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Cognitive Evoked Potentials (P300): Is the Decision To Press a Button Always Conscious?

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Abstract

Evoked cognitive potentials are a promising experimental technique that can be useful in diagnosis of various cognitive disorders, especially connected to the various memory impairments. Of particular interest to researchers is the study of the cognitive evoked potentials' latency when recognition of various stimuli is involved. To study the physiological nature and functional role of evoked cognitive potentials observed during the reaction to stimuli, and to determine the degree of conscious control involved in this reaction, the experimental data were statistically analyzed to determine the numerical correlation between the working memory capacity and the cognitive potential's latency. The cognitive EPs were measured for 166 healthy subjects and 63 others that had some pathological brain condition (discirculatory encephalopathy and other brain discirculatory disorders), varied by the age and gender. Measurements were done with the Neurosoft Neuro-MEP 4 computerized encephalography system, which implemented the standard method of large latency neural response measurement for P300 waves. Measurements were done in the setup where the subject had to recognize the significant stimuli and react to them by pressing a button. The significant stimulus was represented by a 2 kHz tone, while the insignificant stimuli were the frequently repeated 1 kHz tones. The brainwaves were registered in Cz-M1 and Cz-M2 outputs. This method allowed detection and latency measurements of the main response components N2, P3a P3ab and N3. Working memory capacity was determined by the number of words from a 10–15 word sets correctly reproduced shortly after exposures, as outlined by Luria. A statistically significant nonlinear correlation was observed between the memory capacity and the EP's latency, which was fitted by a modified hyperbolic function. Additionally, greater latencies were observed for subjects suffering from the memory disorders, and much shorter latencies were in general noted for the male subjects as opposed to the female ones. One more interesting observation was that in many cases the absolute reaction time was less than the cognitive potential peak taken as a conscious decision, suggesting that it is in many cases an automatic reaction. Cognitive potentials measurements, being an instrumental method, allow a clinical psychologist much greater flexibility in his diagnostic repertory, as it can be used even in the cases where word tests cannot. Also, the reaction times shorter than the latency of conscious reaction to stimuli adds weight to the simultaneous codes theory of automatic reactions.

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1. Introduction

Together with the sensory evoked potentials a lot of research is aimed at the cognitive EPs that appear when the subject recognizes a significant stimulus with a typical latency of 300 ms [3, 10, 13, 21]. This is usually detected when the subject has to consciously react (as in doing a calculation or pressing a button) to a rarely repeated stimulus as a positive so-called P3 or P300 wave (see Figure 1) [3, 4, 12]. The neural response parameters, chiefly of this P300 peak, are dependent on a subject's age, conforming to the so-called aging curve, with the latency significantly increasing with the age [3, 10, 16, 23, 24]. The latency and the amplitude of the P300 peak are frequently used to estimate the memory and attention characteristics in clinical practice [1, 3, 6–8, 10, 13, 15, 25, 32].

2. Methodology

Aside from aforementioned 28 healthy subjects, cognitive EPs were also measured, and P300/WMC analyzed, for 138 additional subjects, of which 75 were healthy, while 63 others had some pathological brain condition (circulatory encephalopathy and other brain circulatory disorders), varied by the age and gender.

Measurements were done with the Neurosoft Neuro-MEP 4 computerized encephalography system at the Clinical Neurophysiology lab of the Neurology Scientific Center in Moscow, which implemented the standard method of large latency neural response measurement for P300 waves. Measurements were done in the setup where the subject had to recognize the significant stimuli and react to them by pressing a button. The significant stimulus was represented by a 2 kHz tone, while the insignificant stimuli were the frequently repeated 1 kHz tones. The brainwaves were registered in Cz-M1 and Cz-M2 derivations. This method allowed detection and latency measurements of the main response components N2, P3 and N3 [2, 3].

Working memory capacity was determined by the number of words from a 10–15 word sets correctly reproduced shortly after exposures, as outlined by Luria in [9] and Revenok in [12].

