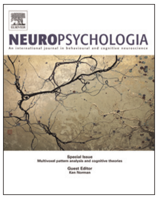
Neuropsychologia 66 (2015) 144–156

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia



Neuropsychological parameters indexing executive processes are associated with independent components of ERPs

Jan Ferenc Brunner [a,b,*], Alexander Olsen [a,c], Ida Emilia Aasen [a], Gro C. Løhaugen [b,d], Asta K. Håberg [b], Juri Kropotov [e,f,g]

[a] *Department of Physical medicine and rehabilitation, St. Olavs Hospital, Trondheim University Hospital, Norway*
[b] *Department of Neuroscience, Norwegian University of Science and Technology (NTNU), Trondheim, Norway*
[c] *MI Lab and Department of Circulation and Medical Imaging (NTNU), Norway*
[d] *Department of Pediatrics and Child Rehabilitation, Arendal, Sørlandet Hospital HF, Norway*
[e] *Department of Psychology, NTNU Trondheim, Norway*
[f] *Institute of the Human Brain of Russian Academy of Sciences, St. Petersburg, Russian Federation*
[g] *Andrzej Frycz Modrzewski Krakow University, Krakow, Poland*

ARTICLE INFO

Article history:
Received 12 May 2014
Received in revised form
10 November 2014
Accepted 16 November 2014
Available online 20 November 2014

Keywords:
Executive processes
ERP
Go/NoGo
Independent Component Analysis

ABSTRACT

Lesion studies have indicated that at least the three executive processes can be differentiated in the frontal lobe: Energization, monitoring and task setting. Event related potentials (ERPs) in Go/NoGo tasks have been widely used in studying executive processes. In this study, ERPs were obtained from EEG recorded during performance of a cued Go/NoGo task. The Contingent Negative Variation (CNV) and P3NoGo waves were decomposed into four independent components (ICs), by applying Independent Component Analysis (ICA) to a collection of ERPs from 193 healthy individuals. The components were named IC $\mathrm{CNV}_{\mathrm{early}}$, IC $\mathrm{CNV}_{\mathrm{late}}$, IC $\mathrm{P3NoGo}_{\mathrm{early}}$ and IC $\mathrm{P3NoGo}_{\mathrm{late}}$ according to the conditions and time interval in which they occurred. A sub-group of 28 individuals was also assessed with neuropsychological tests. The test parameters were selected on the basis of studies demonstrating their sensitivity to executive processes as defined in the ROtman-Baycrest Battery for Investigating Attention (ROBBIA) model. The test scores were categorized into the domain scores of energization, monitoring and task setting and correlated with the amplitudes of the individual ICs from the sub-group of 28 individuals. The energization domain correlated with the IC $\mathrm{CNV}_{\mathrm{late}}$ and IC $\mathrm{P3NoGo}_{\mathrm{early}}$. The monitoring domain correlated with the IC $\mathrm{P3NoGo}_{\mathrm{late}}$, while the task setting domain correlated with the IC $\mathrm{CNV}_{\mathrm{late}}$. The IC $\mathrm{CNV}_{\mathrm{early}}$ was not correlated with any of the neuropsychological domain scores. The correlations between the domains and ICs remained largely unchanged when controlling for full-scale IQ. This is the first study to demonstrate that executive processes, as indexed by neuropsychological test parameters, are associated with particular event-related potentials in a cued Go/NoGo paradigm.

1. Introduction

Few attempts have so far been made to investigate the relationships between neuropsychological indexes of executive processes and event-related potentials (ERPs) (Clayson and Larson, 2012; Lamm et al., 2006; Larson and Clayson, 2011). This scarcity of findings may be related to the relative paucity of testable neuropsychological theories guiding the investigation and selection of appropriate ERP paradigms and parameters.

In the supervisory attentional system (SAS) model it is suggested that information processing in the frontal lobes may be modulated by attention in order to handle situations involving planning, novel sequences of action, and the need to overcome strong habitual responses in decision making (Norman and Shallice, 1986). Inspired by the SAS model, the ROtman-Baycrest Battery for Investigating Attention (ROBBIA) approach argues for fractionating the executive attention system into three anatomically and functionally independent processes: energization, monitoring, and task setting (Stuss et al., 1995). *Energization* refers to a process that facilitates and boosts other SAS processes, especially those necessary for making decisions through initiation and maintenance of optimal response patterns (Stuss, 2011; Stuss et al., 2005). The *Monitoring* process is thought to provide quality control of behavior by checking task performance and outcome over time, which is a prerequisite for appropriate adjustment of behavior. The *Task setting* process refers to the formation of a criterion of how to

---

* Correspondence to: Fysikalsk Medisin, Lian, Vådanveien 39, 7024 Trondheim, Norway. Fax: +47 72822601.
E-mail address: jan.brunner@stolav.no (J.F. Brunner).

http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.019

respond to a defined target, and to organize the schemata to complete a specific task. Although these processes are described as being independent, they act in concert to control lower-order processes and optimize behavior (Stuss and Alexander, 2007).

Essential in the ROBBIA model is the idea that these processes can be reflected in specific neuropsychological parameters. The effect of deficient energization is evident in any speeded behavior, and can in particular be observed as slowing in cued RT tasks (Stuss and Alexander, 2007). The effect of energization can also be observed in performance on fluency tasks in general, and phonemic fluency tasks in particular (Robinson et al., 2012; Stuss et al., 1998). Moreover, performance initiation and the maintained aspect in phonemic fluency can be investigated separately by dividing the task into several time intervals (Stuss et al., 1998). The task setting process can be assessed behaviorally by measures reflecting poor criterion setting, such as increases in false positive errors (Stuss et al., 2002). The effects of suboptimal task setting are particularly evident during the initial phase of learning a new task, such as the Stroop task (Alexander et al., 2007). In the Delis Kaplan Executive Function System (D-KEFS), the Color-Word Interference subtests “Inhibition” and “Inhibition and Switching” put a high demand on task setting, and false positive errors can be argued to index impairment in this process. Additionally, false alarms in Go/NoGo tasks have been used to index impaired task setting (Stuss and Alexander, 2007). In the present study, false alarms in a not-X CPT were also included as a behavioral index of task setting. In this task, where targets are frequently presented (high Go, low NoGo frequency), avoiding commission errors is particularly challenging (Conners et al., 2003). Commission errors in the Stroop and not-X CPT tasks have traditionally been regarded as indexes of inhibition. The ROBBIA model does not, however, regard inhibition as an independent process, but rather postulates that the ability to stop pre-potent responses can be well explained by the three processes of energization, task setting and monitoring (Stuss and Alexander, 2007). In line with this, Vallesi (2012) argues that task setting includes both the selection of task-relevant criteria and operations as well as suppression of irrelevant ones. Monitoring is reflected in all types of errors, including omission errors (false negatives) (Stuss and Alexander, 2007). The detectability parameter (d') is based on both commission and omission errors and indexes how well a subject is able to respond differentially to targets and nontargets, and has been suggested to be a parameter sensitive to the quality of the monitoring process (Stuss et al., 2003). Intra-individual variability in reaction time, as indexed by coefficient of variance (CV), is another parameter proposed to reflect monitoring (Alexander et al., 2005). However, it has been suggested that the CV may rather be a non-specific parameter of attention (Picton et al., 2007).

Lesion studies support a categorization of neuropsychological measures into separate domains reflecting the underlying independent processes in the ROBBIA model (see Stuss and Alexander, 2007 for review). Further support for the model has recently been found through fMRI studies in healthy participants (Vallesi, 2012). No attempt has been made to validate the ROBBIA model through traditional factor analysis. This is probably because previous research has indicated that interpretation of factors derived from exploratory factor analysis is problematic, especially when investigating executive functions (Miyake et al., 2000; Miyake and Friedman, 2012). One reason for this difficulty is that neuropsychological test parameters do not directly measure the component processes required to complete a task. Consequently, individuals might obtain the same final score due to different underlying causes (Stuss et al., 1998). This is often referred to as the task impurity problem (Miyake et al., 2000). To solve parts of this problem and enable identification of specific executive processes, the *dual mechanisms of control* framework suggests investigation of different temporal phases of processing (Braver et al., 2007). In this framework, *proactive* control processes involve an early selection, in which goal-relevant information is actively maintained, prior to the occurrence of cognitively demanding events. *Reactive* control processes, on the other hand, are late correction mechanisms mobilized only as needed, in a just-in-time manner, such as after the detection of a high interference event (Braver, 2012). Based on this framework, measures with higher temporal resolution than behavioral parameters can be useful when investigating control processes at different stages of a task. The high time resolution of ERPs recorded during cued Go/NoGo tasks enables such investigation of executive processes in different temporal phases of a task, even down to the millisecond scale. Optimal performance in the cued Go/NoGo task can be argued to require efficient task setting in order to respond correctly, energization to enable fast responses, and monitoring to adjust the trade-off between speed and accuracy in the task. This paradigm can therefore be considered ideal for studying ERPs reflecting the control processes described in the ROBBIA model.

The Contingent Negative Variation (CNV) (Walter et al., 1964), a slow negative potential appearing between a warning (cue) and an imperative stimulus, is a promising ERP for investigating *proactive* executive processes. The CNV wave comprises several components (Loveless and Sanford, 1974; Rohrbaugh et al., 1997). CNVs presenting with the strongest negativities early in the inter-stimulus interval have been linked to encoding of relevant stimulus characteristics (Bender et al., 2012; Ruchkin et al., 1997), as well as maintenance and rehearsal processes related to the cue information (Rohrbaugh et al., 1997). Stuss et al. (1995) also speculated whether the early parts of the CNV wave might reflect task setting. The late CNV wave, which presents strongest negativity immediately before the imperative stimulus, has been related to maintaining task-set representations over time (Kray et al., 2005; Tieges et al., 2006). There are two aspects to the task-setting process: the process of establishing the task set representations (S–R contingencies) themselves, and the energetic aspect of sustaining attention towards this task set over time. This signifies that the amplitude of the wave may reflect a combination of the task setting process, as well as the level of energization invested in maintaining the focus and reactivating this task set over time. The importance of the latter aspect in the late CNV has been supported in several studies (Brunia and van Boxtel, 2001; Falkenstein et al., 2003; Polich and Kok, 1995; Segalowitz et al., 1997).

The late positive fronto-centrally distributed potential elicited in the NoGo condition (P3NoGo wave) is an ERP candidate for investigating *reactive* executive processes, due to the fact that this condition requires overcoming the routine behavioral schema. Different interpretations of the functional meaning of this component have been proposed, one being response inhibition (Fallgatter and Strik, 1999; Kok et al., 2004; Smith et al., 2007), or more precisely, the voluntary decision to withhold a response (Gajewski and Falkenstein, 2013). In a literature review on the P3NoGo wave, however, it was recently concluded that the P3NoGo wave does not serve as a proper index of inhibition (Huster et al., 2013). Also, a study by Randall and Smith (2011) showed that the P3NoGo wave not only appears in situations where the pre-potent model is suppressed (response to NoGo targets after Go cue), but also in situations where the prepared action must be replaced by an alternative action (response to Go targets after an invalid cue). In fact, going through 30 fMRI studies on Go/Nogo tasks, Criaud and Boulinguez (2013) conclude that rather than reflecting inhibitory processes, the results can better be explained by the engagement of many different and intrinsically related cognitive processes. This view is supported by a study on primates showing that suppression of incorrect responses, as well as facilitation of correct responses activate the same pre-SMA neurons in a saccade task

(Isoda and Hikosaka, 2007). These studies may indicate that, rather than reflecting inhibition, the P3NoGo wave reflects a more general control process of replacing pre-potent response tendencies. Another hypothesis is that the P3NoGo wave reflects outcome evaluation (Bruin et al., 2001; Schmajuk et al., 2006; Sehlmeyer et al., 2010; van Gaal et al., 2011). The review by Huster et al. (2013) concludes that this view has received more empirical support than the inhibition hypothesis.

