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Evoked potentials and abstract thinking

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The aim of this study was to investigate the relationship between measures (latency and amplitude) of evoked potentials (N1, P2, N2, P3 and SW) elicited by a standard visual oddball paradigm, and abstract reasoning measured by the Abstract Reasoning Test (TAM; Kulenović, 2003). Even though the results of most studies of evoked potentials and intelligence have been inconsistent, and although they were mostly concerned with the relationship between P300 and intelligence, it was hypothesized that participants with higher reasoning ability would show significantly shorter latencies of N1, P2 and P3 waves. Because of previously established effects of the experimental task complexity on the relationship between EP amplitude and intelligence, it was not expected for this correlation to be significant, as a very simple standard visual oddball task was used.

The sample consisted of 43 participants, all female, right-handed, in the age range of 19-23 years. The evoked potentials were recorded in two trials for each participant. Active electrodes were placed on O1, O2, P3 and P4 (according to the 10-20 system), and referred to Fz. Significant negative correlation was found only between N1-wave measured on the O1 electrode and scores on the first subtest of TAM. A shorter N1-latency evoked by a visual oddball task in participants with a higher level of abstract reasoning was expected. This finding is discussed in view of psychological-functional role of the N1-wave, information processing demands of specific tasks, perceptive characteristics, and the task complexity level.

Key words: evoked potentials, abstract thinking, visual oddball paradigm, students

Evoked potentials (EPs) or event-related potentials (ERPs) are changes in the electrical activity of the nervous system recorded in response to physical stimuli, in association with psychological processes, or in preparation for motor activity (Picton, 1980). In other words, they present voltage fluctuations that are associated in time with some physical or mental occurrence (Picton et al., 2000). In contrast to the spontaneous EEG waves, ERPs are time-locked, i.e. they appear in a precisely defined period after the given stimulus, and mostly in one part of the human cortex (Polich, 1993). Numerous studies of EPs published in 1940s and 1950s focused on the activity in the first 100 msec after the stimulus. These potentials were viewed as representing activity in sensory pathways. The method of signal averaging in the 1960s enabled the studies of ERPs in awake, behaving humans, and thus allowed the late endogenous components to emerge. The amplitude, latency, and scalp distribution of these components reflect, in a robustly systematic manner, variations in the underlying psychological substrate (Donchin, Ritter, & McCallum, 1978).

Psychophysiology of sensory evoked potentials: N1, P2, N2

Two EP groups can be distinguished: evoked potentials (those which follow the external physical stimuli) and emitted potentials (those which are connected with the processes of preparing for some cognitive or motor activity; Sutton, Braren, John, & Zubin, 1965). Taking into account the context in which a stimulus occurs (Brinar, Brzović, Vukadin, & Zurak, 1996), *evoked (sensory or exogenous) potentials* represent the brain's reaction to some specific sensory stimulus, while *event-related potentials (cognitive or endogenous)* represent the same reaction, albeit one that is time-locked

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with a specific physical of psychological event, and might not appear if the stimulus is irrelevant for a person. In this study we are focusing on sensory evoked potentials.

Exogenous (early or sensory) components represent the brain activity in the first 100 msec after the stimulus onset, with very low amplitudes (0.1 – 20 μV), and with latencies and amplitudes varying according to changes in physical characteristics of the stimuli. Scalp distribution depends upon the sensory system that has been active and not upon the cognitive processing of the stimuli. The lack of any of the early ERP-components implicates some kind of neurological damage and presents the basis for clinical assessment (Donchin & Coles, 1988; Rugg, 1992). All the well-established exogenous ERP-components are shown in Figure 1, but we will describe in some detail only those of interest for this study, i.e. N1 and P2. *Long Latency Exogenous Components (P1, N1, P2)* occur after a stimulus, from 100 msec up to 200-300 msec, and they are called transient since they share some characteristics with the endogenous components. *Visual Evoked Potentials (VEP)* can be recorded in the visual modality, and they are generally grouped around the P1 component. This wave has been used for non-invasive assessment of the functional state of visual fields and the visual cortex (Dabić-Jeftić & Mikula, 1994). *Endogenous (late or cognitive) components*, such as N2 and P3, have longer latencies (more than 100 msec) and higher amplitudes, and depend on the context in which a stimulus appears. Even though the *N2 component* is usually considered as one of the endogenous components, it also shares some characteristics with early, sensory components. It always occurs after the appearance of a rare and unexpected stimulus,

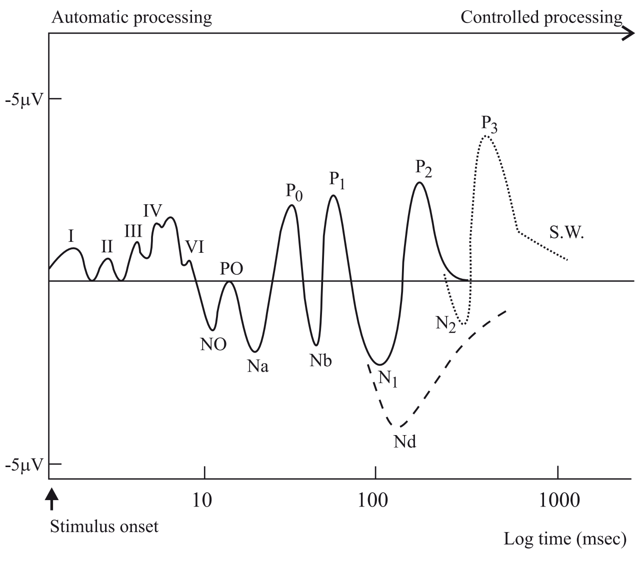

Figure 1. ERPs in the sampling interval (1,000 msec) after the presentation of a stimulus. This example is from an EEG recording of responses to an auditory stimulus of moderate intensity. Note the logarithmic x-axis. (Adapted from Hughdahl, 1995, p. 272)

