Biological Psychology 28 (1989) 227-238
North-Holland

EVENT-RELATED POTENTIALS BEFORE AND AFTER TRAINING: CHRONOMETRY AND LATERALIZATION OF VISUAL Nl AND N2 *

K.T. CIESIELSKI

Department of Applied Sciences in Medicine and Department of Pediatrics, Faculty of Medicine, University of Alberta, Edmonton, Alberta, Canada

C.N. FRENCH

Department of Ophthalmic Optics, University of Manchester, Institute of Science and Technology, Manchester, U.K.

Event-related potentials (ERPs) were recorded from normal right-handed males in visual-matching tasks before and after training to a high level of automaticity. The amplitude and latency of the left and right hemispheric Nl and N2 components were analyzed. While changes of Nl "after training" relative to "before training" were statistically non-significant, the N2 component appeared to be a sensitive indicator of the variability in chronometry and lateralization of cerebral processes modified by training. The N2 results suggest that with practice the physiological processes underlying performance in a visual-cognitive task become more efficient, selective and localized.

1. Introduction

Following Hebb (1949) it is generally assumed that learning involves a change in the functional properties of nerve cells and their synapses. In this framework, learning of a skill, reflected by a gradual shift from slow, laborious and controlled serial processing to fast, effortless and automatic parallel processing (Fitts & Posner, 1967; Shiffrin & Schneider, 1977) has been related to the increase of strength in the interneural connections. John Hopfield (1982), for example, in his mathematical model of neural networks demonstrated that the strength of the connection between one neuron and another determines how the network as a whole responds to an input. Such an influence of neuronal connections, as established through the process of learning, supports the concept of top-down interactions in the cerebral system of selective information processing (Van Essen, 1979) and implies that differences in physiology underlying the processing of novel and familiar stimuli should be expected from the early stages of brain chronometry.

---

* The authors wish to thank Dr. John Lind for consultations in data analysis.

The present experiment examines the neurophysiological correlates of learning in a visual template-matching task when stimuli were novel ("before training") and the same task when it was overtrained to a high degree of automaticity ("after training"). The "before training" and "after training" conditions correspond with "controlled" and "automatic" processing; however, as there is no established criterion for automaticity, these modes of performance will be interpreted as representing varying mixtures of controlled and automatic processes (Shiffrin, Dumais, & Schneider, 1981).

Event-related potentials (ERPs) may provide a unique measure of physiological correlates of learning effects, yet the research in this area is scant. Some neurophysiological indicators have been found for both classical conditioning (Linseman & Olds, 1973) and instrumental conditioning (Evarts, 1973; John, Bartlett, Shimokochi, & Kleinman, 1973). On the basis of such experiments, John (1972) suggested, over a decade ago, that the endogenous components of the ERP can reflect both the release of information which has been stored in neural tissue and the nature of the information stored.

Recent developments in research on ERP correlates of memory and learning (Donchin, 1981) have concentrated upon the P3 component, peaking 300 to 800 ms from the stimulus onset. This component has been found to index cognitive processing in a variety of experimental paradigms. The subject's uncertainty about the nature of a novel stimulus and its discriminability plays a major role in determining both the amplitude and the latency of the P3; the amplitude, for example, is directly dependent on the amount of information represented by a stimulus and varies inversely with the subjective probability of a stimulus (Duncan-Johnson & Donchin, 1977; Johnson & Donchin, 1980; Picton, Campbell, Baribeau-Braun, & Proulx, 1978). The findings in experiments devoted explicitly to the relationship between P3 and memory showed that P3 latency increases monotonically with memory set (Adam & Collins, 1978) and that P3 amplitude is larger for stimuli recognized correctly and consistently (Johnson, Pfefferbaum, & Kopell, 1985; Fabiani, Karos, & Donchin, 1986). The consistent decline of P3 latency during memory acquisition has been interpreted as resulting from the strengthening of memory traces which lead to speedier processing in the stimulus identification and evaluation stages (Johnson, Pfefferbaum, & Kopell, 1985). Although most research on learning/memory effects has concentrated upon P3, if one assumes that the processing of stimuli is influenced by top-down interactions in the cerebral system one may question whether training effects should not be seen on the earlier stages of processing than those indicated by P3, e.g. Nl, and N2.