Like neuropsychological test parameters, ERPs have their own impurity problems. One of these problems is the fact that ERP waves represent the sum of activity from multiple sources at overlapping points in time (Kappenman and Luck, 2012). Attempts have been made to separate these sources by using principal- and independent component analysis (ICA) (Makeig and Onton, 2012; Spencer et al., 2001). ICA has previously been applied to a large collection of ERPs (group ICA) elicited in a cued Go/NoGo paradigm with the goal of projecting multi-channel ERPs into hidden sources with certain localizations so that the activation curves from these sources vary independently across subjects (Kropotov and Ponomarev, 2009). This method allows for dealing with activation waveforms from the selected sources instead of the multi channel ERPs, each of which is a linear combination of these sources. In order to obtain reliable decompositions, ICA depends on a large number of training points (Onton and Makeig, 2006). In group ICA, a sufficient number of training points can be obtained by using ERPs from a large number of individuals (Kropotov et al., 2011). The group ICA method has revealed that the P3NoGo wave consists of two independent components (ICs) with differing latencies and topographies, and strong to excellent test-retest reliability (Brunner et al., 2013). The two ICs of P3NoGo opens up the possibility that different and independent processes might be reflected in the P3NoGo wave. In the present study, group ICA was also used to decompose the CNV wave into ICs, opening the possibility of studying overlapping processes in this wave as well. Decomposing the CNV wave by application of ICA in other paradigms has been shown to be successful in earlier studies (Jervis et al., 2007, Olbrich et al. 2002).

This study investigates the relationship between neuropsychological task parameters and independent components of ERPs in a cued Go/NoGo paradigm. The present study is driven by hypotheses based on the ROBBIA model as well as on previous ERP research. The selection of ERP paradigm (cued Go/NoGo task) and ERPs was driven by the assumption that specific ERPs are sensitive to each of the three processes described in the model. Task setting occurs in different time periods during the task; before the task begins (through instructions), during trial and error in the initial phase of learning, and is probably also reactivated between and during each trial. It is highly plausible that the task setting process may be proactively activated in the inter-stimulus interval when the subject prepares for the response alternatives. Indeed, the definition of the task-setting process and the proposed processes reflected in CNV wave are similar (e.g. contingencies between S and R). In the present study, the CNV ICs were therefore hypothesized to be sensitive to the task setting process. Assuming that the P3NoGo wave reflects both the process of replacing a pre-potent response with an alternative response as well as the process of outcome evaluation, the latter should logically come later in time than the former. As we know that the IC P3NoGo$_{\text{late}}$ always comes after the IC P3NoGo$_{\text{early}}$ (Brunner et al., 2013), we hypothesized that the IC P3NoGo$_{\text{late}}$ would correlate with neuropsychological parameters sensitive to monitoring.

In addition to reflecting a specific process, the amplitudes of ERPs also reflect the degree to which these processes are facilitated. One such process is energization, which could have a facilitating effect on several ICs. More specifically, we hypothesized that the amplitude of two ICs (the IC P3NoGo$_{\text{early}}$ and an IC resembling the late CNV wave) would correlate with neuropsychological parameters sensitive to energization. The basis for expecting this relation to the IC P3NoGo$_{\text{early}}$ was the correlation between the change in IC P3NoGo$_{\text{early}}$ amplitude and change in RT between two recordings found by Brunner et al. (2013). As the ROBBIA model suggests that RT is highly sensitive to energization, such a relation between IC P3NoGo$_{\text{early}}$ and energization was already proposed in that paper. As it has also been suggested that the late CNV wave is modulated by energetic mechanisms, and several studies have shown that the late CNV wave increases on fast as compared to slow trials (Brunia and Vingerhoets, 1980; Falkenstein et al., 2003), we expected one of the resulting IC CNVs to resemble the late CNV wave (IC CNV$_{\text{late}}$) and to correlate with the task parameters sensitive to energization. Furthermore, the two ICs facilitated by energization (IC CNV$_{\text{late}}$ and IC P3NoGo$_{\text{early}}$) should also correlate significantly with each other.

The P3NoGo wave and some of the neuropsychological task parameters used in the present study have been shown to be related to scholastic achievement, IQ or sub indexes of IQ (Ardila et al., 2000; Chen and Li, 2007; Hillman et al., 2012; Liu et al., 2011; Ojeda et al., 2010). It was therefore important to control for these indexes in the correlation analysis between the ICs and neuropsychological parameters in the present study.

2. Materials and methods

2.1. Participants

*ERPs from 193 healthy participants (109 females, mean age: 24.4 years, SD=4.2) were recorded for identification of the ICs of interest in the cued Go/NoGo paradigm. The participants were recruited through ongoing studies of traumatic brain injury and young adults born with very low birth weight (VLBW), where they served as healthy controls. A sub-group (*n*=28, 13 females, mean age: 22.7, SD: 0.6) had been assessed with intelligence- and neuropsychological tests as a part of the ongoing VLBW study, and was hence included in the further analyses in the present study. Years of education for this group were determined based on the number of years of schooling completed. Participants gave their written consent prior to participation in the study. The Regional Committee for Medical Research Ethics approved the study.*

2.2. Neuropsychological tests and domains

Neuropsychological tasks were selected according to their sensitivity for the three processes proposed in the “ROBBIA” model as described in the introduction. The neuropsychological tests were two Go/NoGo tasks; a visual cued Go/NoGo task designed for the ERP study (Kropotov and Ponomarev, 2009) and an in-house version of a not-X CPT (described in Olsen et al., 2013), as well as four tasks from the Delis Kaplan Executive functioning System (D-KEFS; Delis et al., 2001); the phonemic fluency test, the design fluency test (filled dots) and two sub-tests from the color-word interference test (inhibition and inhibition/switching). Test scores were grouped into composite index scores by averaging *z* scores computed for each task. For tests where higher scores indicated worse performance, inverse scores were used. The composite scores were regarded as domains reflecting energization, monitoring and task-setting processes. The energization domain included mean reaction time (RT) from the cued Go/NoGo task (cued RT), total raw score of phonemic fluency and the total raw score of design fluency from D-KEFS. In addition, but not included in the calculation of the energization domain score, the score for the first and last 15 s in the phonemic fluency task were calculated to enable assessment of initiation and sustained processes separately.

For the monitoring domain, detectability scores (d') from both the not-X CPT and the cued Go/NoGo task were included. The calculation of d' is described in detail in our previous study (Olsen et al., 2013). Errors from the two D-KEFS Color-Word Interference tests, and commission errors from the not-X CPT were included to index the task-setting domain.

In addition to the scores included in the domains, and coefficient of variance ($CV = (SD/RT) \times 100$) from the cued Go/NoGo task were calculated. To allow controlling for IQ parameters, IQ was assessed with Wechsler Adult Intelligence Scale—3rd edition [WAIS-III]; (Wechsler, 1997) and four indexes were used; Full-scale (FS) IQ, Verbal Comprehension Index (VCI), Perceptual Organization Index (POI), Processing Speed Index (PSI) and Working memory Index (WMI).

2.3. EEG recording during the cued go/NoGo task

EEG was recorded by an EEG system manufactured by Mitsar (Ltd. http://www.mitsarmedical.com) (bandpass 0.3–50 Hz, sampling rate 250 Hz) with a 19-channel electrode cap (Electro-cap). Having this low frequency cutoff for assessing the CNV waves we relied on studies describing that a 0.5 Hz low frequency cutoff can reliably extract slow wave effects (Padilla et al., 2006). The cap was placed on the scalp according to the standard 10–20 system. Electrodes were referenced to linked earlobes. Impedance of electrodes was kept below 5 kΩ. The participants sat upright in a comfortable chair looking at a 17-in. computer screen at a 1.5 m distance. ERP waveforms were computed offline in the common average montage. Trials with omission and commission errors were automatically excluded from averaging.

The cued Go/NoGo task consisted of 400 trials sequentially presented every 3 s. Three categories of visual stimuli were used: 1) 20 different images of animals – referred to later as A, 2) 20 different images of plants P, 3) 20 different images of people (presented together with an distracting “novel” sound) referred to as H. The inter-stimulus interval within each trial was 1000 ms. The duration of each stimulus presentation was 100 ms. Four categories of trials were used: A–A, A–P, P–P, and P–H. In the trials with A–A and P–P pairs, the two pictures were identical. The trials were grouped into four blocks with one hundred trials each, presented with equal probabilities for each trial category. The participants were instructed to press a button with the index finger of the right hand to all A–A pairs as fast as possible (Go condition), as contrasted to the A–P pairs where responses should not be made (NoGo condition). All trials with **A** (cue) as the first stimulus (A–A and A–P pairs) are assumed to activate proactive processes. This condition is therefore called the “cue condition”. P–P and P–H pairs, on the other hand, did not require any preparation for, or attention to, the second stimulus, and are simply referred to as “P condition”.

2.4. Artefact correction procedure

Eye blink artifacts were corrected by zeroing the activation curves of individual independent components corresponding to eye blinks. These components were obtained by application of Independent Component Analysis (ICA) to the raw EEG fragments (Jung et al., 2000; Vigario, 1997). Epochs with excessive absolute amplitude of filtered EEG and/or excessive faster and/or slower frequency activity were automatically marked and excluded from further analysis. Exclusion thresholds were set as follows: (1) 100 μV for non-filtered EEG, (2) 50 μV for slow waves in 0–1 Hz band, and (3) 35 μV for fast waves filtered in the band 20–35 Hz.

2.5. Decomposition of ERPs into independent components

Because the validity of decomposition depends on the number of training points, the ICA Infomax algorithm was applied to the collection of ERPs from the entire sample of 193 participants. For methodological details, see Brunner et al. (2013), Kropotov and Ponomarev (2009), and Kropotov et al. (2011). Briefly, to identify proactive ICs, ICA was applied for the time interval between the first and the second stimulus (1100 ms) for all trials. The decomposition was performed conjointly for the cue and P conditions, as only ICs showing specific negativity in the cue condition fill the criteria of a CNV. To identify reactive ICs, the ICA was applied on ERP data in the NoGo condition for the 700 ms interval after the second stimulus. ICs with positivity in the time interval of the P3NoGo wave (230–480 ms) were then selected for further analysis. Hence, the input data for the ICA were the two two-dimensional matrixes (19 scalp locations × 193 ERP time series). Taking into account the sampling rate of 250 Hz, the first matrix included 19 rows and 53075 ($250 \times 1.1 \times 193$) columns, and the second matrix included 19 rows and 33775 ($250 \times 0.7 \times 193$) columns. Spatial filters for the selected independent components were obtained and further applied to individual ERPs of 28 participants in order to estimate the corresponding components in single individuals as described previously (Brunner et al., 2013).

