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Event-related brain potential correlates of atypical executive functions

Summary

of the doctoral (PhD) dissertation

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1. General introduction

In my dissertation I investigated the neural basis of atypical *executive functions* (EF) by the method of *event-related brain potentials* (ERPs). Among the various forms of atypical EF, I focused on *trait impulsivity* in the normal population and on childhood *attention-deficit/hyperactivity disorder* (ADHD) in the clinical field. It is crucial to better understand the neuro-cognitive background of atypical EF, since impulsivity is the second most frequent symptom in the DSM (DSM-IV-TR; American Psychiatric Association, 2000; Boy et al., 2011), and also a dominant behavioral manifestation of ADHD. Likewise, ADHD is one of the most common child psychiatric disorders with a prevalence rate of 5-10% in school-age children (Ramtekkar, Reiersen, Todorov, & Todd, 2010). Atypical EF also involves the "upper end" of EF performance; therefore, we studied adults with *superior* EF, as well. By providing insight to the temporal dynamics of executive processes, ERPs could amend behavioral measures of EF and self-report assessment of related impairments.

2. Theoretical background

EF is regarded as an "umbrella term", and can be defined as a set of domain general control mechanisms shaping complex performance and being related to the prefrontal cortex (e.g., Barkley & Fischer, 2011; Elliott, 2003; Miyake & Friedman, 2012). In a wider sense, this concept is closely connected to *cognitive control*, which enables information processing systems and those generating motor responses to flexibly and continuously adapt to relevant task requirements in order to fulfill internally represented goals (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miller & Cohen, 2001; Shiels & Hawk, 2010).

Accumulating evidence suggests that EF can be considered as a system with distinguishable subcomponents (Miyake & Friedman, 2012; Miyake et al., 2000; Wu et al., 2011), and also indicates that for complex cognitive functioning these components should work in an interrelated and organized manner (Bari & Robbins, 2013). The unity/diversity framework proposed *Shifting*, *Updating*, and *Inhibition* as core aspects of the EF (Miyake et al., 2000). A current update of this approach has highlighted the role of a *Common EF* factor that taps the unity of EF and it is interpreted as an ability to actively maintain task goals (Miyake & Friedman, 2012). Among the different subprocesses, inhibitory control in itself might be regarded as an overarching and *multidimensional construct* involving distinguishable inhibition-related abilities (e.g., Barkley, 1997; Friedman & Miyake, 2004; Nigg, 2000). The dissociation of two particular subprocesses is frequently investigated by different methods of cognitive neuroscience: These are *interference suppression* and *response inhibition* (Bryce, Szűcs, Soltész, & Whitebread, 2011; Brydges et al., 2012; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Briefly, response inhibition refers to the ability to suppress prepotent behavioral responses, while interference suppression refers to the ability to prevent interference originating from stimulus competition. Furthermore, the several aspects of EF could be assigned to *cool* (cognitive) and *hot* (affective) EF subsystems (Zelazo, Qu, & Kesek, 2010).

Behavior regulation in emotionally or motivationally significant situations, decision making with important consequences to day-to-day life, and appropriate social functioning are all considered as aspects of the hot EF. Several tasks have been developed to measure different aspects of the EF. In the ERP studies presented in this dissertation, we used variants of the *Eriksen flanker task* (Eriksen & Eriksen, 1974) and of the *Stroop task* (Stroop, 1935) as cool EF measures, and the *Balloon Analogue Risk Task* (BART; Lejuez et al., 2002) as a hot EF measure.

As described above, instead of a single unifying theory explaining the role executive functions and the relation among specific subprocesses, multiple approaches exist. The *cognitive-energetic model* (CEM; Sanders, 1983; Sergeant, 2005) could integrate different EF subcomponents, explains the impact of task-related and state-related factors (task difficulty, task-engagement, level of motivation and arousal) and provides testable hypothesis for research. The CEM supposes that efficient information processing depends on the *computational mechanisms of attention* (encoding, decision making, and motor organization) and on *energetic* or *state factors* (arousal, effort, activation pools), which are monitored by an *evaluation mechanism* (or the EF). In a task with varying cognitive load, the effort pool could provide a *compensatory mechanism* to mobilize and regulate the other two energetic resources in order to adjust behavior and to achieve an optimum level of performance. However, performance improves only at a moderate level of task difficulty, which avoids under-arousal/under-activation and over-arousal/over-activation (Smulders & Meijer, 2008). The effort pool encompasses such factors as motivation, and (external) *reinforcement contingencies* are assumed to influence this pool by inducing the necessary energy to meet task requirements (Luman, Oosterlaan, & Sergeant, 2005). In a more comprehensive version, the CEM was proposed as a general theoretical framework for the conceptualization and research of atypical functioning in ADHD (e.g., Sergeant, 2005).

Several different ERP components could be regarded as neural correlates of the EF. The anterior/central *N2* component is found to peak between 200–450 ms after stimulus onset and it is functionally linked to cognitive control. A frequent finding of ERP studies using the flanker task is that the N2 can be divided into two distinct subcomponents (Gehring, Gratton, Coles, & Donchin, 1992; Kopp, Rist, & Mattler, 1996) reflecting control-related and mismatch-related functions (Folstein & van Petten, 2008). The central/centroparietal *P3* occurring at 250-700 ms after stimulus onset is also related to inhibitory control processes (Johnstone, Barry, Markovska, Dimoska, & Clarke, 2009; Johnstone, Watt, & Dimoska, 2010). Specifically, a larger P3 amplitude is assumed to reflect the employment of increased attentional resources (Kok, 2001).

The *Lateralized Readiness Potential* (LRP) is an index of selective motor preparation (Coles, 1989); therefore, it is useful for studying motor processes in real time. This component summarizes the electrical potential differences of electrodes placed over the motor cortex contra- and ipsilateral to the response hand in a single measure (Coles, 1989; Szűcs, Soltész, Bryce, & Whitebread, 2009). By calculating the LRP, *covert incorrect* response preparation (a positive-going deviation) followed by a correct response preparation (a negative-going deviation) can be detected in *correctly* responded conflicting (incongruent) experimental condition (Szűcs et al., 2009). According to the arguments of Bryce et al. (2011, p. 682), the amplitude and latency of the initial incorrect response preparation can be considered to be indices of interference suppression, while the transition from incorrect to correct activation in the incongruent condition reflects the later response inhibition process.

The *error-negativity* (Ne; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991) or *error-related negativity* (ERN; Gehring, Goss, Coles, Meyer, & Donchin, 1993) is a negative deflection peaking 50-100 ms after an erroneous response with a frontocentral maximum when stimulus-response mappings are known (Ullsperger, Fischer, Nigbur, & Endrass, 2014). In general, the ERN is related to error detection and it rapidly signals the need for behavioral adjustment (Endrass, Klawohn, Gruetzmann, Ischebeck, & Kathmann, 2012). It is usually followed by the *error-positivity* (Pe) that reflects conscious error recognition (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Simons, 2010). The *feedback-related negativity* (FRN) is a frontocentral negative deflection occurring 200-300 ms after the onset of a negative (unfavorable) feedback (Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997; Walsh & Anderson, 2012). The FRN is thought to mirror the rapid evaluation of external feedback. The FRN is usually followed by a *feedback P3* representing a more elaborated evaluation of outcomes (Euser et al., 2013). The *reinforcement learning theory* of the error-related negativity (RL-ERN theory; Holroyd & Coles, 2002) provides a general framework for the underlying neural structure and for the functional relevance of ERN and FRN. These components can be considered as indices of a generic error detection and performance monitoring system that is possibly located in the *posterior medial frontal cortex* (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004).

The modulations of these neural indices are regarded as potential *biomarkers* in trait impulsivity and in ADHD. *Impulsivity* is a multifaceted personality trait that indicates a preference for immediate rewards, risky activities, and novel experiences (Bari & Robbins, 2013). It is characterized by rapid and unplanned reactions to stimuli before thorough processing of information (Arce & Santisteban, 2006). Impulsive symptoms in several psychiatric conditions are often explained as consequences of inhibitory control problems (Bari & Robbins, 2013). It is not clear, however, in what extent impaired subprocesses of inhibitory control underlie trait impulsivity in nonclinical populations (Dimoska & Johnstone, 2007). Deficient inhibitory control in trait impulsivity has not been consistently supported on the basis of previous N2 and P3 findings (e.g., Kam, Dominelli, & Carlson, 2012). Eysenck (1993) proposed that individuals with high impulsivity have lower arousal than those with low impulsivity. Therefore, a task that increases arousal could improve the performance of high impulsive individuals and deteriorate that of low impulsive individuals. Accordingly, inhibitory control and performance monitoring in trait impulsivity could be interpreted in the framework proposed by the CEM. I investigate this assumption in Study 1-2.

The detection and evaluation of internal and external negative feedback plays a fundamental role in guiding human learning and behavior. However, the involvement of EF in feedback processing is not fully understood yet. The study of Schiebener, Wegmann, Pawlikowski, and Brand (2012) suggested that high EF enables negative contextual influences to be overridden in choice situations. A previous study showed that decreased FRN for negative events in the BART was associated with a general risk for alcoholism, and alterations in frontostriatal circuits and in EF have been considered as potential root causes of this attenuation (Fein & Chang, 2008). However, without behavioral measurements of the EF, the association between EF and the FRN remained unclear. Moreover, the influence of EF should be tested *without* the confounding factor of long-term alcohol use. Study 3 aimed to clarify this issue.

The highly *heterogeneous* symptom profile of ADHD has yielded different etiological theories of the disorder (Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003). *Impaired EF* has been proposed as a *primary* neuro-cognitive deficit underlying the disorder (e.g., Barkley, 1997; Coghill, Hayward, Rhodes, Grimmer, & Matthews, 2013; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). However, previous findings suggest that only 35–50% of children with ADHD have EF deficits (Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005; Sjöwall, Roth, Lindqvist, & Thorell, 2013). Nevertheless, it should be elucidated to what extent impaired inhibitory control underlies ADHD, and whether interference control (Cao et al., 2013; van Mourik, Oosterlaan, & Sergeant, 2005) or response inhibition (Nigg, 2001; Willcutt et al., 2005) is disrupted, or both. Moreover, only a few studies have considered the ERP correlates of encoding and response organization in ADHD, i.e., a possible impairment in the peripheral stages of information processing. However, in line with the *regulatory models* of ADHD (e.g., the CEM), it was suggested by Sergeant (2005) that more attention should be paid to the interplay of computational processing stages, state factors, and EF to understand the root cause of a possible inhibitory deficit in ADHD. Only a few studies using ERP methodology provided some support for state regulation deficits and altered performance monitoring in ADHD (for a review, see Johnstone, Barry, & Clarke, 2013). Therefore, I investigated the potential deficiencies in childhood ADHD at multiple stages of information processing in Study 4.

3. Assumptions

Based on the arguments above, the main assumptions of my work are as follows.

1) In trait impulsivity, deficient inhibition is a consequence of suboptimal arousal and effort. In line with the prediction of the CEM, inhibitory control performance of high impulsive participants improves in case of moderate task difficulty.
2) When effortful control in needed at a moderate level of task difficulty to maintain task performance, performance monitoring also enhances in high trait impulsivity.
3) High performance on cool EF measures influence uncertain decision making and feedback processing by inducing a different task-solving strategy.
4) Multiple stages of information processing are impaired in ADHD, and the specific impairment of response inhibition cannot be fully confirmed.

In order to investigate these assumptions, we conducted four ERP experiments with different paradigms. These studies and the main findings are described below.

4. Theses

4.1. Inhibitory control and error processing in trait impulsivity

Thesis 1. *The processing speed and response preparation of high impulsive individuals were generally slower irrespective of congruency and task difficulty. However, delayed latency of the incongruent LRP and the lack of congruency effects on P3 amplitude indicated partially impaired inhibitory control processes.*

Thesis 2. *The amplitude of ERN for errors in incongruent trials was smaller in high impulsive participants than in low impulsive participants in case of moderate and high levels of task difficulty. This result suggests that trait impulsivity is characterized by impaired error detection when more effortful control is needed to maintain task performance. We did not observe an optimization in performance.*

Thesis 3. *The experimental manipulation of energetic pools of the CEM could not provide a better understanding of various inhibitory control problems and altered performance monitoring in trait impulsivity, which contradicts the first and second assumption.*

The first study aimed to test the various inhibitory control problems in trait impulsivity on the basis of the CEM. However, this possible deficiency could be a consequence of suboptimal arousal and task-related effort, which deteriorates overall performance. Therefore, we used a *modified Eriksen flanker task* (see also Johnstone et al., 2010) with different levels of stimulus degradation to influence arousal and effort pools. This way we manipulated *task difficulty* (*low* difficulty: non-degraded stimuli, *medium* difficulty: moderately degraded stimuli, *high* difficulty: highly degraded stimuli). Low (n = 15) and high (n = 15) impulsive adults participated in the study who were assigned to these groups on the basis of the *Barratt Impulsiveness Scale* (BIS; Patton, Stanford, & Barratt, 1995; Stanford et al., 2009). We analyzed RT, accuracy, and ERPs (N2b, N2c, P3 components, LRP) time-locked to the correctly responded flanker stimuli.

On a restricted sample of the same participant pool, those who made a sufficient number of errors during the flanker task ($n_{\text{(low impulsive)}} = 10$; $n_{\text{(high impulsive)}} = 10$), a secondary analysis was conducted. Previous evidence suggests that high impulsive individuals have problems with self-monitoring and learning from their errors (Hall, Bernat, & Patrick, 2007; Olvet & Hajcak, 2008), especially when reinforcement contingencies are manipulated (Martin & Potts, 2009; Potts, George, Martin, & Barratt, 2006). Therefore, we investigated the ERP correlates of error processing in trait impulsivity, and whether these processes are modulated by task difficulty in a common EF task without altering motivational level. Specifically, the flexible regulation of behavior to meet varying task requirements was tested. We analyzed ERN and Pe components elicited by erroneous responses produced on incongruent flanker trials. Moreover, in-depth analysis of RTs (comparing parameters of the ex-Gaussian distribution and analysis of post-error slowing, see Danielmeier & Ullsperger, 2011; Lacouture & Cousineau, 2008) allowed further insight to the responding strategy of high impulsive participants.

Reaction time of high impulsive participants was generally slower than that of low impulsive participants, but accuracy was similar across groups. This slowing effect was also reflected in ERPs: The peak latency of P3 and LRP (see Fig. 1) was delayed in the high as compared to the low impulsive group, irrespective of other experimental effects. The unexpectedly slower RTs on correct trials also remained significant when we analyzed the performance of restricted sample. The ex-Gaussian parameters of μ and σ were larger in the high impulsive group than in the low impulsive group and the τ value also tended to be larger. This indicated that not only the mean RT was overall slower in high impulsive participants, but also the trial-by-trial heterogeneity in their responding was higher, as well as they produced slightly more attentional lapses. However, the compensatory post-error slowing after errors appeared to be comparable across the two groups, suggesting that the slowing effect of high impulsive participants was not restricted to behavioral adjustment.

The N2b was influenced by stimulus degradation and it was insensitive to congruency manipulation (see also Johnstone et al., 2010), however, the amplitude increase for more difficult visual stimulus discrimination was statistically significant only in the low impulsive group for incongruent stimuli. The N2c showed that monitoring of response conflict was modulated by task requirements, independent of impulsivity. This result shows that response conflict monitoring was intact in the high impulsive group, which corresponds to the similar accuracy across group at the behavioral level. The P3 latency was delayed in the impulsive group indicating slower stimulus evaluation (Polich, 2007). The P3 amplitude was reduced *only* in the low impulsive group for moderately degraded incongruent trials suggesting that the attentional resources were employed less (Kok, 2001). Furthermore, the P3 was enhanced for non-degraded incongruent trials only in the low impulsive group suggesting a partial interference effect (Ridderinkhof & van der Molen, 1995). In some degree, the lack of this interference effect on P3 amplitude in the high impulsive group corroborates the notion that inhibitory problems are present in high trait impulsivity.

The LRP peaked later in the high impulsive group irrespective of other experimental effects. Contrary to our assumption, the amplitude of the positive-going LRP recorded in the incongruent condition (incorrect response activation) was comparable across groups, but the latency was delayed partly supporting a stronger susceptibility to stimulus interference of high impulsive participants (Bryce et al., 2011). Their delayed incongruent negative-going LRP might have reflected a weaker response inhibition (Aichert et al., 2012; Bari & Robbins, 2013) and a slower secondary correct response organization. In sum, we could not unequivocally demonstrate impaired inhibitory functions in trait impulsivity, but we found a *generalized lapse* of motor activation.

The amplitude of ERN for erroneous responses was attenuated in high impulsive participants as compared to low impulsive participants in case of medium and high task difficulty levels (see Fig. 2). This result indicates that error detection was only impaired in trait impulsivity when more effortful control was needed to fulfill task requirements (Martin & Potts, 2009; Potts et al., 2006; Ruchsow, Spitzer, Gron, Grothe, & Kiefer, 2005). At the same time, the groups did not differ either in the amplitude or in the latency of Pe, suggesting that the more elaborated evaluation of errors was not impaired in high trait impulsivity. The attenuated performance monitoring was only observed at the neural level since accuracy was comparable between the groups (see also Hall et al., 2007).

Interestingly, the within-group change in ERN amplitude across task difficulty levels differed between high and low impulsive participants. The ERN significantly increased from non-degraded to moderately degraded trials in the low impulsive group, while in the high impulsive group, it decreased from non-degraded to highly degraded trials. This finding should be clarified in further studies, since the motivational significance theory (e.g., Hajcak, Moser, Yeung, & Simons, 2005) of the ERN offers more plausible explanation for the change in the low impulsive group, while the mismatch theory (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000) more easily predicts the change in the high impulsive group.

4.1.1. Implication for the CEM

The majority of our findings could not support the predictions of the CEM in regard to atypical inhibitory control and performance monitoring in trait impulsivity. Some weak evidence was found supporting the CEM in certain indices across stimulus degradation levels, but not in relevance to high trait impulsivity. We found enhanced accuracy for moderately degraded incongruent trials in the whole sample in line with the lower perceived effort. The P3 amplitude was also attenuated for moderately degraded stimuli as compared to non-degraded and highly degraded stimuli (especially in the incongruent condition) suggesting that attentional resources were employed in a lesser degree (Kok, 2001), but this only pertained to the low impulsive group. Error percentage in incongruent trials slightly decreased from non-degraded to moderately degraded trials (at least at the descriptive level), and correspondingly, ERN significantly increased from non-degraded to moderately degraded trials, that we might interpret as an optimization in performance. However, this pattern was only observed in *low impulsive participants*, who might have increased self-monitoring in case of more difficult circumstances.

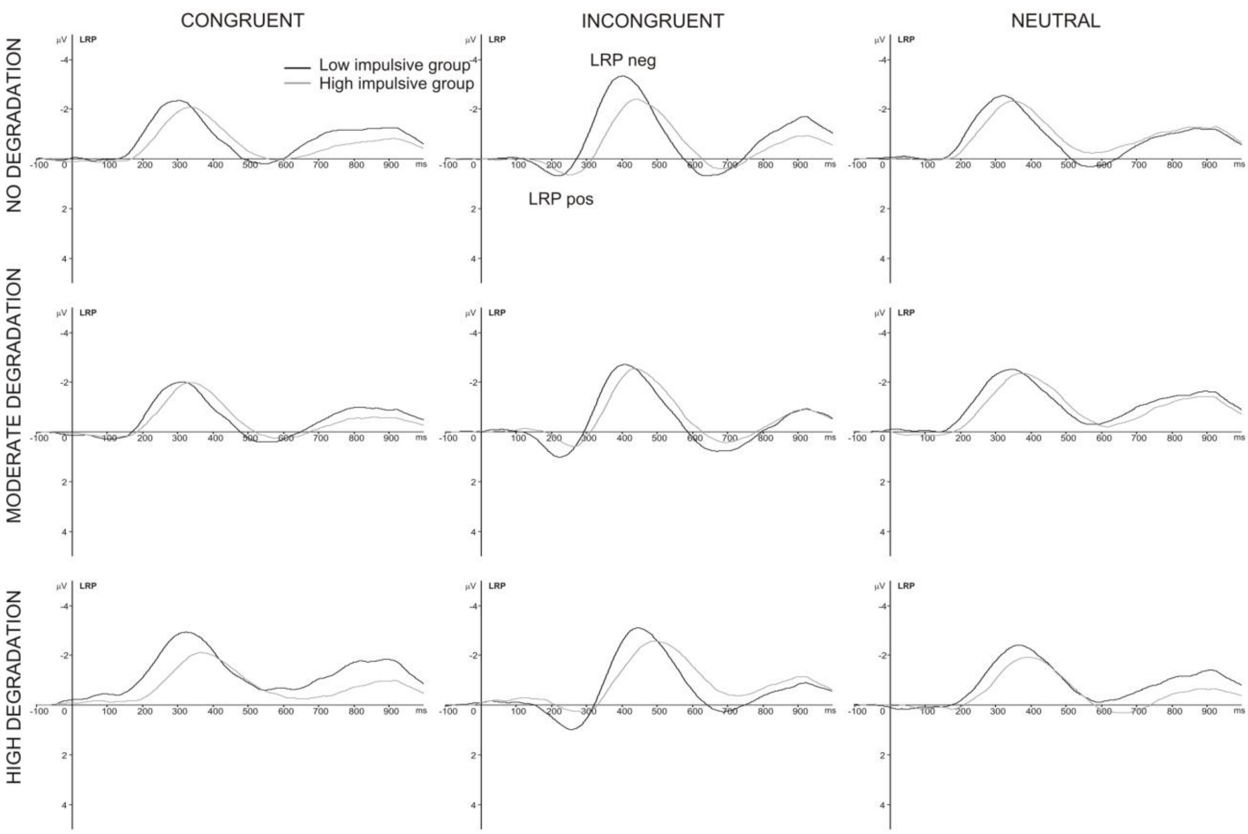

Fig. 1. Grand average LRPs (from C3 and C4) for low and high impulsive groups split by condition. LRP pos denotes incorrect response preparation, LRP neg denotes correct response preparation.

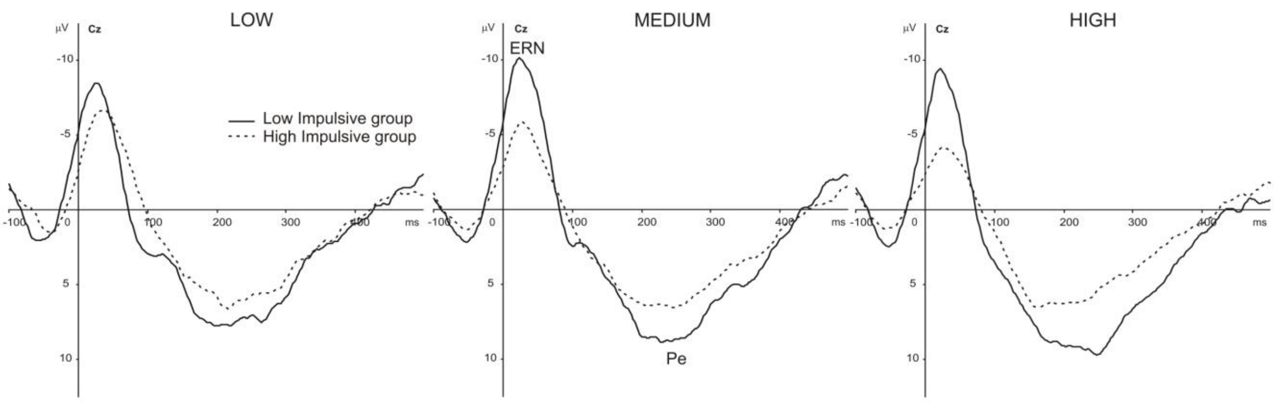

Fig. 2. Grand average ERP waveforms (ERN and Pe) at electrode Cz for low and high impulsive groups in the three task difficulty conditions.

4.2. Different strategies underlying uncertain decision making

Thesis 4. *We showed that higher level of cool EF performance modulated FRN and P3 components for negative outcomes in the BART that involves uncertain decision making. At the same time, no EF-related differences were found at the behavioral level. In our interpretation, the enhanced amplitude of FRN and P3 reflects a model-based strategy used by the high EF group, which confirms the third assumption.*

The concept of EF measured by cool EF tasks and *decision uncertainty* that is present in many hot EF tasks (Brand, Labudda, & Markowitsch, 2006) overlap in a sense that during task-solving, individuals face response conflict, and behavioral adaptation is needed to fulfill task requirements (Mushtaq, Bland, & Schaefer, 2011; Ridderinkhof et al., 2004). In certain groups of individuals (e.g., those with bilingual language background, professional translators, congenitally blind individuals) it is suggested that some aspects of the EF are superior compared to controls (Hugdahl et al., 2009; Martin-Rhee & Bialystok, 2008). However, it has not been investigated by ERP methodology how an enhanced level of cognitive control influence performance on the BART. The BART measures risk-taking behavior and involves decision uncertainty, and it can be solved by different strategies. With the third study, we purported to cover the “upper end” of the EF dimension by investigating adults (undergraduate students) with superior EF, which is also atypical.

Adult participants were assigned to high EF (n = 16) or low EF (n = 16) groups according to their performance on various tasks measuring the main subcomponents of EF (Shifting – Verbal Fluency Task, Updating – Listening Span Task, Inhibition – Go/No-Go Task). ERPs were recorded while participants performed the BART. In this task, participants are asked to gradually inflate an empty virtual balloon presented on a screen. For each successful pump, reward (virtual score) is provided. After each pump, participants could choose to stop inflating the actual balloon and collect the accumulated reward (which is then transferred to a “permanent bank”), or to pump the balloon further and increase earnings. However, if the balloon bursts, the accumulated reward is lost, and a new empty balloon is displayed. Participants were instructed to collect as much reward as possible. Importantly, the probability of a balloon burst increases with each successive pump, but the regularity that determines balloon bursts is unbeknown to participants (Lejuez et al., 2002). Therefore, each additional pump is considered as a risky choice, and since the probability of outcomes (balloon burst or balloon increase) is unknown to participants, the structure of the task could be more close to everyday risk-taking behavior than other hot EF or gambling tasks (Helfinstein et al., 2014).

In this study, the BART behavioral measures did not show between-group differences denoting a similar decision making behavior, however, the ERP correlates differed. The FRN associated with undesirable outcomes (balloon bursts) was enhanced and delayed in the high EF group as compared to the low EF group (see Fig. 3). Although to a lesser degree, the feedback-related P3 following the FRN showed a similar between-group difference. Since the FRN represents salience prediction error, our results suggest a model-based strategy used by high EF participants.

Specifically, in decision making situations involving uncertainty, there are at least two ways for adaptive response modification. Model-based learning could guide choices through testing different hypotheses about the structure of the task, but this could be learned in a hypothesis-free way, as well, with less reliance on models (Nemeth, Janacsek, Polner, & Kovacs, 2013). The hypothesis-driven strategy is more related to executive control processes (Nemeth et al., 2013), which seems to be less useful in tasks with implicit rules and decisions under uncertainty (Filoteo, Lauritzen, & Maddox, 2010). Furthermore, the essential role of cognitive control has been directly confirmed in *risk averse* response style in relation to the BART (i.e., lower number of pumps, higher probability of accumulating the reward) (Fecteau et al., 2007; Helfinstein et al., 2014).

High EF participants relying on their control processes would have solved the task by testing outcome expectations derived from their inner models, which have been worked up on the basis of their early experiences. Accordingly, each negative outcome represented salient new information (a prediction error) inducing a larger FRN (Talmi, Atkinson, & El-Deredy, 2013).

At the same time, we could understand the enhancement in FRN as a manifestation of enhanced sensitivity to negative outcomes (Onoda, Abe, & Yamaguchi, 2010), which is connected to hypothesis-driven strategies. Specifically, individuals with high EF might have considered these events more salient in relation to task performance since these outcomes violated their inner models. The FRN signals the relevance of feedback for task performance (Yeung, Holroyd, & Cohen, 2005), and individuals with high EF might have considered a balloon burst as a more significant negative event than those with low EF. The increased P3 amplitude in the high EF group might show an enhanced attention to further process salient events of motivational importance. In sum, our results provided ERP evidence for the EF influencing task-solving strategies in risky decision making. In addition, by demonstrating the relevance of EF in feedback processing in healthy young adults, we could indirectly contribute to previous findings on the BART in alcoholic patients (Fein & Chang, 2008).

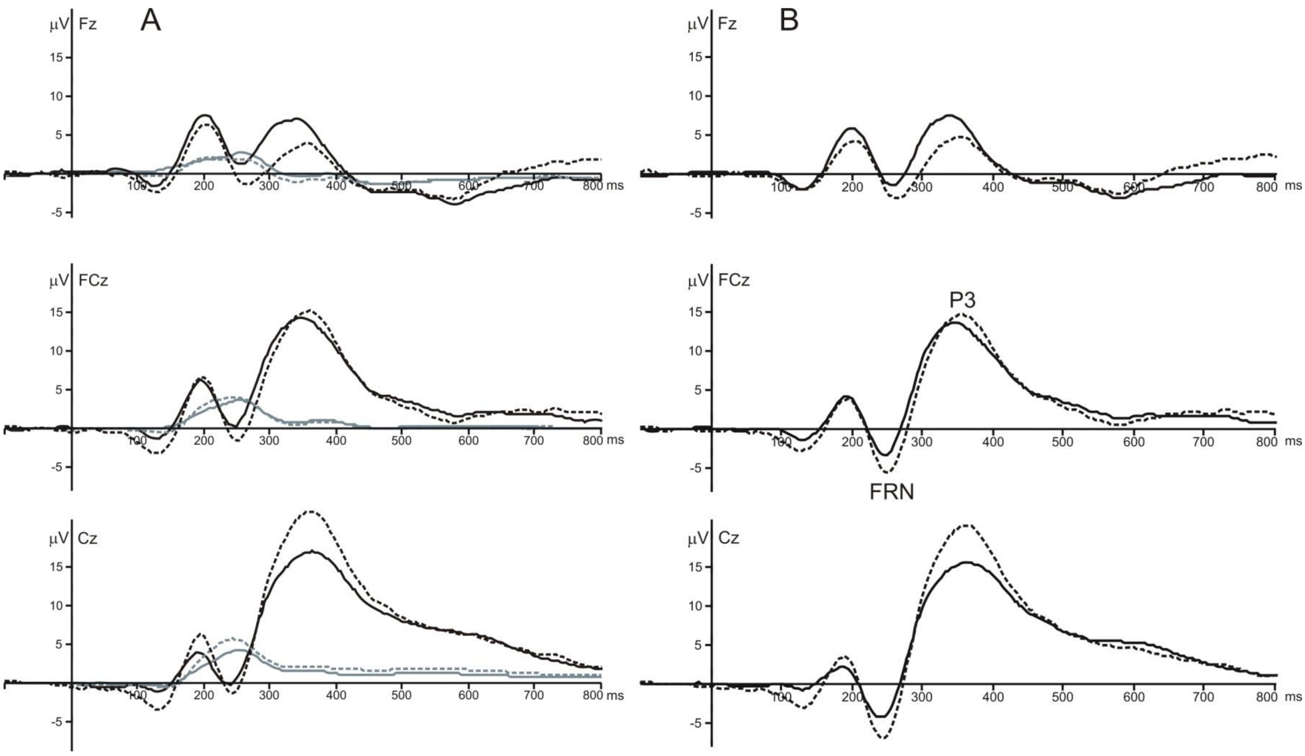

Fig. 3. Grand average ERP waveforms (A) after the onset of positive (grey) and negative (black) feedback split by group and electrode position. Difference waves (B) were calculated by subtracting the positive feedback-locked waveform from the negative feedback-locked waveform. Solid line depicts the low EF group, dashed line depicts the high EF group. Please, note that positivity is plotted upwards here.

4.3. Impairments at multiple stages of the perceptual-motor chain in ADHD

Thesis 5. *On the basis of the parieto-occipital ERP findings and the slower correct response preparation reflected in the incongruent LRP, we emphasize the existence of deficits at multiple stages of information processing in childhood ADHD rather than a specific impairment of response inhibition, which is in line with the fourth assumption. The delayed preparation of correct responses in incongruent trials in ADHD could result from enhanced effort allocation at earlier processing phases.*

To the best of our knowledge, no studies have tested motor preparation in a Stroop paradigm in children with ADHD to date, and following the whole perceptual-motor processing chain by means of ERPs is still infrequent in this field (Steger, Imhof, Steinhausen, & Brandeis, 2000; van Mourik, Sergeant, Heslenfeld, Konig, & Oosterlaan, 2011). By tracking the LRP in an incongruent condition we intended to separately measure processes that contribute to inhibitory control (interference suppression, response inhibition). The specificity of the Stroop task in showing impaired interference control at the behavioral level in ADHD has not been confirmed, and the efficacy of the task in distinguishing ADHD and typically developing (TD) children is somewhat dependent on the scoring method and measurement protocol (Lansbergen, Kenemans, & van Engeland, 2007; van Mourik et al., 2005). However, it is possible that clear group differences could be obtained at the neural level. Moreover, previous ERP evidence showed that *suboptimal energetic regulation* in ADHD could affect multiple stages of information processing (e.g., orientation, sensory processing, stimulus categorization, allocation of visual attention), as well (Benikos & Johnstone, 2009; Johnstone et al., 2010; Steger et al., 2000).

Therefore, the fourth study investigated the inhibitory control performance of children with ADHD (n = 14) and TD children (n = 14) in an adaptation of the Stroop task (all children were in the age range of 9-12 years). Participants performed the same *animal Stroop task* as in the study of Bryce et al. (2011). Stimuli were colored pictures of two animals differing in real-life size simultaneously presented on a computer screen. One animal image was physically larger than the other and the task was to select by key-press which animal was larger in real-life. In the congruent condition, the larger in real-life animal was displayed physically larger on the screen than the smaller in real-life animal. In the incongruent condition, it was physically smaller than the other on the screen. Different neuropsychological tasks and IQ measures were also administered to investigate short-term memory, interference suppression, basic reading skills, and general IQ. We used various ERP measures time-locked to the presentation of correctly responded congruent/incongruent stimuli. Moreover, the variability in response times indicating non-optimal arousal has been quantified by ex-Gaussian distributional analyses of correct RTs.

We observed slower correct RTs in the ADHD group irrespective of congruency (see also Cao et al., 2013), but both groups were equally successful at resolving response conflict at the behavioral level (comparable response accuracy, see also Johnstone et al., 2009). The overall slower responding of children with ADHD could be a consequence of the larger number of excessively long RTs shown by the higher τ values. These indicate poor attention or attentional lapses and greater trial-by-trial variability that generally describe children with ADHD (Karalunas & Huang-Pollock, 2013; Leth-Steensen, Elbaz, & Douglas, 2000). However, the ex-Gaussian μ and σ parameters also tended to be larger in the ADHD group, and the latter could also be attributed to the larger heterogeneity of RTs in the clinical group. In regard to the neuropsychological measures, children with ADHD showed marked impairments in phonological awareness and rapid naming skills compared to TDs, which strengthens the observation that various *language dysfunctions* are among the symptoms of ADHD (McGrath et al., 2011; Takács, Kóbor, Tárnok, & Csépe, 2014). Additional between-group differences emerged in short-term memory and in abstract reasoning, indicating poorer performance in the ADHD group. These behavioral results altogether support the *multiple deficit models* of ADHD and its etiology (Willcutt et al., 2010).

Unexpectedly, neither group showed correct response preparation (negative-going LRP) in the congruent condition, nor an incorrect response preparation (positive-going LRP) in the incongruent condition. Consequently, the two processes that contribute to inhibitory control were not distinguishable (cf. Bryce et al., 2011). However, the secondary correct response preparation was present in both groups in the incongruent condition. The organization and initiation of this correct response tendency was delayed in children with ADHD as compared to TD children.

We also found that the perceptual processing of incongruent stimuli differed from congruent stimuli only in children with ADHD indicated by larger P1 and attenuated N1 amplitudes. The delayed preparation of correct responses in the incongruent condition could have resulted from enhanced effort allocation at earlier processing phases as indicated by the amplitude of these occipital ERPs. This group difference also appeared in the phase of stimulus evaluation since the P3b was larger for incongruent than for congruent trials in the clinical sample, and we did not observe this effect in the TD group (the ERP waves in both conditions were rather similar in the entire time range, see Fig. 4). The delayed P3b latency in children with ADHD suggests that stimulus evaluation as a more central stage of processing was also somewhat slower. We could assume that children with ADHD invested more effort in processing incongruent stimuli than their TD peers to maintain task performance by reason of having been in a non-optimal state. This study provided a subsequent evidence for the notion that impaired inhibitory control is neither specific nor obligatory to ADHD (Nigg et al., 2005; Willcutt et al., 2005).

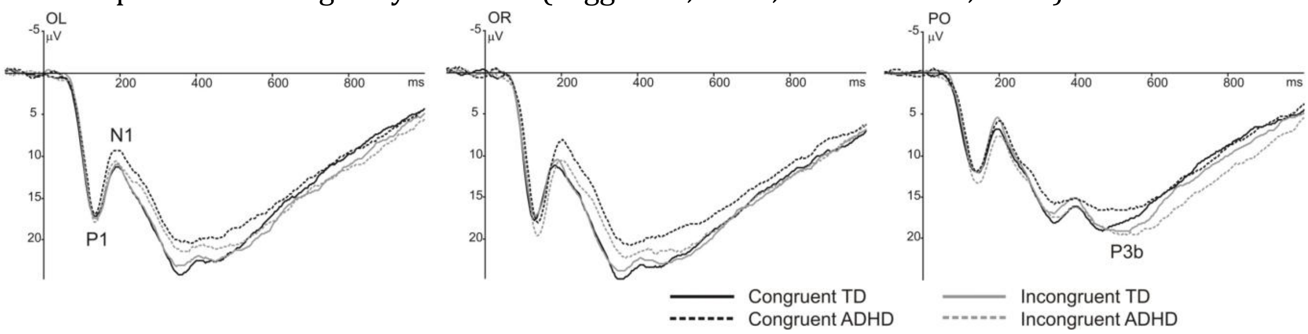

Fig. 4. Grand average ERP waveforms associated with perceptual processing (P1 and N1) and stimulus

evaluation (P3b) split by congruency for each group at left and right occipital electrode pools (OL and OR) and at parieto-occipital electrode pool (PO), respectively.

5. General discussion and conclusions

According to *theses 1-3*, we did not confirm the predictions of the CEM in regard to trait impulsivity. In other words, enhancing task related-effort to a moderate level could not optimize the inhibitory control performance of individuals with high trait impulsivity. These findings argue for the consideration of other task-related factors, and of different approaches to handle the multidimensional nature of trait impulsivity (Bari & Robbins, 2013). We could also assume that the present RT and accuracy data might reflect a more cautious task-solving strategy in the case of the impulsive participants (Kam et al., 2012). Although rapid response style has been considered as an important feature of trait impulsivity (Pailing, Segalowitz, Dywan, & Davies, 2002; Ruchsow et al., 2005), some evidence also suggests that impulsive participants show greater response tendencies, especially in long and monotonous task requiring sustained attention (Arce & Santisteban, 2006; Russo, De Pascalis, Varriale, & Barratt, 2008). Slower responding of high impulsive participants could also reflect the low inter-correlations among different self-report scales and behavioral assessments of impulsivity, which originates from the fact that these instruments measure different aspects of trait impulsivity (Sharma, Markon, & Clark, 2014). The overall pattern of behavioral findings could be a result of deficient allocation of attentional resources, as well. Nonetheless, the current results on delayed response preparation and on overall slowing demonstrate that while impaired inhibitory control is frequently found in the clinical expressions of impulsivity, the deficit underlying the personality trait in nonclinical populations is probably functionally distinct (Dimoska & Johnstone, 2007).

The *fourth thesis* indicates that superior EF modulates uncertain decision making by inducing a different task-solving strategy. This was reflected in enhanced FRN and P3 amplitudes in the BART. Since modulation of the FRN has been proposed as a potential biomarker in psychopathology, a clearer understanding of the functional significance of this component, and the different neural/cognitive systems supporting decision making is essential for further studies (Talmi et al., 2013).

As I concluded in *thesis 5*, we did not find unequivocally impaired inhibitory control *either* in relation to childhood ADHD (cf. Barkley, 1997). Instead, we confirmed previous findings about the existence of impairments at multiple stages of information processing in ADHD (cf. Benikos & Johnstone, 2009; Johnstone et al., 2010). Further group differences in neuropsychological measures and in ex-Gaussian parameters of correct RTs corroborate dysfunctions at multiple cognitive processes and higher variability in overall performance (Douglas, 1999). Accordingly, we support the view that the cognitive profile of ADHD is *highly heterogeneous* (e.g., Nigg et al., 2005; Sjöwall et al., 2013). We tentatively suggest that the lack of expected LRP patterns (see also Szűcs, Soltész, Jármi, & Csépe, 2007) could have emerged from differences between the samples in the present and previous studies (e.g., age range, nationality/educational system), and from a different task-solving strategy. The latter might be a language-based or *semantic strategy*, which involves a more demanding recall of the animals' size from semantic memory. Therefore, decisions might have depended on individual differences in the semantic knowledge about real-life sizes, inferring that this version of the Stroop task might not clearly measure the standard Stroop effect.

To summarize, the neuro-cognitive basis of trait impulsivity and ADHD measured by ERPs appeared to be far more complicated than to confine these phenomena as a manifestation of impaired inhibitory control or EF. A great challenge is that the concept of impulsivity is differently defined in the various fields of psychology (Sharma et al., 2014), and the diagnosis of ADHD has remained controversial (Valo & Tannock, 2010). A more elaborated neuro-cognitive model of EF and adaptive control is needed that might better explain mild, moderate, and severe EF impairments, and also the upper end of the performance dimension.

6. List of publications related to dissertation

6.1. Journal articles

Kóbor, A., Takács, Á., Honbolygó, F., & Csépe, V. (2014). Generalized lapse of responding in trait impulsivity indicated by ERPs: The role of energetic factors in inhibitory control. *International Journal of Psychophysiology, 92*(1), 16-25.

Kóbor, A., Takács, Á., Urbán, R., & Csépe, V. (2012). The latent classes of subclinical ADHD symptoms: Convergences of multiple informant reports. *Research in Developmental Disabilities, 33*(5), 1677-1689.

Kóbor, A., Takács, Á., & Csépe, V. (2012). Towards a dimensional approach: Screening and diagnosing subclinical groups. *ADHD in practice, 4*(1), 7-9.

Kóbor A., Takács Á., Csépe V. (2010). A végrehajtó funkciók neuro-pszichometriai perspektívából. *Pszichológia, 30*(3), 233-252.

Takács, Á., **Kóbor, A.**, Honbolygó, F., & Csépe, V. (under review). Does rare error count in impulsivity? Difference in error-negativity. *Journal of Psychophysiology*.

Kóbor, A., Takács, Á., Janacsek, K., Németh, D., Honbolygó, F., & Csépe, V. (under review). Different strategies underlying uncertain decision making: Higher executive performance is associated with enhanced feedback-related negativity. *Psychophysiology*.

Kóbor, A., Takács, Á., Bryce, D., Szűcs, D., Honbolygó, F., Nagy, P., & Csépe, V. Children with ADHD show impaired early visual processing and inhibitory control in a Stroop task: An ERP study. To be submitted to *Developmental Neuropsychology*.

6.2. Conference papers

Takács, Á., **Kóbor, A.**, Honbolygó, F., & Csépe, V. (2013). Does rare error count in impulsivity? Differences in error-related ERPs. *Eighteenth Meeting of the European Society for Cognitive Psychology*, Budapest (poster).

Kóbor, A., Takács, Á., Bryce, D., Szűcs, D., Honbolygó, F., Nagy, P., & Csépe, V. (2013). Impaired inhibitory control in ADHD: Evidence from an ERP study. *Eighteenth Meeting of the European Society for Cognitive Psychology*, Budapest (poster).

Kóbor, A., Takács, Á., Honbolygó, F., & Csépe, V. (2012). ERPs reflect delayed motor activation in trait impulsivity. 16th World Congress of the International Organization of Psychophysiology, Pisa (poster). *International Journal of Psychophysiology, 85*(3), 428.

Kóbor A., Takács Á., Honbolygó F., Csépe V. (2012). A kognitív kontrollra ható erőfeszítési és motivációs tényezők impulzivitásban. *A Magyar Pszichológiai Társaság XXI. Országos Tudományos Nagygyűlésén elhangzott szimpózium előadás*, Szombathely.

Takács, