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CONDENSATION TASK AS AN EXPERIMENTAL MODEL FOR STUDYING INDIVIDUAL DIFFERENCES IN COGNITIVE CONTROL[5]

Successful performance in complex tasks depends upon the functioning of the cognitive control system involving the maintenance of sustained attention, retention and activation of task rules, as well as the inhibition of preliminary responses. Failure of any of these functions can lead to performance errors. In this study, we investigated behavioral data obtained from participants performing the auditory condensation task, which is highly demanding of the level of cognitive control but does not require participants to inhibit or override any prepotent automatic responses. We identified pre-error speeding and error slowing, while post-error slowing was not evident. Our results suggest that there are three factors contributing to the variability within the behavioral measures obtained. The first factor is related to the overall response latency, the second to the main individual mechanism of performance errors, and the third to the subject's ability to increase motor threshold in the event of uncertainty and choice ambiguity. The data obtained evidence that the auditory condensation task is a promising model for studying cognitive control.

JEL Classification: Z

Keywords: condensation task, cognitive control, inter-individual differences, response latency.

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Introduction

"Cognitive control" is an increasingly used term describing collectively a number of interrelated processes that control goal-directed behavior, such as retention of focused attention, keeping in memory the goals and the rules of their implementation, activation of relevant motor programs and inhibition of irrelevant motor programs [Yeung, 2014]. Deteriorated functioning of any of these processes may lead to error commission during task performance [van Driel et al., 2012; Navarro-Cebrian et al., 2013]. Error commission may lead to specific adaptations of cognitive control, which may be studied both through behavioral measures and by way of recording psychophysiological indices of brain activity. Cognitive control adaptations may involve both an enhancement in stimulus processing and an increase in the motor threshold depending upon the type of errors committed and the nature of the task itself.

Cognitive control is usually studied with the use of tasks involving some kind of a prepotent automatic response that needs to be overridden or inhibited in order to perform well in terms of performance accuracy; such studies are mostly aiming at investigation of the influence the conflict between the correct and the erroneous motor programs exerts upon performance indices [Cohen, 2014]. Such studies typically involve two kinds of trials – congruent ones creating no conflict, and incongruent ones, leading to a conflict between two alternative motor programs; examples include the Stroop task, the Simon task and the flanker task. Studies of this kind have revealed a number of behavioral effects such as error speeding and post-error slowing; response slowing at high levels of conflict; and adaptations to the conflict in the following trials [Botvinick et al., 2001; Egner, 2007; Dudschig and Jentzsch, 2009].

At the same time, to the best of our knowledge, behavioral manifestations of spontaneous decreases in the cognitive control level and its subsequent adaptations have not been studied yet in tasks that involve no overt inhibition or overriding of prepotent automatic responses, whereas such tasks are generally more common in real life and in cognitive experimental studies.

Here we used the condensation task [Posner, 1964], which requires a high level of cognitive control [Chernyshev et al., 2015]. Unlike many other tasks used in cognitive control studies, the condensation task does not involve any overt need to inhibit automatic responses, and it is based on series of target trials that are relatively homogenous and do not differ in the level of conflict (unlike the Stroop task, the Simon task and the flanker task) or in the level of "targetness" (unlike the oddball task and the sustained-attention-to-response tasks).

We hypothesize that under the auditory condensation task we will detect basic phenomena known in cognitive studies with several important differences compared with typical experimental tasks used in this area: (1) the role of factors reflecting activation of task rules and motor programs will be more clearly pronounced, while the role of motor inhibition will be less pronounced; (2) error slowing rather than error speeding will be observed.

Methods

Participants

Seventy-eight healthy volunteers with normal or corrected-to-normal vision and normal hearing participated in the present study (mean age 20.1 ± 0.2 years, 18 males). All volunteers reported no history of auditory, neurological or mental disorders. The experiments were carried out in accordance with the Declaration of Helsinki and its amendments and were approved by the ethics committee of the National Research University 'Higher School of Economics'. Informed consent was signed by each participant before the experiment.