thus representing automatic extraction and determination of the stimulus' properties, and target choice. N2 consists of a negative deflection occurring about 200 msec after the stimulus, and its amplitude is reversely proportional to the probability of a stimulus occurrence. It is elicited by rare changes in the stimulus, regardless of the participant's focusing on the stimulus. If the change is relevant for the task, N2 is followed by a P3 component (Donchin et al., 1978). In summary, N2 is related to the process of discrimination and stimulus novelty (Nätäänen, 1992), it has fronto-central distribution, and consists of two peaks: N2a and N2b. N2a reflects the automatic extraction of physical characteristics of the stimuli (automatic information processing), while N2b reflects the designation of the stimuli properties and target choice (controlled information processing).

Evoked potentials have been widely measured by an auditory or visual oddball paradigm – the task of simple stimuli discrimination. During such a task the participant listens (looks) to a sequence of tones (visual stimuli), where one tone (visual stimulus) is usually the target. The participant's task is to press the button on hearing (seeing) the target stimulus (Polich, 2004).

Abstract reasoning is characterized by the ability to use concepts and to make and understand generalizations, e.g. the properties or a pattern shared by a variety of specific items or events. Abstract thinking is often equalled with General ability (G), which is largely synonymous with General Fluid ability (Gf), which in turn is a stand-in for Inductive Reasoning ability (IR), as has been successfully demonstrated by Gustafsson (1988). This ability to manipulate ideas and symbols has often been investigated using the nonverbal problem solving task.

Studies of the relationship between evoked potentials and intelligence have obtained consistent results concerning the relationship between psychometric measures of intelligence and EP-amplitude (N1, P2, N2): significantly higher amplitudes have been found in participants with higher intelligence level (Haier, Robinson, Braden, & Williams, 1983; Josiassen, Shagass, Roemer, & Slepner, 1988; Osaka & Osaka, 1980; Rhodes, Dustman, & Beck, 1969; Shagass, Roemer, & Straumanis, 1981; Eysenck, 1987). As for the relationship between intelligence and EP latencies, the findings are especially conflicting: some studies have found no significant correlation between EP-latencies and intelligence measures (Barnet & Lodge, 1967; Engel & Fay, 1972; Engel & Henderson, 1973; Callaway, 1975; Rust, 1975; Haier et al., 1983; Barrett & Eysenck, 1992); some have found a positive correlation between intelligence and EP-latency (Callaway, 1975; Callaway & Halliday, 1973; Vogel, Kruger, Schalt, Schnobel, & Hassling, 1987; Stough, Nettelbeck, & Cooper, 1990; Stelmack, Knott, & Beauchamp, 2003); while in the third group of studies a negative relationship was established (Rhodes, Dustman & Beck, 1969; Osaka & Osaka, 1980; Eysenck, 1987; Bates & Eysenck, 1993; Widaman et al., 1993; Barrett & Eysenck, 1994; Zurron &

Diaz, 1998). Generally, there was a tendency for the participants involved in a task to show shorter latencies and higher amplitudes of earlier components of evoked potentials: N1, P2 and N2. These findings, especially the negative relationship between EP latencies and intelligence, support the phenomenon referred to as neural efficiency (Neubauer & Fink, 2008), suggesting that more intelligent individuals use their brains more efficiently than less intelligent people do, when engaged in the performance of demanding cognitive tasks. In this context, neural efficiency is reflected in more localized brain activation during cognitive task performance, resulting with lower total cortical activation in more intelligent as compared to less intelligent individuals (Haier et al., 1992). Furthermore, Neubauer et al. (2004) analysed brain activation during the performance of various working memory tasks and determined that neural efficiency was more strongly related to fluid (compared to crystallized) intelligence.

Therefore, the aim of this study was to examine the relationship between latency and amplitude of evoked potentials (N1, P2 and N2), measured by a simple visual oddball task, and scores on an abstract reasoning test. This relationship will be studied separately for the EP-amplitudes measured in the first and second trials, and for each of the electrodes. Taking into account the previous findings, it is assumed that participants with higher levels of reasoning ability would show shorter latencies and higher amplitudes of earlier components of the evoked potentials: N1, P2 and N2.

METHOD

Participants

A total of 43 participants were selected from a preliminary sample of 91 undergraduates studying at the Department of Psychology, University of Rijeka. To obtain a homogeneous sample and to control for as many relevant variables as possible, the participants were selected according to several criteria. They were all female, within the age range 19-23 years (*M*=20.50 years, *SD*=1.32), right-handed, nad've to electrophysiological studies, and with no reported visual or neurological/psychiatric problems. The participants received course credits for their partaking in the study.

Abstract reasoning measurement

Reasoning ability was measured by the Abstract Reasoning Test (TAM; Kulenović, 2003), developed for the purpose of entrance exam selection procedures at the University of Zagreb Faculty of Humanities and Social Sciences. TAM is a nonverbal test, designed for measuring the level of symbol manipulation and inductive reasoning. It consists of 60 items divided in three subscales. Examples of the practice trials for each subtest are shown in Figure 2. In the first subtest each item consists of an incomplete progressive series. The participants' task is to select, among 5 choices provided, the answer with the figure which best completes the series. In the second subtest the task is to correctly complete the matrix presented within each item, where the complexity of matrix designs varied between the items of the subtest. The participants' task in the third subtest is to find the "odd one out", i.e. to find the figure not sharing the relevant features with the rest of the figures. The time limit was 15 minutes for the first and the third subtest, and 20 minutes for the second subtest. Before each subtest the participants solved a practice trial under the experimenter's guidance to ensure their full comprehension of the instructions. The scores on each of the subtests were calculated as a sum of correctly solved items. According to the validity data on TAM 2003, based on 972 participants, internal consistency of the test measured by Cronbach Alpha coefficient was α=.83 (Kulenović, 2004).