Data were analyzed using the Statistica 10 and Excel 2010 software.

3. Results

The most diagnostically significant parameters of a P300 wave are its aforementioned latency period (LP thereafter) and amplitude [3, 20, 24]. Most cognitive disorders are manifested as the LP elongation and the amplitude decrease, [3, 13, 23, 24, 26, 31]; however, the latter is less significant as P300 height is variable and can easily decrease with the reduced attention even in the absence of any pathological process [12, 23, 24, 27, 28].

3.1. Evoked cognitive potentials and memory

3.1.1. Interpretation evoked cognitive potential

Most cognitive disorders are manifested as the LP elongation and the amplitude decrease, [3, 13, 23, 24, 26, 31]; however, the latter is less significant as P300 height is variable and can easily decrease with the reduced attention even in the absence of any pathological process [12, 23, 24, 27, 28].

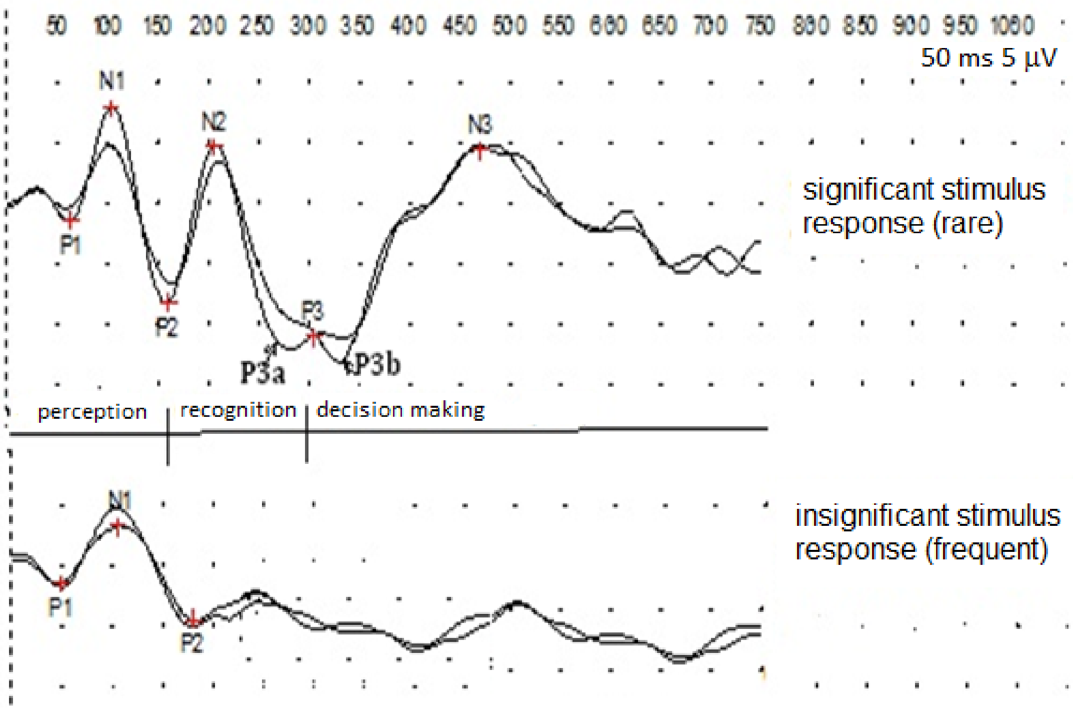

Figure 1: Cognitive evoked potentials(P300) for a 49 y.o. male.

Two neural response plots are demonstrated for a significant (above) and insignificant (below) stimuli, respectively, superimposed for the variability estimation.

Insignificant stimuli only generate a first, sensory peak (N1), while the reaction to a significant stimulus leads to a detection of a whole cognitive complex including a P300 (P3) peak with the average latency of 305 ms.

