



NATIONAL RESEARCH UNIVERSITY
HIGHER SCHOOL OF ECONOMICS

*Boris Chernyshev, Ivan Lazarev, Maksim Ivanov,
Evgeniya Osokina, Alyona Vyazovtseva*

ATTENTIONAL LAPSES UNDER DECISION-MAKING: AN EVENT-RELATED POTENTIAL STUDY

BASIC RESEARCH PROGRAM

WORKING PAPERS

SERIES: PSYCHOLOGY
WP BRP 06/PSY/2012

SERIES: PSYCHOLOGY

*Boris V. Chernyshev¹, Ivan E. Lazarev², Maksim V. Ivanov³,
Evgeniya S. Osokina⁴, Alyona A. Vyazovtseva⁵*

**ATTENTIONAL LAPSES UNDER DECISION-MAKING:
AN EVENT-RELATED POTENTIAL STUDY⁶**

The causes of everyday errors made by most people remain largely unknown. In order to investigate spontaneous lapses in attentional processing a new task was designed. This task creates an increased attentional load because it is based on impeded decision making involving both stimuli feature binding and response selection. Participants made errors in $9.6 \pm 1.1\%$ of trials and response omissions in $5.4 \pm 0.7\%$ of trials. In the ERP pattern the N1 and P2 peaks were well pronounced, while P3 peak was almost indistinguishable. The P2 peak was greater in trials with errors and response omissions compared to correct responses. The results obtained substantiate the hypothesis that attentional lapses may be a consequence of mind-wandering, which may compete with the overt task for the attentional resources.

JEL Classification: Z

Keywords: cognitive processes, event-related potentials, P2, attention, attentional lapses, response omissions, performance errors, mind-wandering.

¹ National Research University Higher School of Economics. Laboratory of Cognitive Psychophysiology, Head; National Research University Higher School of Economics. Department of Psychophysiology, Assistant Professor; E-mail: bchernyshev@hse.ru

² National Research University Higher School of Economics. Laboratory of Cognitive Psychophysiology, Senior Researcher; E-mail: ilazarev@hse.ru

³ National Research University Higher School of Economics. Laboratory of Cognitive Psychophysiology, Junior Researcher; E-mail: mivanov@hse.ru

⁴ National Research University Higher School of Economics. Laboratory of Cognitive Psychophysiology, Trainee Researcher; E-mail: eosokina@hse.ru

⁵ National Research University Higher School of Economics. Laboratory of Cognitive Psychophysiology, Trainee Researcher; E-mail: ma1-21@yandex.ru

⁶ The study was implemented in the framework of The Basic Research Program of the National Research University Higher School of Economics in 2012

Introduction

All people are prone to make errors. In many professions involving prolonged routine activity – such as a typist or a proofreader – a certain number of errors are tolerated in the respective professional standards. Everybody has encountered the errors made by professional programmers in computer software – computer crashes, and data loss – and we reconcile ourselves to them just as we do to bad weather and TV commercials. In other words, a certain percentage of erroneous actions are generally tolerated in many kinds of human activity.

Theoretically there can be many causes of errors; here we do not address such errors as those caused by incompetence, mental illness, sabotage etc. We assume that even if someone is competent, healthy and willing enough to act accurately, such a person will still occasionally make errors (or commit an erroneous inaction instead of a timely action). Nor do we consider errors in someone's actions caused by an objective lack of information, disinformation or irrelevant emotional bias. The remaining casual type of everyday errors is usually attributed to "absent-mindedness" or other similar forms of inattention. The only way to explain them is to search for the causes of faults in information processing in the brain, which is in some way guided by the attentional system.

According to Kahneman's resource theory [1973], the amount of cognitive resources is limited, and their absolute amount available at any given moment of time depends on the current level of effort/activation. The single pool of resources is distributed between several cognitive processes if they are to be executed simultaneously. Thus an obvious cause of errors may lie in the lack of cognitive resources in the face of a current task – both in absolute amount (if the pool of available resources is insufficient due to low level of effort/activation/arousal) and in relative amount (if some portion of the resources is spent on some secondary cognitive process).

Early preattentive stages of perception as well as internal programming of muscular actions (including speech production) are mostly automated and thus can be performed in parallel: evidently they do not compete for resources. Noticeable competition for the resources arises only at the central stage of information processing which can be described as decision-making – as was clearly demonstrated in a series of studies with thorough chronometry of parallel execution of two cognitive tasks [Sigman, Dehaene, 2005; 2006]. Competition for the resources leads to sequential information processing and thus to delays in behavioral responses.

The physiological validity of the theoretical construct of competition for a limited pool of resources was indirectly demonstrated in a body of encephalographic research aimed at the study

of selective and distributed attention with the help of the technology of event-related potentials (ERPs). For example, a thoroughly studied experimental paradigm involves the presentation of two highly similar concurrent streams of auditory signals, one of which had to be attended to and the other one ignored. Moreover, within each stream (termed herein "channel") some stimuli deviated from the predominant pattern thus attracting attention (in way of the traditional oddball paradigm). A number of important phenomena were discovered in these studies, including the generation of a steady negative potential deflection in an attended channel compared to an unattended channel; this negative deflection was termed "processing negativity" (or "difference negativity") [Hillyard et al., 1973; Näätänen et al., 1978]. This phenomenon was interpreted by Näätänen [1992] as more intensive information processing of the relevant information; thus in the irrelevant channel incoming information processing is reduced compared to the attended channel. In other words irrelevant information is denied certain resources that are allocated to the processing of relevant information. The time when this effect appears – approximately at the time of the auditory N1 peak or a little later – corresponds to late preattentive stages of information processing, which take place in the secondary sensory and associative cortical areas.

In the studies made within the methodology of the "attentional blink" and the "psychological refractory period" later electrophysiological correlates of completion for resources were found – such as suppression of the P300, which involves the activation of broad associative cortical areas and is apparently linked to memory updating and conscious awareness [for review see Luck et al., 2000].

The studies described above involved conditions of overt competition between two channels of incoming information or between two explicit tasks. Still it is clear that many errors are committed by people in conditions that require neither selective attention needed for inhibition of processing in irrelevant channels nor divided attention needed to deal with two concurrent tasks. Can we expect any competition for the limited pool of resources in conditions of a single task?

It is known that in many conditions – particularly in conditions that do not require significant effort – a specific mental state of mind-wandering arises, that is subjectively perceived as a flow of task-unrelated thoughts leaping from one subject to another. One of the first scientific descriptions of this state was provided by Varendonck [1921]. Especially characteristic is this state of people involved in prolonged monotonous work [Klinger, 1977].

The mental state of mind-wandering entails a deterioration in concentration on the currently executed overt task [Smallwood, Schooler, 2006; Smallwood et al., 2003]. In electrophysiological studies it was demonstrated that the mental state of mind-wandering suppresses the processing of both relevant and irrelevant information. In particular, under a sustained attention to response task (SART) it was demonstrated that the erroneous responses of the subjects, which

tightly coincided with their self-reports of mind-wandering, were accompanied with the reduction in the P300 amplitude [Smallwood et al., 2008]. Similarly during the execution of a simple visual discrimination task and testing the brain responsiveness with additional task-irrelevant probe stimuli, it was found that visual P1 and auditory N1 to probe stimuli were suppressed in those trials, after which the participants gave reports of mind-wandering [Kam et al., 2011].

Currently it is well known that the human brain when not involved in any explicit activity manifests a characteristic pattern of activity in a number of brain structures (among the most important ones are medial frontal and parietal areas); these brain structures were collectively termed the "default mode network" [Raichle et al., 2001]. Although initially this state puzzled researchers, later it was proved that activation of the "default mode network" is clearly linked to the state of mind-wandering – which was thus described as going deep into one's thoughts, introspection, access to the episodic memory, considering one's relation to other people etc. [Christoff et al., 2009; Mason et al., 2007].

Thus mind-wandering is a normal state occurring in a person who is not involved in any explicit task – or is involved in a monotonous task for a prolonged period. In terms of brain activity, this state is far from being a quiescent inhibited state: functional magneto-resonance imaging data show that this state is accompanied by increased activation of brain structures belonging both to the "default mode network" and the executive brain system [Christoff et al., 2009]. The "default mode network" is known to cooperate with the frontal-parietal network [Smallwood et al., 2012], which is the main player in the attentional system – and so it requires access through the bottleneck of the attentional control. Being a specific form of cognitive load that involves central restrictions in information processing, mind-wandering must compete for the pool of cognitive resources with explicit tasks in the same way as two explicit tasks compete in the traditional understanding [Sigman, Dehaene, 2005; 2006].

Most traditional behavioral tasks used for the study of cognitive processes with the help of ERPs (such as the oddball) are relatively simple; they can be performed by most participants with a negligible percentage of errors. The virtual absence of errors does not allow for their statistical analysis in such tasks. It is likely that such tasks do not create any significant cognitive load, they can be easily automated and can be performed in parallel to any other cognitive task, including mind-wandering. For these reasons electrophysiological correlates of spontaneous attentional lapses remain almost unexplored. Pioneering studies, mentioned above [Smallwood et al., 2008; Kam et al., 2011] opened a new direction in cognitive research. However, these studies have an important inherent methodological drawback: in order to prove that attentional lapses are caused by mind-wandering, experimenters had to interrupt their participants very often (every 60-90 s) throughout the experiment for a self-report – which apparently distracted them and cre-

ated certain bias in their reasoning and behavior. Moreover, these studies were based on rather simple tasks, which are usually executed accurately by all normal subjects. And the high percentage of errors reported could be caused by those experimenters' intrusions rather than by spontaneous processes in the brain.

In order to be able to study spontaneous lapses in attentional processing, we designed a new task, which was based on decision making involving feature binding in the auditory domain and response selection [Osokina et al., 2012]. During this task participants make a significant number of errors and omissions - while their overall performance still remains highly above chance.

This task is compatible with the methodology and technique of ERP recording. At the same time a perceptual decision based on a conjunction of features requires attention [Treisman, 1986; Treisman, Gelade, 1980]. Attention, in turn, is viewed as a process imposing a load on the limited pool of cognitive resources [Norman, Bobrow, 1975; Wickens, 1980]. The resource-consuming nature of the task is also enhanced because it involves intensive decision-making [Norman, Shallice, 1986]: not only perceptual decision making related to a conjunction of features and identifying the auditory object, but also executive decision making related to choosing the appropriate response. Thus the task used in our research consumes a large amount of central resources and consequently it must compete with other concurrent cognitive tasks. During the experiment the participants were maximally deprived of any irrelevant external sensory stimulation and they did not receive any explicit secondary task. The purpose of our study was to investigate the ERPs during spontaneous attentional lapses – errors and omissions – in comparison to correct responses.

Methods

Participants

The study was performed in 30 university students aged 19-26 years ($M \pm SD = 20.9 \pm 1.3$ years) (19 females and 11 males, including 25 right-handed and 5 left-handed persons). All participants had normal hearing, normal or corrected to normal vision and reported no history of auditory, neurological or mental illness. An informed consent was obtained and signed by the participants before the experiment, and they were also asked to fill a short questionnaire concerning their current physical and mental state.

Materials

Experimental settings. The experiments were performed in a sound-attenuated chamber with standard ceiling lighting, located in a quiet room. Participants were comfortably seated in an encephalographic chair with adjustable headrest and armrests. A 19" LCD monitor was in front of them at chest level.

Electrophysiological recording. The electroencephalogram (EEG) was recorded with an NVX-52 system (Medical Computer Systems, Russia) with Neocortex Pro software (Neurobotics, Russia) from 32 symmetrical electrodes in accordance with the international 10-10% system and 1 electrooculogram electrode referred to linked earlobes, with a forehead ground and impedance lower than 10 k Ω in all channels. The filter bandpass was 0.5–200 Hz.

Auditory stimulation and recording behavioral responses. Auditory stimuli were presented to the participants using E-Prime software (Psychology Software Tools, Inc., U.S.A.) through a high-quality stereo headset with in-ear design, which additionally reduced ambient noise. Four pre-recorded auditory tones were presented. Each tone was a sinusoidal signal of either 500 Hz ("low") or 2000 Hz ("high"), either a pure tone ("pure") or the same tone with broadband noise admixed to the signal ("noised"). Thus the 4 stimuli were named in the instruction presented to the participants as (1) "low pure", (2) "low noised", (3) "high pure", and (4) "high noised". The duration of all stimuli was 40 ms, with rise and fall time 10 ms each, and at approximately 85 dB.