The reaction time (RT) can also serve as a sensitive indicator of the effects of training. Thus, the reaction time in a recognition task markedly decreases after a great deal of practice with the same stimulus set, or with a consistent search task (Ross, 1970; Simpson, 1972; Schneider & Fisk, 1980). In ERP research a strong covariation has been found between perceptual processing time and N2 latency, peaking between 200 and 300 ms after stimulus onset (Ciesielski, 1989; McCallum, 1980; Renault, Ragot, Lesevre, & Remond, 1982). In contrast to P3, N2 almost precedes the response and its latency is more strongly correlated with the RT than is the parietal P3 latency (Renault & Lesevre, 1979; Ritter, Simson, Vaughan, & Macht, 1982). In addition, its scalp distribution varies with stimulus modality (Simson, Vaughan, & Ritter, 1977). In this respect it has been suggested that parieto-occipital N2 is an independent indicator of on-line visual perceptual processing (Renault, 1983). For example, the latency of N2 varies as a function of the physical differences between stimuli during discrimination (Fitzgerald & Picton, 1983; Ford, Roth, & Kopell, 1976; Towey, Rist, Hakerem, Ruchkin, & Sutton, 1980). N2 has also been described as reflecting the dominance of the right parieto-occipital region in visual cognition (Ciesielski, 1982; Cohn, Kircher, Emmerson, & Dustman, 1985; Harter, Aine, & Schroeder, 1982).

Different N2 components have been distinguished within the framework of the automatic and controlled processing (Naatanen & Picton, 1986). Attention-independent N2 mismatch was isolated by Naatanen, Gaillard, and Mantysalo (1978) from the N2 or the N2-P3a complex (Snyder & Hillyard, 1976) and described as elicited by a physically deviant event in a homogeneous repetitive sequence of stimuli. It appears to reflect a genuine, automatic comparison process (Naatanen, 1985). Another component, processing negativity (PN), described as reflecting the integrative processes occurring between the sensory input and the content of the working memory (Naatanen, 1987), is the sensory-specific component emerging in a situation of selective attention (Naataen, Gaillard, & Mantysalo, 1978). Naatanen (1982) suggested that processing negativity (larger for "matches" than "mismatches") reflects the attentional selection of stimuli for further processing. This selection occurs on the basis of certain pre-set physical stimulus criteria, which are stored and maintained for a short time in the working memory ("attentional trace"). Processing negativity is, according to Naatanen, an "on-line" reflection of a comparison process between the sensory input and the attentional trace. Ritter, Simson, Vaughan, and Macht (1982) described an N2 which may be related to stimulus classification; it has posterior topography and its latency and duration are dependent on the nature of the classification tasks and the stimulus quality. As such it has been suggested that it reflects sequential processes or on-line cerebral classification processes.

The attention-related negative ERP components in the N2 latency range, described above, are of particular relevance to our experimental paradigm in which attention-demanding, slow and highly controlled performance becomes, in the process of training, gradually faster and more automatic. If N2 latency is positively correlated with RT (Ritter, Simson, Vaughan, & Fridman, 1979; Renault & Lesevre, 1979) and if RT decreases with training (Fits & Posner, *1961* \ Shiffrin & Schneider, 1977) there should be a decrease in N2 latency as a function of overtraining.

The Nl, generated between 50 and 200 ms after the onset of a stimulus, has been regarded as an exogenous component associated with the physical and temporal features of the perceived stimuli. Recently it has been described, however, as a non-unitary process, subserving different psychophysiological functions, including the state of subject arousal (Naatanen & Picton, 1987). Picton et al. (1978) suggested that Nl might represent the processes necessary for the evaluation of incoming information. In the context of the overtrained visual matching task, the most attractive property of Nl is its definite attentional enhancement (Hillyard, Hink, Schwent, & Picton, 1973). Although the present study does not employ a typical selective attention paradigm, in which Nl has been investigated before, it does use an experimental procedure in which the task allocation of attentional resources might be expected to vary as a function of training. It has been argued that in trained tasks, in contrast to new tasks, performance is more automatic and consequently that the attention and effort requirements are minimized (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977); will Nl reflect such changes in attentional requirements?