Apparatus and procedure

After the general instructions were given to participants, TAM was administered first, and then each participant underwent the measurement of the evoked brain potentials (N1, P2, N2, P3 and SW) in two trials. All recordings were made in the course of four months, always on Wednesdays and always at the same time – noon. EP-responses were elicited by the standard visual oddball paradigm, chosen according to the possibilities of the device. A Medelec/TECA SapphireII 4E device (1996) with five Ag/AgCl disc electrodes was used. The active electrodes were placed on O1, O2, P3 and P4 (according to the 10-20 system), and referred to Fz. The electrode impedance was kept below 5kΩ and the filter bandpass was 0.1-50 Hz. A pattern reverse binocular full-field stimulation was performed in a dark, quiet room using a 16x16 checkerboard pattern, 70 cm away from the nasion, with 1Hz frequency and 100% contrast. Fifteen percent of the stimuli were rare (target) checkerboards (consisting of smaller quadrangles), whereas the remaining ones were frequent (nontarget) checkerboards (consisting of the larger quadrangles), presented in random order. Participants were instructed to look at the red circle in the centre of the monitor and to react to the target stimuli by pressing the pen.

The marking of the amplitudes and latencies of the evoked potentials (N1, P2, N2, P3 and SW) was performed manually, using a cursor, by the same medical technician for both trials. In the first trial, the first major negative peak between 80-100 msec for the rare stimuli was identified as the N1 response and marked. Other evoked potentials have been marked accordingly: P2 as a major positive peak between 170-200 msec; N2 as a major negative peak between 200-300 msec; P3 as a major positive peak between 300-600 msec; and SW as a major negative peak between 600-800 msec. To avoid the effect of the latency jitter (Coles,

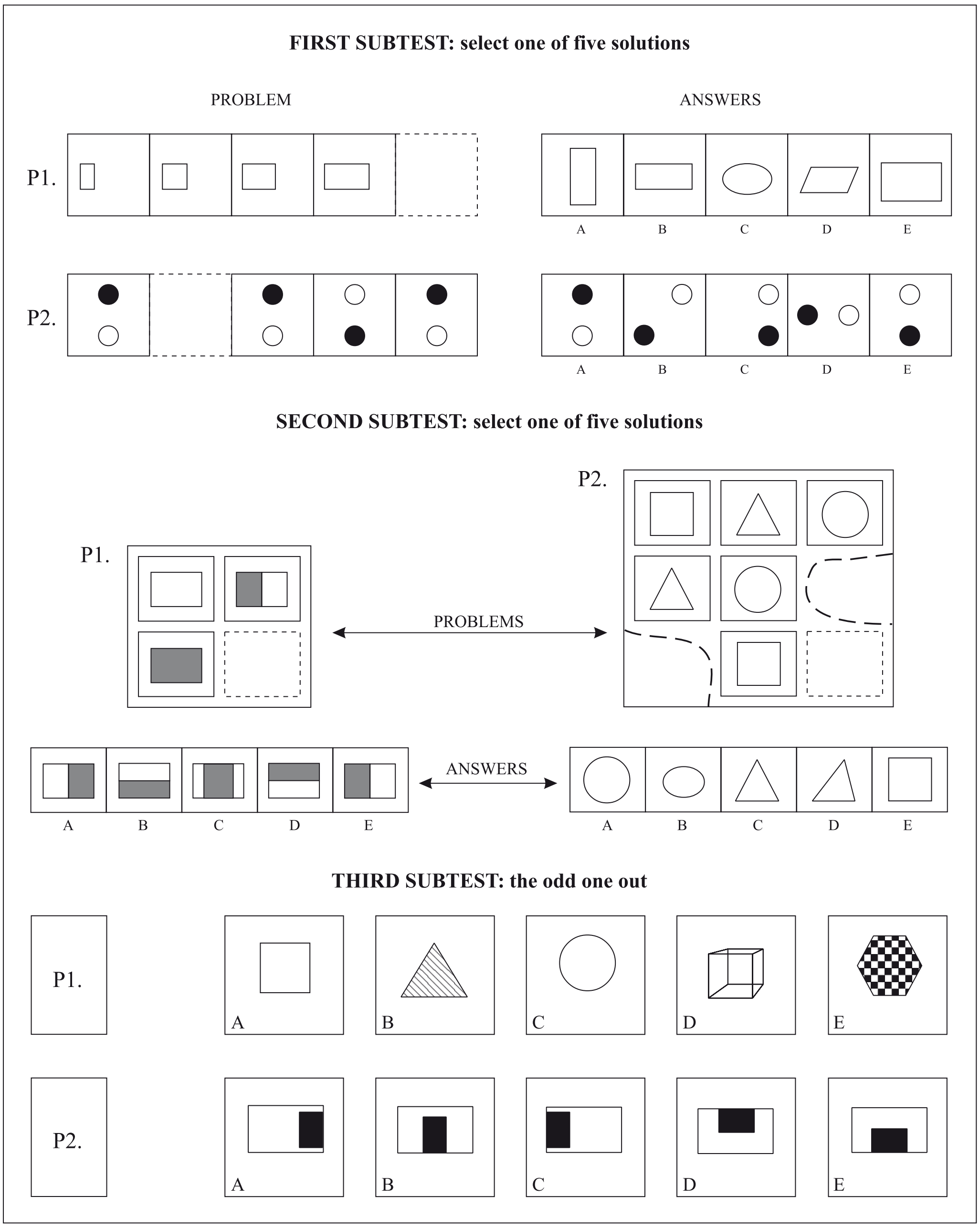

Figure 2. Practice trials for tasks from three TAM subtests (Kulenović, 2003)

Gratton, Kramer, & Miller, 1986; Hoormann, Falkenstein, Schwarzenau, & Hohnsbein, 1998), and to make evoked potentials more stable over trials, in the second trial they were marked by the same latencies as those from the first trial. Therefore, for each participant there was a same EP-latency (as measured only in one trial) for both trials, but different EP-amplitudes. An example of the averaged and artefact-corrected ERP curves for one participant in the first and the second trial block are shown in Figure 3.