EP curve manifests several characteristic peaks: N2, P3 and N3 [2–4]. P3's appearance might be connected to a working memory refresh, [18] or the beginning of a decision process [2, 3].

The cognitive process frequently gets modified by the 'folding' of simultaneous code cognitive procedures in this case, leading to the performance increase, but also the possible loss of a conscious control of the process [9].

There exist cases where a hypnotized or feverish person could remember in detail the circumstances encountered decades ago, including the texts in unknown foreign languages, which obviously suggest the unconscious activation of a long-time memory [1].

In this work the working memory is interpreted in a multi-component model that includes a central processing node controlled by an attention system, variable-sized event buffer and the long-time memory interface, that is, a modification of a well-known three-component model with a phonological loop, spatial information entry system and main operator [1].

The goal of this work is the determination of the degree of consciousness in the decision to press the button when encountering a respective stimulus, based on a physiological study of the evoked brain potentials and their role in the process of significant stimuli recognition.

One of the task connected to the aforementioned goal, is a determination of the nonlinear correlation between the verbal working memory capacity (WMC) and the LP300 neural response latency in the mixed sample of the healthy subjects and those suffering from memory disorders.

The second task is a determination of a degree of consciousness in the decision to press a button, which is based on a neural response graph and reaction time.

Comparison between the 28 healthy adult subjects varying in age and gender (16 females and 12 males).

The standard cognitive EP detection experiment can be represented by the so-called oddball paradigm. According to a standard interpretation, the mismatch between the significant stimulus and the memory image left by the repeating insignificant standard stimuli generates a negative mismatch signal that increase the negative amplitude of a front-central derivation [31]. Here authors point three peaks in the cognitive EP curve, with the characteristic latencies of 116 ms, 132 mas, and 236 ms. The last peak

Table 1: Statistical properties of a sample of 138 test subjects.

Property	Sample mean	Sample median	95% interval
Working memory capacity (words)	6.86 + 2.37	7.3	(6.46; 7.26)
LP300 (ms)	379.2 + 79.23	350	(365.8; 392.5)

is characterized by an additional positive component and is localized at the anterior cingulate gyrus.

Thus, if the stimulus doesn't match the memory image, formed by the previous repetitive stimulation, a strongly negative response is generated, which is the followed by a positive one. The P3a components are usually linked with an orientation reflex when a sensory model of the environment, kept in a brain's sensory system, is rebuilt. This mechanism is unconscious [8], and allows the living being to adapt when their environment changes.

3.1.2. Linear correlation of cognitive potentials and memory

The measured data have shown that cognitive EP latency P300 and working memory capacity were normally distributed according to the $\chi 2$ criterion. The sample's statistical properties are shown in Table 1.

This sample was fitted to the linear equation, the results of which are displayed in Figure 2, with the correlation coefficient of $r = -0.779$. As seen in the image, linear regression plot is above the measured data in the 350 to 500 ms range, and below the data when the latency is < 350 ms or > 500 ms.

Another downside of the linear regression is that its plot crosses the plot axes. This implies the maximum WMC capacity of 14.6 words at the zero latency, and negative capacity at the latencies above 730 ms, which doesn't have any meaning. On the other hand, the maximum WMC of approximately 15 doesn't allow the use of the resulting formula in the larger word set tests. Moreover, this linear regression doesn't even fit the minimum square condition.

3.1.3. Nonlinear approximation of the statistical connection of cognitive potentials and memory

Accordingly, two nonlinear functions were tested for better fit of the experimental set. The requirements for them were the lack of negative WMC and impossibility of touching the plot axis. First was the negative exponent, for which the minimal square fit is shown at the Figure 3. This shows a good fit for the central and right parts of the

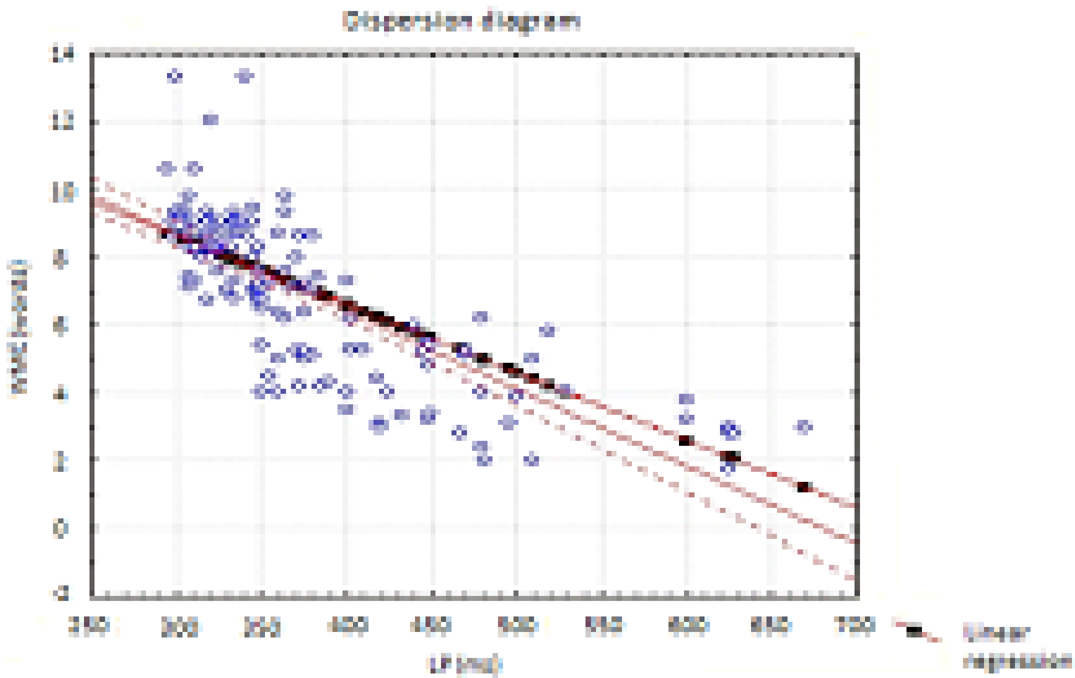

Figure 2: Linear regression plot of the working memory capacity against the response latency parameter LP for the general sample of 138 subjects. Open circles – experimental P300 data, black squares – regression plot data. WMC = 14.6–0.02LP, r = –0.776.

plot, but for the low latency (> 350 ms) cases the fit is still below the experimental data, much like the linear fit above. The correlation coefficient of r = –0.803 suggest the stronger correlation than for the linear fit. Another nonlinear fit tried in this work was the hyperbolic function describing the reverse proportional dependency of the WMC on the latency parameter (see Figure 4).

It was also fitted using the minimal squares method. It resulted in the following regression equation (1) with the correlation coefficient of r = –0.812

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$$WMC_h = \frac{e^{12,401}}{LP^{1,787}}$$

Figure 4 suggests that while the fit is generally better, the low-latency part of the plot is still below the experimental data. To compensate for that the shifted hyperbola was used, as defined by the following equation (2):

$$WMC_h = \frac{WMC_h - 1.89600}{0.67891}$$

This corrected formula was used for the cases with LP < 350 ms, while the previous formula used for LP > 350 ms. The result is shown on Figure 5. The resulting nonlinear dependency better corresponds to the experimental data than the linear one. The