Behavioral responses were obtained from the participants with the help of handheld gamepad. Participants were instructed to hold the gamepad in their dominant hand, which was lying comfortably on their lap, and press one or the other of the two buttons with their thumb, trying to avoid moving their hand and arm.

Procedure

The sustained attention auditory task based on feature conjunction was partially reported earlier [Osokina et al., 2012].

Instruction. Participants were instructed before the experiment to press one or the other of the two buttons of a handheld gamepad in response to the stimuli. The participants were also instructed that if he/she would press the correct button, a "smiley" would be briefly presented on a LCD screen in front of them.

The participants were offered to familiarize themselves with the following table (Table 1) which was given to them printed in a large typeface on a sheet of paper for free viewing and then

removed from the chamber before the start of actual EEG recording. Table 1 specifies the conjunction contingencies between the two stimulus features ("high/low" and "pure/noised") comprising the set of the 4 stimuli, and the response required to the left and right buttons of the gamepad. Though the rule is very simple, the task can not be solved at above chance level via processing of any single feature but rather it requires a mental conjunction of the features.

Table 1. Response contingencies in the experimental task: this table was read as well as handed in printed form to the participants immediately before the experiment.

	High	Low
Pure	Left button	Right button
Noised	Right button	Left button

While the printed table was in front of the subject, all four stimuli were manually played to him/her twice with all stimuli loudly named by the experimenter ("low pure", "low noised" etc.). Then the stimuli were manually repeated without the experimenter's oral annotations as many times as needed until the subject confirmed that he/she could identify each of them. After that the instruction table was removed and the participant was left alone in the chamber.

Experimental procedure. The experiment involved 5 or 6 experimental sessions, after each session participants were asked about their condition and recommended to relax and/or to move their muscles and stretch a little within the armchair.

Each session included 100 stimuli of 4 types (see above) intermixed in a truly random order (calculated at the moment of presentation) with equal probability ratio (1:1:1:1).

Although all 4 stimuli were presented with equal probability, in most sessions stimuli percentages were not exactly equal to 25%: overall $M \pm SD$ for the 4 stimuli were 24.9 ± 3.8 , 25.3 ± 4.1 , 25.1 ± 4.1 , and 24.8 ± 4.1 , the difference between them being nonsignificant ($F(3, 648) = 0.46, ns$). Due to the purely random algorithm, the participants had no way to predict the order of the stimuli. The stimuli were presented with random stimulus onset asynchrony (SOA) of 2500 ± 500 ms (flat distribution).

The following feedback procedure was used. Correct responses within the time interval 300-1700 ms after the stimulus onset were reinforced by a "smiley" (a schematic smiling face depicted by eyes and mouth in a ring filled with yellow on a neutral grey background), which was presented for 500 ms immediately after correct responses in the center of the screen of LCD

monitor located in front of the participants. The screen was neutral grey between the presentations of the "smilies".

The time interval from the moment of a key pressing by the participant till the next auditory stimulus onset was kept to no less than 500 ms by prolonging the particular SOA when needed. The resulting SOA throughout the experiment was 2657 ± 321 ms ($M \pm SD$), with minimum and maximum 2063 and 5010 ms correspondingly.

The instruction only informed the participants that they had to press one of the two the buttons according to the rule, but it did not tell them that they had to react as fast as possible, and it did not tell them to make a random choice if they were unsure. In other words, the trials were not "forced" and subjects were implicitly allowed to omit responses (without any explicit point on that matter in the instruction).

Data extraction and analysis

Behaviour. Behavioral outcome of each trial could be one of the following: a correct response (pressing the correct button), an error (pressing the wrong button), and a response omission (failure to press any button). In the event of multiple key presses only the first response was considered for the analysis. Mean response latencies as well mean latency SDs within each participant were calculated separately for correct responses and errors within each experimental session, as well as within all sessions performed by each participant. Behavioral analysis was performed in the first 5 sessions with all 100 trials taken into account regardless of the quality of EEG recording. Statistical analysis in the participants, who performed 6 sessions, showed that for all the behavioral parameters studied session 5 and 6 did not differ ($p > 0.05$).

EEG and ERPs. For the purpose of the ERP analysis, all sessions performed by a participant were taken into account. EEG and ERPs were analyzed within EEGLAB [Delorme, Makeig, 2004] and ERPLAB software. EEG artifacts were manually rejected, and electrooculographic artifacts were corrected with the use of the conventional recursive least squares regression [Gómez-Herrero et al., 2006] implemented in EEGLAB. The data were post hoc filtered with 1 Hz high-pass and 30 Hz low-pass using fast Fourier transformation, which does not affect signal phase.

Evoked activity was calculated by way of coherent averaging of trials separately for correct responses, errors and omissions. Zero line was adjusted separately for each record based on prestimulus interval of 250 ms before stimulus onset.

In order to measure ERPs in sufficient and comparable numbers of averaged trials, the following procedure was applied to the data. ERPs for errors and omissions were calculated only

for those participants, whose recordings contained no less than 20 artifact-free trials of a given response type (which corresponds to no less than 25 total trials with a given behavioral response). If within a given participant's data and a given response type there were less than 20 artifact-free trials, this participant was excluded from the ERP analysis. On the contrary, if the recording contained more than 25 artifact-free trials of a given response type, only 25 randomly taken trials were used for averaging. Likewise for correct responses only 25 artifact-free trials were randomly taken into averaging. Thus, the ERP analysis reported here was carried out for 24 participants for errors and for 16 participants for omissions.

ERP peaks were automatically marked in averaged ERP recordings in each electrode separately in the ERPLAB software as most negative and most positive potential deflections (for positive and negative ERP components respectively) in the following time ranges: N1 — 60-140 ms, P2 — 140-260 ms. Peak amplitudes and latencies were measured from zero line. ERP analysis reported here was performed in 15 pericentral electrodes (F3, Fz, F4, Fc3, Fcz, Fc4, C3, Cz, C4, Cp3, Cpz, Cp4, P3, Pz, P4) where the N1 and P2 were most clearly pronounced.

Statistical analysis

An analysis of variance (ANOVA) with repeated measures was used with the following repeated measure factors: SESSION (5 levels from the 1st to the 5th experimental session), RESPONSE (3 levels for correct response, error and omission, or 2 levels for paired comparisons of correct responses vs. errors and correct responses vs. omissions). For ERP analysis the following factors were used: RESPONSE (3 levels for correct response, error and omission, or 2 levels for paired comparisons of correct responses vs. errors and correct responses vs. omissions), ANTERALITY (5 levels for anterior-posterior gradient) and LATERALITY (3 levels for left-right gradient). Tukey's HSD (honestly significant difference) test was applied after ANOVA in order to reveal, which levels of factors significantly differed. Greenhouse-Geisser correction was applied if needed.

Data are presented as $M \pm SEM$ unless otherwise specified. Significance levels reported are rounded to the first non-zero high-order digit. Exact significance levels are given only for p-values below 0.1.

Results

Behavior

Thirty participants were included in the study. The percentage of erroneous responses varied significantly within the participants: while the mean (M) percentage of errors within all the experimental sessions was 11.1%, its standard deviation (SD) was 8.1%. To ensure that we included only those participants who correctly understood the instruction and were willing to cooperate, we excluded from all further analyses those participants whose percentage of errors exceeded the population $M + 2 SD$, i.e. 27.3%; thus two participants with the error percentage of 32.0% and 33.0% were left out.

In the remaining 28 participants the behavioral performance was sufficiently good. The summary data are presented in Table 2.

Percentages of correct responses, errors and omission. The overall percentage of correct responses, errors and omissions was 85.1 ± 1.6 , 9.6 ± 1.1 and 5.4 ± 0.7 correspondingly (Table 2).

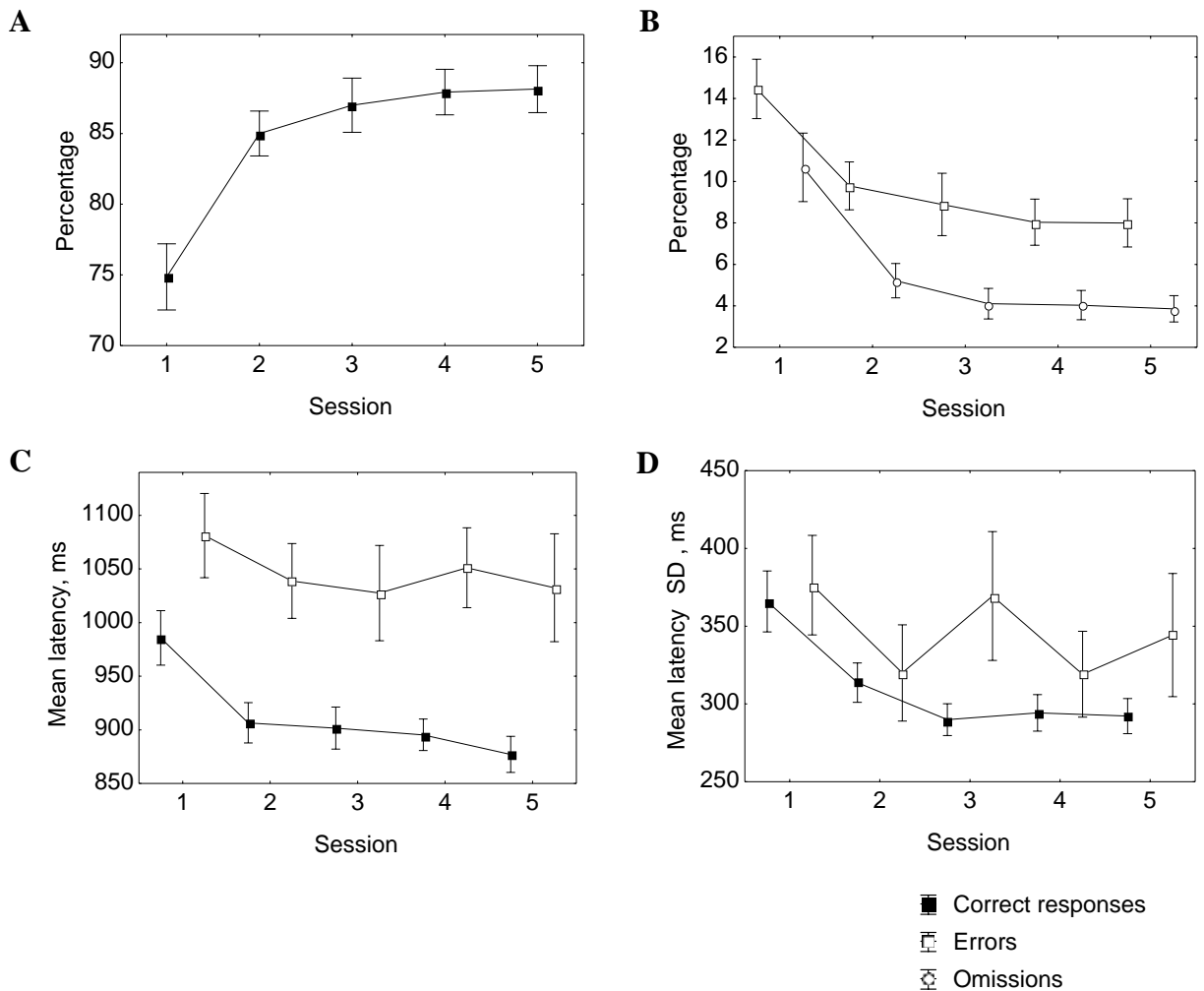
Table 2. Overall behavioral statistics.