RESULTS AND DISCUSSION

Abstract thinking

As can be seen in Table 1, the group average for the total TAM scores was higher than the average obtained for the reference group. Kolmogorov-Smirnov test of conformity showed the distributions of all TAM subtests to be normal.

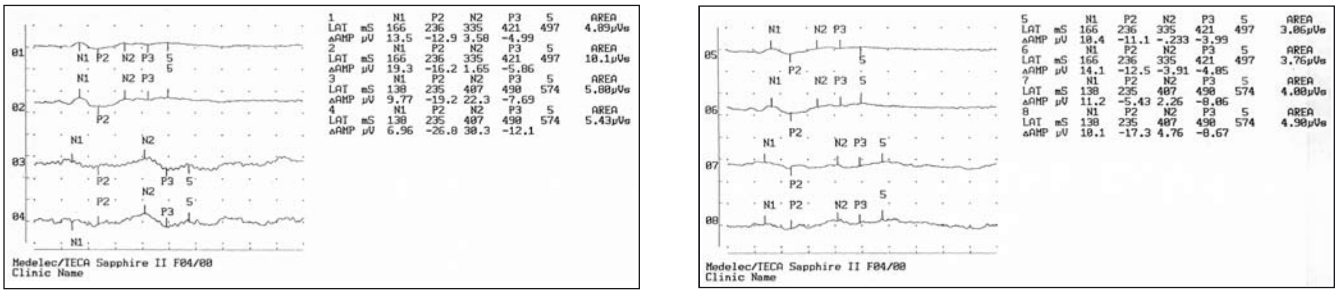

Figure 3. An example of recorded evoked potentials (above: sharpened marked waves measured in a first trial block; below: sharpened marked waves measured in a second trial block)

Table 1
Means, standard deviations, and total ranges for scores on three TAM subtests and the total TAM scores for the sample in this study (*N*=43) and according to the validation data (Kulenović, 2004; *N*=972)

	TAM 1	TAM 2	TAM 3	TAM TOTAL	TAM TOTAL (2004)
M (SD)	14.44 (2.56)	13.21 (2.93)	11.98 (2.66)	39.63 (5.83)	33.50 (8.16)
Total range	9-19	5-19	5-17	28-52	10-54

Table 2
Means (*M*) and standard deviations (*SD*) for latencies (L) and amplitudes (A1-first trial, A2-second trial) of evoked potentials (N1, P2, N2, P3 and SW) (*N*=43)

		N1	P2	N2
		M (SD)	*M (SD)*	*M (SD)*
O1	L	146.05 (29.49)	221.09 (15.81)	298.26 (31.83)
	A1	10.59 (5.51)	9.27 (5.19)	4.69 (4.42)
	A2	10.31 (5.63)	8.79 (4.57)	4.92 (5.18)
O2	L	146.05 (29.49)	220.65 (15.44)	298.21 (31.62)
	A1	13.01 (6.46)	11.25 (6.21)	5.20 (5.80)
	A2	12.47 (6.77)	10.75 (5.83)	5.40 (5.44)
P3	L	141.02 (31.44)	211.40 (24.32)	291.12 (52.73)
	A1	14.04 (7.36)	13.75 (7.72)	9.64 (6.29)
	A2	13.71 (6.86)	12.67 (8.73)	8.40 (6.17)
P4	L	140.86 (31.48)	212.09 (24.58)	291.00 (52.80)
	A1	15.57 (8.06)	14.17 (8.94)	8.13 (5.38)
	A2	14.69 (7.75)	12.95 (8.80)	6.85 (5.16)

The Cronbach alpha internal consistency coefficient for the total TAM scores was α=.79.

ERP results

Mean amplitudes and latencies of all evoked potentials (N1, P2 and N2), measured in two trials, are shown in Table 2. They were determined according to their points of maximum negativity or positivity. The basic principle for marking the EP-waves in the first trial block was the peak amplitude, and each ERP-component was marked one by one as described in the Method section. Due to this method of marking, the latencies on the O1 and O2 electrodes are identical (as can be seen in Table 2 and Figure 3), as the peak amplitude of N1 emerging on those electrodes served as a starting point for manual marking. Because of the technical limitations of the device used, a possibility of a latency jitter could not be avoided by using the Woody filter method, and therefore the EP-latencies were made constant over trial blocks and used for marking all EP-waves in the second trial block. Although a lot of valuable information has been lost in this way, the additional reason for using this method was the evidence of a very small impact of habituation on latencies, especially on late components, and when pauses between the trial blocks were very short (1-2 minutes) (Polich, 1989; Lin & Polich, 1999; Bruin, Kenemans, Verbaten, & Van der Heijden, 2000). As can be seen from Table 2, the sensory evoked brain potentials (N1, P2 and N2) were established with their standard parameters of latencies and amplitudes.