Stimuli

Four auditory tones were presented. Each tone had two features: (1) "pitch" – a sinusoidal signal of either 500 Hz ('low') or 2000 Hz ('high'), and (2) "noisiness" – either a pure sinusoidal tone ('pure') or the same sinusoidal tone with a broadband noise added to the signal ('noised'). Root mean square amplitude of the noise was -14 dB relative to pure tones. The four 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; sound pressure level was 95 dB. The stimuli were presented to the participants using E-Prime software (Psychology Software Tools, Inc., USA) through a high-quality stereo headset with in-ear design.

Experimental design and procedure

An auditory two-choice version of the condensation task was used [Chernyshev et al., 2015]. The experiment involved six experimental blocks. During each block, a sequence of 100 stimuli was presented; each sequence consisted of four audio stimuli (see above) intermixed randomly with equal probability ratio. The stimuli were presented with random stimulus onset asynchrony (SOA) of 2500 ± 500 ms. Visual feedback was given during the experiment: correct responses within the time interval of 300-1700 ms after stimulus onset were reinforced by a ‘smiley’ for 500 ms in the center of the screen. Otherwise, the screen remained uniformly grey.

The time interval from the moment of a key pressing until 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 (mean ± standard deviation).

Participants were instructed to hold the gamepad in their dominant hand and to press with a thumb one or the other of the two buttons in response to the stimuli.

The participants were asked to familiarize themselves with the following table (Table 1), which was given to them printed in large typeface on a sheet of paper for free viewing during familiarization with the stimuli, and removed from the chamber immediately before the start of the EEG recording. The Table specifies the conjunction contingencies between the two stimulus features and the response required. Though the rules are apparently simple, the task requires a mental conjunction of both features. The instruction informed the participants that they had to press one of two buttons according to the rule specified, but the instruction did not emphasize time pressure, and participants were implicitly allowed to omit responses.

Before the start of the experimental blocks, the participants were familiarized with the auditory stimuli: the experimenter manually played them to the participants and named them orally, and then the participants were blind tested with the stimuli. The experimental sessions were not started until a participant could quickly name all of the stimuli correctly. All of them stated confidently that they could clearly feel the difference between all of the stimuli and knew which button corresponded to each stimulus.

Table 1. Response contingencies in the experimental task.

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

Behavioral data analysis

We considered three types of responses: correct responses, errors, and omissions. A response was considered correct or erroneous if it was committed within the 300-1700 ms time interval after stimulus onset depending on the button pressed; trials with no response or with responses committed later than 1700 ms were considered omissions.

The percentage and average latency of correct and erroneous responses was calculated for each participant using all of the trials (600 trials from 6 blocks).

Next, we selected trials belonging to each of the following conditions:

(1) correct responses immediately following correct responses committed on the previous trial – “post-correct correct responses” (cC);

(2) correct responses immediately preceding correct responses committed on the following trial – “pre-correct correct responses” (Cc);

(3) errors immediately following correct responses committed on the previous trial – “post-correct erroneous responses” (cE);

(4) correct responses immediately following errors committed on the previous trial – “post-error correct responses” (eC).

Trials containing more than one response (double button hits) were excluded from the analysis. The data for each particular participant were included into analysis only if a given behavioral measure was within the group mean ± 2.5 standard deviations; otherwise, the data points were discarded as outliers.

Then we calculated the following behavioral measures for each participant:

(1) pre-error speeding, defined as the ratio of the latency of correct responses preceding correct responses ("pre-correct correct responses", Cc) to the latency of correct responses preceding errors (Ce);

(2) error slowing, defined as the ratio of the latency of errors (E) to the latency of correct responses (C);

(3) post-error slowing, defined as the ratio of the latency of correct responses following errors (eC) to the latency of correct responses following correct responses (cC).

Each measure was defined computationally in such a way that the higher the value, the stronger the phenomenon. Values below 1 mean that a phenomenon is inverted.