		<i>N</i>	<i>M</i>	<i>Mdn</i>	<i>Min.</i>	<i>Max.</i>	<i>SD</i>	<i>SEM</i>
Percentage	Correct responses	28	85.1	88.0	65.0	96.0	8.6	1.6
	Errors	28	9.6	7.6	2.5	21.8	5.8	1.1
	Omissions	28	5.4	5.3	0.7	14.8	3.7	0.7
Mean latency, ms (<i>all participants</i>)	Correct responses	28	905	916	715	1074	80	15
	Errors	28	1030	1030	739	1294	143	27
Mean latency, ms (<i>participants with ≥ 25 errors</i>)	Correct responses	24	911	924	715	1074	82	17
	Errors	24	1020	1028	739	1248	136	28
Mean latency SD, ms (<i>all participants</i>)	Correct responses	28	316	320	226	383	49	9
	Errors	28	373	371	193	743	117	22
Mean latency SD, ms (<i>participants with ≥ 25 errors</i>)	Correct responses	24	321	339	226	383	50	10
	Errors	24	365	371	226	537	83	17

The behavioral percentage data manifested a clear dynamics mirroring the overall improvement in performance (Fig. 1A). The mean percentage of correct trials increased from 74.9 ± 2.3 during the 1st session to 85.0 ± 1.6 during the 2nd session and then continued to monotonically increase with each session, reaching 88.1 ± 1.7 during the 5th session. The effect of SESSION factor was highly significant ($F(4, 108) = 33.17, p < 0.001$). Tukey's HSD test showed that only the 1st session significantly differed from all the others ($p < 0.001$).

The mean percentage of errors (Fig. 1B) monotonically decreased from 14.5 ± 1.4 during the 1st session through 9.8 ± 1.2 during the 2nd session and finally to 8.0 ± 1.2 during the 5th session. The effect of SESSION factor was highly significant ($F(4, 108) = 13.79, p < 0.001$).

Fig. 1. The time-courses of the behavioral percentage measures (N = 28). (A) Percentage of correct responses; (B) Percentage of errors and omission; (C) Mean latency of correct responses and errors; (D) Mean latency SD of correct responses and errors. Data are presented as $M \pm SEM$.



According to Tukey's HSD test, again, only the 1st session significantly differed from the others ($p < 0.001$).

The mean percentage of omissions (Fig. 1B) displayed similar monotonous decrease from 10.7 ± 1.6 during the 1st session through 5.2 ± 0.8 during the 2nd session to 3.9 ± 0.6 during the 5th session. Just like in the cases above, the effect of SESSION factor was also highly significant ($F(4, 108) = 14.81, p < 0.001$). Again, according to Tukey's HSD test, only the 1st session differed from the others ($p < 0.001$).

All of the data shown above jointly attest that a detectable learning process occurred during the experiment, with the most critical change from the 1st to the 2nd experimental session.

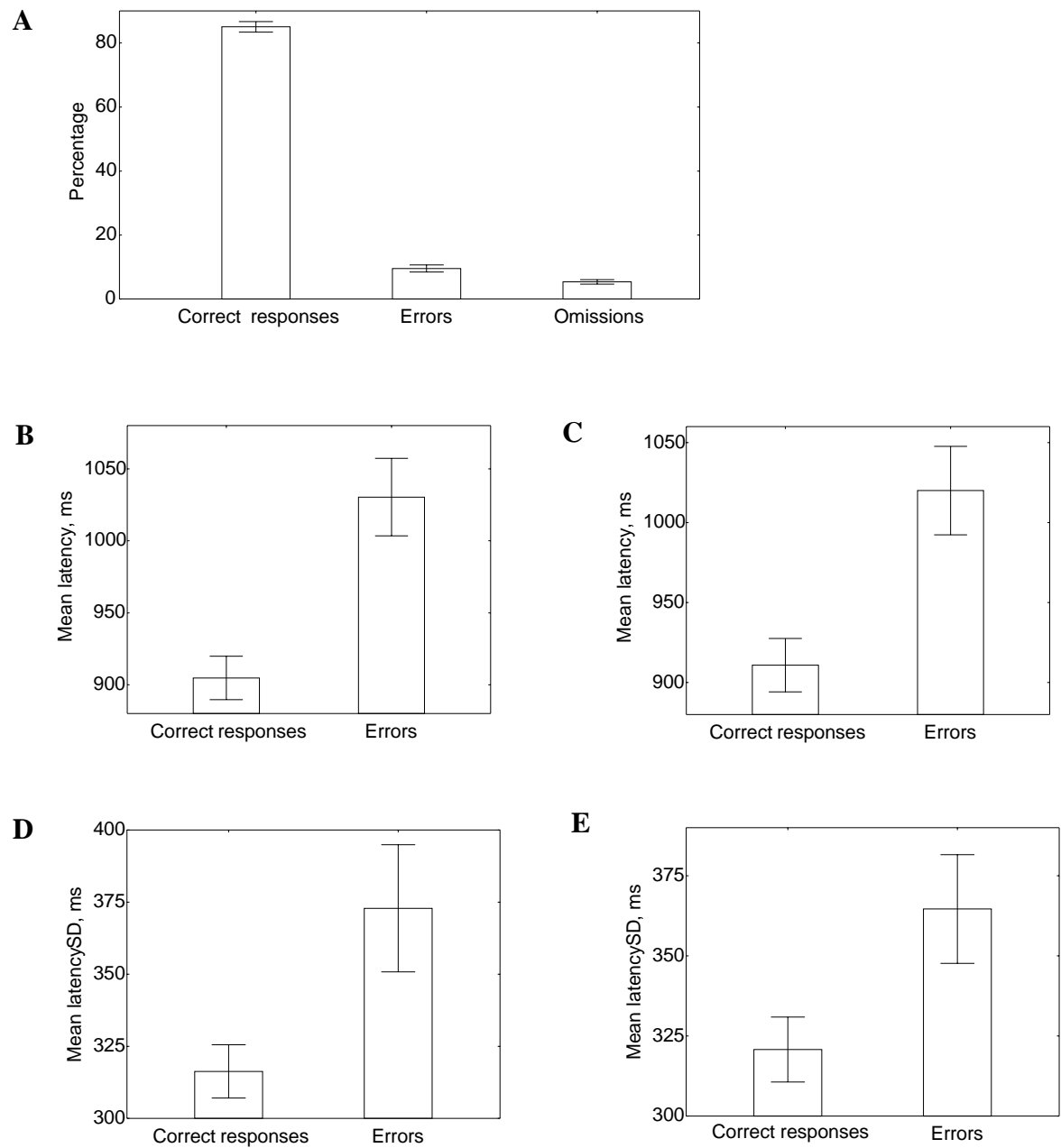
The percentage of correct responses was significantly higher than the percentage of errors (factor RESPONSE, $F(1, 27) = 771.12, p < 0.001$) (Fig. 2A). Tukey's HSD test showed that both responses during the 1st session invariably significantly differed from all responses in all other sessions, and that within each session the two kinds of responses were always significantly different one from the other. Interaction of SESSION x RESPONSE was also highly significant ($F(4, 108) = 28.98, p < 0.001$).

Likewise the percentage of correct responses was significantly higher than the percentage of omissions ($F(1, 27) = 1222.80, p < 0.001$) (Fig. 2A). Tukey's HSD test produced the same result as in the case above. Significant interaction of SESSION x RESPONSE was also observed ($F(4, 108) = 28.87, p < 0.001$). The high significance of interaction in this and in the above case can be explained by the opposite directions of the time courses of the percentages of correct responses vs. errors and omissions.

The percentage of errors was significantly higher than the percentage of omissions ($F(1, 27) = 21.70, p = 0.001$) (Fig. 2A). Tukey's HSD test showed significant differences between the two responses in all sessions except for the 1st one: as can be seen in Fig. 1B, the two plots start at similar values, and then the percentage of omission drops faster than the percentage of errors. SESSION x RESPONSE interaction in this case was nonsignificant ($F(4, 100) = 0.46, ns$) because the dynamics of reduction in the number of errors and omission was co-directed.

Latencies of correct responses and errors. Overall mean response latency for correct responses was 905 ± 15 ms ($N = 28$) and it was almost the same (911 ± 17 ms) in the subpopulation of participants with higher error rate, who were included into the analysis of ERPs during errors (see below) ($N = 24$) (Table 2). Overall mean response latency for errors was 1030 ± 27 ms ($N = 28$) and it was similar (1020 ± 28 ms) in the subpopulation of participants with higher error rate ($N = 24$) (Table 2). Since the mean values did not significantly differ between the total population and the subpopulation, the further behavioral analysis is reported for the total population ($N = 28$).

Fig. 2. Behavioral statistics. (A) Percentage of correct responses, errors and omissions for all participants (N = 28); (B) Mean latency of correct responses and errors for all participants (N = 28); (C) Mean latency of correct responses and errors for participants with number of errors greater than 25 (N = 24); (D) Mean latency SD of correct responses and errors for all participants (N = 28); (E) Mean latency SD of correct responses and errors for participants with number of errors greater than 25 (N = 24). Data are presented as $M \pm SEM$.



The mean response latency for correct responses manifested a noticeable monotonic decrease throughout experimental sessions (Fig. 1C). Repeated measures factor SESSION was highly significant ($F(4, 108) = 10.37, p < 0.001$). Tukey's HSD test showed that a significant drop in latency occurred between the 1st and the 2nd sessions, while the further decrease was insignificant.

Unlike the latency of correct responses, the latency of errors did not manifest any significant change throughout the experiment (Fig. 1C), and repeated measures factor SESSION was nonsignificant ($F(4, 100) = 0.42, ns$).

Two participants made no errors in some sessions (each in one session), thus the following comparison could be done in 26 participants ($N = 26$). Response latencies were significantly shorter in correct responses compared to errors (factor RESPONSE $F(1, 25) = 33.25, p = 0.001$) (Fig. 2B). Tukey's HSD test showed that the difference between correct responses and errors was significant in all sessions except for the 1st one. This can be explained by the observation that response latencies in correct trials clearly dropped after the 1st session, while no clear drop could be seen for errors (Fig. 1C). SESSION x RESPONSE interaction was insignificant ($F(4, 100) = 0.46, ns$).

This same analysis for the subpopulation of participants with higher error rate ($N = 24$), who participated in the analysis of ERPs during errors (see below), produced approximately the same result: the effect of RESPONSE factor was significant ($F(1, 23) = 38.51, p < 0.001$) (Fig. 2C), and SESSION x RESPONSE interaction was insignificant ($F(4, 92) = 0.85, ns$).

Latency SDs of correct responses and errors. The overall mean response latency SD for correct responses was 316 ± 9 ms ($N = 28$) and it was almost the same (321 ± 10 ms) in the subpopulation of participants with higher error rate ($N = 24$) (Table 2). The overall mean response latency SD for errors was 373 ± 22 ms ($N = 28$) and it was almost the same (365 ± 17 ms) in the subpopulation of participants with higher response rate ($N = 24$) (Table 2). Again, since there was no noticeable difference between the total population and its subpopulation, the further behavioral analysis is reported only for the total population ($N = 28$).

The mean response latency SD for correct responses strongly decreased throughout the experiment (Fig. 1D). Repeated measures factor SESSION was highly significant ($F(4, 108) = 8.90, p < 0.001$). Tukey's HSD test revealed a significant drop in latency between the 1st and the 2nd sessions, while further decrease was insignificant.

Mean response latency SD for errors did not show any apparent tendency (Fig. 1D), and the effect of the repeated measures factor SESSION was nonsignificant ($F(4, 100) = 0.80, ns$).

Two participants made no errors in some sessions (each in one session), thus the following comparison could be done for 26 participants ($N = 26$). The mean response latency SDs were

significantly shorter in correct responses compared to errors, although the significance level was not as high as in other behavioral comparisons described above ($F(1, 25) = 5.75, p = 0.02$) (Fig. 2D). Tukey's HSD test found no significantly differing pairs of values. SESSION x RESPONSE interaction was insignificant ($F(4, 100) = 0.72, ns$).

This same analysis for the subpopulation of participants with higher error rate ($N = 24$), who participated in the analysis of ERPs during errors (see below), produced similar result, but the effect of RESPONSE factor lost significance and can be spoken of as a tendency only ($F(1, 23) = 3.65, p = 0.07$) (Fig. 2C), and SESSION x RESPONSE interaction remained insignificant ($F(4, 92) = 1.28, ns$).

ERP parameters

Since the main purpose of the current study was to analyze the ERPs preceding behavioral errors and omissions in comparison to correct responses, two participants with insufficient number of errors and omissions were left out, and the following analysis was performed for 26 participants. Appropriate subpopulations were taken for the analysis of errors and omissions: the minimum criterion for inclusion into analysis was set at 20 artifact-free trials with errors and omission through the whole experiment. Thus the comparison of errors vs. correct responses was carried out for 24 participants, and the comparison of omissions vs. correct responses for 16 participants. The measurements for each participant were made in the ERPs obtained by averaging 20-25 trials (excessive trials were excluded from averaging in order to avoid ERP measurement bias entailed by non-comparable numbers of averaged trials).