The relationship between evoked potentials and abstract thinking

Pearson's correlation coefficients were calculated among all ERP-components and TAM results. Due to the fact that only some of the correlations between N1-wave and scores on TAM were significant, only the relationship between this first EP-component and TAM-scores is presented, for latencies (Table 3) and for amplitudes (Table 4). A significant negative correlation (r=-.38, p<.01) has been found between N1-latencies measured on the two occipital electrodes (O1 and O2) and scores on the first TAM-subtest. The participants who showed higher level of abstract reasoning measured by the first TAM-subtest needed significantly shorter time for the selective attention processes used during the completion of the visual oddball task. This result partly confirms the hypothesis about the relationship between EP-latencies and abstract thinking found in previous research (Osaka & Osaka, 1980; Eysenck, 1987; Bates & Eysenck, 1993; Widaman, Carlson, Saetermoe, & Galbraith, 1993; Barrett & Eysenck, 1994; Neubauer, 1995; Zurron & Diaz, 1998). Only one significant correlation was found between the second TAM subtest and N1 amplitude (measured on the parietal electrode in the second trial): r_{N1P4}=.35, p<.05. The participants with higher abstract reasoning ability showedn significantly higher N1-amplitudes on this electrode in the second trial, which was also in accordance with our hypothesis. These findings were not consistent for all the electrodes in both trials. There are numerous possible explanations for these findings. The first of them is a small variability in TAM-scores due to the sample characteristics: the subjects were a highly selected group of psychology students (the enrolment procedure includes intelligence testing). Secondly, because of the practical limitations, the overall number of electrodes was small and the frontal ones were not used, and the device characteristics required the manual marking of the components. Finally, one of the reasons for not finding more significant correlations could be the characteristics of the visual oddball task itself, as the oddball paradigm used in this study was an easy task, which could have easily induced monotony. However, these findings indicate, although partially, a significant relationship between the N1-wave and subjects' achievement on the TAM, in accordance with the hypothesis that students with higher abstract reasoning ability would show shorter time and greater selective attention in completing the visual oddball task. Zurrón and Diaz (1998) found that EP-latency correlated with IQ measures only for those waves generated after the stimuli information has reached the associative cortex, and even then only if the subject was performing a task involving controlled attention and the subsequent evaluation of the stimulus. Probably the most plausible explanation of our findings can be found in Neubauer's (1995) review of studies relating EP latencies and intelligence. He showed that while eight studies confirmed the expected negative EP-latency-intelligence relationship, i.e. shorter latencies associated with higher IQ, in the eleven studies no such relationship could be observed. Neubauer postulates that the main reason for the heterogeneity of those findings could lie in the fact that most of the EP-intelligence studies used only one or a very small number of cortical derivations. In other words, the lack of correlations could be explained by the fact that the measurements used did not involve the whole cortex or the whole brain, as can be done by other imaging techniques such as PET or event-related desynchronization (ERD). The ERD,

Table 3
The correlations (r) between results on the TAM (TAM1, TAM2, TAM3, and TAM-total) and latencies of N1-wave on 4 electrodes (O1, O2, P3 and P4) (N=43)

	Latency		
	N1 on O1 and O2	N1 on P3	N1 on P4
TAM 1	-.38**	-.04	-.02
TAM 2	.12	-.00	.02
TAM 3	.04	-.17	-.15
TAM Σ	-.08	-.09	-.07

**p<.01.

Table 4
The correlations (r) between results on the TAM (TAM1, TAM2, TAM3, and TAM-total) and amplitudes (A1-first trial; A2-second trial) of N1-wave on 4 electrodes (O1, O2, P3 and P4) (N=43)

	N1 on O1		N1 on O2		N1 on P3		N1 on P4	
	A1	A2	A1	A2	A1	A2	A1	A2
TAM 1	-.00	-.06	.10	.10	.11	.25	.13	.20
TAM 2	-.05	-.12	.13	.07	.26	.24	.19	.35*
TAM 3	-.22	-.20	-.02	.05	-.03	-.08	-.02	-.05
TAM Σ	-.13	-.18	.10	.10	.16	.19	.14	.24

*p<.05.

involving measurements over the whole cortex, could probably give us a better chance of understanding the relationship between brain functioning and intelligence (Neubauer, Grabner, Freudenthaler, Beckmann, & Guthke, 2004). Thus, a significant relationship between N1 and TAM-scores on the one hand, and absence of a significant relationship between TAM-scores and other evoked potentials on the other, could be a consequence of compound influences of a range of factors on evoked potentials, the most important ones probably being in the measurement methodology used.

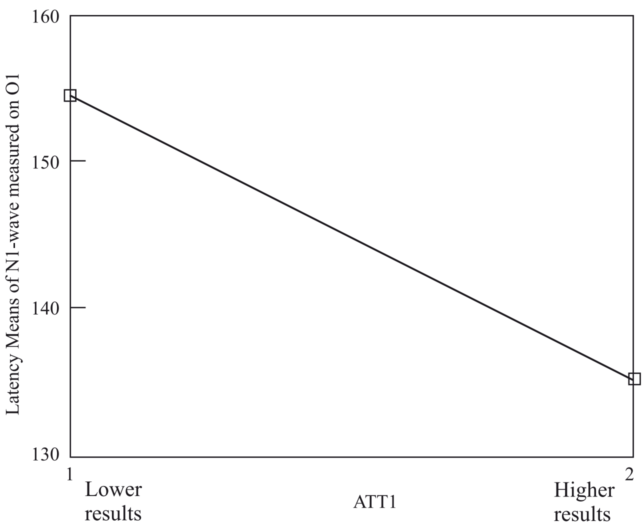

Figure 4. N1-latency measured on O1 and O2 electrodes in the groups of students with lower and higher scores on TAM1