2.6. Measurement of amplitude of ERP components

To measure the amplitude of ERPs, the relative criterion version of the fractional area (FA) approach was used for both ICs of P3NoGo. In the FA approach, the onset of the waveform is defined as the time point where the amplitude exceeds 50% of the peak-to-peak amplitude, and the offset is set to the time point where the amplitude reaches the same level as at onset. The amplitude of the ERP is then measured as the mean amplitude of the FA. (For illustration, see Brunner et al., 2013). The total time window for calculation of FA was limited to 230–410 ms for the IC $\text{P3NoGo}_{\text{early}}$ and 270–480 ms for the IC $\text{P3NoGo}_{\text{late}}$. For the IC $\text{CNV}_{\text{early}}$, the time-window of 600–900 ms after S1 was used to compute the mean amplitude of this component. This time-window was chosen based on a 300 ms time-interval around the peak amplitude of the group's averaged IC $\text{CNV}_{\text{early}}$. For IC CNV_{late}, the last 100 ms before the second stimulus was used for computing mean amplitude. Only the amplitudes of the ICs were used in the correlational analyses.

2.7. Statistics

All extracted data from ERPs and behavioral data were analyzed with IBM SPSS 19.0. Cronbach's α was used to measure internal consistency among the neuropsychological parameters within the domains. For investigating the relationship between ICs and neuropsychological test/domain scores, correlation analyses were performed (parametric Pearson's r or non-parametric Spearman's rho as appropriate). Correlations between domains and ICs were adjusted for multiple comparisons, as comparisons were made between all four ERP parameters and all three domains, even though explicit hypotheses were only formulated for five of these twelve comparisons. The False Discovery Rate (FDR) method was applied to correct for multiple comparisons (Benjamini and Hochberg, 1995). Correlations between each neuropsychological parameter within the domains and ICs were not adjusted for multiple comparisons, as these analyses were conducted post hoc to explore how each of the parameters contributed to the relations found on the level of the domain scores and help the interpretation of the global findings (Schochet, 2008). The correlations between CV and ICs and domains were also corrected for multiple comparisons using FDR correction, as the ROBBIA model does not specify clearly how this parameter is related to executive processes.

To control for possible effects of FS IQ or sub-domains of IQ on the ERP derived parameters, ICs and neuropsychological test scores, partial Pearson or Spearman correlations were used. Descriptive data are presented as mean/median and standard deviation (SD) or inter-quartile ranges (IQR).

3. Results

3.1. Neuropsychological data

3.1.1. Descriptive statistics

The demographic data and neuropsychological test scores for the group of 28 participants are presented in Table 1. Note that the age range for the group was only one year.

3.1.2. Correlations between neuropsychological parameters

Cronbach's α for the neuropsychological parameters within each domain were .77 for Task Setting, .65 for Energization, and .61 for Monitoring, indicating acceptable internal consistency. As a comparison to these alpha levels, we also calculated Cronbach's α on the 18 possible combinations of three test parameters from different domains, that is, one parameter from each domain. These results gave alpha values ranging from .26 to .61, with a mean alpha of .43 (SD=.11). Only one of these alpha values reached the level of the lowest alpha for the investigated domains, the domain consisting of only two parameters (monitoring).

The energization domain correlated significantly with FS IQ ($r=.54$ $p<.01$), as well as the sub indexes VCI ($r=.48$, $p<.01$), WMI ($r=.49$, $p<.01$) and PSI (rho=.58, $p<.01$). None of the other domain scores correlated significantly with FS IQ or any of the sub indexes. Correlations between IQ parameters and the specific neuropsychological parameters are presented in Table A1 in Appendix.

Table 1
Demographic and neuropsychological statistics.

	n	Mean/ median	SD/IQR	Range
Age (years)	28	22.7	0.6	21.6–22.7
Gender (F/M)	13/15			
Ethnicity, (Caucasian)	28			
Years of education	28	12.1	1.2	11–15
Cued RT (ms)	28	345	37	283–411
Design fluency task (raw score)	27	12.0	3.3	5–21
Phonemic fluency task (raw score)	27	39.4	11.4	21–62
d' in the cued Go/NoGo task[a]	28	0.99	0.02	0.9–1
d' in the Not-X CPT	27	2.75	0.89	1.2–4.2
Commission errors in Not-X CPT	27	16.29	8.46	2–32
Stroop III errors (raw score)[a]	28	2.0	2.0	0–5
Stroop IV errors (raw score)[a]	28	2.0	3.0	0–5
Commission errors in the cued Go/NoGo task	28	0.5	0.0	0–4
Omission errors in the cued Go/NoGo task[a]	28	3.0	6.0	0–6
Coefficient of variance (CV)[a]	28	20.0	3.4	14–33
WAIS-III full scale IQ	28	102.0	11.8	84–127
WAIS-III verbal comprehension domain	28	101.8	13.8	82–134
WAIS-III perceptual organization domain	28	110.1	12.9	88–130
WAIS-III Processing speed[a]	28	97.5	14.5	81–143
WAIS-III Working Memory Index	28	91.9	13.7	63–121

Descriptive statistics and neuropsychological test scores for the group of 28 subjects. For parametric variables, means and standard deviations (SD) are reported, while for non-parametric variables medians and inter-quartile ranges (IQR) are reported.

[a] Non-parametric variables.

3.2. Event-related potentials (ERP)

3.2.1. Grand average ERP WAVES

The grand average ERPs for the whole group of 193 subjects, which were only used to identify the ICs in the cued Go/NoGo task, are presented in Fig. 1b. Presentation of the cue (A) evoked a large, slow negative fluctuation preceding the second stimulus, which is a classic CNV wave. This CNV wave had a central–parietal distribution (see Fig. 1c). Go and NoGo stimuli presented as the second stimulus elicited the classic strong positive P3Go and NoGo waves with different peak latencies and distributions. The P3NoGo wave had a central–frontal distribution (in contrast to the central–parietal distribution of the P3Go wave) with a peak latency measured at 340 ms measured in Cz.

3.2.2. CNV independent components

Of the 19 ICs from the cue and P conditions, only three showed negativities that were more prominent in the cue as compared to P condition. Of these 3 components, one component was three times weaker in relative power as compared to the other two components (2.6% for the weakest component against 9.8% and 8.6% for the other two components) and was discarded from further analysis. The time courses and topographies of these two components are presented in Fig. 1d. One component (labeled IC $\text{CNV}_{\text{early}}$) had negativity with a maximum about 700 ms after the onset of stimulus 1 and a parietal distribution. The other component (labeled IC CNV_{late}) had a central–parietal distribution and the strongest negativity preceding the presentation of the second stimulus. In the subgroup of 28 individuals, the mean amplitude of the back projected IC $\text{CNV}_{\text{early}}$ was $-1.52\,\mu\text{V}$ (SD=1.06), while the mean amplitude of the back projected IC CNV_{late} was $-1.50\,\mu\text{V}$ (SD=0.8).

3.2.3. P3NoGo independent components

Application of ICA on the full sample of 193 individual ERPs in the 700 ms time interval after the second stimulus resulted in 19 ICs, whereof two components displayed positivity with onset and offset within the time interval of the P3NoGo wave (230–480 ms). The time courses and topographies of these two components are presented in Fig. 1e. The first component had a central distribution with a maximum peak at 330 ms, and will be referred to as the IC $\text{P3NoGo}_{\text{early}}$. The second component demonstrated a fronto-central distribution with later (about 380 ms) peak latency, and will be referred to as the IC $\text{P3NoGo}_{\text{late}}$. In the subgroup of 28 individuals, the median fractional area (FA) amplitude of the back projected IC $\text{P3NoGo}_{\text{early}}$ was 8.2 µV (IQR=7.3), while the median amplitude of the back projected IC $\text{P3NoGo}_{\text{late}}$ was 3.8 µV (IQR=2.1).

3.3. Correlations between neuropsychological and ERP data

3.3.1. Correlations between amplitudes of ICs and the domains

As shown in Table 2, the energization domain score correlated selectively with the IC $\text{P3NoGo}_{\text{early}}$ and the IC CNV_{late}. As was predicted, these ICs also correlated significantly with each other (rho=−.61 $p<.001$). The monitoring domain score correlated selectively with IC $\text{P3NoGo}_{\text{late}}$, while the task setting domain score correlated selectively with the IC CNV_{late}. The significance levels of the correlations between domains and ICs were not changed when controlling for Full scale IQ. The correlations between the ERP waves and the neuropsychological domains can be seen in Table A2 in Appendix.