Given the different neurophysiological significance of Nl and N2, one might expect that each of them may uniquely reflect the effects of training, specifically that Nl amplitude and N2 latency should decrease. Also, as N2 recorded during a visual recognition task generally predominates over the right cerebral hemisphere, the latter effect may be more prominent over the right cerebral site.

2. Method

2.1. Subjects

Eight healthy males (average age 27 years) served as subjects (three others failed to achieve a plateau during the training session; and another was rejected due to excessive blinking). All subjects had right hand and right eye dominant, as indicated by dextral scores on the Harris lateralization test (Harris, 1958). All were familiar with the experimental laboratory but were naive concerning the purpose of this study.

2.2. *Procedure and task*

Three amoeboid patterns (see fig. 1 and Nevskaya, 1974) were presented in vertical pairs, either two identical ("same") or two different ("different") yielding nine combinations. In one block of trials 32 pairs of stimuli were

Fig. 1. The amoeboid patterns based on Nevskaya (1974).

presented, of which 10 were the same and 22 different. The pairs were presented tachistoscopically in random order 3° 30' to the right or to the left of a red fixation spot, each pair subtending a visual angle of 1° 30′ vertically and 38' horizontally. The luminance of the screen and stimuli were 1.7 cd/m^2 and 4.1 cd/m^2 respectively, the exposure time 60 ms with an irregular interstimulus interval (ISI) varying 8 to 11 s. Eye movements were monitored via a specifically designed glass frame with an infrared detector (Abadi, Garden, & Simpson, 1979). Trials contaminated by eye movements were discarded. With steady fixation on the red spot (LED) the subject's task was to decide whether the presented pair consisted of the same or different patterns and to press buttons accordingly using both forefingers simultaneously; a bimanual response being used to balance hemispherically motor cortex activity (Ciesielski, 1982). There were three thermosensitive buttons arranged in a vertical line: Bl, B2, B3. The subject's right forefinger rested between Bl and B2, and the left between B2 and B3. Selective response comprised pressing the further pair or the near pair - the subjects being divided as to which pair signified "same", and which "different".

2.3. Training

The subjects were familiarized with the equipment and procedure with substitute patterns, then set to train with the experimental patterns. The reaction times (RTs) and ERPs for the "before training" performance were collected during the early runs, then the process continued until each subject reached a plateau (±50 ms) in RT; this took about *2* h. On achieving criterion, the ERPs and RTs were recorded for "after training" performance, the subject not being informed until completion. A control test was applied irregularly after the ERPs had been recorded, the experimenter asking the subject to respond verbally whether patterns that he had just replied to were "similar" or "different". Seldom could the subject verbalize the answer despite giving a correct motor response, sometimes giving incorrect verbal answers when the motor response was correct; this dissociation of verbal and motor responses suggests that the trained task was performed with a decreased level of attentional control.

2.4. Recordings

P3 and P4 electrode locations (according to the 10-20 system) were chosen as representative for visual-spatial information processing (Harter & Guido, 1980; Renault et al., 1982) and were referenced to common ear lobes. The limitations of the equipment did not allow for more than two channels in the present study. Signals were amplified with a frequency band 0.7-30 Hz. For each visual field of presentation, 32 brain signals were averaged. Only ERPs to "different" pairs were recorded. The equipment, however, did not permit the recordings to be differentiated between erroneous and correct responses. The RTs were determined for each trial and measured from the moment of stimulus onset to the moment of pressing the key by the subject.

2.5. ERP measurements

Nl was defined as a negative deflection with latency of 50-150 ms following stimulus onset. N2 was defined as a negative peak with latency of 180-300 ms following stimulus onset. Amplitudes were obtained by peak-to-peak measurements of the distance along the voltage axis between the peak of the preceding, positive component and the peak of Nl and of N2. An example waveform is shown in fig. 2.