ERP peaks preceding correct behavioral responses. The ERP grand average for correct responses and the ERP scalp maps are shown in Fig. 3 and Fig. 4. Table 3 represents summary ERP data. As can be seen from Fig. 3 and Fig. 4, both the N1 and P2 peaks had an almost symmetrical frontocentral distribution.

The N1 component was distributed mostly frontocentrally with maximum amplitude at Cz ($-7.60 \pm 0.79 \mu V$), and latency of about 100 ms from the stimulus onset (from 99 ± 4 ms at Pz, to 114 ± 4 ms at Fz). As can be seen from the Fig. 4A, the N1 peak first appeared at the centro-parietal area, reached its maximum in the vertex area (Cz) and then moved to the frontocentral area, where it disappeared.

Fig. 3. ERP grand mean for correct responses (N = 26). (A) ERP grand mean recorded at Cz. (B) ERP scalp maps at 40 – 360 ms, showing the N1 and P2 peaks. Scale: μV .

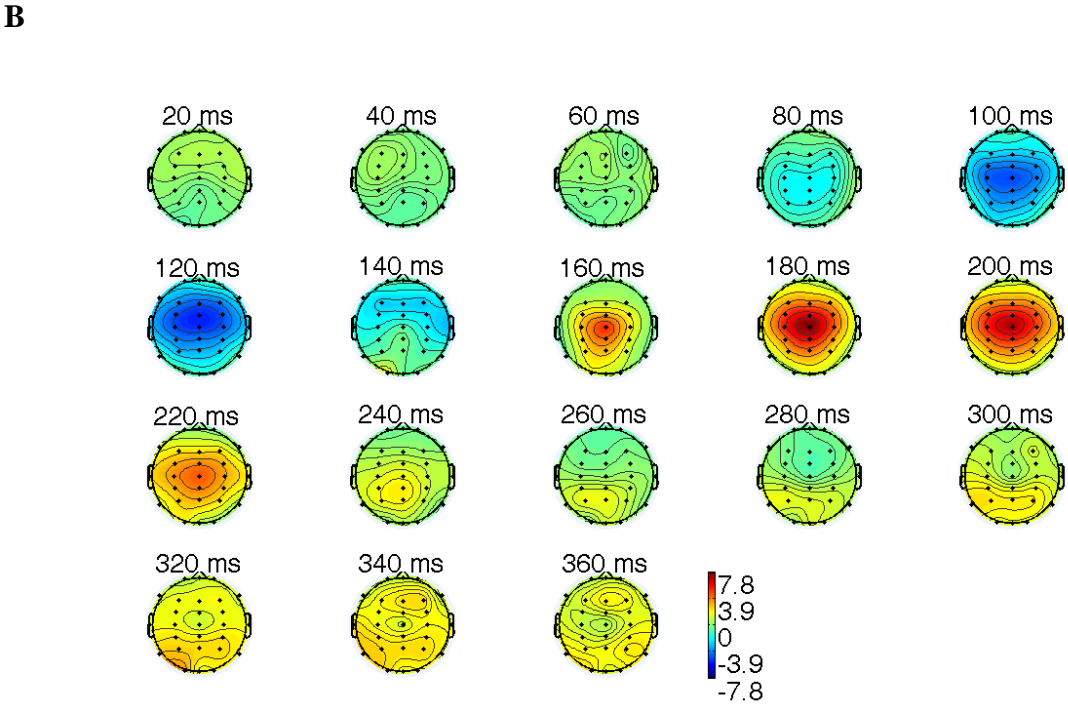
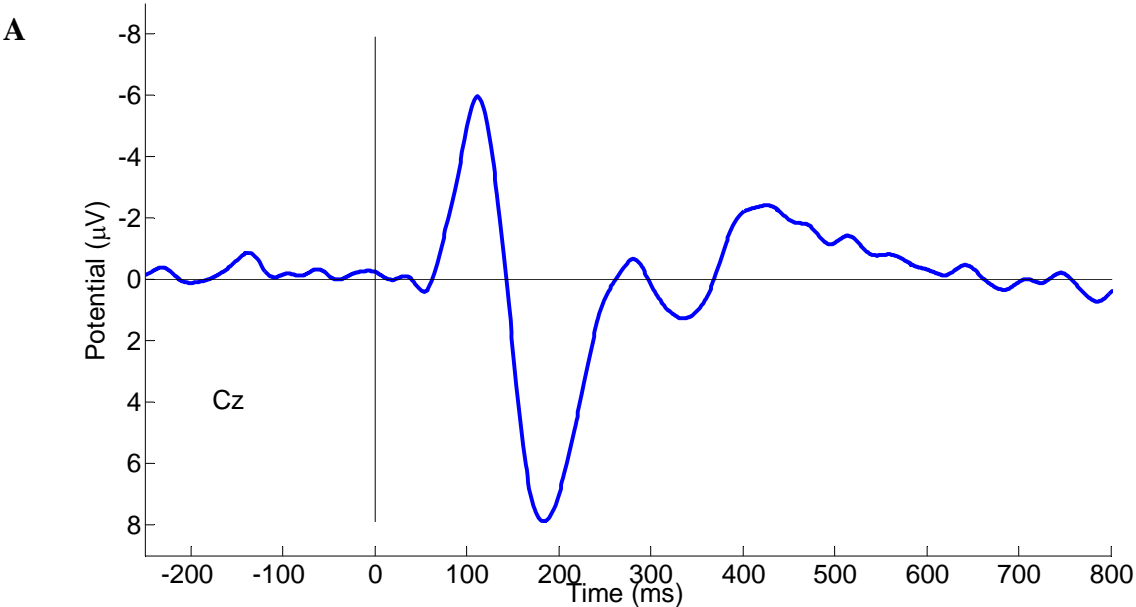


Fig. 4. Detailed ERP scalp maps for correct responses (N = 26). (A) ERP scalp maps at 85 – 140 ms, showing the N1 peak. (B) ERP scalp maps at 145 – 240 ms, showing the P2 peak. Scale: μV .

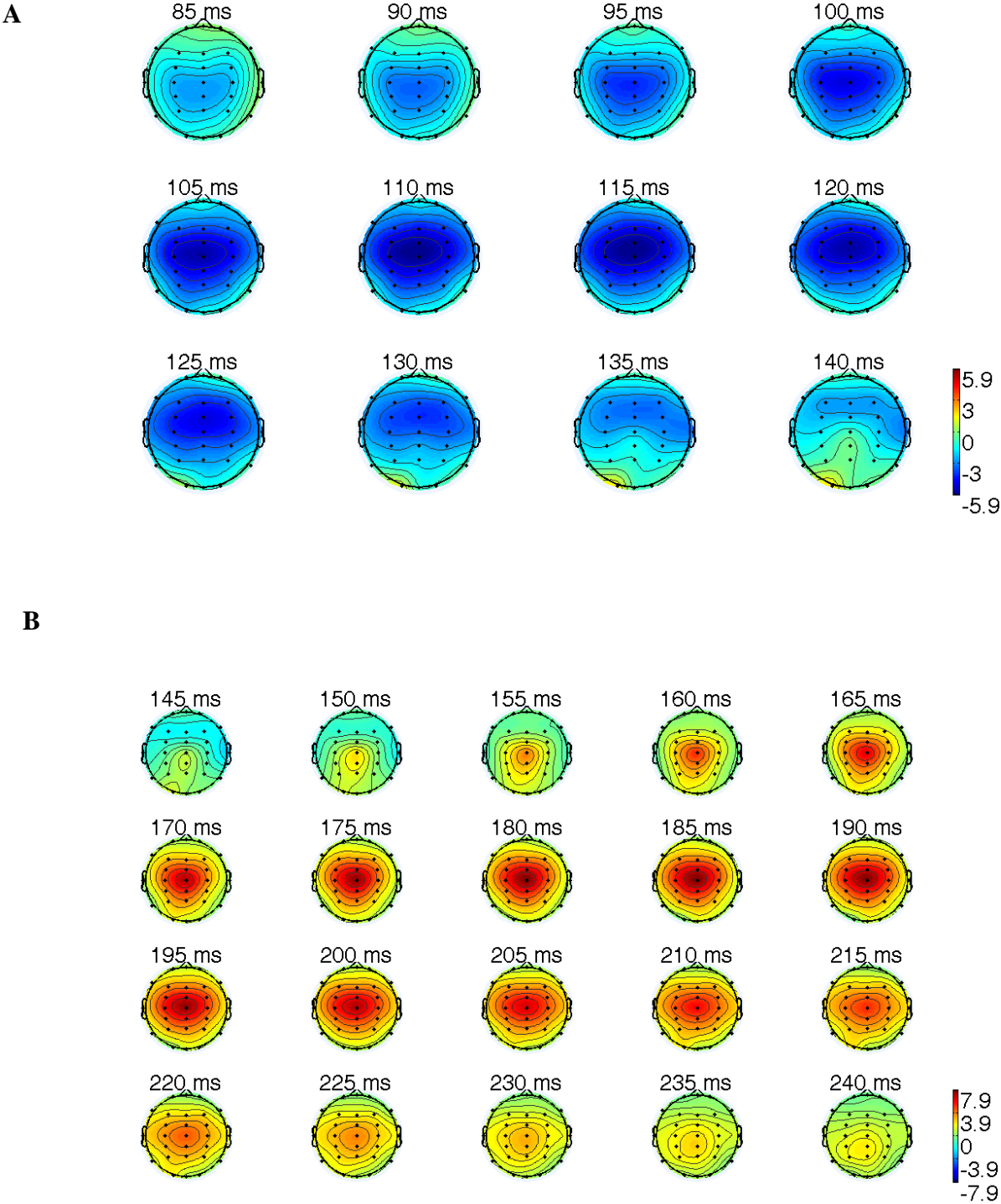


Table 3. Summary ERP data statistics to correct, erroneous and omitted responses (averaged data from 15 pericentral electrodes).

		N	M	Min.	Max.	SEM	SD
N1 amplitude, μV	correct responses	26	-6.02	-11.49	-1.43	0.56	2.84
	errors	24	-5.68	-9.54	-1.47	0.48	2.37
	omissions	16	-4.98	-9.05	-1.20	0.62	2.47
N1 latency, ms	correct responses	26	107	74	132	2	14
	errors	24	108	77	130	3	14
	omissions	16	113	93	123	1	7
P2 amplitude, μV	correct responses	26	6.14	2.15	11.26	0.51	2.59
	errors	24	7.41	3.82	15.23	0.58	2.83
	omissions	16	7.30	3.96	10.59	0.51	2.02
P2 latency, ms	correct responses	26	193	166	247	3	16
	errors	24	193	156	221	3	15
	omissions	16	187	171	199	2	9

The P2 peak, which similarly to N1 was distributed frontocentrally, had maximum amplitude at Cz ($9.27 \pm 0.77 \mu\text{V}$) and reached its maximum at about 200 ms after stimulus onset (from 183 ± 3 ms at Cz to 201 ± 5 ms at P4) (Fig. 4B).

The N2 and P3 peaks could not be identified with confidence in most participants, although the grand mean displays minor deflections in the appropriate time range (Fig. 3A). Due to instability in the morphology and low signal to noise ratio we did not measure and do not report here data on the N2 and P3 peaks.

The N1 component in the three behavioral conditions. The ERPs preceding all the three behavioral conditions (correct responses, errors and omissions) manifested a pronounced N1 peak of about the same amplitude (-7.6 ± 0.79 , -7.46 ± 0.70 and $-6.54 \pm 0.80 \mu\text{V}$ for correct responses, errors and omissions correspondingly) at about the same latency (107 ± 4 , 109 ± 3 and 114 ± 3 ms for correct responses, errors correspondingly) and with similar scalp distribution, reaching its maximum at Cz (Fig. 5, Fig. 6). Statistical analysis did not reveal any significant differences between the three behavioral conditions in N1 amplitudes ($F(2, 26) = 1.59$, ns) or in N1 latencies ($F(2, 26) = 0.50$, ns).

Fig. 5. ERP grand mean for correct and erroneous responses (N = 24). (A) ERP grand mean recorded at Cz. (B) ERP grand mean recorded at Fz.