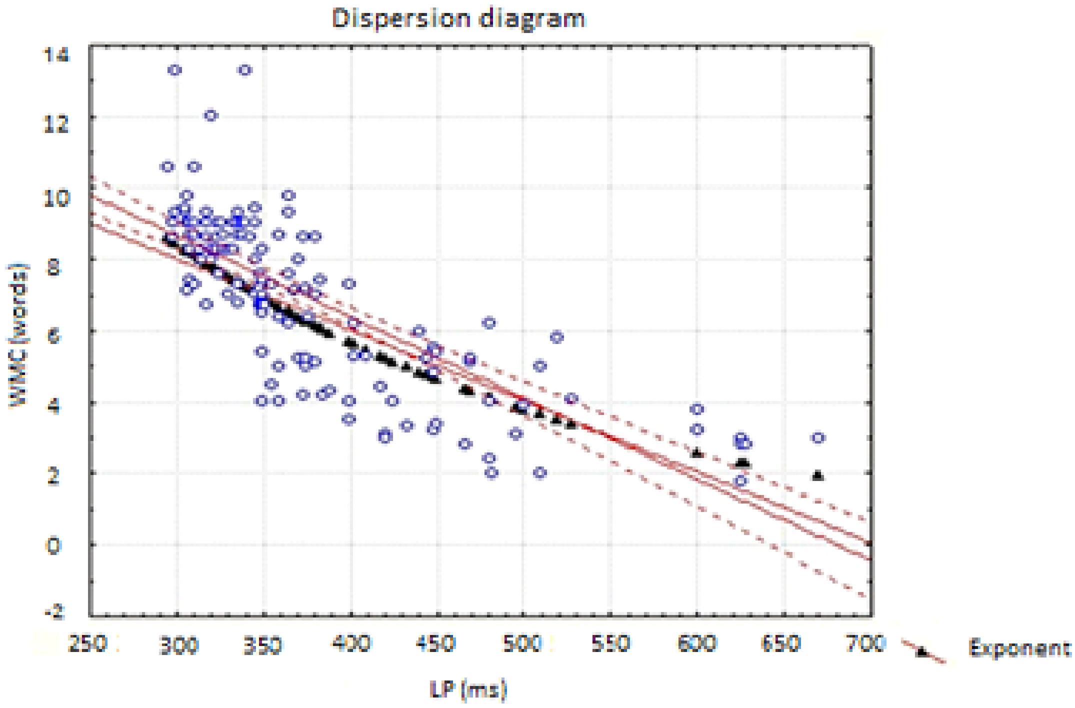

Figure 3: Negative exponential regression plot of the working memory capacity against the response latency parameter LP for the general sample of 138 subjects. Open circles – experimental P300 data, black squares – regression plot data. WMC = 28.12exp(−0.004LP), r = −0.803.