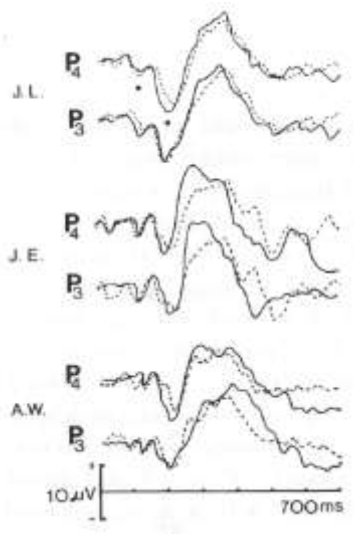

Fig. 2. ERPs for three subjects recorded from P_3 and P_4 "before" (...) and "after" (----) training; Nl and N2 marked by dots.

3. Results

3.1. Behavioral data

The percentage of correct recognitions rose rapidly after several first trials, from 89% up to 98% on average, keeping near this level through all training sessions. The RT values (table 1) gradually decreased with training in all subjects. The effect of training was examined using repeated measures analysis of variance (ANOVA) and found to be significant (F(3,21) = 42.4, $p < .05$). Tukey's multiple range test (Kirk, 1982) was used to examine differences between "before" and "after" training and between hemispheres. The analysis of RT showed a significant reduction by training for both hemispheres (RH: q (4,21) = 18,45; $p < .05$. LH: q (4,21) = 9.95; $p < .05$), but this change was much more pronounced for the right, the interhemispheric RT difference going from insignificant before training (q(4,21) = 2.69; $p > .05$) to significantly different after (q(4,21) = 4.20 $p < .05$), with shorter RT when stimuli were addressed to the right hemisphere.

3.2. ERPs

Table 1 presents the mean values for Nl and N2 latency and amplitude. To examine mean differences before and after training, an ANOVA for repeated measures was performed (Dixon, 1981). The effect of training was significant for overall N2 latency (F(3,21) = 7.92; $p < .05$) and N2 amplitude (F(3,21) = 4,71; $p < .05$), latency decreasing and amplitude increasing. Tukey's multiple range test was then used to examine differences between hemispheres. The mean value for right hemispheric N2 latency before training was significantly greater than after training (q(4,21) = 5.346; $p < .05$), but there were no descernible effects for N2 latency in the left hemisphere (q (4,21) = 1.41; $p > .05$). Although the N2 amplitudes appear smaller before training than after, the difference was not significant (q (4,21) = 3.82; $p > .05$) for the

Table 1
Mean values for Nl and N2 latency (ms) and amplitude (μV) recorded over the left (L) and right (R) cerebral hemisphere before and after training

		N1		N2	
		Latency	Amplitude	Latency	Amplitude
Before training	R	133	3.0	236	7.8
	L	133	2.8	240	7.6
After training	R	128	2.3	215	9.2
	L	134	2.3	235	7.4

Table 2
Mean RTs (ms) when the task was addressed to the right and left hemisphere before and after training

	Right hemisphere	Left hemisphere
Before training	939	990
After training	728	805

critical value of q .05 (4,21) = 3.95. The interhemispheric (L-R) differences in latency and amplitude before training were not significant (latency: q (4,21) = 1.2; $p > .05$; amplitude: q (4,21) = 0.7; $p > .05$); after training N2 latencies in the right hemisphere were significantly shorter than in the left hemisphere (q (4,21) = 5.0; $p < .05$) and the amplitudes of N2 were significantly larger over the right than over the left hemisphere (q (4,21) = 4.04; $p < .05$).

A similar set of ANOVAs for repeated measures was done for the Nl component. Although the mean values for Nl amplitudes over both the left and the right side of the brain tend to be lower after training (L: 2,3 /µV; R: 2.1 µV) than before (L: 2.75 µV; R: 3.1 µV), the differences were not significant (F=2.78; (1.7); $p = .06$); nor were the differences between the mean values of Nl latencies before (L: 132; R: 133) and after (L: 135; R: 128) training (F= 0.46; (1,7); $p > .05$).

4. Discussion

The key observations in this study are that training in a visual matching task affects N2 significantly while having little impact in Nl, and that this effect is essentially over the right hemisphere. The effect is a reduction of N2 latency and an increase of N2 amplitude, and has as an associated reduction in RTs when the task was addressed to the right hemisphere.