Response latencies between different response latencies were compared using a two-tailed paired t-test.

Relations between measures were assessed using the Pearson correlation coefficient. Significance was assessed using Bonferroni correction.

In order to assess the nature of interrelation of any two measures (1 and 2) with a third one (3) we built two linear regression models: in the first one measure 3 was predicted by measure 1, in the second one measure 3 was predicted by both measures 1 and 2 included into the regression model. The residues obtained in the two models were compared with the F-test. If the residues in the second model were significantly lower compared with the first model, we took this as an evidence that there was an interrelation between measures 2 and 3 that was not mediated by measure 1.

All behavioral data analyses were performed with MATLAB software (MathWorks Inc., USA) using custom-made scripts.

All values are represented below as group means ± standard errors of mean unless specified otherwise.

Results and discussion

Overall behavioral performance measures

Correct responses comprised 82.9 ± 1.0% of all responses, errors – 11.0 ± 0.8%, response omissions – 5.1 ± 0.4%.

Average latency of correct responses was 876.6 ± 8.6 ms; average latency of errors – 985.7 ± 14.2 ms. Latency of errors was significantly greater than the latency of correct responses ($p<0.001$) (Fig. 1A). Thus, error slowing was very significant in the current behavioral data at group level.

The latency of correct responses preceding errors (Ce) was 859.9 ± 7.5 ms; the latency of correct responses following errors (eC) was 875.3 ± 8.3 ms. The latency of correct responses preceding errors (Ce) was significantly shorter than the latency of correct responses preceding correct responses (Cc) ($p=0.009$) – thus reflecting pre-error speeding, which was strongly evident in the current data at group level (Fig. 1B).

No significant difference between the latency of correct responses after errors (eC) and correct responses after correct responses (cC) was found ($p=0.68$), thus reflecting the absence of post-error slowing at group level (Fig. 1C).

The speed of responding is known to depend upon two factors: (1) activation of the representation of the respective motor program, and (2) motor threshold the program has to exceed in order to be implemented in behaviour. Under an optimal level of cognitive control, the stimulus activates the representation of a task rule, which may push the balance between the competing motor programs in favor of the program that leads to the correct behavioral response [Botvinick et al., 2001].