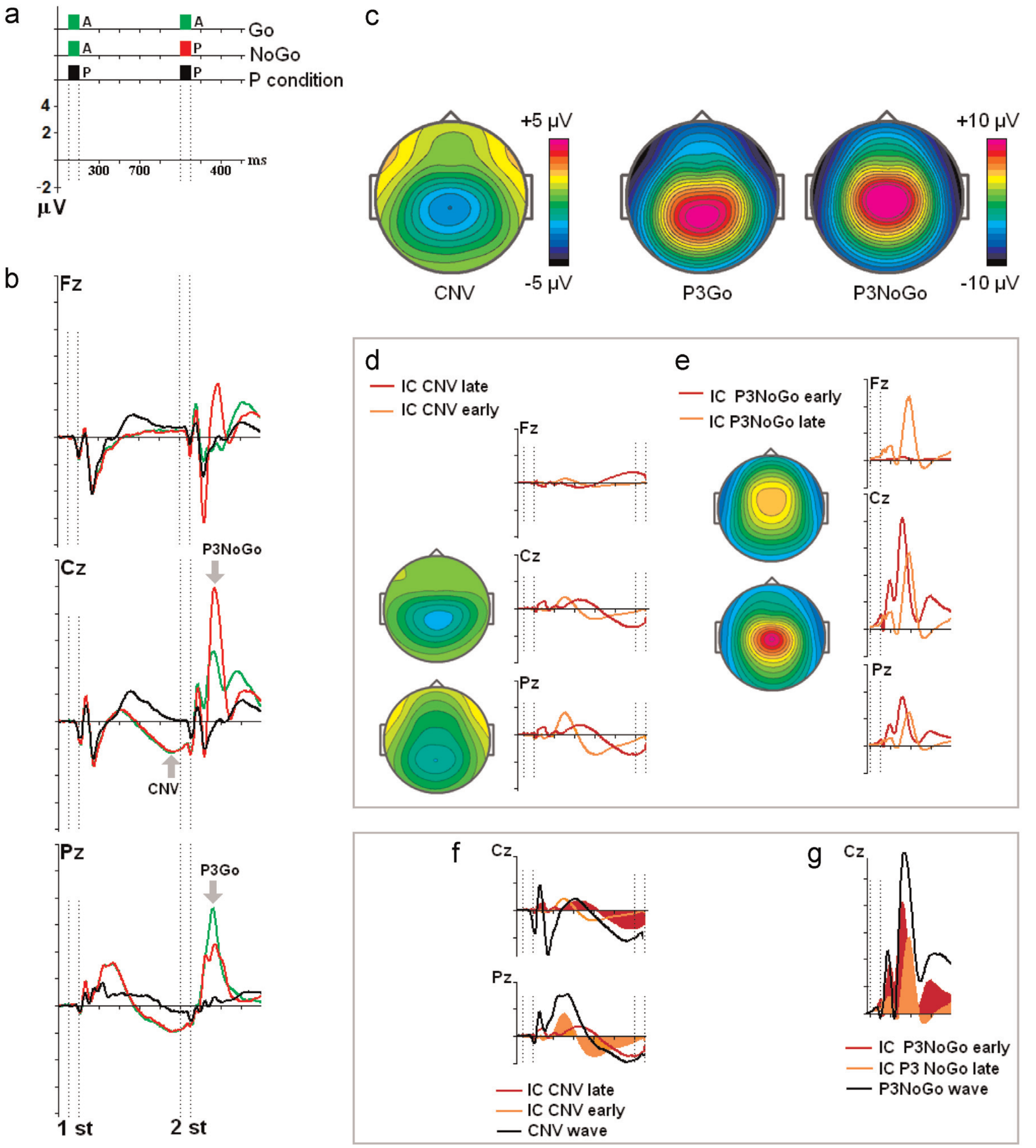


Fig. 1. Grand average ERP waves and independent components for the group of participants ($n = 193$) in the visual cued Go/NoGo task. (a) Schematic representation of the task. Images of animals (A) and plants (P) are presented in pairs. The subject's task is to press a button as fast as possible to A–A pairs (Go condition), and to withhold pressing to A–P pairs (NoGo condition). No preparation or response is required for trials starting with P. (b) ERP waves at Fz, Cz and Pz in Go, NoGo and P-conditions. *X*-axis – Time scale as in (a). *Y*-axis – amplitude in µV. (c) Maps of CNV, Go and NoGo waves taken at their extremes as indicated by arrows in (b). (d). The proactive independent components (ICs) back-projected to Fz, Cz and Pz for the 193 participants: IC $\text{CNV}_{\text{early}}$ and IC CNV_{late}. Left – topography, in the same scale as the CNV wave (± 5 µV). Right – time course. *X*-axis – Time scale as in (a). *Y*-axis – amplitude in µV. (e) The reactive ICs back-projected to Fz, Cz and Pz for the 193 participants: IC $\text{P3NoGo}_{\text{early}}$ and IC $\text{P3NoGo}_{\text{late}}$. Left – topography, in the same scale as the P3NoGo wave (± 10 µV). Right – time course. *X*-axis – Time scale as in (a). *Y*-axis – amplitude in µV. (f) Illustration of the timing and overlap of the CNV wave and ICs. (g) Illustration of the timing and overlap of the P3NoGo wave and ICs.

3.3.2. Correlations between ICs and neuropsychological task parameters

Correlations between ICs and the test parameters within each domain are presented in Table 3. The test parameters correlated significantly and selectively with the electrophysiological parameters in the same manner as for the domain scores. Indeed, all the three test parameters in the energization domain correlated significantly with the amplitude of IC $\text{P3NoGo}_{\text{early}}$ and IC CNV_{late}. The two *d′* values included in the monitoring domain correlated significantly and selectively with the amplitude of IC $\text{P3NoGo}_{\text{late}}$, and all the three the test parameters of the task-setting domain correlated significantly with the amplitude of IC CNV_{late}. Differentiation of phonemic fluency into time intervals revealed that the correlation between the IC $\text{P3NoGo}_{\text{early}}$ and the initial 15 s of Phonemic fluency was particularly strong.

As VCI correlated significantly with both IC $\text{P3NoGo}_{\text{early}}$ and phonemic fluency (see Table 3 and Table A in Appendix), VCI was controlled for in the correlational analyses. However, this did not alter the significance of the correlation between these parameters (partial rho$= -.58$, $p < .01$). Similarly, the phonemic fluency and IC $\text{P3NoGo}_{\text{early}}$ correlated significantly with PSI, but again controlling for PSI in the correlation did not change the significance of the correlation (rho$=.56$, $p < .01$).

Table 2
Correlations between independent component ERPs and neuropsychological domain scores.

	Energization	Monitoring	Task setting
IC $P3NoGo_{early}$[a]	$.78^{***}$ ($.69^{***}$)	.21 (.18)	.32 (.38)
IC $P3NoGo_{late}$[a]	.32 (.24)	$.56^{**}$ ($.54^{**}$)	.30 (.13)
IC CNV_{early}	−.25 (−.07)	.01 (.04)	−.03 (.06)
IC CNV_{late}	$-.72^{***}$ ($-.80^{***}$)	−.42 (.42)	$-.71^{***}$ ($-.71^{***}$)

Correlations between the neuropsychological domains of Energization, Monitoring and Task Setting and the independent component ERP amplitudes. The results are corrected for multiple comparisons using Benjamini–Hochberg FDR correction. In parentheses are the partial correlation coefficients when controlled for Full scale IQ. Pearson's or Spearman's correlations are reported as appropriate for parametric and non-parametric variables, respectively.

[a] Non-parametric variables.

** $p < .01$

*** $p < .001$

3.3.3. *Analyses of parameters not included in the domains*

CV was significantly correlated with IC CNV_{late} (rho=.65 $p < .001$), IC $P3NoGo_{early}$ (rho=−.39 $p < .05$) and IC $P3NoGo_{late}$ (rho=−.50 $p < .01$). CV also correlated significantly with all the domain indexes (Energization rho=−.68 $p < .001$, Monitoring rho=−58. $p < .001$ and Task setting rho=−.74 $p < .001$). All of these correlations were still significant ($p < .05$) after Benjamini–Hochberg FDR correction for multiple comparisons. When controlling for CV in the correlational analyses between domains and ICs, all correlations remained significant at the same level as before.

4. Discussion

The present study demonstrates that ICs from a cued Go/NoGo paradigm can be meaningfully associated with the processes of energization, monitoring and task setting as operationalized in the “ROBBIA” model. As predicted, the neuropsychological domain-score of energization correlated significantly with the amplitudes of IC CNV_{late} and IC $P3NoGo_{early}$. These components also correlated with each other, supporting the hypothesis of a common underlying process. We hypothesized that both ICs of CNV would correlate with domain scores of task setting. However, the task-setting domain-score was only correlated with the amplitude of IC CNV_{late}, and not with the IC CNV_{early}. Finally, the monitoring domain-score significantly correlated with the amplitude of the IC $P3NoGo_{late}$. The advantage of decomposing ERP waves into ICs was particularly evident in the observed relationship between the monitoring domain and the IC $P3NoGo_{late}$. This relationship was not detectable for the P3NoGo wave (for details, see Table A2 in Appendix).

4.1. *Energization*

According to its definition, energization cannot be measured directly, but only through its facilitating effects on other processes (Stuss and Alexander, 2007). In the “ROBBIA” model, energization is described as facilitation different from motivation, fatigue or drowsiness, which is believed to have more general effects on task performance (Stuss, 2006a; Stuss et al., 2005). We suggest differentiating motivation from energization by describing motivation as neural mechanisms effortlessly arousing an organism to act toward a desired goal, while energization is the ability to *voluntarily invest attentional effort* to optimize behavior for achieving a goal. As energization is needed for controlled initiation *and* maintenance of responses, we suggest referring to the initiation and maintaining aspects as reactive and proactive energization, respectively. In the present study the energization domain score correlated with IC CNV_{late} (a proactive and sustained process), as well as IC $P3NoGo_{early}$ (a reactive initiation process). Both proactive and reactive energization has been suggested to be important for the performance on fluency tasks (Robinson et al., 2012). In this study the first 15 s of phonemic fluency was more strongly correlated with the IC $P3NoGo_{early}$ than the last 15 s. This supports the hypothesis by Stuss (2006b) that the initial part of phonemic fluency being sensitive to initiation (reactive energization).

Table 3
Correlations between ERP amplitudes, neuropsychological test scores and IQ indexes.

		IC CNV_{early}	IC CNV_{late}	IC $P3NoGo_{early}$	IC $P3NoGo_{late}$
Energization	RT Cued Go	.36	$.49^{***}$	$-.70^{***}$	−.22
	Design fluency	−.02	$-.43^{*}$	$.40^{*}$	.24
	Phonemic fluency	−.31	$-.46^{*}$	$.66^{***}$	.17
	First 15 s	−.30	$-.43^{*}$	$.62^{***}$	.09
	Last 15 s	−.37	$-.43^{*}$	$.41^{*}$	.28
Monitoring	d' (Cued Go)	.07	−.18	.12	$.39^{*}$
	d' (Not-X CPT)	−.12	−.35	.13	$.62^{***}$
Task setting	Stroop III errors	−.01	$.68^{***}$	$-.45^{*}$	−.19
	Stroop IV errors	−.10	$.49^{**}$	−.16	−.19
	Not-X CPT Comm. errors	.10	$.59^{***}$	−.26	$-.51^{**}$
IQ WAIS III	VCI	−.32	.03	$.40^{*}$	.04
	POI	−.04	.12	.20	.02
	PSI	.05	−.19	$.42^{*}$	.26
	WMI	−.16	−.00	.37	$.39^{*}$
	Full scale IQ	−.35	.01	$.48^{**}$	.24

Correlations between the neuropsychological test parameters within each domain, and the ERP parameters from the 28 subjects. Pearson's or Spearman's correlations are reported as appropriate for parametric and non-parametric variables, respectively. RT=reaction time, VCI=verbal comprehension index (WAIS-III), POI=Perceptual organization index (WAIS-III), PSI=Processing speed index (WAIS-III), WMI=Working memory Index (WAIS-III). Significant correlations are marked by *.

* $p < .05$.

** $p < .01$

*** $p < .001$

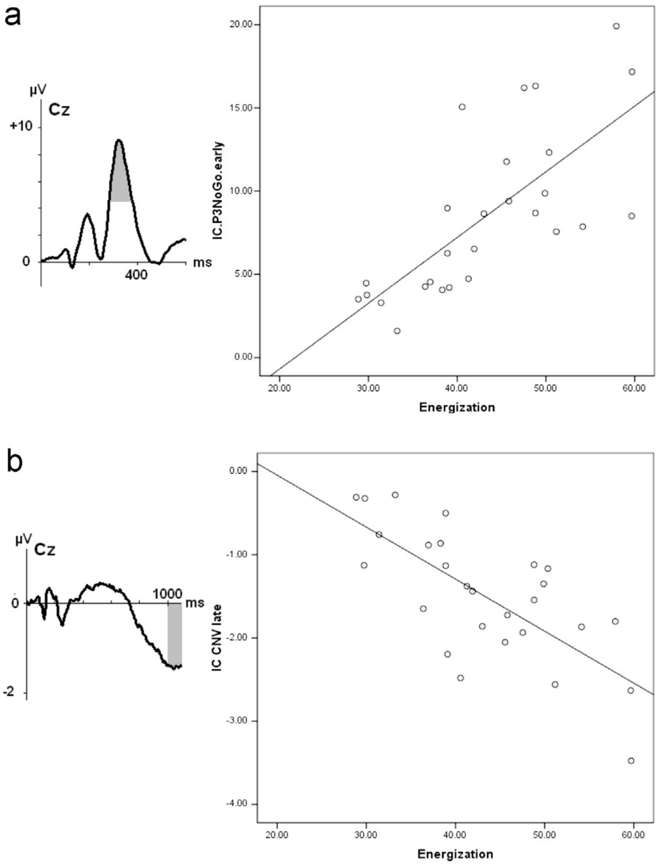


Fig. 2. Scatter-plots of the relationship between the neuropsychological domain of energization and the amplitude of the independent components P3NoGo$_{early}$ and CNVlate in the group of participants (n=28). (a) Left: time course of the grand average back-projected IC P3NoGo$_{early}$ for the group of 28 participants. The gray area on depicts the area for calculation of the FA amplitude of the component. Right: Scatter-plot with energization domain scores (X-axis), and amplitudes of the IC P3NoGo$_{early}$ (Y-axis). Each dot corresponds to one individual. (b) Left: Time course of the grand average back-projected IC CNV$_{late}$ for the group of 28 participants. The gray area depicts the time window for averaging the amplitude of the component. Right: scatter-plot with energization domain scores (X-axis), and amplitudes of the IC CNV$_{late}$ (Y-axis).

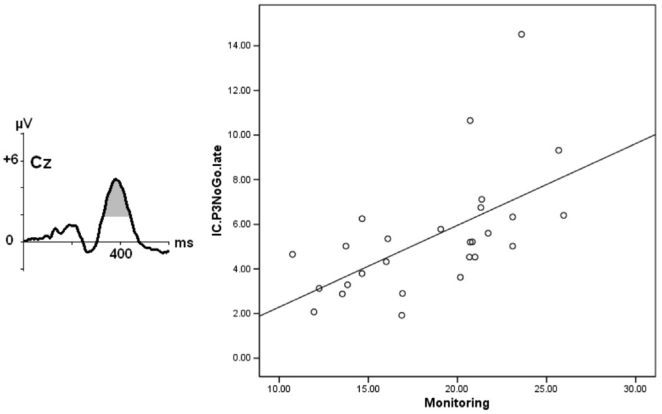


Fig. 3. Scatter-plots of the relationship between the neuropsychological domain of monitoring and the amplitude of the P3NoGo$_{late}$ independent component in the group of participants (n=28). Left: Time course of the grand average back-projected IC P3NoGo$_{late}$ for the group of 28 participants. The gray area on depicts the area for calculation of the FA amplitude of the component. Right: Scatter-plot with monitoring domain scores (X-axis), and amplitudes of the IC P3NoGo$_{late}$ (Y-axis). Each dot corresponds to one individual.

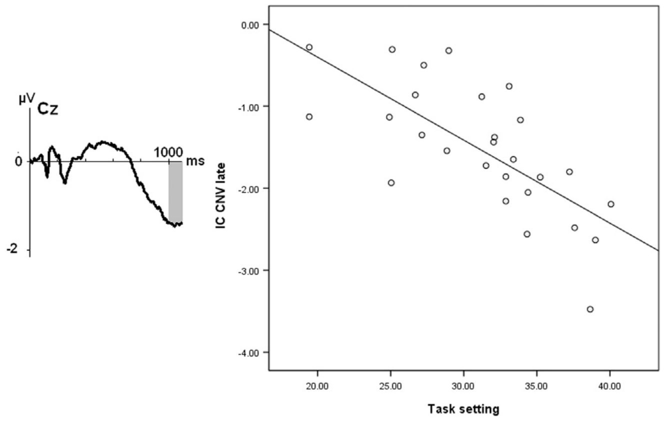


Fig. 4. Scatter-plots of the relationship between the neuropsychological domain of task setting and the amplitude of the CNV$_{late}$ independent component in the group of participants (n=28). Scatter-plot of task setting domain scores (X-axis) and amplitudes of the IC CNV$_{late}$ (Y-axis). Each dot corresponds to one individual.

4.2. Task-setting

The task-setting domain score correlated significantly with the amplitude of the IC CNV$_{late}$, but not the IC CNV$_{early}$. This is in line with research indicating that the late CNV wave reflects specification of the contingency templates, or schema, for when and how to respond to the upcoming stimuli (Boehm et al., 2014; Brunia et al., 2012). The results in the present study also support the previous finding by Padilla et al. (2006) that a low-amplitude late CNV wave predicted false positive errors. They also suggested that the late CNV wave is responsible for generating the context-dependent representations of the stimulus–response associations.

The IC CNV$_{early}$ did not correlate significantly with any of the investigated neuropsychological parameters, indicating that this component reflects other processes than investigated in this study. Previous studies have indicated that CNVs presenting with the strongest negativities early in the inter-stimulus interval may be related to encoding and memory processes (Bender et al., 2012; Rohrbaugh et al., 1997; Ruchkin et al., 1997).

4.3. Monitoring

Action monitoring is needed in all situations where non-routine actions are performed, and where errors are likely to occur. In ERP research there are at least four ERP waveforms suggested to reflect different aspects of monitoring: error related negativity and positivity, N2 and P3NoGo waves. The P3NoGo wave has been suggested to represent monitoring of successful inhibitions (Bruin et al., 2001; Roche et al., 2005; Schmajuk et al., 2006; Sehlmeyer et al., 2010). The present study supports the monitoring hypothesis of the P3NoGo wave by identifying one of the ICs (IC P3NoGo$_{late}$) as being specifically related to how well the participants behaviorally differentiated targets from non-targets (d'). We have previously shown that the latencies of the two P3NoGo ICs strongly correlate with each other, with the IC P3NoGo$_{early}$ always preceding the IC P3NoGo$_{late}$ (Brunner et al., 2013). This temporal relationship between the two components supports the idea that they reflect consecutive processes, where the IC P3NoGo$_{late}$ reflects monitoring of the process reflected in the preceding IC P3NoGo$_{early}$.

In the “ROBBIA” model, energization is argued to facilitate other SAS processes. However, in the present study there was no correlation between the monitoring and energization domains. There was also no correlation between the IC P3NoGo$_{late}$ and the energization domain or any of the task parameters included in this domain. In other words, the present data indicate that the monitoring process might not be modulated by energization, but rather through some other mechanism. For instance, studies on action monitoring have often focused on possible relations to emotional rather than effortful processes (Ichikawa et al., 2011; Sehlmeyer et al., 2010). Future experimental studies should be designed to investigate modulators of the monitoring process and IC $\text{P3NoGo}_{\text{late}}$.

In sum, the present study has revealed meaningful relations between the processes described in the "ROBBIA" model and independent component ERPs from a cued Go/NoGo paradigm. These results do, however, raise several questions regarding how the correlations between the specific neuropsychological parameters and ICs should be interpreted.

4.4. The IC P3NoGo_{early} – controlled implementation of an alternative response

The first question to consider is what kind of process the IC $\text{P3NoGo}_{\text{early}}$ may reflect. As mentioned in the introduction, the support for the inhibition hypothesis of the P3NoGo wave is rather sparse. The IC $\text{P3NoGo}_{\text{early}}$ also appears too late to reflect inhibition, a point that has also been made for the P3NoGo wave (Gajewski and Falkenstein, 2013). In the present study, there was no significant correlation between the amplitude of the IC $\text{P3NoGo}_{\text{early}}$ and the amount of commission errors in the not-X CPT, a parameter assumed to index failed inhibition. This finding further weakens the inhibition hypothesis of IC $\text{P3NoGo}_{\text{early}}$. In the NoGo condition several process may occur sequentially. First, the response-conflict must be detected. Secondly, the prepared task set must be overridden and replaced by an alternative task set, enabling initiation of a correct response (the non-response) in the NoGo condition. Finally, the outcome of the chosen action must be monitored. The difficulty of separating these processes is illustrated by studies showing that the neural circuits required to initiate controlled, non-prepared actions are similar to those previously shown to mediate response inhibition (Fleming et al., 2010).

Provided that the IC $\text{P3NoGo}_{\text{early}}$ reflects the controlled implementation of an alternative response, there are other common processes than energization that could drive the correlations found between the IC $\text{P3NoGo}_{\text{early}}$ and the fluency tasks. In particular, three processes have recently been proposed to be important for performance on fluency tasks: selection, creation of novel responses and energization (Robinson et al., 2012). A selection process in phonemic fluency can be activated because *multiple* verbal responses are linked to the same cue, and so compete for generation. This competition between response alternatives may also be an issue in the cued Go/NoGo task, although only two response alternatives compete. A closer parallel to the cued Go/NoGo task could be the demand to overcome pre-potent responses. The phonemic fluency task demands overcoming the pre-potent and routine generation of language based on semantic relations. In this sense, phonemic fluency demands the voluntary and controlled implementation of alternative responses, corresponding to the suggested process reflected in the IC $\text{P3NoGo}_{\text{early}}$. In design fluency, on the other hand, there is no pre-potent response pattern, but rather a creation of novel responses. In the present study, a stronger correlation was found between the IC $\text{P3NoGo}_{\text{early}}$ and phonemic as compared to design fluency, perhaps because of fewer common underlying factors.

4.5. Task setting-IC CNVlate and fluency tasks

Another question concerns whether some other process than energization can drive the correlations between IC CNV_{late} and the fluency tasks. The main task-set in phonemic fluency is formed by instructions given to the individual (say as many words as possible beginning with the given letter, except proper nouns, numbers, and the same word with a different suffix). The use of organized search strategies like clustering (generation of words from the same phonemic or semantic sub-category) seems to increase performance on this task (Troyer et al., 1997). In a study by Unsworth et al. (2011) switching between clusters was the most important factor explaining performance in the phonemic fluency task. These clustering strategies are self-generated and can be regarded as sub-task-sets (e.g. phonological or semantic clustering). If the ability to quickly form new task sets is a central contributor to fluency performance, it is possible that this, rather than energization, may be the factor driving the correlation between the IC CNV_{late} and fluency tasks.

4.6. Do we need energization to explain the correlations?

The preceding two questions lead us to ask whether the concept of a facilitating process like energization is necessary to explain the findings in the present study. As indicated, other common processes than energization can explain the correlations between the two ICs and fluency tasks, possibly rendering the concept of energization redundant. In the "ROBBIA" model, slowing in RT is regarded as a core index of decreased energization. A close relationship between RT and effort is shown in many experimental studies where RT can easily be decreased by instructing participants to invest more effort in responding as fast as possible (Carrillo-de-la-Peña and Cadaveira, 2000; Falkenstein et al., 2003; Forstmann et al., 2008). As it is possible to influence RT by voluntary effort, a neural process mediating this optimization must necessarily exist. Without such a facilitating process, the individual would not be capable of adjusting performance in concordance with changing demands. The IC $\text{P3NoGo}_{\text{early}}$ and the IC CNV_{late} both correlate strongly with RT. This is in line with several earlier ERP studies for the corresponding waves. The amplitude of the late CNV wave has been shown to increase when participants receive instructions to invest more effort in speeding up responses (Brunia and Vingerhoets, 1980; Loveless and Sanford, 1974; Verleger et al., 2000). As participants are able to voluntarily adapt to these instructions and, through this, achieve direct modulation of the process reflected in the late CNV wave amplitude, it is reasonable to assume the presence of an effortful modulating process like energization. The P3NoGo wave has been demonstrated to have higher amplitude in fast as compared to slow responders (Smith et al., 2006), although the intra-individual effects of instructions to speed up on the amplitude of the P3NoGo wave or ICs have not yet been investigated. However, without manipulating instructions to speed up, a test–retest study showed that the change in RT had a significant negative correlation to the change in amplitude of the IC $\text{P3NoGo}_{\text{early}}$ between two recordings (Brunner et al. 2013).

In sum, we consider energization to be a necessary and well-suited concept when interpreting the inter-correlation between fluency tasks, RT and the two ICs. It is increasingly recognized that it is important to consider the influence of effort (energization) when interpreting both neuropsychological and neurophysiological data (An et al., 2012; Bigler, 2012; Falkenstein et al., 2003).

4.7. Can IQ or sub-indexes of IQ explain the results?

The P3NoGo and CNV waves have not previously been correlated with IQ or subscales of IQ, although the P3NoGo wave has been found to have higher amplitude in people with higher education and IQ (Hillman et al., 2012; Liu et al., 2011). Correlations between the subtests within the energization domain, and full- and sub-indexes of IQ have been found in several studies (Ardila et al., 2000; Cauthen, 1978; Ojeda et al., 2010). In the present study, both the energization domain and the IC $\text{P3NoGo}_{\text{early}}$

correlated significantly with FS IQ, VCI and PSI. None of the other ICs were significantly correlated with FS IQ or the sub-indexes, except the IC $\text{P3NoGo}_{\text{late}}$, which was significantly correlated with WMI. Therefore, to rule out the possibility of IQ being a third variable explaining the present findings, it was important to control for IQ indexes in the correlation analysis, especially for the correlation between energization and IC $\text{P3NoGo}_{\text{early}}$. However, this did not change the significance levels of the correlations between any of the ICs and domains.

4.8. Can fatigue explain the present findings?

Whether considering mean RT, the number of errors or successful responses in a task, most of the neuropsychological task parameters included in the present study are the result of performance over time. Both efficiency and error rate parameters have previously been shown influenced by fatigue (Barwick et al., 2012). Similarly, the investigated ERPs are the result of averaged neural activations in response to stimuli in a task lasting 20 min, and both the late CNV and P3NoGo waves have been shown to decrease in amplitude with prolonged time on task (Boksem et al., 2006; Kato et al., 2009; Lorist et al., 2000). Individual differences in fatigue could therefore be a factor driving some of the present correlations. Fatigue is proposed to weaken the SAS processes (Norman and Shallice, 1986), and reduce task performance (Stuss et al., 2005). However, no specific neuropsychological parameter has been proposed to index fatigue in the "ROBBIA" model. On the basis of the results from the present study, we suggest the CV parameter to be a good candidate. In line with a factor having generalized effects on performance, CV correlated significantly with three of the four investigated ICs, as well as all the investigated domains. Support for a relation between fatigue and CV also comes from studies showing that CV is especially sensitive to the effect of prolonged time on task, more so than mean RT and error percentage (Kato et al., 2009; Steinborn et al., 2010; Wang et al., 2014). Considering the ERPs, the correlation between CV and IC CNV_{late} was particularly strong, supporting similar findings for the late CNV wave (Segalowitz et al., 1997). The interpretation of the IC CNV_{late} as a reflection of the process of maintaining (energizing) the task set over time is strengthened by the demonstration of this ERP being especially related to fatigue as indexed by CV.

As CV correlated significantly with all the domains and three of the four ICs in the present study, it can be argued that CV should be controlled for in the correlation analysis between ICs and domains. However, when this was performed in the present study, all correlations mentioned above remained at the same level of significance.

4.9. Strengths and limitations of the present study

A particular strength of the present study was the normal distribution of educational level and IQ in the sub group of 28 participants. This is potentially very important, since indexes of executive processes, including ERP parameters, seem to be better in people with higher education and IQ (Hillman et al., 2012; Liu et al., 2011). A more restricted population, such as university students, would therefore most likely have a more limited variation in parameters indexing executive processes. It should also be noted that studies have indicated age related changes in ERPs in cued Go/NoGo paradigms (Hammerer et al., 2010), as well as for neuropsychological task parameters that were included in the present study (Cona et al., 2013; Rodriguez-Aranda and Martinussen, 2006; Van der Elst et al., 2006). The low age variance in the present study (1 year) allowed us not to control for age.

The neuropsychological task parameters making up the three domains were based on the ROBBIA model, and not on psychometrical properties like for instance factor structure. Due to the low number of participants in the present study, confirmatory factor analysis to support the domains derived from the theory was not appropriate. The lack of such an analysis limits the possibility of concluding that the grouping of test parameters according to the ROBBIA model actually gives a good fit to the observed data. To obtain an indication of internal consistency given the low number of participants, Cronbach's α was calculated for the parameters within each domain. Cronbach's α as a measure of internal consistency has limitations as it depends not only on the *magnitude* of the correlations among parameters within a domain, but also on the *number* of parameters in the domain, with domains comprising a large number of parameters more easily achieving higher α (Streiner and Norman, 2003). This is particularly evident for the monitoring domain, which only consisted of two parameters. Although not strong, Cronbach's α for the three domains still indicated acceptable internal consistency (Nunnally, 1978), and was comparable to those generally found in studies using executive tasks (Burgess, 1997). Moreover, some indirect support for the grouping of test parameters in the present study was found, as Cronbach's α was considerably lower when calculated across domains than within domains.

Generally, the present study would profit from including more of the neuropsychological task parameters used in the original ROBBIA studies as well as a higher number of participants. As already discussed, while the results demonstrated that that ERP independent components selectively correlate with indexes of neuropsychological domains, only an experimental study systematically manipulating task- and situational variables would make it possible to for example investigate to what degree energization can modulate the involved processes (ICs) to optimize behavior/task performance.

5. Conclusion

This is the first study to demonstrate that neuropsychological task parameters indexing executive processes are closely associated with independent component ERPs from a cued Go/NoGo task. These results could only be achieved through a solid neuropsychological model specifying task parameters, application of ERP paradigm suggested to be sensitive to the same processes, as well as decomposition of ERP waves into independent components. Although there are limitations to correlational analyses, the present results are promising with regard to identifying meaningful links between electrophysiological and neuropsychological measures. These findings should be further explored through experimental studies with the possibility of testing the specific hypotheses and relations suggested here. Figs. 2–4

Acknowledgments

The Liaison Committee between the Central Norway Regional Authority (RHA) and the Norwegian University of Science and Technology (NTNU) funded this work.

Appendix

See Table A1 and Table A2.

Table A1
Correlations between IQ-parameters and the neuropsychological test scores.

	RT Cued Go	Phonemic fluency	Design fluency	d' Cued Go	d' Not-X CPT	Stroop III errors	Stroop IV errors	Not-X CPT Comm. errors
VCI	−.45*	.52**	.19	.02	−.05	−.23	.06	.07
POI	−.26	.12	.40*	.09	−.14	.04	.39*	.24
PSI	−.36	.50**	.46*	.36	.19	−.25	−.14	−.25
WMI	−.28	.46*	.30	.21	−.06	−.00	−.04	−.09
Full scale IQ	−.46*	.43*	.32	.15	−.05	−.21	.07	.03

Correlations between IQ parameters and the neuropsychological test scores from the 28 participants. Pearson's or Spearman's correlations are reported as appropriate for parametric and non-parametric variables, respectively. RT=reaction time; VCI=verbal comprehension index (WAIS-III), POI=Perceptual organization index (WAIS-III); PSI=Processing speed index (WAIS-III); WMI=Working memory Index (WAIS-III). Significant correlations are marked by *.

* $p < .05$.
** $p < .01$

Table A2
Correlations between neuropsychological domains and ERP waves and ICs.

	Energization	Monitoring	Task setting
P3NoGo wave	.77*** (.71***)	.22 (.20)	.33 (.35)
IC $\text{P3NoGo}_{\text{early}}$	.78*** (.69***)	.21 (.18)	.32 (.38)
IC $\text{P3NoGo}_{\text{late}}$	.32 (.24)	.56 **(.54**)	.30 (.13)
CNV wave	−.74*** (−.71***)	−.28 (−.26)	−.52* (−.53*)
IC $\text{CNV}_{\text{early}}$	−.25 (−.07)	.01 (.04)	−.03 (.06)
IC CNV_{late}	−.72*** (−.80***)	−.42 (.42)	−.71*** (−.71***)

Results after Benjamini–Hochberg FDR correction for multiple comparisons. Values in parentheses are results after controlling for full scale IQ.

* $p < .05$.
** $p < .01$
*** $p < .001$

References

Alexander, M.P., Stuss, D.T., Picton, T., Shallice, T., Gillingham, S., 2007. Regional frontal injuries cause distinct impairments in cognitive control. Neurology 68, 1515–1523. http://dx.doi.org/10.1212/01.wnl.0000261482.99569.fb.

Alexander, M.P., Stuss, D.T., Shallice, T., Picton, T.W., Gillingham, S., 2005. Impaired concentration due to frontal lobe damage from two distinct lesion sites. Neurology 65, 572–579. http://dx.doi.org/10.1212/01.wnl.0000172912.07640.92.

An, K.Y., Zakzanis, K.K., Joordens, S., 2012. Conducting research with non-clinical healthy undergraduates: does effort play a role in neuropsychological test performance? Arch. Clin. Neuropsychol. 27, 849–857. http://dx.doi.org/10.1093/arclin/acs085.

Ardila, A., Pineda, D., Rosselli, M., 2000. Correlation between intelligence test scores and executive function measures. Arch. Clin. Neuropsychol. 15, 31–36. http://dx.doi.org/10.1016/s0887-6177(98)00159-0.

Barwick, F., Arnett, P., Slobounov, S., 2012. EEG correlates of fatigue during administration of a neuropsychological test battery. Clin. Neurophysiol. 123, 278–284. http://dx.doi.org/10.1016/j.clinph.2011.06.027.

Bender, S., Rellum, T., Freitag, C., Resch, F., Rietschel, M., Treutlein, J., Laucht, M., 2012. Time-resolved influences of functional DAT1 and COMT variants on visual perception and post-processing. PLoS One 7, e41552. http://dx.doi.org/10.1371/journal.pone.0041552.

Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc. Ser. B Methodol. 57, 289–300.

Bigler, E.D., 2012. Symptom validity testing, effort, and neuropsychological assessment. J. Int. Neuropsychol. Soc. 18, 632–640. http://dx.doi.org/10.1017/s1355617712000252.

Boehm, U., van Maanen, L., Forstmann, B., van Rijn, H., 2014. Trial-by-trial fluctuations in CNV amplitude reflect anticipatory adjustment of response caution. Neuroimage 96, 95–105. http://dx.doi.org/10.1016/j.neuroimage.2014.03.063.

Boksem, M.A., Meijman, T.F., Lorist, M.M., 2006. Mental fatigue, motivation and action monitoring. Biol. Psychol. 72, 123–132. http://dx.doi.org/10.1016/j.biopsycho.2005.08.007.

Braver, T.S., 2012. The variable nature of cognitive control: a dual mechanisms framework. Trends Cognit. Sci. 16, 106–113. http://dx.doi.org/10.1016/j.tics.2011.12.010.

Braver, T.S., Gray, J.R., Burgess, G.C., 2007. Explaining the many varieties of working memory variation: dual mechanisms of cognitive control. In: Conway, A., Jarrold, C., Kane, M., Miyake, A., Towse, J. (Eds.), Variation in Working Memory. Oxford University Press, St. Louis, MO, pp. 76–106.

Bruin, K.J., Wijers, A.A., van Staveren, A.S., 2001. Response priming in a go/nogo task: do we have to explain the go/nogo N2 effect in terms of response activation instead of inhibition? Clin. Neurophysiol. 112, 1660–1671. http://dx.doi.org/10.1016/s1388-2457(01)00601-0.

Brunia, C.H., van Boxtel, G.J., 2001. Wait and see. Int. J. Psychophysiol. 43, 59–75. http://dx.doi.org/10.1016/s0167-8760(01)00179-9.

Brunia, C.H., van Boxtel, G.J., Böcker, B.E., 2012. Negative slow waves as indices of anticipation. In: Steven, J. Luck, Kappenman, Emily S. (Eds.), Oxford handbook of Event-Related Potentials. Oxford University Press, New York, pp. 189–209.

Brunia, C.H., Vingerhoets, A.J., 1980. CNV and EMG preceding a plantar flexion of the foot. Biol. Psychol. 11, 181–191. http://dx.doi.org/10.1016/0301-051(80)90054-X.

Brunner, J.F., Hansen, T.I., Olsen, A., Skandsen, T., Haberg, A., Kropotov, J., 2013. Long-term test-retest reliability of the P3 NoGo wave and two independent components decomposed from the P3 NoGo wave in a visual Go/NoGo task. Int. J. Psychophysiol. 89, 106–114. http://dx.doi.org/10.1016/j.ijpsycho.2013.06.005.

Burgess, P.W., 1997. Theory and methodology in executive function research. In: Rabbitt, P. (Ed.), Methodology of Frontal and Executive Functions. Psychology Press, Hove, UK.

Carrillo-de-la-Peña, M.T., Cadaveira, F., 2000. The effect of motivational instructions on P300 amplitude. Neurophysiol. Clin. 30, 232–239. http://dx.doi.org/10.1016/s0987-7053(00)00220-00223.

Cauthen, N.R., 1978. Verbal fluency: normative data. J. Clin. Psychol. 34, 126–129.

Chen, T., Li, D., 2007. The roles of working memory updating and processing speed in mediating age-related differences in fluid intelligence. Aging Neuropsychol. Cognit.: A J. Norm. Dysfunct. Dev. 14, 631–646. http://dx.doi.org/10.1080/13825580600987660.

Clayson, P.E., Larson, M.J., 2012. Cognitive performance and electrophysiological indices of cognitive control: a validation study of conflict adaptation. Psychophysiology 49, 627–637. http://dx.doi.org/10.1111/j.1469-8986.2011.01345.x.

Cona, G., Arcara, G., Amodio, P., Schiff, S., Bisiacchi, P.S., 2013. Does executive control really play a crucial role in explaining age-related cognitive and neural differences? Neuropsychology 27, 378–389. http://dx.doi.org/10.1037/a0032708.

Conners, C.K., Epstein, J.N., Angold, A., Klaric, J., 2003. Continuous performance test performance in a normative epidemiological sample. J. Abnorm. Child Psychol. 31, 555–562 (Retrieved from)⟨http://search.proquest.com/docview/204985614?accountid=12870⟩.

Criaud, M., Boulinguez, P., 2013. Have we been asking the right questions when assessing response inhibition in go/no-go tasks with fMRI? A meta-analysis and critical review. Neurosci. Biobehav. Rev. 37, 11–23. http://dx.doi.org/10.1016/j.neubiorev.2012.11.003.

Delis, D.C., Kaplan, E., Kramer, J.H., 2001. D-KEFS; Delis-Kaplan Executive Function System: Technical Manual. Harcourt Assessment Company, San Antonio, TX.

Falkenstein, M., Hoormann, J., Hohnsbein, J., Kleinsorge, T., 2003. Short-term mobilization of processing resources is revealed in the event-related potential. Psychophysiology 40, 914–923. http://dx.doi.org/10.1111/1469-8986.00109.

Fallgatter, A.J., Strik, W.K., 1999. The NoGo-anteriorization as a neurophysiological standard-index for cognitive response control. Int. J. Psychophysiol. 32, 233–238. http://dx.doi.org/10.1016/s0167-8760(99)00018-5.

Fleming, S.M., Thomas, C.L., Dolan, R.J., 2010. Overcoming status quo bias in the human brain. Proc. Natl. Acad. Sci. U.S.A. 107, 6005–6009. http://dx.doi.org/10.1073/pnas.0910380107.

Forstmann, B.U., Dutilh, G., Brown, S., Neumann, J., von Cramon, D.Y., Ridderinkhof, K.R., Wagenmakers, E.J., 2008. Striatum and pre-SMA facilitate decision-making under time pressure. Proc. Natl. Acad. Sci. U.S.A. 105, 17538–17542. http://dx.doi.org/10.1073/pnas.0805903105.

Gajewski, P.D., Falkenstein, M., 2013. Effects of task complexity on ERP components in Go/Nogo tasks. Int. J. Psychophysiol. 87, 273–278. http://dx.doi.org/10.1016/j.ijpsycho.2012.08.007.

Hammerer, D., Li, S.C., Muller, V., Lindenberger, U., 2010. An electrophysiological study of response conflict processing across the lifespan: assessing the roles of conflict monitoring, cue utilization, response anticipation, and response suppression. Neuropsychologia 48, 3305–3316. http://dx.doi.org/10.1016/j.neuropsychologia.2010.07.014.

Hillman, C.H., Pontifex, M.B., Motl, R.W., O'Leary, K.C., Johnson, C.R., Scudder, M.R., Castelli, D.M., 2012. From ERPs to academics. Dev. Cognit. Neurosci. 2 (Suppl 1), S90–S98. http://dx.doi.org/10.1016/j.dcn.2011.07.004.

Huster, R.J., Enriques-Geppert, S., Lavallee, C.F., Falkenstein, M., Herrmann, C.S., 2013. Electroencephalography of response inhibition tasks: Functional networks and cognitive contributions. Int. J. Psychophysiol. 87, 217–233. http://dx.doi.org/10.1016/j.ijpsycho.2012.08.001.

Ichikawa, N., Siegle, G.J., Jones, N.P., Kamishima, K., Thompson, W.K., Gross, J.J., Ohira, H., 2011. Feeling bad about screwing up: emotion regulation and action monitoring in the anterior cingulate cortex. Cognit. Affect. Behav. Neurosci. 11, 354–371. http://dx.doi.org/10.3758/s13415-011-0028-z.

Isoda, M., Hikosaka, O., 2007. Switching from automatic to controlled action by monkey medial frontal cortex. Nat. Neurosci. 10, 240–248. http://dx.doi.org/10.1038/nn1830.

Jervis, B., Belal, S., Camilleri, K., Cassar, T., Bigan, C., Linden, D.E., Muscat, J., 2007. The independent components of auditory P300 and CNV evoked potentials derived from single-trial recordings. Physiol. Meas. 28, 745–771. http://dx.doi.org/10.1088/0967-3334/28/8/001.

Jung, T.P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., Sejnowski, T.J., 2000. Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. Clin. Neurophysiol. 111, 1745–1758. http://dx.doi.org/10.1016/s1388-2457(00)00386-2.

Kappenman, Emily S., Luck, Steven J., 2012. ERP Components: the ups and downs of brainwave recordings. In: Steven, J. Luck, Kappenman, Emily S. (Eds.), The Oxford Handbook of Event-Related Potential Components. Oxford UNiversity Press, New York, NY, pp. 3–30.

Kato, Y., Endo, H., Kizuka, T., 2009. Mental fatigue and impaired response processes: event-related brain potentials in a Go/NoGo task. Int. J. Psychophysiol. 72, 204–211. http://dx.doi.org/10.1016/j.ijpsycho.2008.12.008.

Kok, A., Ramautar, J.R., De Ruiter, M.B., Band, G.P., Ridderinkhof, K.R., 2004. ERP components associated with successful and unsuccessful stopping in a stop-signal task. Psychophysiology 41, 9–20. http://dx.doi.org/10.1046/j.1469-8986.2003.00127.x.

Kray, J., Eppinger, B., Mecklinger, A., 2005. Age differences in attentional control: an event-related potential approach. Psychophysiology 42, 407–416. http://dx.doi.org/10.1111/j.1469-8986.2005.00298.x.

Kropotov, J.D., Ponomarev, V.A., 2009. Decomposing N2 NOGO wave of event-related potentials into independent components. Neuroreport 20, 1592–1596. http://dx.doi.org/10.1097/WNR.0b013e3283309cbd.

Kropotov, J.D., Ponomarev, V.A., Hollup, S., Mueller, A., 2011. Dissociating action inhibition, conflict monitoring and sensory mismatch into independent components of event related potentials in GO/NOGO task. Neuroimage 57, 565–575. http://dx.doi.org/10.1016/j.neuroimage.2011.04.060.

Lamm, C., Zelazo, P.D., Lewis, M.D., 2006. Neural correlates of cognitive control in childhood and adolescence: disentangling the contributions of age and executive function. Neuropsychologia 44, 2139–2148. http://dx.doi.org/10.1016/j.neuropsychologia.2005.10.013.

Larson, M.J., Clayson, P.E., 2011. The relationship between cognitive performance and electrophysiological indices of performance monitoring. Cognit. Affect. Behav. Neurosci. 11, 159–171. http://dx.doi.org/10.3758/s13415-010-0018-6.

Liu, T., Xiao, T., Shi, J., Zhao, D., 2011. Response preparation and cognitive control of highly intelligent children: a Go-Nogo event-related potential study. Neuroscience 180, 122–128. http://dx.doi.org/10.1016/j.neuroscience.2011.02.022.

Lorist, M.M., Klein, M., Nieuwenhuis, S., De Jong, R., Mulder, G., Meijman, T.F., 2000. Mental fatigue and task control: planning and preparation. Psychophysiology 37, 614–625. http://dx.doi.org/10.1111/1469-8986.3750614.

Loveless, N.E., Sanford, A.J., 1974. Slow potential correlates of preparatory set. Biol. Psychol. 1, 303–314. http://dx.doi.org/10.1016/0301-0511(74)90005-2.

Makeig, S., Onton, J., 2012. ERP features and EEG dynamics: an ICA perspective. In: Steven, J. Luck, Kappenman, Emily S. (Eds.), The Oxford Handbook of Event-Related Potentials. Oxford University Press, New York, pp. 51–86.

Miyake, A., Friedman, N.P., 2012. The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions. Curr. Dir. Psychol. Sci. 21, 8–14. http://dx.doi.org/10.1177/0963721411429458.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.D., 2000. The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: a latent variable analysis. Cognit. Psychol. 41, 49–100. http://dx.doi.org/10.1006/cogp.1999.0734.

Norman, D.A., Shallice, T., 1986. Attention to Action: Willed and Automatic Control of Behaviour. 4. Plenum, New York.