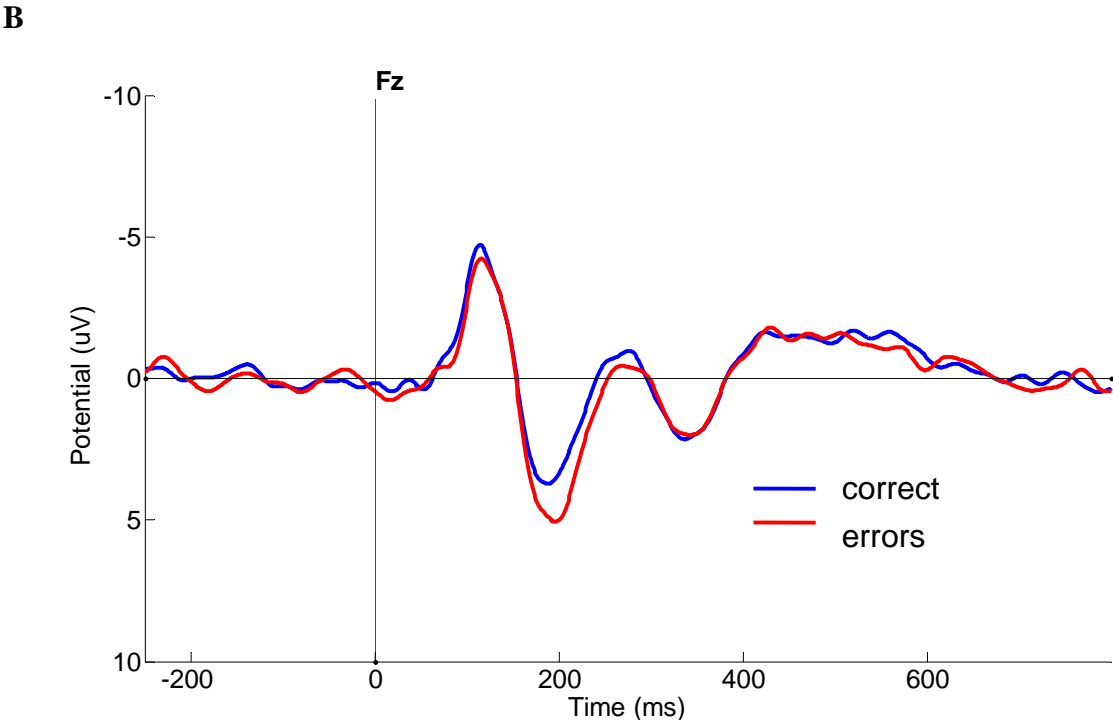
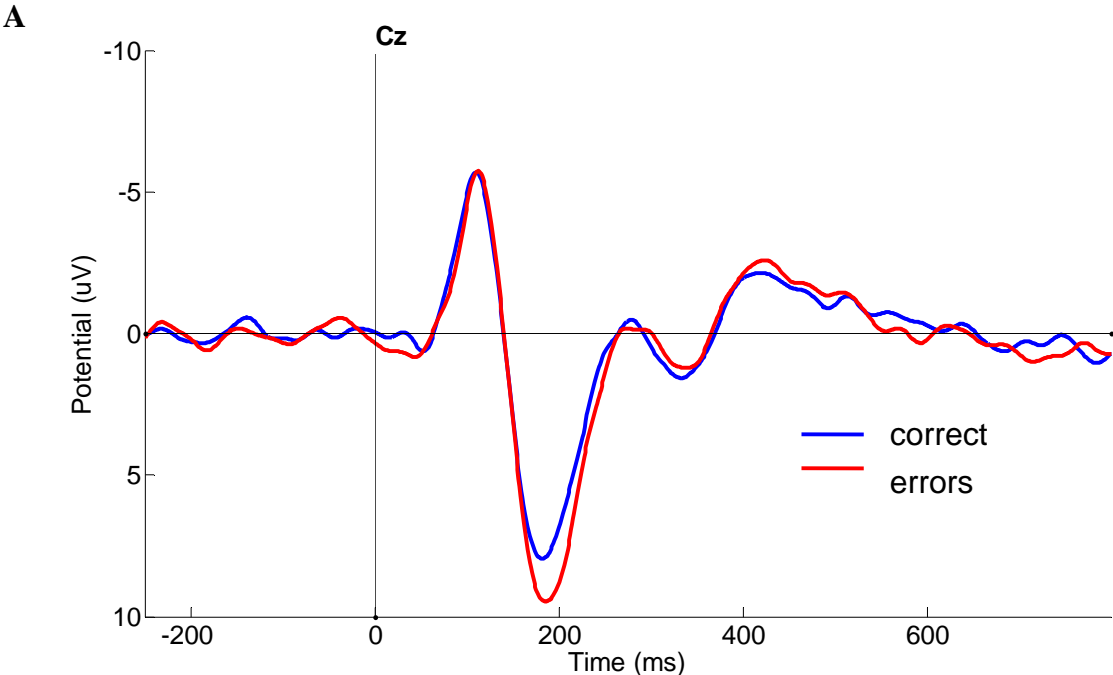
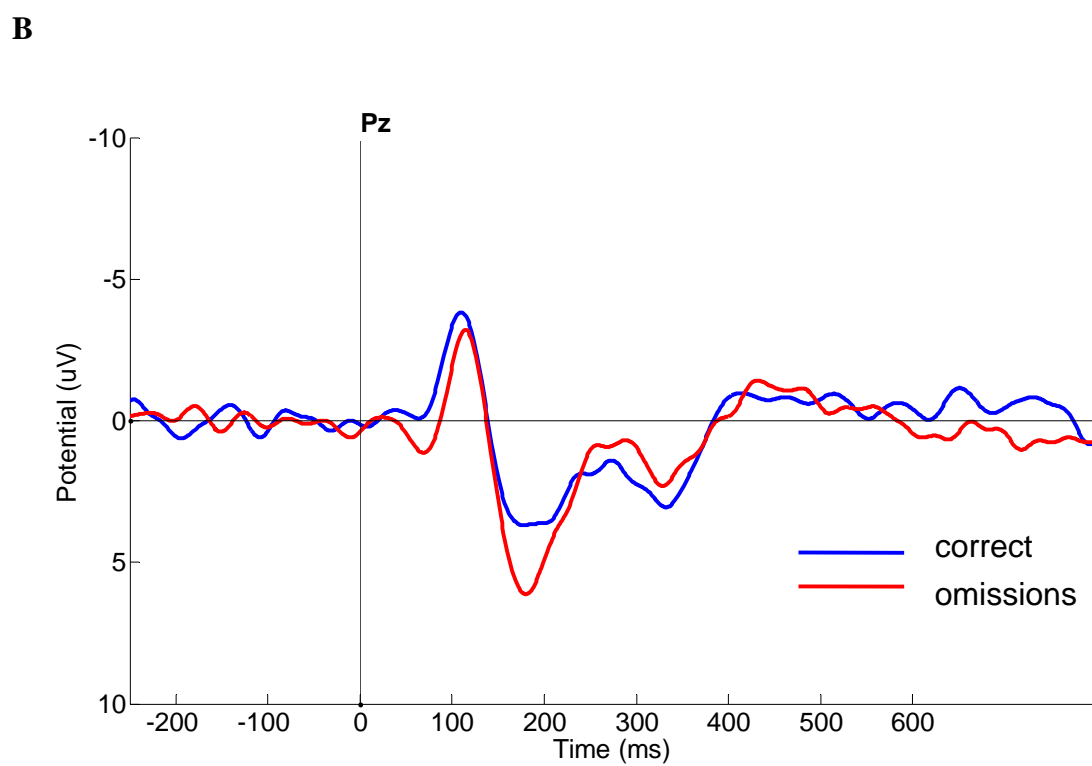
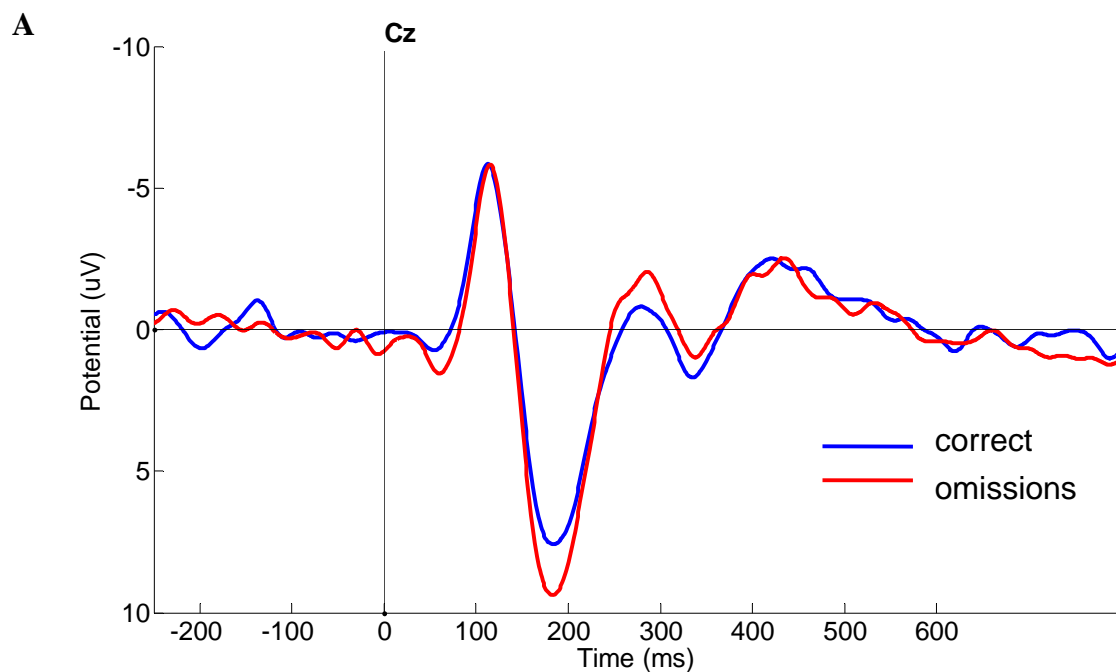


Fig. 6. ERP grand mean for correct responses and omissions (N = 16). (A) ERP grand mean recorded at Cz. (B) ERP grand mean recorded at Pz.



The P2 component in the three behavioral conditions. The scalp distribution and dynamics of the P2 were similar for correct responses, errors and omissions. Like the N1 peak, the P2 was most pronounced at Cz (9.27 ± 0.77 , 10.89 ± 0.92 and 10.33 ± 0.79 μV for correct, erroneous and omitted responses accordingly), reaching its maximum at Cz at almost the same time (185 ± 3 ms for errors, 184 ± 3 ms for correct responses and 183 ± 3 ms for response omission) (Fig. 5, Fig. 6). As can be seen from the data above, the P2 amplitude was higher for omissions and errors compared to correct responses. Statistical analysis confirmed a significant influence of the behavioral performance on the P2 amplitude ($F(2, 26) = 4.65$, $p = 0.02$). No such effect was found for the P2 latency ($F(2, 26) = 3.49$, $p = 0.06$, ns).

Since only 24 of 26 participants made sufficient number of errors to obtain averaged ERPs, and only 16 of 26 made sufficient amount of omissions, ERPs for errors and omissions are also discussed separately below.

The P2 peak comparison for correct responses vs. errors (in 24 participants). The P2 distribution across the scalp and its dynamics were similar for two types of responses. P2 maximum was recorded at Cz both for correct responses (mean value was 9.16 ± 0.82 μV) and errors (10.89 ± 0.92 μV). As mentioned above, P2 amplitude was higher for erroneous responses (Fig. 5). This difference was statistically significant ($F(1, 23) = 10.63$, $p = 0.003$). As can be seen in the scalp difference maps, the difference was more pronounced in left frontocentral sites during the rear slope of the P2 (Fig. 7A). Still there was no statistically significant interaction between performance quality and site. P2 latency did not significantly differ between correct responses and errors ($F(1, 23) = 0.11$, ns) (Fig. 5).