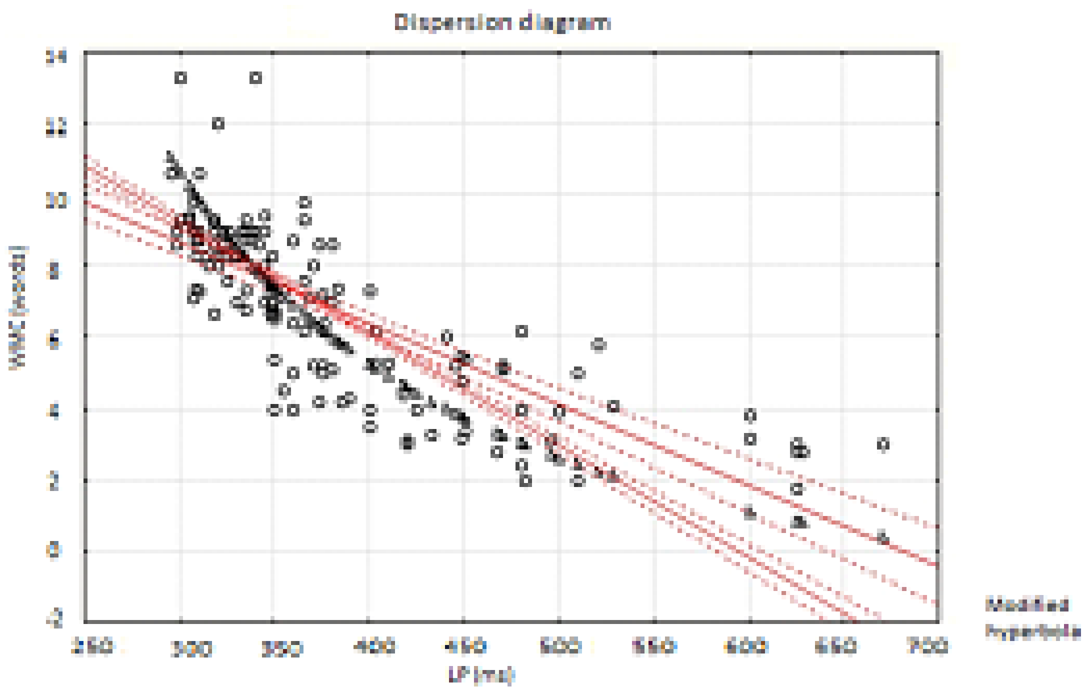

Figure 4: Hyperbolic regression plot of the working memory capacity against the response latency parameter LP for the general sample of 138 subjects. Open circles – experimental P300 data, black squares – regression plot data. r = −0.812.

correlation coefficient for a linear dependency is r = −0.776 (Figure 2), while for the composite hyperbola it is r = −0.814 (Figure 5). The 350 ms point that separates two parts of the curve corresponds to a sample median, according to the Table 1, and is a norm for the subjects aged 50–60 years (Gnezditsky, & Korepina, 2011).

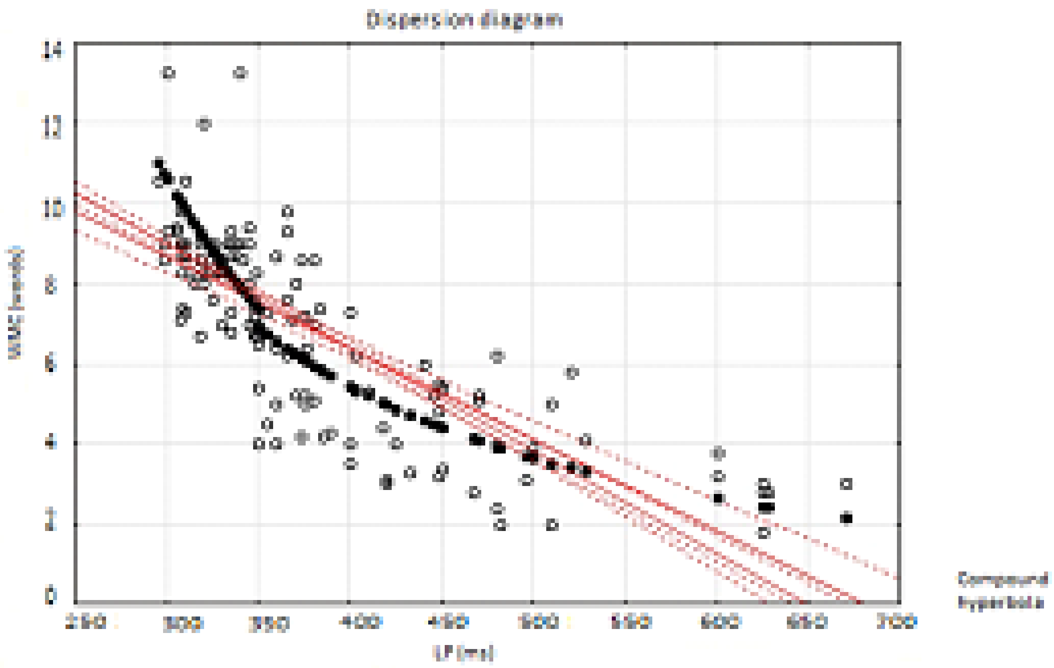

Figure 5: Composite hyperbolic regression plot of the working memory capacity against the response latency parameter LP for the general sample of 138 subjects. Open circles – experimental P300 data, black squares – regression plot data. Equation (1) was used for LP < 350 ms, equation (2) for LP > 350 ms. $r = -0.814$.

3.1.4. Comparison of the average response time and the average peak of latency of the N3 cognitive potential

Among the 28 healthy subjects, the average age of a male subject was 40.25 years within the 95% interval of (31.55, 48.55), while for 16 female subjects the average age was 36.43 years within the (30.20, 42.55) interval. The age variation was non-significant according to the either parametric and non-parametric criteria. Table 2 gives the average characteristic values of the cognitive EP for male and female subjects, together with the two examples: a 44 years old male and 58 years old female for the ease of explanation. For each subjects further data were recorded: average reaction time (RT) in milliseconds, average peak latency of the P3 component (indicated as LP (P3) in the table), average peak latency of the N3 component (indicated as LP (N3)), and the time before the button press. Each subject participated in two tests, resulting in 56 measurements overall.

Cognitive EP curve measured for a significant stimulus has all characteristic peaks, including the N2, P3 and the finishing component of N3, absent for a non-significant stimulus one, where only the P1, N1 and P2 components are observed (see Figure 1).

The N2 response peak is usually linked to the comparison operations, and P3 peak corresponds to the act of decision taking [1]. In this experiment there's only one comparison, as there's the singly significant stimulus.

Peak latencies of P3 component are contained in the 95% interval of (331.65; 355.18) and (332.86; 353.51) ms for males and females, respectively, while for the N2 peak the corresponding intervals are (215.18; 243.90) and (224.36: 244.84) ms (Table 1), with the maximum standard deviation of 34.01 ms. Average P3 latency for the whole sample is (341.57 + 28.72) ms, N2 latency is (232.20 + 30.14) ms for two tests. Average reaction time is (295.59 + 48.30) ms, with the statistically significant gender difference, supported by the Kolmogorov–Smirnov and Mann–Whitney non-parametric criteria, and parametric t-criterion for the $t < 0.05$ significance level.

From the subjects' reaction time histograms (see the examples in Figures 6 and 7) the reaction time for each button press was extracted. The percentage of the fast presses (where the LP parameter of the evoked potential curve was less than the reaction time) is shown in Table 2. For the male subjects this percentage was no less than 84%, for example for the Subject M, whose reaction time histogram is shown in the Figure 6, the fast presses constituted 90% of the whole set.

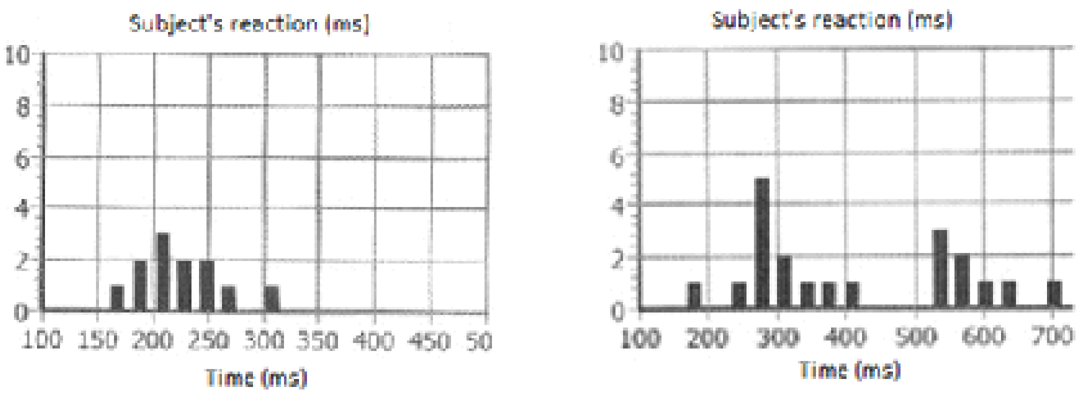

Figure 6: The Subject M's (44 y.o) reaction time histogram. The Subject F's (52 y.o)reaction time histogram.