The changes in N2 as recorded over the parietal region are reminiscent of those reported for P3, showing the enhancement of the amplitude and shortening latencies for well-memorized and recognized events (Fabiani et al., 1986; Johnson et al., 1985). Considering that N2 varies in latency as a function of the degree of physical differences between stimuli during discrimination (Ford et al., 1976; Harter & Guido, 1980) and strongly correlates in latency with RT (Renault & Lesevre, 1979; Renault et al., 1982; Ritter et al., 1979) the time changes of the N2 component may indicate reorganization of the mechanisms of the stimulus information processing.

One possible explanation of the observed changes is that training leads to the formation of automatic comparisons between stimuli. Just as automatic motor skills can be performed simultaneously (e.g. walking, clapping), it is possible that perceptual processes can be executed in parallel and therefore in a shorter time. Thus, serial processing of information for novel visual stimuli may change into more effective parallel processing when the stimuli are learned well. Evidence for such parallel processing has been demonstrated for "overlearned" patterns, for example, Posner's (1978) data suggesting parallel processing of letters for shape and for name, when information arriving at the cortex is both analyzed as pattern and categorized, in parallel, by different subsystems. This may lead to speculation about the perceptual readiness within a system, which appears pre-programmed to analyze the incoming information in a particular mode more rapidly and selectively as an effect of training. From a neurophysiological perspective such perceptual readiness might be interpreted in terms of interactive central processes and/or may involve efferent modulation of afferent neural input. Indeed it has been shown that there are top-down centrifugal connections in the visual system (Singer, 1977; Van Essen, 1979) responsible for the efferent modulation. One may postulate that these connections are activated as a result of training.

Another possible explanation of the more effective and selective physiological processes associated with the effects of training is that the system in the process of learning may extract only the imperative features of the stimuli and adapt to ignore all features that are redundant for the final match/mismatch decision. The economizing of the processing to only principal features would involve a smaller number of synapses in transmission and therefore would decrease the time of processing. Such a consideration supports the top-down interactive model of information processing in which the number of neurons involved on the lower level is determined by the complexity of the memory trace or "gnostic unit" on the higher level of the system (Konorski, 1967).

Our results included the development of a hemispheric asymmetry as a result of training, with right hemisphere showing the reduction in latency and increase in amplitude of N2, while there was no significant evidence of asymmetry in the early phase of training. Such predominant involvement of the right brain hemisphere has been associated with parallel and holistic information processing (Cohen, 1973); this is also compatible with our hypothesis of parallel information processing after training.

In our behavioral data it is important to note that the magnitude of the decrease in RT over the training sessions is much greater than the decrease in N2 latency and therefore appears too large to result exclusively from the shortening of information processing time in the nervous system with training. Some other process may be occurring in a behavioral dimension. One may speculate that this large decrement in RT is due mostly to increased efficiency within the motor efferent system. A control experiment with simple RT collected before and after training may help to verify this hypothesis. The N2 latency changes, on the other hand, seem to provide a much more accurate and precise measure of the actual changes in information processing time in the cerebral system. It is interesting to note that some subjects showed already before training shorter RTs when the task was addressed to the right hemisphere.

The results of the above experiment lead to two major conclusions. First, the physiological cerebral processes associated with the visual matching task are significantly altered by training and become more efficient and rapid, more selective and more localized within the cerebral system; these observations argue for careful control of the degree of familiarity with stimuli or tasks used in experiments on cerebral information processing, before any conceptualization about the structure and cerebral chronometry of cognitive mechanisms is warranted. Second, the parietal N2 component recorded in a visual matching task clearly indicates an increased efficiency, specificity and localization of the physiological processes modified by training; thus it may be considered as reflecting the processes involved in forming a long-term memory code or "gnostic unit", which may constitute a basis for the top-down interactions within the system.

References

Abadi, R.V., Garden, D., & Simpson, J. (1979). Controlling abnormal eye movements. *Vision Research, 19,* 961-963.

Adam, N., & Collins, G. (1978). Late components of the visual evoked potential to search in short-term memory. *Electroencephalography and Clinical Neurophysiology, 44,* 147-156.

Ciesielski, K.T. (1982). Lateralization of visual cognitive potentials. *Biological Psychology, 14,* 259-270.

Ciesielski, K.T. (1988). Event related potentials in children with specific visual cognitive disabilities, *Neuropsychologia* (in press).