P2 peak comparison for correct responses vs. omissions (in 16 participants). The P2 scalp distribution for omissions was similar to that for correct and erroneous responses. The difference in amplitude was even more pronounced in 16 participants (8.47 ± 0.88 μV for correct responses and 10.33 ± 0.79 μV for omissions) (Fig. 6). Statistical analysis confirmed this observation ($F(1, 15) = 9.05$, $p = 0.009$). The difference between correct responses and omissions was more pronounced in the parietal sites (see Fig. 7B), although no statistically significant interaction between behavioral performances and electrode site was found (just like in the above mentioned comparisons of errors and corrects). Some difference was found in comparison of P2 latencies in the two conditions: the P2 peak was found to occur a little earlier for omissions than for correct responses ($F(1, 15) = 4.86$, $p = 0.04$) (Fig. 6).

All four ERPs for different behavioral outcomes discussed above are shown superimposed in Fig. 8.

Fig. 7. ERP grand mean difference map between pairs of behavioral outcomes. (A) Correct vs. erroneous responses (N = 24). Blue represents higher P2 amplitude for errors. (B) Correct responses and omissions (N = 16). Blue represents higher P2 amplitude for response omission. Scale: μV .

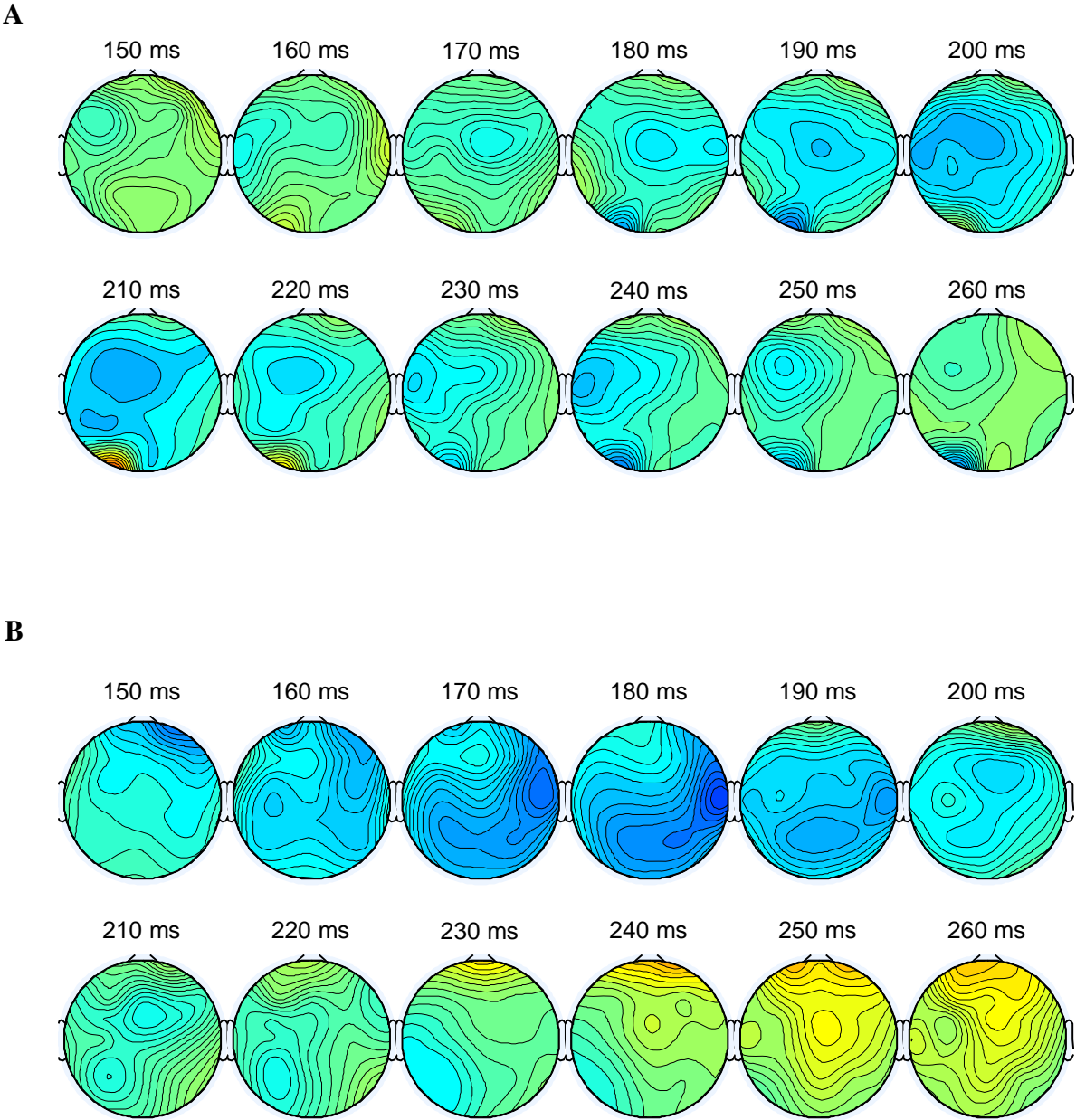
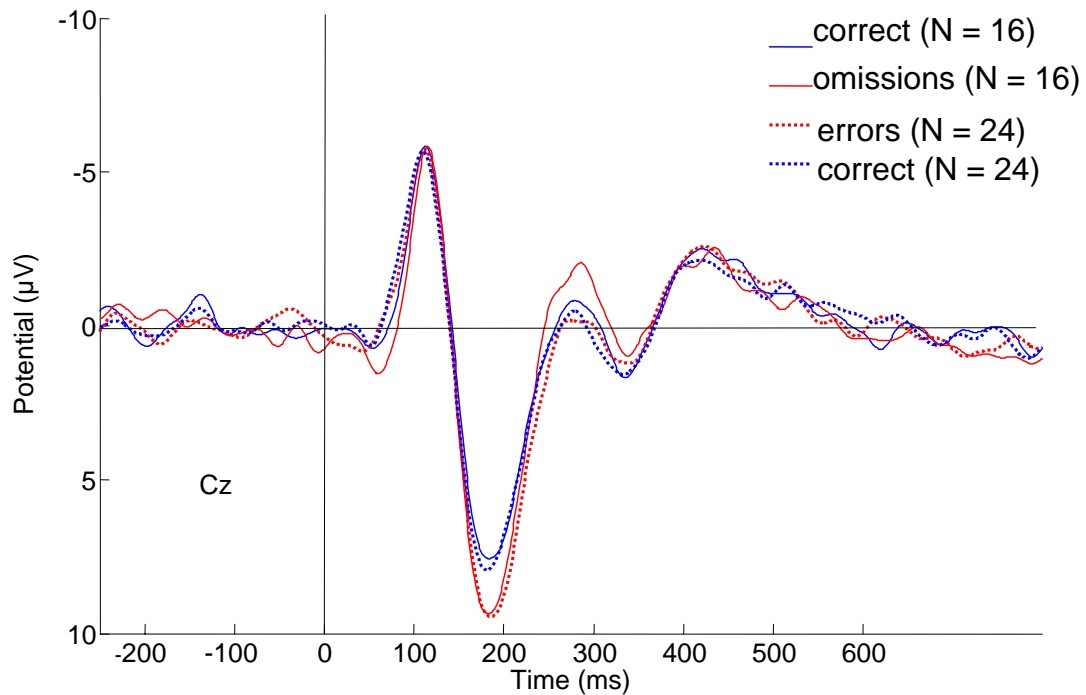


Fig. 8. ERP grand means for correct, erroneous and omitted responses.



Discussion

We used an original attentional task, which we described earlier [Osokina et al., 2012]. This task was designed for use in traditional auditory ERP methodology, but it was supposed to be more demanding to attentional resources compared to the majority of traditional ERP methodology tasks such as oddball and go/no-go. The task involved not only binding of the two stimulus features, each with two alternatives ("high/low" and "pure/noised"), into four distinct "objects" (Table 1) [Treisman, 1986; Treisman, Gelade, 1980], but also required binding of each "object" with the appropriate response (left/right button of the gamepad) [cf. Hommel, 2007; Hommel et al., 2001]. Thus theoretically the attentional load was increased by the need to make two consecutive decisions rather than one: a perceptual decision needed to identify an auditory object through a conjunction of features [Treisman, 1986; Treisman, Gelade, 1980], and an executive decision needed to choose a response, which creates additional mental load [Norman, Shallice, 1986].

Importantly, we used rather long intertrial intervals, thus leaving plenty of time for the decision. As one can see from Table 2, the mean response latency was no greater than a half of the shortest intertrial interval. It should be also mentioned that we did not ask the participants to

make a response quickly and nor did we ask them to make an obligatory response in every trial. Although there was no overt point in the instruction in this respect, participants themselves felt free to omit the response if they were not sure about their decision. Such task design allowed us to obtain new data on the ERP manifestations of attentional processing.

Behavior

The participants' overall performance. The response rules set in our attentional task were apparently quite simple (Table 1), and the participants had no problems in understanding them. All participants performed the task quite well. Even the minimum rate of correct responses (65%) was still well above chance performance given the number of trials (500 trials, t-test for proportions, $p < 0.001$), while the mean rate of correct responses was 85.1% (the median was even greater and reached 88%). This attests to the fact that all participants properly understood the instruction and were able to follow it in their performance. Thus behavioral lapses – errors and omissions – could not be attributed to the participants' failure to understand the task instruction.

The stimuli themselves were easily discriminated by all participants in a pre-task test. Before the experimental sessions all of the participants were made acquainted with the stimuli (the experimenter manually played them to the participants and named them orally), and then the participants were blind tested with all the four stimuli to find out if they could recognize and name them correctly. During this test all of the participants easily named all of the stimuli correctly, and all of them stated that they could clearly feel the difference between all of the stimuli. Thus errors and omissions were not committed due to sensory reasons such as inability to discern the pitch of a tone or the presence of a noise admixed with the tone.

Still the participants stated after the experiment that the task required a signification effort on their part to maintain good quality of responding. Only two of them almost completely avoided errors and omissions – their overall percentage of correct responses was greater than 95%, thus not permitting the ERP analysis of errors and omissions. During the experiment most of the participants found it difficult to respond in a continuous manner – notwithstanding the fact that intertrial intervals were relatively long (2-3 s), thus being among the longest among the auditory ERP experiments. This means that the real difficulty of the task lay in the process of decision making, which had to be routinely done in a continuous manner. All of the above allows us to view the behavioral lapses as manifestations of some temporary mental or physical state which suppresses cognitive processing of external stimuli.

The participants were not asked to make an obligatory response on each trial, so they sometimes preferred to omit their response if they were not sure which button to choose. The mean percentage of omissions (5.4%) was smaller but still comparable to the percentage of errors (9.6%).

Behavioral response latencies and latency dispersions. We calculated not only the mean response latencies for each participant, but also within-participant standard deviations (SDs) of response latencies – the latter being a measure of instability in the response speed.

We found that erroneous responses took significantly longer time and were less stable in time than correct ones; the difference was greater than 10% for both measures in both subpopulations analyzed. Errors and omissions were present in all sessions throughout the experiment. Therefore, notwithstanding the noticeable overall task performance improvement, errors were not occasional, but rather were related to some persistent information processing regularities.

Here it should be noted that in the literature there are controversial reports on the relative latency of erroneous responses in relation to correct responses. In easy tasks which involve small numbers of easily discernable stimuli and easy response contingencies (in comparison to difficult tasks, see below), the latency of erroneous responses is usually shorter or equal to the latency of correct responses [Green, Von Gierke, 1984; Rabbit, Banerji, 1989; Wilding, 1971].

The tendency revealed in our experiments is in line with a number of studies referring to the issue of different response type timing characteristics in relatively difficult tasks. For instance, latencies of errors were found to be longer than latencies of correct responses in experimental settings with a large number of trials [Parasuraman, Davies, 1976], with a large variety of alternatives and low perceptual discriminability [Wilding, 1971]. The same effect was shown in tasks involving processing of speech sounds [Shwartz, Goldman, 1975] and visual feature integration [Maddox et al., 1998]. Altogether, the above-mentioned studies provide evidence that errors are connected with time cost enhancement, ensuing from the level of task complexity.

Trends in behavioral data. The data concerning the percentage of correct responses, errors and omissions jointly attest that a detectable learning process occurred during the experiment, with the most critical change from the 1st to the 2nd experimental session. These results confirm the findings of our previous study which used the same task [Osokina et al., 2012] where a similar behavioral picture was obtained: a significant increase in the percentage of correct responses, a reduction of the percentage of errors and a decrease of the mean latencies of correct responses and their mean latency SDs occurred after the 1st experimental session. The results can be interpreted in terms of Hommel's theory of event coding [Hommel, 2007; Hommel et al., 2001]: it can be concluded that during the 1st session an internal conjunction (binding) of stimuli features ("high/low" and "pure/noised") and response features (left/right button of the

gamepad) was formed and “event files”, i.e. cognitive representations of stimulus-response bindings, were shaped, making grounds for further task performance automation. Still the automation was not complete throughout the course of the experiment, since errors and omissions were committed by most participants in all experimental sessions until the very end of the experiment. Moreover, since the latency of erroneous responses remained significantly greater than the latency of correct responses throughout the experiment and did not fall (Fig. 1), the task never became sufficiently easy for the participants. In fact, when automation of even simpler tasks was attempted, this goal required at least several days of training with consolidation periods between training sessions [e.g. Melara et al., 2002]. Since this was not the goal of our experiment, we did not introduce extensive training in the current research.

The nature of prolonged latencies. In a number of studies it has been shown that an increase in response latencies is observed in cases when task performance relies on extensive information processing and decision making [Sigman, Dehaene, 2005; 2006] (although these studies do not address the question of response accuracy). In other words, response time is influenced by cognitive conflicts at the central processing stage (also known as the capacity limited stage, central executive system or the global workspace), which is responsible for effortful mental actions, conscious processing and working memory [Sigman, Dehaene, 2006].

Considering the long response latencies for correct responses and even longer mean latencies of erroneous responses in the current study, in view of the literature data described above, we might speculate as follows. It is possible that “event files”, combining stimulus features and responses as provided by instruction, were not formed at all, and corresponding stimulus-response binding exclusively relied on the top-down executive mechanisms. Evidently, this is not true, since visible learning occurred, with significant progress from the 1st to the 2nd session, and later minor drift through the remaining sessions. On the other hand, as described above, the process of automation was far from complete, and, apparently the task required a strong and continuous top-down control.

On the other hand, it might be supposed that errors were caused by some additional mental load, causing competition for the central top-down resources. The nature of the task excluded all possible external sources of such cognitive load, since we did not introduce any secondary tasks, and the environment of the experiment was kept quiet and constant throughout the experiment, while the interior of the experimental chamber was also very simple so as not to distract the participants (a narrow table with a standard LCD computer monitor in front of a monotonously colored wall with no texts or pictures or other sources of distracting information).

The most likely explanation of the behavioral lapses is mind-wandering, or the experience of flow of thoughts not related to the task [Christoff et al., 2009; Mason et al., 2007]. As

Smallwood and his collaborators demonstrated in a sustained attention to response task while recording both behavioral measures of accuracy and collecting self-reports of the participants on the contents of their thoughts [Smallwood et al., 2008; Kam et al., 2011], behavioral lapses in an attentional task seem to be a good indicator of mind-wandering episodes. After our experiments most participants reported that occasionally they were "off-task", drifting off in their own thoughts during this somewhat boring experimental situation.

ERP parameters

Our study was dedicated to the electrophysiological exploration of the spontaneous attentional lapses which happen when people digress from their main task. The stimuli used were typical to ERP studies of attention, thus allowing us to compare the data obtained to the massive body of studies done with the help of the oddball paradigm and other similar methods. The pattern of ERPs obtained in our experiment consisted primarily of a well-pronounced N1 peak followed by a strong P2 peak. Later components such as N2 and P3 were not easily distinguishable.

N1 peak. Being the most prominent component of auditory ERPs, the N1 was clearly manifested in our study. It was characterized by frontocentral distribution with the maximum recorded at Cz, at about 100 ms after the stimulus onset, in accordance with the body of studies dedicated to auditory evoked potentials [see, for example García-Larrea et al., 1992; Barrett et al., 1987; Anderer et al., 1996].

The N1 is considered to be an exogenous ERP component, since it is strongly affected by such physical parameters of stimuli as loudness, tone pitch, interstimulus interval [Hyde, 1997; Crowley, Colrain, 2004]. Still N1 can be modified by attention: as it was shown by Hillyard et al. [1973], an attentional process superimposes a slow negative deflection leading to enlarged N1 and decreased P2 (and thus, inversely, to decreased N1 and enhanced P2 under inattention). The onset time of the difference wave between attended and unattended channels is known to depend upon the intertrial interval. Hillyard et al. [1973] used very short intertrial intervals. In another classical study [Näätänen et al., 1978] the intertrial intervals were a little longer: this caused the difference wave, termed there "processing negativity", to become delayed and to start during the rear slope of N1, thus not affecting its peak.

In the present study, we did not observe any effects of attentional lapses on N1 amplitude or latency. Taking into account that in our task we used much longer interstimulus intervals than in the above mentioned studies, it seems reasonable to expect that N1 also should not be affected by variation in attention in our study.

Our attentional task, like the tasks in the above mentioned studies, was purely auditory. It should be noted that in a recent study of mind-wandering with the help of a visual primary task and auditory probe stimuli, it was shown that N1 to auditory probes was reduced in amplitude [Kam et al., 2011]. This study differs from ours in many respects; importantly, it actually involved two explicit tasks – the primary visual task and probe stimuli, while we used the auditory task only. Also we tested ERPs to relevant stimuli, while in the abovementioned study the N1 effect was found in the responses to irrelevant stimuli, which themselves tend to produce reduced N1 [Hillyard et al., 1973]. In the study of Kam et al. [2011] the effect of inattention to task-irrelevant stimuli plus inattention to any external stimuli during mind-wandering could produce a cumulative effect, with intermodal competition creating conditions for a more pronounced suppression of early information processing in the auditory domain. In a study of mind-wandering that involved unimodal stimulation [Smallwood et al., 2008] no effect of mind wandering on N1 was observed.

N1 is known to be modulated by a general state of arousal [Crowley, Colrain, 2004; Näätänen, 1992]. The constancy of the N1 peak in our study indirectly attests that the observed effects of attentional lapses should not be explained by changes in the general state of arousal in participants.

P2 peak. The P2 peak was also clearly prominent and, just like the N1 peak, its main characteristics (frontocentral scalp distribution, latency of about 200 ms) were also in accordance with data obtained by many researchers in earlier studies [Anderer et al., 1996; Barrett et al., 1987].

Unlike N1, P2 was strongly influenced by the task performance: the P2 amplitude was significantly increased in both conditions of attentional lapses – errors and omissions. A minor effect was also found in the P2 latency in cases of omissions compared to correct performance.

The role of the P2 component is not completely clear at the moment. As Tong et al. [2009] summarized, depending on the experimental paradigm used the P2 may be related to: stimuli classification [see Novak et al., 1992], protection against interference from irrelevant stimuli [García-Larrea et al., 1992], an inhibitory process modulating conscious perception [Melara et al., 2002] or accuracy of short-time memory traces [Atienza et al., 2002]. The P2 also depends upon task difficulty: in the oddball paradigm, higher difficulty produces significant decreases in P2 amplitude [Cranford et al., 2004]. P2 amplitude was also demonstrated to be higher after successful discrimination training [Tong et al., 2009], which probably leads to automation of task performance.

Thus there are both "positive" and "negative" interpretations of the role of P2 in information processing. According to the "positive" interpretation, P2 represents a classification stage

prerequisite for the capture of attention – and in this role a late enhanced P2-like peak to ignored stimuli (termed "P250") may actually be regarded an analog of P3a and represent a correlate of involuntary attention [García-Larrea et al., 1992]. If this interpretation is true, than enhanced P2 during attentional lapses signifies increased processing and classification of relevant stimuli. This interpretation is difficult to reconcile with our data showing that increased P2 accompanies decreased processing of relevant external processing. One could suppose that it is not enhanced processing per se that stands behind the P2 increase, but rather an enhanced effort to process the stimuli in such conditions of inattention. Still this is also unlikely, since increasing the difficulty of discrimination actually reduces P2 [Cranford et al., 2004]. Moreover, the P2 latency in our study – about 200 ms – does not resemble the P250 latency in the study of García-Larrea et al. [1992].

According to the "negative" interpretation of P2, it represents some inhibitory process that is needed to stop the processing of information to be ignored [Melara et al., 2002]. First of all, this interpretation does not contradict the phenomenon of "processing negativity" [Näätänen et al., 1978] – a sustained negative deflection in the attended channel compared to the unattended channel. Processing negativity usually starts during or after the N1 peak and is well pronounced during the P2. This view is substantiated by the observation that P2 is enhanced after extensive training, which likely leads to the automation of the task execution (towards a reflex-like response), thus reducing the need for attentional processing.

Thus in the view of the "negative" interpretation of P2, it is likely that during the state of attentional lapses some inhibitory process develops which suppresses external information processing – or simply denies it the benefits of certain later stages of information processing, which happen after the initial rough analysis within the first 100-150 ms after stimulus onset.

In our study, enhanced P2 was associated both with erroneous responses and response omissions. Given these data, we can speculate that in our study higher P2 amplitude was associated with failures to discriminate stimuli caused by reduced or prematurely terminated information processing. Such termination of information processing could be the result of competition for the limited pool of central processing resources.

Independence of N1 and P2. Another detail, worth some attention, is that for a long time the N1 and P2 components were viewed as parts of a unitary N1-P2 complex, but for the moment there is some evidence that P2 is independent of N1. In a review by Crowley and Colrain [2004], some criteria of their independence are given. First of all, it is different maturation time of these components. P2 appears earlier in development, reaching an adult value at the age of 3, while N1 is reported to become maximal only by the age of adolescence. Some experimental procedures affect these components differently: for example, during sleep N1 amplitude is re-

ported to decrease, while P2 amplitude increases. Lesion studies give another argument for the independence of these components: unilateral temporal-parietal lesions lead to decreased amplitude of N1, while amplitude of P2 remains almost unaffected.

Our results may provide other evidence for the independence of N1 and P2. As has been shown in Results section, errors and omissions lead to a higher amplitude of the positive peak, while negative deflection remains constant for all three conditions; thus our data produce additional evidence for the functional dissociation of these components.

Genuine P2 effect vs. a superimposed wave. Another question which can be raised is whether it was truly a functional dissociation between the two components, or it was the influence of some superimposed wave which led to a change in the P2 amplitude in the case of response omission or error/correct answers.

Mismatch negativity and processing negativity are the two processes which can contribute both to enlarged N1 and/or diminished P2. The first, according to Näätänen [1992], reflects operation of the so-called permanent feature detector, the second, the temporary feature detector. The two components can be dissociated [Pang, Fowler, 1999]. Since the mismatch negativity is seen when there is a clear difference between the physical features of the presented stimuli, for example, in frequency [Näätänen et al., 2007], and mismatch negativity is unaffected by the voluntary processes, this is unlikely to be the cause of the observed differences in P2 amplitude. Processing negativity is observed, when the subject has to voluntarily monitor the chain of stimuli: thus processing negativity, reflecting the process of the comparison of the incoming stimulus to the representation in the working memory, may be a good candidate for an explanation of the observed differences in ERPs described in the current work. While the processing negativity recorded in Näätänen's experiments [Näätänen, 1990] lasts up to 500 ms, it can be clearly seen in Fig. 4 and 5, that in the present study the P2 difference lasts for a much shorter period of time and does not exceed the limits of the P2 duration. It is obvious that the difference wave in the present study is of a different nature to the one obtained by the comparison of the non-target stimuli in the attended and non-attended condition, but if it reflects the process of stimulus comparison with some pattern held in memory, it is logical to expect it to be similar in some ways, which is not the case. So, probably, the difference seen in the peak amplitude relates solely to the P2 component, and not to some superimposed waves.

P3 peak. We did not find any reliable P3 in individual ERPs of most participants. As pointed out by many authors [see for example Squires et al., 1975], the extent to which P3 is pronounced depends on two factors: the relative target stimulus frequency of occurrence (higher frequency leading to a smaller P3 amplitude) and active attention toward target stimulus significance (a higher level of attention to stimulus significance leading to a higher P3 amplitude). The

oddball paradigm, which was used in many of the tasks dedicated to the exploration of attentional processes, allows us to obtain highly pronounced P3 peaks. In our experiment all of the stimuli were equally probable and each stimulus required a response. Likewise under a simple response task (which involves presentation monotonous repetitions of a single stimulus and unconditional responding to it) no P3 was observed [Novak et al., 1992].

It is generally believed that P3 represents context updating in memory [Donchin, Coles, 1988] – this effect being most pronounced when rare deviant stimuli are represented against a monotonous sequence of standard stimuli. If the context is not monotonous, the target stimuli become less prominent against the background experience, and P3 decreases – the effect observed in the study of Melara et al. [2002]. Since our task involved 4 stimuli, which were randomly intermixed with equal probability, and all of which were targets, there was no conceivable contrast between the target stimuli and the context at all. This is the most likely explanation of the poor manifestation of the P3 in the current study. Our results show that a high attentional load to the stimuli does not necessarily manifest in the late components such as P3, and that the frequency of the stimuli as well as their context is much more important.

Conclusions

In the current study, which was based on a task designed to rely strongly upon central limited pool of cognitive resources, we observed the following: participants properly understood the task, they could reliably discern the stimuli used in the task, but they still committed errors and omissions in a considerable percentage of trials. Since the participants were not instructed to perform any secondary task, and they were generally deprived of any irrelevant external stimulation, it is unlikely that their attention was diverted from the task by any external events. The two possible explanations are possible – both of them ensue from Kahneman's resource theory [1973]: either the general level of arousal was occasionally dropping, or cognitive resources were recruited for some internal task – presumably, mind-wandering.

Our data do not allow us to unequivocally distinguish these two possibilities and call for further experimental analysis. Still we can claim that no major drops in the level of arousal can explain our data, since the N1 peak, which is sensitive to the level of arousal, did not differ between the three behavioral outcomes – correct trials, errors and omissions.

Moreover, in the study of Smallwood et al. [2008] behavioral measures of inattention (i.e. errors) proved to have a tight link with mind-wandering, and as far as it goes to ERP analysis, behavioral measures proved to be a better statistical predictor of ERP variability than self-reports

of mind-wandering. The method of direct probing of the state of mind-wandering by intrusive interruption of the experiment for self-reports is the only known way to prove that mind-wandering took place at specific periods of time. Still this method of probing the state of mind-wandering has many drawbacks, including the likely introduction of covert urge for intentional rather than spontaneous mind-wandering. We instead studied spontaneous changes in the accuracy of responding. After the experiment the participants in our study admitted they did occasionally catch themselves on being off-task and deep in their own thoughts.

We have to admit that by relying on behavioral measures only, we get partially mixed behavioral data: since a participant had to choose between only two responses, even if he or she chose a response randomly, there is a 50% chance that such a response would be accounted for as a correct response. This could have blurred the contrast between correct behavior and attentional lapses. Still, taking into account the percentages of correct responses, errors and omissions (Table 2), we can assume that no more than 10-15% of apparently correct responses could be due to such chance guesses, while others were genuine attempts at correct responses.

Both behavioral manifestations of inattention – errors and omissions – produced the same pattern of changes in the ERPs, namely a reduction in P2 amplitude. As far as we are aware, there are no studies on ERPs during omissions in attentional tasks – with the exception of early works by Hillyard [Hillyard et al. 1971, 1973; Hansen, Hillyard, 1980] who reported decreased P3 both during errors and omissions compared to correct trials. We thus demonstrated that not only in respect to P3, but also in respect to a functionally different P2 the two manifestations of attentional lapses – errors and omissions – have a similar nature. In other words, as far as we speak about decision-making, erroneous decisions and inability to make a decision have their origin in one and the same kind of temporal limitations in attentional processing.

In general, our results hint that during continuous attentional performance cognitive information processing is occasionally cut short at early preattentive stages, so that information does not receive further detailed processing. This event in the brain leads to inaccuracy in behavioral responses. In terms of the resource theory, this means occasional denials of the central processing resources needed for the execution of the overt experimental task.

References

- Anderer P., Semlitsch H.V., Saletu B. (1996). Multichannel auditory event-related brain potentials: effects of normal aging on the scalp distribution of N1, P2, N2 and P300 latencies and amplitudes. *Electroencephalography and clinical neurophysiology*, 99(5), 458–472.
- Atienza M., Cantero J.L., Dominguez-Marin E. (2002). The time course of neural changes underlying auditory perceptual learning. *Learning & memory (Cold Spring Harbor, N.Y.)*, 9(3), 138–150. doi:10.1101/lm.46502
- Barrett G., Neshige R., Shibasaki H. (1987). Human auditory and somatosensory event-related potentials: effects of response condition and age. *Electroencephalography and clinical neurophysiology*, 66(4), 409–419.
- Christoff K., Gordon A.M., Smallwood J., Smith, R., Schooler J.W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences of the United States of America*. 106(21), 8719-24.
- Cranford J. L., Rothermel A. K., Walker L., Stuart A., Elangovan S. (2004). Effects of discrimination task difficulty on N1 and P2 components of late auditory evoked potential. *Journal of the American Academy of Audiology*, 15(6), 456–461.
- Crowley K. E., Colrain I. M. (2004). A review of the evidence for P2 being an independent component process: age, sleep and modality. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 115(4), 732–744. doi:10.1016/j.clinph.2003.11.021
- Donchin E. Coles V.G.H. (1988). Is the P300 component a manifestation of context updating? *The Behavioral and Brain Sciences*, 11(3), 357.
- García-Larrea L., Lukaszewicz A. C., Mauguière F. (1992). Revisiting the oddball paradigm. Non-target vs neutral stimuli and the evaluation of ERP attentional effects. *Neuropsychologia*, 30 (8), 723–741.
- Gómez-Herrero G., De Clercq W., Anwar H., Kara, O., Egiazarian K., Van Huffel S., and Van Paesschen W., (2006). Automatic removal of ocular artifacts in the EEG without a reference EOG channel. *Proceedings of the 7th Nordic Signal Processing Symposium (NORSIG'2006)*, Reykjavik, Iceland, 130-133.
- Hillyard S. A., Hink R. F., Schwent V. L., Picton T. W. (1973). Electrical signs of selective attention in the human brain. *Science*. 182(4108), 177-180. doi:10.1126/science.182.4108.177

- Hommel B. (2007). Feature integration across perception and action: event files affect response choice. *Psychological research*, 71, 42-63.
- Hommel B., Musseler J., Ascherleben G., Prinz W. (2001). The Theory of event coding (TEC): a framework for perception and action planning. *Behavioral and brain sciences*, 24, 849-878.
- Hyde M. (1997). The N1 response and its applications. *Audiology & neuro-otology*, 2(5), 281–307.
- Kahneman D. (1973). *Attention and Effort*. Englewood Cliffs: Prentice-Hall.
- Kam J.W.Y., Dao E., Farley J., Fitzpatrick K., Smallwood J., Schooler J.W., Handy T.C. (2011). Slow fluctuations in attentional control of sensory cortex. *Journal of Cognitive Neuroscience*, 23(2): 460-470. doi:10.1162/jocn.2010.21443
- Klinger E. (1977). *Meaning [and] Void: Inner Experience and Incentives in People's Lives*. Minneapolis (Minn.): University of Minnesota
- Luck S. J., Woodman G. F., Vogel E. K. (2000). Event-related potential studies of attention. *Trends in Cognitive Science*, 4(11), 432-440.
- Maddox W.T., Ashby F.G., Gottlob L.R. (1998). Response time distributions in multidimensional perceptual categorization. *Perception and psychophysics*, 60 (4), 620-637.
- Mason M.F., Norton M.I., Van Horn J.D., Wegner D.M., Grafton S.T., Macrae C.N. (2007). Wandering minds: The default network and stimulus-independent thought. *Science*, 315, 393–395.
- Melara, R. D., Rao, A., Tong, Y. (2002). The duality of selection: excitatory and inhibitory processes in auditory selective attention. *Journal of experimental psychology. Human perception and performance*, 28(2), 279–306.
- Näätänen R. (1992). *Attention and Brain Function*. Lawrence Erlbaum Associates, Hillsdale, NJ.
- Näätänen R., Gaillard A. W., Mantysalo S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta psychologica*, 42(4), 313-329.
- Näätänen R., Paavilainen P., Rinne T., Alho K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 118(12), 2544–2590. doi:10.1016/j.clinph.2007.04.026
- Näätänen R., Gaillard A. W. K., Mäntysalo S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42(4), 313–329. doi:10.1016/0001-6918(78)90006-9

Näätänen R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences*, 13(02), 201–233. doi:10.1017/S0140525X00078407

Norman D.A., Shallice T. (1986). Attention to action: willed and automatic control of behaviour. In R. Davidson, G. Schwartz and D. Shapiro (eds), *Consciousness and Self Regulation: Advances in Theory and Research*, 4, Academic Press, 515-549.

Norman D. A., Bobrow D. G. (1975). On data-limited and resource limited processes. *Cognitive Psychology*, 7, 44–64.

Novak G., Ritter W., Vaughan Jr. H.G. (1992). Mismatch detection and the latency of temporal judgments. *Psychophysiology* 29(4), 398–411.

Novak G., Ritter W., Vaughan Jr. H. G., (1992). The chronometry of attention-modulated processing and automatic mismatch detection. *Psychophysiology*, 29(4), 412–430.

Osokina E.S., Chernyshev B.V., Chernysheva E.G. (2012). Auditory attention under binary choice of response based on feature integration in dependence on temperament. *Experimental psychology*. 5 (4). In press.

Pang E. W., Fowler B. (1999). Dissociation of the mismatch negativity and processing negativity attentional waveforms with nitrous oxide. *Psychophysiology*, 36(5), 552–558. doi:10.1111/1469-8986.3650552

Parasuraman R., Davies D.R. (1976). Decision theory analysis of response latencies in vigilance. *Journal of experimental psychology: human perception and performance*, 2 (4), 578-590.

Polich J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 118(10), 2128–48.

Raichle M.E., MacLeod A.M., Snyder A.Z., Powers W.J., Gusnard D.A., Shulman G.L.(2001). A default mode of brain function. *Proceeding of the National academy of Science of the United States of America*, 98(2), 676-82.

Shwartz A.H., Goldman R. (1975). Another dimension for assessment of speech-sound discrimination: latency of response. *Perceptual and motor skills*, 40, 819-826.

Sigman M., Dehaene S. (2006). Dynamics of the central bottleneck: dual-task and task uncertainty. *Public Library of Science: Biology*, 4 (7), 1227-1238.

Sigman M., Dehaene S. (2005). Parsing a cognitive task: a characterization of the mind's bottleneck. *Public Library of Science: Biology*, 3(2), 334-349.

Smallwood J., Brown K., Baird B., Schooler J.W. (2012). Cooperation between the default mode network and the frontal–parietal network in the production of an internal train of thought. *Brain research*, 1428, 60 – 70.

Smallwood J., Schooler J.W. (2006). The Restless Mind. *Psychological Bulletin*, 132(6), 946-958.

Smallwood J., Beech E.M., Schooler J.W., Handy T.C. (2008). Going AWOL in the brain – mind wandering reduces cortical analysis of the task environment. *Journal of Cognitive Neuroscience*, 20(3), 458-469.

Smallwood J., Obonsawin M.C., Heim D. (2003). Task Unrelated Thought: the role of distributed processing. *Consciousness and Cognition*, 12(2), 169-189.

Squires N. K., Squires K. C., Hillyard S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and clinical neurophysiology*, 38(4), 387–401.

Tong Y., Melara R. D., Rao A. (2009). P2 enhancement from auditory discrimination training is associated with improved reaction times. *Brain Research*, 1297, 80–88. doi:10.1016/j.brainres.2009.07.089

Treisman A. (1986) Features and objects in visual processing. *Scientific American*, 254(11), 114–125.

Treisman A., Gelade G. (1980). A feature integration theory of attention. *Cognitive Psychology*, 12, 97-136.

Varendonck J. (1921). *The Psychology of Day-Dreams* London: Allen & Unwin.

Wickens C.D. (1980). The structure of attentional resources. In R. Nickerson (Ed.), *Attention and performance VIII*. Hillsdale, NJ: Erlbaum. 239–257

Wilding J.M. (1971). The relation between latency and accuracy in the identification of visual stimuli: I. The effects of task difficulty. *Acta Psychologica*, 35, 378-398.

Boris V. Chernyshev

National Research University Higher School of Economics. Laboratory of cognitive psychophysiology: Head of laboratory; National Research University Higher School of Economics. department of psychophysiology: assistant professor.

E-mail: bchernyshev@hse.ru

Phone: +7-916-716-3993

Any opinions or claims contained in this Working Paper do not necessarily reflect the views of HSE