Nunnally, J.C., 1978. Psychometric Theory. McGraw-Hill, New York.

Ojeda, N., Sanchez, P., Pena, J., Elizagarate, E., Yoller, A.B., Larumbe, J., Ezcurra, J., 2010. Verbal fluency in schizophrenia: does cognitive performance reflect the same underlying mechanisms in patients and healthy controls? J. Nerv. Ment. Dis. 198, 286–291. http://dx.doi.org/10.1097/NMD.0b013e3181d61748.

Olbrich, H.M., Maes, H., Valerius, G., Langosch, J.M., Gann, H., Feige, B., 2002. Assessing cerebral dysfunction with probe-evoked potentials in a CNV task – a study in alcoholics. Clin. Neurophysiol. 113, 815–825. http://dx.doi.org/10.1016/s1388-2457(02)00060-3.

Olsen, A., Brunner, J.F., Evensen, K.A., Garzon, B., Landro, N.I., Haberg, A.K., 2013. The functional topography and temporal dynamics of overlapping and distinct brain activations for adaptive task control and stable task-set maintenance during performance of an fMRI-adapted clinical continuous performance test. J. Cognit. Neurosci. 25, 903–919. http://dx.doi.org/10.1162/jocn_a_00358.

Onton, J., Makeig, S., 2006. Information-based modeling of event-related brain dynamics. Prog. Brain Res. 159, 99–120. http://dx.doi.org/10.1016/s0079-6123(06)59007-7.

Padilla, M.L., Wood, R.A., Hale, L.A., Knight, R.T., 2006. Lapses in a prefrontal-extrastriate preparatory attention network predict mistakes. J. Cognit. Neurosci. 18, 1477–1487. http://dx.doi.org/10.1162/jocn.2006.18.9.1477.

Picton, T.W., Stuss, D.T., Alexander, M.P., Shallice, T., Binns, M.A., Gillingham, S., 2007. Effects of focal frontal lesions on response inhibition. Cereb. Cortex 17, 826–838. http://dx.doi.org/10.1093/cercor/bhk031.

Polich, J., Kok, A., 1995. Cognitive and biological determinants of P300: an integrative review. Biol. Psychol. 41, 103–146. http://dx.doi.org/10.1016/0301-0511(95)05130-9.

Randall, W.M., Smith, J.L., 2011. Conflict and inhibition in the cued-Go/NoGo task. Clin. Neurophysiol. 122, 2400–2407. http://dx.doi.org/10.1016/j.clinph.2011.05.012.

Robinson, G., Shallice, T., Bozzali, M., Cipolotti, L., 2012. The differing roles of the frontal cortex in fluency tests. Brain 135, 2202–2214. http://dx.doi.org/10.1093/brain/aws142.

Roche, R.A., Garavan, H., Foxe, J.J., O'Mara, S.M., 2005. Individual differences discriminate event-related potentials but not performance during response inhibition. Exp. Brain Res. 160, 60–70. http://dx.doi.org/10.1007/s00221-004-1985-z.

Rodriguez-Aranda, C., Martinussen, M., 2006. Age-related differences in performance of phonemic verbal fluency measured by Controlled Oral Word Association Task (COWAT): a meta-analytic study. Dev. Neuropsychol. 30, 697–717. http://dx.doi.org/10.1207/s15326942dn3002_3.

Rohrbaugh, J.W., Dunham, D.N., Stewart, P.A., Bauer, L.O., Kuperman, S., O'Connor, S. J., Begleiter, H., 1997. Slow brain potentials in a visual-spatial memory task: topographic distribution and inter-laboratory consistency. Int. J. Psychophysiol. 25, 111–122. http://dx.doi.org/10.1016/s0167-8760(96)00714-3.

Ruchkin, D.S., Berndt, R.S., Johnson Jr., R., Ritter, W., Grafman, J., Canoune, H.L., 1997. Modality-specific processing streams in verbal working memory: evidence from spatio-temporal patterns of brain activity. Cognit.Brain Res. 6, 95–113. http://dx.doi.org/10.1016/s0926-6410(97)00021-9.

Schmajuk, M., Liotti, M., Busse, L., Woldorff, M.G., 2006. Electrophysiological activity underlying inhibitory control processes in normal adults. Neuropsychologia 44, 384–395. http://dx.doi.org/10.1016/j.neuropsychologia.2005.06.005.

Schochet, P.Z., 2008. Guidelines for Multiple Testing in Impact Evaluations of Educational Interventions (MPR Reference No.: 6300-080). US Department of Education, Washington, DC.

Segalowitz, S.J., Dywan, J., Unsal, A., 1997. Attentional factors in response time variability after traumatic brain injury: an ERP study. J. Int. Neuropsychol. Soc. 3, 95–107.

Sehlmeyer, C., Konrad, C., Zwitserlood, P., Arolt, V., Falkenstein, M., Beste, C., 2010. ERP indices for response inhibition are related to anxiety-related personality traits. Neuropsychologia 48, 2488–2495. http://dx.doi.org/10.1016/j.neuropsychologia.2010.04.022.

Smith, J.L., Johnstone, S.J., Barry, R.J., 2006. Effects of pre-stimulus processing on subsequent events in a warned Go/NoGo paradigm: response preparation, execution and inhibition. Int. J. Psychophysiol. 61, 121–133. http://dx.doi.org/10.1016/j.ijpsycho.2005.07.013.

Smith, J.L., Johnstone, S.J., Barry, R.J., 2007. Response priming in the Go/NoGo task: the N2 reflects neither inhibition nor conflict. Clin. Neurophysiol. 118, 343–355. http://dx.doi.org/10.1016/j.clinph.2006.09.027.

Spencer, K.M., Dien, J., Donchin, E., 2001. Spatiotemporal analysis of the late ERP responses to deviant stimuli. Psychophysiology 38, 343–358. http://dx.doi.org/10.1111/1469-8986.3820343.

Steinborn, M.B., Flehmig, H.C., Westhoff, K., Langner, R., 2010. Differential effects of prolonged work on performance measures in self-paced speed tests. Adv. Cognit. Psychol. 5, 105–113. http://dx.doi.org/10.2478/v10053-008-0070-8.

Streiner, D.L., Norman, G.R., 2003. Health Measurement Scales: A Practical Guide to their Development and Use. Oxford University Press, New York.

Stuss, D.T., 2006a. Frontal lobes and attention: processes and networks, fractionation and integration. J. Int. Neuropsychol. Soc. 12, 261–271. http://dx.doi.org/10.1017/S1355617706060358.

Stuss, D.T., 2006b. New approaches to prefrontal lobe testing. In: Miller, B.L., Cummings, J.L. (Eds.), The Human Frontal Lobes. Guilford Press, New York, NY, pp. 292–305.

Stuss, D.T., 2011. Functions of the frontal lobes: relation to executive functions. J. Int. Neuropsychol. Soc. 17 (5), 759–765. http://dx.doi.org/10.1017/s1355617711000695.

Stuss, D.T., Alexander, M.P., 2007. Is there a dysexecutive syndrome? Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 362, 901–915. http://dx.doi.org/10.1098/rstb.2007.2096.

Stuss, D.T., Alexander, M.P., Hamer, L., Palumbo, C., Dempster, R., Binns, M., Izukawa, D., 1998. The effects of focal anterior and posterior brain lesions on verbal fluency. J. Int. Neuropsychol. Soc. 4, 265–278.

Stuss, D.T., Alexander, M.P., Shallice, T., Picton, T.W., Binns, M.A., Macdonald, R., Katz, D.I., 2005. Multiple frontal systems controlling response speed. Neuropsychologia 43, 396–417. http://dx.doi.org/10.1016/j.neuropsychologia.2004.06.010.

Stuss, D.T., Binns, M.A., Murphy, K.J., Alexander, M.P., 2002. Dissociations within the anterior attentional system: effects of task complexity and irrelevant information on reaction time speed and accuracy. Neuropsychology 16, 500–513. http://dx.doi.org/10.1037/0894-4105.16.4.500.

Stuss, D.T., Murphy, K.J., Binns, M.A., Alexander, M.P., 2003. Staying on the job: the frontal lobes control individual performance variability. Brain 126, 2363–2380. http://dx.doi.org/10.1093/brain/awg237.

Stuss, D.T., Shallice, T., Alexander, M.P., Picton, T.W., 1995. A multidisciplinary approach to anterior attentional functions. Ann. N. Y. Acad. Sci. 769, 191–211. http://dx.doi.org/10.1111/j.1749-6632.1995.tb38140.x.

Tieges, Z., Snel, J., Kok, A., Wijnen, J.G., Lorist, M.M., Richard Ridderinkhof, K., 2006. Caffeine improves anticipatory processes in task switching. Biol. Psychol. 73, 101–113. http://dx.doi.org/10.1016/j.biopsycho.2005.12.005.

Troyer, A.K., Moscovitch, M., Winocur, G., 1997. Clustering and switching as two components of verbal fluency: evidence from younger and older healthy adults. Neuropsychology 11, 138–146. http://dx.doi.org/10.1037/0894-4105.11.1.138.

Unsworth, N., Spillers, G.J., Brewer, G.A., 2011. Variation in verbal fluency: a latent variable analysis of clustering, switching, and overall performance. Q. J. Exp. Psychol. 64, 447–466. http://dx.doi.org/10.1080/17470218.2010.505292.

Vallesi, A., 2012. Organisation of executive functions: hemispheric asymmetries. J. Cognit. Psychol. 24, 367–386. http://dx.doi.org/10.1080/20445911.2012.678992.

Van der Elst, W., Van Boxtel, M.P., Van Breukelen, G.J., Jolles, J., 2006. The Stroop color-word test: influence of age, sex, and education; and normative data for a large sample across the adult age range. Assessment 13, 62–79. http://dx.doi.org/10.1177/1073191105283427.

van Gaal, S., Lamme, V.A., Fahrenfort, J.J., Ridderinkhof, K.R., 2011. Dissociable brain mechanisms underlying the conscious and unconscious control of behavior. J. Cognit. Neurosci. 23, 91–105. http://dx.doi.org/10.1162/jocn.2010.21431.

Verleger, R., Wauschkuhn, B., van der Lubbe, R., Jaśkowski, P., Trillenberg, P., 2000. Posterior and anterior contribution of hand-movement preparation to late CNV. J. Psychophysiol. 14, 69–86. http://dx.doi.org/10.1027//0269-8803.14.2.69.

Vigario, R.N., 1997. Extraction of ocular artefacts from EEG using independent component analysis. Electroencephalogr. Clin. Neurophysiol. 103, 395–404. http://dx.doi.org/10.1016/s0013-4694(97)00042-8.

Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C., Winter, A.L., 1964. Contingent negative variation: an electric sign of sensorimotor association and expectancy in the human brain. Nature 203, 380–384.

Wang, C., Ding, M., Kluger, B.M., 2014. Change in intraindividual variability over time as a key metric for defining performance-based cognitive fatigability. Brain Cognit. 85, 251–258. http://dx.doi.org/10.1016/j.bandc.2014.01.004.

Wechsler, D., 1997. Wechsler Adult Intelligence Scale—third ed. The Psychological Corporation, San Antonio, TX.