V., Woods, D.L., Van Voorhis, S., Münti, T.F., 1984. Event-related brain potentials and selective attention to different modalities. In: Reinoso-Suarez, F., Ajmone-Marsan, C. (Eds.), *Cortical Integration*. Raven Press, New York, pp. 395–414.
- Hopfinger, J.B., Mangun, G.R., 1998. Reflexive attention modulates processing of visual stimuli in human extrastriate cortex. *Psychol. Sci.* 9, 441–447.
- Jonides, J., 1981. Voluntary vs. automatic control over the mind's eye's movement. In: Long, J.B., Baddeley, A.D. (Eds.), *Attention and Performance IX*. Erlbaum, Hillsdale, NJ, pp. 187–203.
- Jonides, J., Yantis, S., 1988. Uniqueness of abrupt visual onset as an attention-capturing property. *Percept. Psychophys.* 43, 346–354.
- Kilgard, M.P., Merzenich, M.M., 1995. Anticipated stimuli across skin. *Nature* 373, 663.
- Lu, Z.-L., Doshier, B.A., 2000. Spatial attention: different mechanisms for central and peripheral precues? *J. Exp. Psychol.: Hum. Percept. Perform.* 26, 1534–1548.
- Lu, Z.-L., Williamson, S.J., Kaufman, L., 1992. Human auditory primary and association cortex have differing lifetimes for activation traces. *Brain Res.* 572, 236–241.
- Luck, S.J., Hillyard, S.A., Mouloua, M., Woldorff, M.G., Clark, V.P., Hawkins, H.L., 1994. Effects of spatial cuing on luminance detectability: psychophysical and electrophysiological evidence for early selection. *J. Exp. Psychol.: Hum. Percept. Perform.* 20, 887–904.
- Luo, Y., Wei, J.H., 1999. Cross-modal selective attention to visual and auditory stimuli modulates endogenous ERP components. *Brain Res.* 842, 30–38.
- Mangun, G.R., Hillyard, S.A., 1991. Modulations of sensory-evoked brain potentials provide evidence for changes in perceptual processing during visual-spatial priming. *J. Exp. Psychol.: Hum. Percept. Perform.* 17, 1057–1074.
- McDonald, J.J., Ward, L.M., 1999. Spatial relevance determines facilitatory and inhibitory effects of auditory covert spatial orienting. *J. Exp. Psychol.: Hum. Percept. Perform.* 25, 1234–1252.
- McDonald, J.J., Ward, L.M., 2000. Involuntary listening aids seeing: evidence from human electrophysiology. *Psychol. Sci.* 11, 167–171.
- McDonald, J.J., Ward, L.M., Kiehl, K.A., 1999. An event-related brain potential study of inhibition of return. *Percept. Psychophys.* 61, 1411–1423.
- Müller, H.J., Rabbitt, P.M.A., 1989. Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption. *J. Exp. Psychol.: Hum. Percept. Perform.* 15, 315–330.
- Näätänen, R., 1967. Selective attention and evoked potentials. *Annales Academiae Scientiarum Fennicae: Dissertationes Humanum Litterarum B-151*, 226.
- Näätänen, R., Picton, T.W., 1987. The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology* 24, 375–425.
- Nakayama, K., Mackeben, M., 1989. Sustained and transient components of focal visual attention. *Vision Res.* 29, 1631–1647.
- Pantev, C., Hoke, M., Lehnertz, K., Lütkenhöner, B., Anogianakis, G., Wittkowski, W., 1988. Tonotopic organization of the human auditory cortex revealed by transient auditory evoked magnetic fields. *Electroencephalogr. Clin. Neurophysiol.* 69, 160–170.
- Pantev, C., Hoke, M., Lehnertz, K., Lütkenhöner, B., 1989. Neuromagnetic evidence of an amplitopic organization of the human auditory cortex. *Electroencephalogr. Clin. Neurophysiol.* 72, 225–231.
- Pantev, C., Hoke, M., Lütkenhöner, B., Lehnertz, K., 1991. Neuromagnetic evidence of functional organization of the auditory cortex in humans. *Acta Otolaryngologica Suppl.* 491, 106–115.