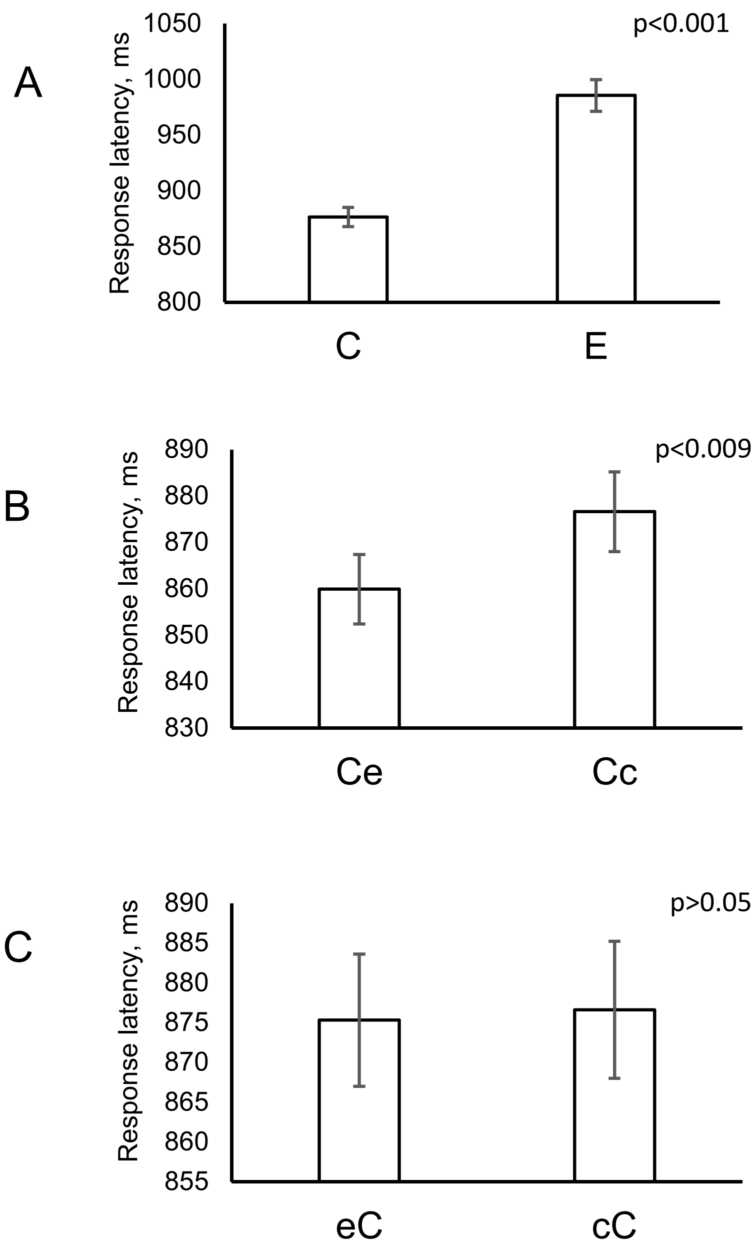

Fig. 1. Comparison of response latencies under different behavioral outcomes. (A) Correct responses (C) vs. errors (E); (B) Correct responses preceding errors (Ce) vs. correct responses preceding correct responses (Cc); (C) Correct responses after errors (eC) vs. correct responses after correct responses (cC).

We speculate that occasionally participants lower the level of cognitive control and perform the task at a more automatic level. Under such a state, the responses are committed faster, but at the same time this state predisposes to a higher probability of error commission because actually the task cannot become fully automated within the duration of the experiment [Lazarev et al., 2014]. Such a "pseudo-automated" mode of action may explain the fact that the latencies of correct responses preceding errors (pre-error correct responses, Ce) are shorter, leading to pre-error speeding.

In this study, we observed longer response latencies for erroneous responses compared to correct ones. Most tasks used in cognitive control studies (including the SART, the Simon task, the flanker task, etc.) require an overriding of some prepotent "automatic" responses, and, moreover, participants are usually instructed to respond as fast as possible. In such tasks, the probability of error commission is higher during spontaneous decreases of the motor threshold, thus leading to "error speeding" [Ridderinkhof, 2002; Dudschig and Jentzsch, 2009; Ratcliff and McKoon, 2008].

In contrast, the condensation task used in our experiment involves no obvious prepotent responses one needs to override; at the same time, this task is demanding for the activity of stimulus-processing systems because complex bivalent stimuli and non-intuitive stimulus-to-response mapping are used. Errors in complex or accuracy demanding tasks tend to occur in situations of decision uncertainty, which leads to the slowing of erroneous responses [Wilding, 1971; Luce, 1986; Dyson and Quinlan, 2003; Ratcliff and McKoon, 2008; O'Connel et al., 2009b; van Driel et al., 2012; Cohen and van Gaal, 2013].

Supposedly, under current task conditions, a temporarily lowered level of cognitive control leads to an insufficient activation of task rules, resulting in an equally low level of activation of both the correct and incorrect motor programs [Ratcliff and McKoon, 2008]. Thus, the time needed to reach a motor threshold as well as the probability of incorrect response both increase, compared with the normal performance state; this in turn leads to the increased average latency of erroneous responses compared with the average latency of correct responses. In accordance with this logic, latency of errors in our task was predictably larger than latency of correct responses. This phenomenon was clearly evident in the current study as error slowing.

There may yet be a complementary explanation for the error slowing observed in the current study. The current task did not overtly require a prepotent response to be inhibited [Chernyshev et al., 2015], and the instruction given to participants in the current study (unlike many other studies in this field) did not persuade them to respond as quickly as possible. Thus, it is likely that under conditions of uncertainty – when both motor programs are far from reaching the motor threshold – an additional adaptive increase of motor threshold may develop, leading to an even greater delay in erroneous responding [van Driel et al., 2012]. We should stress again that the current task did not require the participants to respond quickly – thus, the motor threshold buildup could have affected the very same trial rather than the next one. It is probable that in more traditional tasks with faster responding, this same increase of motor threshold leads to delays of responding in the following trial – the effect known as post-error slowing [Botvinick et al., 2001; Ridderinkhof et al., 2004].

It should be noted that even under suboptimal states of lowered cognitive control, as discussed above, some of the responses might still accidentally be behaviorally correct. Due to the nature of the two-alternative response choice, the number of "accidental hits" should be approximately equal to the number of "accidental misses". This issue cannot be resolved within the behavioral paradigm, but since the number of errors is significantly less than the number responses, the number of "accidental hits" should be also significantly less than the number of "true hits". Myographical or accelerometric recording may potentially help resolve this issue in future experiments [Cohen, van Gaal, 2014].

In the current study, we did not observe any significant post-error slowing effect at group level. As we point out above, the current task implies no fast prepotent responses and does not involve any strong time pressure. In such a situation, participants may have had enough time to slow down during the erroneous trial itself – we indeed observed strong error slowing as discussed above. Under such conditions, the effect of increased motor threshold may largely subside by the time of the following trial.

The absence of significant post-error slowing can be explained by the presence of two different effects that push the response latency in opposite directions. Generally, error-related adaptations of cognitive control fall into two major groups: (1) a non-specific increase of motor threshold ("proactive" strategy), and (2) a specific enhancement of task-relevant information processing ("preemptive" strategy) [Ridderinkhof, 2002; Ridderinkhof et al., 2011]. The motor threshold increase is related to post-error slowing [Dudschig and Jentzsch, 2009; Cohen, 2014], while the specific adaptation may presumably lead to response latency shortening due to enhanced stimulus processing [Cavanagh and Frank, 2014]. It was established that the intensity of specific and non-specific adaptations may differ between subjects [King et al., 2010], a fact that can explain the absence of a group-level post-error slowing effect in the current task.

We found no correlation between post-error slowing and the percentage of errors (see below); this suggests that neither of the two adaptations was more successful than the other – a finding in keeping with other studies [e.g. Danielmeier and Ullsperger, 2011].

Interrelations between the behavioral measures

The correlation matrix between the behavioral measures is represented in Table 2, and the layout of interrelations between the behavioral measures is shown in Fig. 2.

Percentages of behavioral outcomes. The percentage of correct responses negatively correlated both with the percentage of errors and with the percentage of omissions (Fig. 2, black lines). These correlations likely reflect "technical" coupling resulting from the method used to categorize participants' responses into correct responses, errors and omissions. Yet the percentage of errors did not correlate with the percentage of omissions, thus indirectly hinting at the differential nature of these two incorrect behavioral outcomes.

Percentage of response types and response latencies. Latency of correct responses positively correlated with the percentage of omissions and negatively with the percentage of correct responses (Fig. 2, red lines); no correlation of this measure with the percentage of errors was found. This means that participants with lower performance speed did worse on the task due to a greater number of omissions. It should be noted here that both failures to commit any response and commissions of extremely late responses (later than 1700 ms after stimulus onset) were considered omissions; in both events, participants did not receive the reinforcing feedback.

Table 2. Correlation matrix between behavioral measures.

		1	2	3	4	5	6	7
1	Percentage of correct responses							
2	Percentage of errors	-0.82***						
3	Percentage of response omissions	-0.74***	0.21					
4	Latency of correct responses	-0.53***	0.14	0.73***				
5	Latency of errors	-0.16	-0.21	0.53***	0.71***			
6	Pre-error speeding	-0.01	0.12	-0.12	-0.27	-0.46**		
7	Error slowing	0.27	-0.42**	0.05	0.07	0.75***	-0.40*	
8	Post-error slowing	0.16	-0.21	-0.04	-0.17	0.02	-0.05	0.19

* - $p<0.05$; ** - $p<0.01$; *** - $p<0.001$

The latency of correct responses positively correlated with the latency of errors. Similar to the latency of correct responses, the latency of errors also positively correlated with the percentage of omissions (Fig. 2, red lines).