On the other hand, female subject had shown much smaller rate of the fast presses, no more than 69%, and the Subject F from Figure 7 had only 36% of the fast presses.

Comparing the reaction time histograms with the EP curves latency, it is evident that for the male Subject M (Figure 6) the histogram is compact and has a distinct peak in the 210–230 ms range, which is less than the average EP peak latency of 325.3 ms (Table 2). Conversely, for the female Subject F the reaction time histograms have a

Table 2: The reaction time in the standard experiment to measure cognitive evoked potential.

Subject	Age	LP P3 (ms)	Fast press rate(RT < LP P3)	LP N2 (ms)	Reaction time (ms)
Male (average)	40.3 ± 13.7	343.42 ± 27.86	84.6% – 95.3%	229.54 ± 34.00	295.59 ± 48.30
M	44	325.3 ± 10.6	90% – 85%	207.5	242.5 ± 19.09
Female (average)	36.4 ± 11.7	343.19 ± 28.64	30% – 69%	234.19 ± 27.27	300.59 ± 58.30
F	58	373 ± 21.21	36% – 50%	180	407.5 ± 10.61

multi-modal shape, with the largest peak in the 250–290 ms range, which is also less than the EP latency (373 ms).

Thus, not all histogram peaks fall into the reaction time interval (Table 2), with the outliers appearing outside it for both male (Figure 6) and female (Figure 7) subjects.

4. Discussion

The problems of cognition and cognitive disorders are widely discussed in literature [1, 3–5, 17, 29, 30, 32]. The known dependence of cognitive potential and working memory capacity on the subject's age on the one hand, and the connection between the subject's age [2–4] and the number of neurons used for learning [14] on the other one, implies an existence of the connection between the Luria-test determined WMC and the LP300 latency. This work experimentally demonstrates this connection and determines it's character depending not only on the subject's age, but also on the other characteristics.

It's been demonstrated earlier that the LP300 increases linearly with the decreasing working memory capacity in the patients suffering from cognitive disorders [4, 5]. This article builds on this work, demonstrating that the better correlation between the latency and the Luria-test measured memory capacity might be obtained if the compound hyperbola is used to fit the experimental data instead of the linear fit, especially if the latency parameter is less than 350 milliseconds.

Conversely, this means that the latency parameters might be used to indirectly estimate the working memory capacity from the experimentally measured cognitive potential latency without taking word tests. As a strong correlation between those parameters shows the validity of such a method, this allows using it in the cases when a word-based psychological testing is impossible, which might be an advantage in certain circumstances.

These results also match the hypothesis of the linked simultaneous codes [9] and the model of psychological operations in the working memory [8]. It is possible that all stages of psychological operation might be folded into a linked simultaneous code that can be unconsciously invoked after a repeated stimuli, as suggested by the percentage of the fast (potentially, not consciously controlled) button presses in Table 2. This might be the mechanism of the unconscious multitasking between the routine operations, like thinking of something disconnected while driving, and returning to the conscious control when the circumstances require it.

5. Conclusions

1. Working memory capacity and evoked cognitive potentials latency (P300 peak) data obtained for a sample of 138 subjects of varied ages between 10 and 90 years.

2. A significant nonlinear negative correlation observed between those parameters, with the correlation coefficient of r = −0.8.

3. Using a minimum square fit with a 95% interval, an analytic expression for this correlation obtained, with the negative exponent and hyperbolic fits tried. The best fit observed for a compound hyperbola

$$WMC = \begin{cases} \dfrac{e^{12,401}}{LP^{1.787}}, & LP > 350ms \\ \dfrac{\frac{e^{12.401}}{LP^{1.787}} - 1.89600}{0.67891}, & LP < 350ms \end{cases}$$

   (Figures 4 and 5)

4. Identified a possibility to estimate a working memory capacity from the measured latency parameters without taking a word test.

5. The reaction time to a stimulus is often less than a cognitive potential latency, suggesting an unconscious(automatic) reaction.

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