- Perlstein, W.M., Fiorito, E., Simons, R.F., Graham, F.K., 1993. Lead stimulation effects on reflex blink, exogenous brain potentials, and loudness judgements. *Psychophysiology* 30, 347–358.
- Picton, T.W., Hillyard, S.A., Galambos, R., Schiff, M., 1971. Human auditory attention: a central or peripheral process? *Science* 173, 351–353.
- Posner, M.I., 1980. Orienting of attention. *Q. J. Exp. Psychol.* 32, 3–25.
- Posner, M.I., Cohen, Y., 1984. Components of visual orienting. In: Bouma, D., Bonwhuis, D. (Eds.), *Attention and Performance X*. Erlbaum, Hillsdale, NJ, pp. 137–157.
- Posner, M.I., Nissen, M.J., Ogden, W.C., 1978. Attended and unattended processing modes: the role for spatial location. In: Pick, N.H.L., Salzman, I.J. (Eds.), *Modes of Perceiving and Processing Information*. Erlbaum, Hillsdale, NJ, pp. 137–157.
- Putnam, L.E., Roth, W.T., 1990. Effects of stimulus repetition, duration, and rise time on startle blink and automatically elicited P200. *Psychophysiology* 27, 275–297.
- Romani, G.L., Williamson, S.J., Kaufman, L., 1982. Tonotopic organization of the human auditory cortex. *Science* 216, 1339–1340.
- Schröger, E., 1993. Event-related potentials to auditory stimuli following transient shifts of spatial attention in a go/nogo task. *Biol. Psychol.* 36, 183–207.

- Schröger, E., 1994. Human brain potential signs of selection by location and frequency in an auditory transient attention situation. *Neurosci. Lett.* 173, 163–166.
- Schröger, E., Eimer, M., 1993. Effects of transient spatial attention on auditory event-related potentials. *Neuroreport* 4, 588–590.
- Schröger, E., Eimer, M., 1997. Endogenous covert spatial orienting in audition: 'cost-benefit' analyses of reaction times and event-related potentials. *Q. J. Exp. Psychol.* 50A, 457–474.
- Simons, R.F., Perlstein, W.M., 1997. A tale of two reflexes: An ERP analysis of prepulse inhibition and orienting. In: *Attention and orienting: Sensory and motivational processes* (Simons R.F., Lang P.J., eds), Mahwah, NJ: Lawrence Erlbaum Associates, Inc., pp 229–255.
- Spence, C.J., Driver, J., 1994. Covert spatial orienting in audition: exogenous and endogenous mechanisms facilitate sound localization. *J. Exp. Psychol.: Hum. Percept. Perform.* 20, 555–574.
- Spence, C., Driver, J., 1996. Audiovisual links in endogenous covert spatial orienting. *J. Exp. Psychol.: Hum. Percept. Perform.* 22, 1005–1030.
- Spence, C., Driver, J., 1997. Audiovisual links in exogenous covert spatial orienting. *Percept. Psychophys.* 59, 1–22.
- Teder-Sälejärvi, W.A., Münte, T.F., Sperlich, F.-J., Hillyard, S.A., 1999. Intra-modal and cross-modal spatial attention to auditory and visual stimuli: an event-related brain potential (ERP) study. *Cognit. Brain Res.* 8, 327–343.
- Van Voorhis, S., Hillyard, S.A., 1977. Visual evoked potentials and selective attention to points in space. *Percept. Psychophys.* 22, 54–62.
- Ward, L.M., 1994. Supramodal and modality-specific mechanisms for stimulus-driven shifts of auditory and visual attention. *Can. J. Exp. Psychol.* 48, 242–259.
- Woods, D.L., Alho, K., Algazi, A., 1992. Intermodal selective attention: I. Effects on event-related potentials to lateralized auditory and visual stimuli. *Electroencephalogr. Clin. Neurophysiol.* 82, 341–355.
- Yantis, S., Jonides, J., 1984. Abrupt visual onsets and selective attention: evidence from visual search. *J. Exp. Psychol.: Hum. Percept. Perform.* 10, 601–621.