Thus, here we deal with a factor representing a complex of interrelated measures that characterize the individual participants' performance speed. The lower the performance speed is, the more responses are omitted. This is the first major factor contributing to the individual variability emerging within the current behavioral analysis.

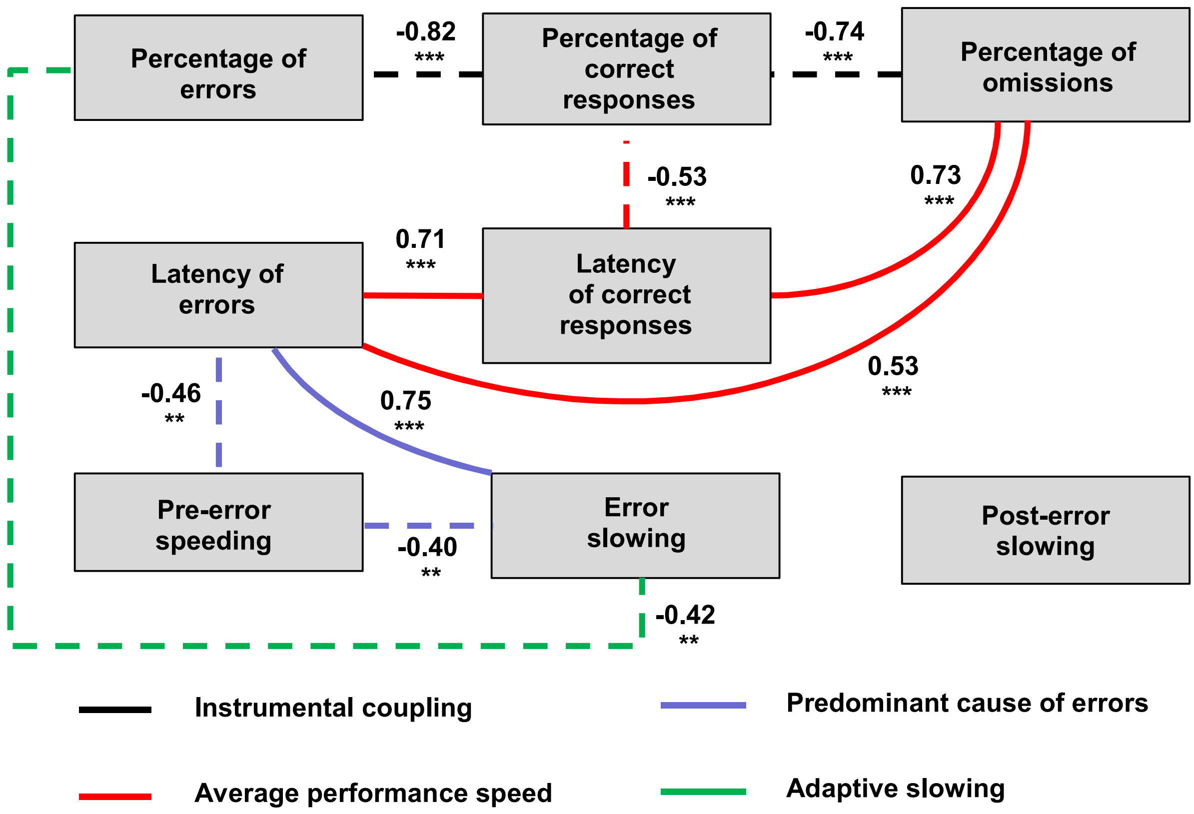

Fig. 2. – Schematic drawing of interrelations between behavioral measures. Solid lines denote positive correlations, dashed line – negative correlation.

* - p<0.05; ** - p<0.01; *** - p<0.001.