Cohen, G. (1973). Hemispheric differences in serial versus parallel processing. *Journal of Experimental Psychology, 97,* 349-356.

Cohn, N.B., Kircher, J., Emmerson, R.Y., & Dustman, R.E. (1985). Pattern reversal evoked potentials: Age, sex and hemispheric asymmetry. *Electroencephalography and Clinical Neurophysiology, 62,* 399-405.

Dixon, N.J. (1981). *B.M.D.P. statistical software* (pp. 359-387). Berkeley: University of California Press.

Donchin, E. (1981). Surprise! Surprise! *Psychophysiology, 18,* 493-513.

Duncan-Johnson, C.C., & Donchin, E. (1977), On quantifying surprise: The variation in event-related potentials with subjective probability. *Psychophysiology, 14,* 456-467.

Evarts, E.V. (1973). Motor cortex reflexes associated with learned movement. *Science, 179,* 501-503.

Fabiani, M., Karos, D., & Donchin, E. (1986). P300 and recall in an incidental memory paradigm. *Psychophysiology, 23,* 298-308.

Fitts, P.M., & Posner, M.I. (1967). *Human performance*. Belmont, CA: Brooks/Cole.

Fitzgerald, P.G., & Picton, T.W., (1983). Event-related potentials recorded during the discrimination of improbable stimuli. *Biological Psychology, 17,* 241-276.

Ford, J.M., Roth, W.T., & Kopell, B.S. (1976). Attention effects on auditory evoked potentials to infrequent events. *Biological Psychology, 4,* 65-77.

Harris, A.J. (1958). *Harris test of lateral dominance* (3rd edn.) New York: Psychological Corporation.

Harter, M.R., & Guido, W. (1980). Attention to pattern orientation: Negative cortical potentials, reaction time and the selection process. *Electroencephelography and Clinical Neurophysiology, 49,* 461-475.

Harter, M.R., Aine, Ch., & Schroeder, C. (1982). Hemispheric differences in the neural processing of stimulus location and type: Effects of selective attention on visual evoked potentials. *Neuropsychologia, 20,* 421-438.

Hebb, D.O. (1949). *The organization of behavior.* New York: Wiley.

Hillyard, S.A., Hink, R.F., Schwent, V.L., & Picton, T.W. (1973). Electrical signs of selective attention in the human brain. *Science, 182,* 177-180.

Hopfield, J. (1982). Neural networks and physical systems with emergent computational capabilities. *Proceedings of the National Academy of Sciences, 79,* 2554-2558.

John, E.R. (1972). Switchboard versus statistical theories of learning and memory. *Science, 177,* 850-864.

John, E.R., Bartlett, F., Shimokochi, M., & Kleinman, D. (1973). Neural readout from memory. *Journal of Neurophysiology, 36,* 893-924.

Johnson, R., Jr., & Donchin, E. (1980). P300 and stimulus categorization: Two plus one is not so different from one plus one. *Psychophysiology, 17,* 167-178.

Johnson, R., Jr., Pfefferbaum, A., & Kopell, B.S. (1985). P300 and long-term memory: Latency predicts recognition performance. *Psychophysiology, 22,* 497-507.

Kirk, R.E. (1982). *Experimental design* (2nd edn.). Belmont, CA: Brooks-Cole.

Konorski, J. (1967). *Integrative activity of the brain.* Chicago: University of Chicago Press.

Linseman, M.A., & Olds, J. (1973). Activity changes in rat hypothalamus, preoptic area, and striatum associated with Pavlovian conditioning. *Journal of Neurophysiology, 36,* 1038-1050.

McCallum, W.C. (1980). Some sensory and cognitive aspects of ERPs: A review. In: *Motivation, motor and sensory processes of the brain: Electrical potentials, behaviour and clinical use. Progress in Brain Research, 54,* 261-278.

Naatanen, R. (1982). Processing negativity: Evoked potential reflection of selective attention. *Psychological Bulletin, 92,* 605-640.

Naatanen, R. (1985). Selective attention and stimulus processing: Reflections in event-related potentials, magnetoencephalogram and regional cerebral blood flow. In M.I. Posner & O.S. Marin (eds.), *Attention and Performance XI* (pp. 355-373). Hillsdale, NJ: Erlbaum.