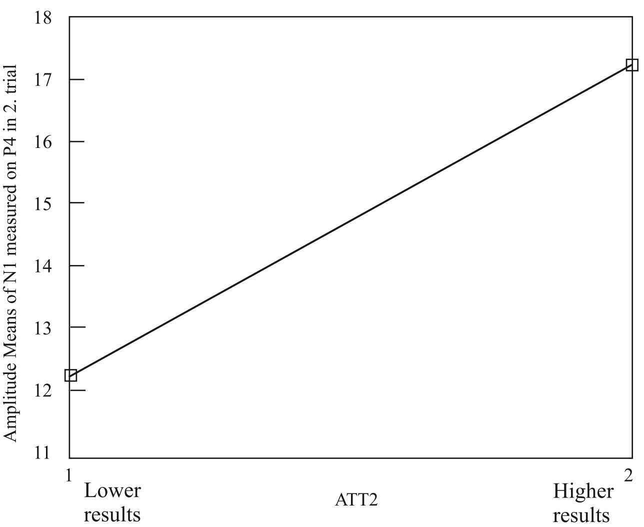

Figure 5. N1-amplitude measured on P4 electrode in the second trial in the groups of students with lower and higher scores on TAM2

A repeated measures ANOVA was performed to examine the differences in N1-waves between groups with higher and lower scores on the abstract reasoning test. The groups were divided by the group mean on TAM subtests. There were N=23 students with lower and N=20 with higher results at TAM1; N=22 students with lower and N=21 with higher results at TAM2; N=24 students with lower and N=19 with higher results at TAM3; and N=20 students with lower and N=23 with higher results at TAM-total.

The significant main effects of abstract thinking measured by the first TAM-subtest were found for the N1-latency on O1 and O2 electrodes (F=5.04, p<.03) (Figure 4).

The significant main effect of abstract thinking measured by the second TAM-subtest was found for the N1-amplitude measured in the second trial block on P4-electrode (F=5.08, p<.03), as shown in Figure 5.

As expected, the group of participants with higher abstract reasoning ability showed significantly shorter N1-latencies measured on two occipital electrodes and higher N1-amplitudes measured on one parietal electrode in the second trial, compared to the group with lower abstract reasoning ability. The results confirmed previous findings of an inverse relationship between EP-latencies and results on intelligence tests, supporting a concept of "neural efficiency" as the biological substrate of individual differences in behavioural intelligence. In other words, "the more intelligent brains" (as opposed to "less intelligent brains") seem to be characterised by more efficient brain functioning, indicated by less overall and/or a more focused activation during cognitive activity (Neubauer et al., 2004). *"Participants performing a complex task well may use a limited number of brain circuits and/or fewer neurons, thus requiring minimal glucose use, while poor perfomers use more circuits and/or more neurons, some of which are inessential or detrimental to task performance, and this is reflected in higher overall brain glucose metabolism*" (Haier et al., 1992, p. 134). Various studies confirmed the so-called neural efficiency hypothesis using different brain imaging techniques which involved the whole brain: PET (Haier et al., 1992), SPECT (Charlot, Tzourio, Zilbovicius, Mazoyer, & Denis, 1992), fMRI (Rypma, Berger, & D'Esposito, 2002), LORETA (Jausovec & Jausovec, 2003), and the analysis of EEG alpha power and event-related desynchronization (Grabner, Stern, & Neubauer, 1993; Jausovec, 1996, 1998, 2000; Neubauer & Fink, 2003; Neubauer, Fink & Schrausser, 2002). The interpretation of these findings could be related to the psychological-functional role of the N1-component. It is well known that the N1-wave appears when subjects engage their attention during the perception of stimuli and a selection according to a certain criterion (shape, colour, size, etc.). Thus, as can also be seen in this study, this measure of abstract thinking is also sensitive to the selective attention of participants. Furthermore, the absence of a significant relationship between other earlier EP-components and the TAM scores is in accordance with usual inconsistent findings of correlations between abstract thinking and components other than the N1-wave. As already mentioned, these findings could be explained by various relevant variables that separately or interactively influence the sensitive relationship between intelligence measures and evoked potentials. Finally, as earlier studies have used various intelligence measures, it makes the comparisons with their findings even more difficult. Our results show a certain relation between the abstract thought and a psychophysiological measure of electrocortical activity. As we have found only a few significant correlations, it is necessary to broaden future research exploring the same relationship: by using a better measuring technology with more electrodes during various cognitive tasks, more subjects, and a wider range of intelligence tests. A possible improvement in methodology could be achieved by the use of the method of event-related desynchronization (ERD), i.e. measuring alpha brain activity during complex cognitive tasks. An example of a frequently used cognitive task is a figural-spatial Posner task, where subjects are instructed to judge whether the presented stimuli semantically differ from the target stimulus (Neubauer & Fink, 2008). Also interesting are the reasoning tasks from the Tool for Analyzing Reasoning Ability – Figural (TARA-F), used by Guthke et al. (2000), where subjects were instructed to complete a sequence of figures by choosing one of the answer options.

Having in mind a great complexity of research into the relation between intelligence and evoked potentials, in planning future studies it is crucial to use tasks of varying complexity within different oddball paradigms, and to try to isolate the influence of various relevant variables and determine their effects. This implies the use of tasks that are more similar to the intelligence tests in general (and, in our research, TAM in particular) in regard to the mental operations needed to solve them. The TARA tasks (Guthke et al., 2000) could fulfil such criteria: they are of varying complexity, which could also be enhanced by e.g. presenting the geometrical elements in various colours to add another dimension needed for correct solution, or by including a semantic component, etc. Only a detailed and demanding protocol, such as the one relating the alpha brain activity during performance of those tasks with the results of intelligence testing, can give us insight into the biological substrate of individual differences in behavioural intelligence.

REFERENCES

Barnet, A. B., & Lodge, A. (1967). Click evoked EEG responses in normal and developmentally retarded infants. *Nature, 214,* 252-255.