Pre-error speeding and error slowing. The more pronounced was pre-error speeding, the less pronounced was error slowing (Fig. 2, blue lines).

Both measures – pre-error speeding and error slowing – correlated with the latency of errors (Fig. 2, blue lines): positive correlation between error slowing and the latency of errors, and negative correlation between pre-error speeding and the latency of errors. In other words, speculatively, the faster the correct precocious "pseudo-automated" responses preceding errors were committed, the faster the errors themselves (in absolute values) were committed. And, the faster errors were committed in relative values of latency, the faster they were committed in absolute values of latency.

Still, it is necessary to note that error slowing (in relative values) and latency of errors (in absolute values) are essentially different measures, since error slowing is the result of the normalization of error latency by the latency of correct responses. Raw non-normalized latency contains a large portion of a variance shared with the latency of correct responses (i.e. it partially reflects the overall speed of participants' responding). Error slowing is normalized by the latency of correct responses, thus it reflects the relative increase in the latency of errors relative to the performance speed of the responding characteristic of each participant. Correlational analysis revealed no link between error slowing and the latency of correct responses: this means that in this case there is no shared inter-individual variance related to differences in participants' performance speed.

Additional analysis based on comparisons between regression models demonstrated that each of the two measures considered above (pre-error speeding and error slowing) do not mutually enhance each other's prediction of the latency of errors (p=0.39). Thus, one common link exists between the three measures – pre-error speeding, error slowing and latency of errors (Fig. 2, blue lines).

It is important to note that two measures within this block – pre-error speeding and error slowing – have no direct relation with the overall performance speed, since these measures did not correlate with the latency of correct responses.

The addition of pre-error speeding to the latency of correct responses significantly enhances prediction of the latency of errors (p=0.002) (Fig. 3, upper block). Thus, the latency of errors depends upon two factors. First, obviously, it depends upon the overall performance speed – which, as discussed above, is manifested in the latencies of any responses committed and in the percentage of omissions.

Second, it depends upon a less obvious internal variable that stands behind pre-error speeding and error slowing.

It is possible that both measures of this internal variable – pre-error speeding and error slowing – are manifestations of a single individual factor that, supposedly, reflects the predominant cause of error commission by individual participants under conditions of lowered cognitive control. This cause may be either a decrease in the motor threshold (leading to stronger pre-error speeding and weaker error slowing), or a decrease in the activation of the task rule representation (leading to weaker pre-error speeding and stronger error slowing) [van Driel et al., 2012; Mazaheri et al., 2009; Ratcliff and McKoon, 2008].

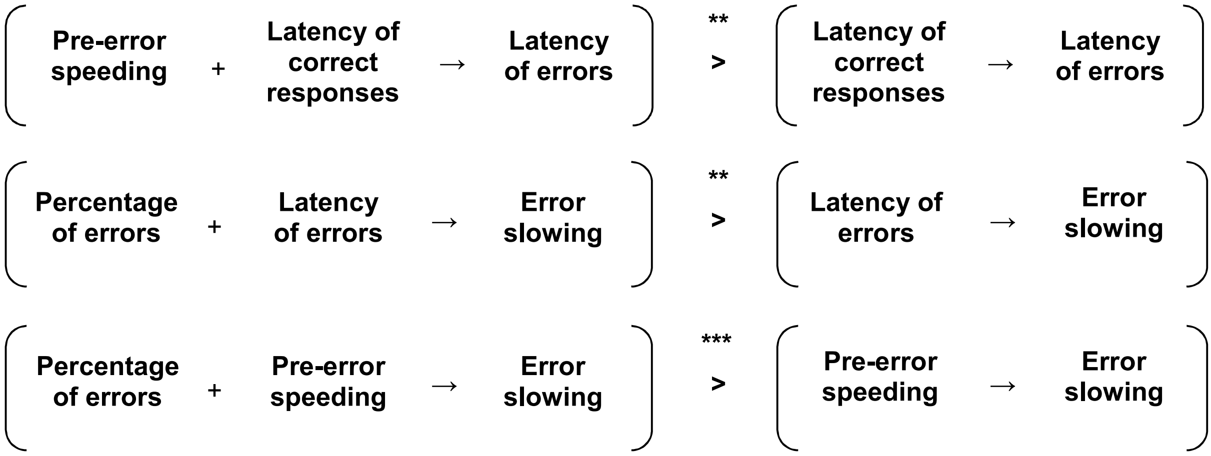

Fig. 3. Comparisons between regression models for behavioral measures.
* - p<0.05; ** - p<0.01; *** - p<0.001

Thus, this mechanism caused by a decline in the level of motor control may develop along two marginal scenarios. In the case of decreased motor threshold, participants' responding will be faster, but this will lead to an increased probability of committing an error as well. In the case of insufficient activation of task rule representation, one may expect a slowing of responses, especially strong for errors. In such conditions, both motor programs will have too low an activation level and this will result in increased time needed to reach a motor threshold, and consequently to delayed responding and an increased probability of committing an error [Ratcliff and McKoon, 2008].

This bipolar gradual individual characteristic seems to emerge only under lowered levels of cognitive control since it is related exclusively to erroneous responses. Gradations within this bipolar axis are not related to the overall performance accuracy, therefore presupposing similar consequences of the two marginal scenarios. Thus, this is the second mayor factor contributing to the individual variability emerging within the current behavioral analysis.

We also discovered a negative correlation between error slowing and the percentage of errors (Fig. 2, green line).

The addition of the percentage of errors to the latency of errors significantly enhances prediction of error slowing ($p=0.002$) (Fig. 3, middle block); a similar result can be obtained by adding the percentage of errors to pre-error speeding in prediction of error slowing ($p<0.001$) (Fig. 3, lower block).

Thus, in this case we see the evidence of two complementary mechanisms that may influence the inter-individual differences in error slowing.

One of the mechanisms has already been discussed above; presumably, it is a factor that reflects the participants' tendency to commit errors either due to insufficient activation of the task rule representation or due to an excessive drop in the motor threshold.

The other mechanism is presumably reflecting the third major factor contributing to the individual variability emerging in the current analysis - a behavioral adaptation involving an increase in the motor threshold under conditions of uncertainty of choice between two responses. This mechanism may be viewed as an adaptive increase in the level of cognitive control. The higher the participant's ability to increase the motor threshold, the higher the probability that the task rule representation will be sufficiently activated before an accidental premature erroneous response is precipitated; correspondingly, this increases performance accuracy due to the decrease in the percentage of errors [Cavanagh, Shackman, 2015].

Conclusions

The analysis of response latencies under the auditory condensation task revealed the following phenomena:

(1) the latency of correct responses preceding errors is decreased – i.e. pre-error speeding can be observed under the auditory condensation task;

(2) erroneous responses are committed slower than correct responses – i.e. error slowing is characteristic of the auditory condensation task;

(3) responses on trials following errors were not slower – i.e. no post-error slowing was found under the auditory condensation task at group level of analysis;

This clearly distinguishes the auditory condensation task from most of the tasks used in studying cognitive control, for which error speeding (rather than error slowing) and post-error slowing are typically reported.

The correlational analysis revealed three major factors that determine the individual differences in behavioral measures under the auditory condensation task:

(1) the first factor is reflecting the overall performance speed;

(2) the second factor is reflecting the predominant cause of error commission under conditions of lowered level of cognitive control – the tendency either towards pre-error speeding or towards error slowing; this factor does not influence the overall performance accuracy.

(3) The third factor is reflecting the ability to adaptively increase the motor threshold under conditions of uncertainty, and it influences the percentage of errors.

The data presented here evidence that the condensation task is a promising model for studying cognitive control, because it can be successfully treated in the analytical framework of the cognitive control methodological paradigm, while at the same time this task offers new vistas for the analysis of cognitive control failures and of adaptive cognitive control adjustments unavailable within traditional experimental tasks.

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