Naatanen, R. (1987). Event-related brain potentials in research of cognitive processes: A classification of components. In E. van der Meer and J. Hoffmann (Eds.), *Knowledge aided information processing* (pp. 241-273). Amsterdam: North-Holland.

Naatanen, R., Gaillard, A.W.K., & Mantysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica, 42,* 313-329.

Naatanen, R., & Picton, T. (1986). N2 and automatic versus controlled process. In W.C. McCallum, R. Zappoli & D. Denoth (Eds.), *Cerebral psychophysiology: Studies in Event-Related potentials. Electroencephalography and Clinical Neurophysiology* (suppl.).

Naatanen, R., & Picton, T. (1987). The Nl wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. *Psychophysiology, 24,* 375-425.

Nevskaya, A.A. (1974). Subjective space of visual images and some pecularities of its organization. In: V. Bacalska & V.D. Glezer, (eds.), *Visual information processing* (pp. 99-109). Bulgarian Academy of Sciences.

Picton, T.W., Campbell, K.B., Baribeau-Braun, J., & Proulx, G.B. (1978). The neurophysiology of human attention: A tutorial review. In J. Requin, (ed.), *Attention and performance VII* (pp. 429-467). Hillsdale, NJ: Erlbaum.

Posner, M.I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

Renault, B. (1983). The visual emited potentials: Clues for information processing. In A.W.K.

Gaillard & W. Ritter, (Eds.), *Tutorials in ERP research: Engodenous components.* Amsterdam: North-Holland. Renault, B., & Lesevre, N. (1979). In D. Lehmann & E. Callaway (Eds.), *Human evoked potentials:*
Applications and problems (p. 317). New York: Plenum. Renault, B., Ragot, R., Lesevre, N., & Remond, A. (1982). Onset and offset of brain events as
indices of mental chronometry. *Science, 215,* 1413-1415. Ritter, W., Simson, R., Vaughan, H.G., Jr., & Fridman, D. (1979). A brain event related to the
making of a sensory discrimination. *Science, 203,* 1358-1361. Ritter, W., Simson, R., Vaughan, H.G., Jr., & Macht, M. (1982). Manipulation of event-related
potential manifestations of information processing stages. *Science 218,* 909-911. Ross, J. (1970). Extended practice within a single-character classification task. *Perception and*
Psychophysics, 8, 276-278. Schneider, W. and Fisk, A.D. (1980). *Degree of consistent training and the development of automatic*
processing (Report No. 8005) Champaign, IL: University of Illinois, Department of Psychology, Human Attention Research Laboratory. Schneider, W., & Shiffrin, R.M. (1977). Controlled and automatic human information processing:
I: Detection, search, and attention. *Psychological Review, 84,* 1-66. Shiffrin, R.M., Dumais, ST., & Schneider, W. (1981). *Attention and Performance IX.* (pp.
223-241). Hillsdale, NJ: Erlbaum. Shiffrin, R.M., & Schneider, W. (1977). Controlled and automatic human information processing:
II. Perceptual learning, automatic attending, and general theory. *Psychological Review, 84,*
127-190.
Simpson, P.J. (1972). High-speed memory scannings: Stability and generality. *Journal of Experimental Psychology, 96,* 239-246. Simson, R., Vaughan, Jr., H.G., & Ritter, W. (1977). The scalp topography of potentials in
auditory and visual discrimination tasks. *Electroencephalography and Clinical Neurophysiology,*
42, 528-535. Singer, W. (1977). Control of thalamic transmission by corticofugal and ascending reticular
pathways in the visual system. *Physiological Review, 57,* 386-420. Snyder, E., & Hillyard, S.A. (1976). Long latency evoked potentials to irrelevant, deviant stimuli.
Behavioural Biology, 16, 319-331. Towey, J., Rist, F., Hakerem, G., Ruchkin, D.S., & Sutton, S. (1980). N250 latency and decision
time. *Bulletin of the Psychonomic Society, 15,* 365-368. Van Essen, D.C. (1979). Visual areas of the mammalian cerebral cortex. *Annual review of*
Neurosciences, 2, 227-263.