Barrett P. T., & Eysenck, H. J. (1992). Brain Electrical Potentials and Intelligence. In A. Gale, M. W. Eysenck (Ur.), *Handbook of Individual Differences: Biological Perspectives* (255-285), John Wiley & Sons, Ltd. New York, USA.

Barrett, P. T., & Eysenck, H. J. (1994). The relationship between evoked potential component amplitude latency, contour lenght, variability, zero-crossing, and psychometric intelligence. *Personality and Individual Differences, 16(1),* 3-32.

Bates, T., & Eysenck, H. J. (1993). String lenght, attention and intelligence: Focused attention reverses the string length – IQ relationship. *Personality and Individual Differences, 15(4),* 363-371.

Brinar, V., Brzović, Z., Vukadin, S., & Zurak, N. (1996). *Neurologija – udžbenik za medicinske sestre, rentgen tehničare i fizioterapeute* [Neurology – a handbook for nurses, roentgen technicians, and physiotherapists]. Zagreb: Prometej, Znanstvena biblioteka, Knjiga 3.

Bruin, K. J., Kenemans, J. L., Verbaten, M. N., & Van der Heijden, A. C. H. (2000). Habituation: An event-related potential and dipole source analysis study. *International Journal of Psychophysiology, 36,* 199-209.

Callaway, E. (1975). *Brain electric potentials and individual psychological differences.* New York: Grune & Stratton.

Callaway, E., & Halliday, R. A. (1973). Evoked potential variability: Effects of age, amplitude and methods of measurement. *Electroencephalography and Clinical Neurophysiology, 34,* 125-133.

Charlot, V., Tzourio, N., Zilbovicius, M., Mazoyer, B., & Denis, M. (1992). Different mental imagery abilities result in different regional cerebral blood flow activation patterns during cognitive tasks. *Neuropsychologia, 30,* 565-580.

Coles, M. G. H., Gratton, G., Kramer, A. F., & Miller, G. A. (1986). Principles of signal acquisition and analysis. In M. G. H. Coles, E. Donchin & S. W. Porges (Eds.), *Psychophysiology: Systems, Processes and Applications* (pp. 183-221). New York: The Guilford Press.

Dabić-Jeftić, M., & Mikula, I. (1994). *Evocirani potencijali kore mozga – Osnovne postavke i klinička primjena* [Evoked potentials – basic assumptions and clinical application]. Zagreb: Školska knjiga.

Donchin, E., Ritter W., & McCallum W. C. (1978). Cognitive Psychophysiology: The Endogenous components of the ERP. In E. Callaway, P. Tueting, S. Koslow (Eds), *Event-related Brain Potentials in man* (55-118). New York: Academic Press.

Donchin, E., & Coles, M.G.H. (1988). Precomentary: Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences, 11(3),* 355-372.

Engel, R., & Fay, W. (1972). Visual evoked responses at birth, verbal scores at three years, and IQ at four years. *Developmental Medicine and Child Neurology, 14,* 283-289.

Engel, R., & Henderson, N. B. (1973). Visual evoked responses and IQ scores at school age. *Developmental Medicine and Child Neurology, 15,* 136-145.

Eysenck, H. J. (1987). Speed of information processing, reaction time, and the theory of intelligence. In P. A. Vernon (Ed.), *Speed of Information-Processing and Intelligence*, (pp. 21-67). Ablex, Norwood.

Grabner, R. H., Stern, E., & Neubauer, A. (1993). When intelligence loses its impact: Neural efficiency during reasoning in a familiar area. *International Journal of Psychophysiology, 49,* 89-98.

Gustafsson, J-E. (1988). Hierarchical models of individual differences in cognitive abilities. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence (vol 4),* Hillsdale, NJ: Lawrence Erlbaum Associates.

Guthke, J., Beckmann, J. F., Seiwald, B. B., & Hegel, T. (2000). *Wie «identisch» sind Arbeitsgedächtnis und Schlußfolgerndes Denken?* (How identical are working memory and reasoning?) Zwischenbericht zum DFG-Projekt GU 297/9, Leipzig: Universität Leipzig, Institute für Psychologie.

Haier, R. J., Robinson, D. L., Braden, W., & Williams, D. (1983). Electrical potentials of the cerebral cortex and psychometric intelligence. *Personality and Individual Differences, 4(6),* 591-599.

Haier, R. J., Siegel, B. V., Tang, C., Abel, L., & Buchsbaum, M. S. (1992). Intelligence and changes in regional cerebral glucose metabolic rate following learning. *Intelligence, 16,* 415-426.

Hoormann, J., Falkenstein, M., Schwarzenau, P., & Hohnsbein, J. (1998). Methods for the quantification and statistical testing of ERP differences across conditions. *Behavior Research Methods, Instruments, & Computers, 30(1),* 103-109.

Hugdahl, K. (1995). Event-related potentials. U: *Psychophysiology: The Mind-Body Perspective* (266-308). Harvard University Press, USA.

Jausovec, N. (1996). Differences in EEG alpha activity related to giftedness. *Intelligence, 23,* 159-173.

Jausovec, N. (1998). Are gifted individuals less chaotic thinkers? *Personality and Individual Differences, 25,* 253-267.

Jausovec, N. (2000). Differences in cognitive processes between gifted, intelligent, creative, and average individuals while solving complex problems: An EEG study. *Intelligence, 28*, 213-237.

Jausovec, N., & Jausovec, K. (2003). Spatiotemporal brain activity related to intelligence: A low resolution brain electromagnetic tomography study. *Cognitive Brain Research, 16,* 267-272.

Josiassen, R.C., Shagass, C., Roemer, R.A., & Slepner, S. (1988). Evoked potential correlates of intelligence in nonpatient participants. *Biological Psychology, 27,* 207-225.

Kulenović, A. (2003). *Abstract reasoning test (TAM 2003*). Unpublished manuscript. Zagreb: Faculty of Philosophy.

Kulenović, A. (2004). Izabrano netočno rješenje u zadacima višestrukog izbora kao osnovica za poboljšanje dijagnoze mjerenog atributa? [Selected incorrect answer in multiple choice items as a basis for improvement of the assessment of the construct.] Paper presented at "Psychology Days in Zadar". Zadar: Department of Psychology, May 2004.

Lin, E., & Polich, J. (1999). P300 habituation patterns: Individual differences from ultradian rhythms. *Perceptual and Motor Skills, 88,* 1111-1125.

Nätäänen, R. (1992). *Attention and brain function.* Lawrence Erlbaum Associates, Inc. Hillsdale, New Jersey, USA.

Neubauer, A. C. (1995). *Intelligenz und Gescwindigkeit der Informationsverarbeitung* [Intelligence and speed of inromation processing]. Wien: Springer.

Neubauer, A. C., Fink, A., & Schrausser, D. G. (2002). Intelligence and neural efficiency: The influence of task content and sex on brain-IQ relationship. *Intelligence, 30,* 515-536.

Neubauer, A.C., & Fink, A. (2003). Fluid intelligence and neural efficiency: Effects of task complexity and sex. *Personality and Individual Differences, 35,* 811-827.

Neubauer, A.C., Grabner, R.H., Freudenthaler, H.H., Beckmann, J.F., & Guthke, J. (2004). Intelligence and individual differences in becoming neurally efficient. *Acta Psychologica, 116,* 55-74.

Neubauer, A.C., & Fink, A. (2008). Intelligence and neural efficiency: Measures of brain activation versus measures of functional connectivity in the brain. *Intelligence, doi: 10.1016/j.intell.2008.10.008.*

Osaka, M., & Osaka, N. (1980). Human intelligence and power spectral analysis of visual evoked potentials. *Perceptual and Motor Skills, 50,* 192-194.

Picton, T.W. (1980). The use of human event-related potentials in psychology. In I. Martin & P. H. Venables (Eds.), *Techniques in psychophysiology* (pp. 357-395). New York: Wiley.

Picton, T.W., Bentin, S., Berg, P., Donchin, E., Hillyard, S.A., Johnson, R.Jr., Miller, G.A., Ritter, W., Ruchkin, D.S., Rugg, M.D., & Taylor, M.J. (2000). Guidelines for Using Human Event-Related Potentials to Study Cognition: Recording Standards and Publication Criteria – Committee Report, *Psychophysiology, 37,* 127-157.

Polich, J. (1989). Habituation of P300 from auditory stimuli. *Psychobiology, 17(1),*19-28.

Polich, J. (1993). Cognitive brain potentials. *Current Directions in Psychological Science, 2,* 175-179.

Polich, J. (2004). Neuropsychology of P3a and P3b: A theorethical overwiev. In K. Arikan & N. Moore (Eds.), *Brainwaves and mind: Recent developments* (pp. 15-29). Wheaton, IL: Kjellberg.

Rhodes, L. E., Dustman, R. E., & Beck, E.C. (1969). The visual evoked response: A comparison of bright and dull children. *Electroencephalography and Clinical Neurophysiology, 27,* 364-372.

Rugg, M.D. (1992). Event-related Potentials in Clinical Neuropsychology. U: J. R. Crawford, D. M. Parker, W. W. McKinlay (Eds.), *A Handbook of Neuropsychological Assessment* (393-411). Hove (UK), Hilsdale (USA): Lawrence Erlbaum Associates Publishers.

Rust, J. (1975). Cortical evoked potential, personality, and intelligence. *Journal of Comparative and Physiological Psychology, 89(10),* 1220-1226.

Rypma, B., Berger, J. S., & D'Esposito, M. (2002). The influence of working-memory demand and subject performance on prefrontal cortical activity. *Journal of Cognitive Neuroscience, 14,* 721-731.

Medelec, Vickers Medical & Teca Vickers Medical (1996). *SapphireII User Manual 003W009A*. Ltd, England: Medical Device Directive, Medelec.

Shagass, C., Roemer, R.A., & Straumanis, J.J. (1981). Intelligence as a factor in evoked potential studies of psychopathology: II. Correlations between treatment-associate changes in IQ and evoked potentials. *Biological Psychiatry, 16,* 1031-1040.

Stelmack, R.M., Knott, M.V., & Beauchamp, C.M. (2003). Intelligence and neural transmission time: a brain stem auditory evoked potential analysis. *Personality and Individual Differences, 34,* 97-107.

Stough, C. K. K., Nettelbeck, T., & Cooper, C. J. (1990). Evoked brain potentials, string length and intelligence. *Personality and Individual Differences, 11(4),* 401-406.

Sutton, S., Braren, M., John, E. R., & Zubin, J. (1965). Evoked potential correlates of stimulus uncertainty. *Science, 150,* 1187-1188.

Vogel, F., Kruger, J., Schalt, E., Schnobel, R., & Hassling, L. (1987). No consistent relationships between oscillations and latencies of visually and auditory evoked EEG potentials and measures of mental performance. *Human Neurobiology, 6,* 173-182.

Widaman, K.F., Carlson, J.S., Saetermoe, C.L., & Galbraith, G.C. (1993). The relationship of auditory evoked potentials to fluid and crystallized intelligence. *Personality and Individual Differences, 15(2),* 205-217.

Zurron, M., & Diaz, F. (1998). Conditions for correlation between IQ and auditory evoked potential latencies. *Personality and Individual Differences, 24(2),* 779-287.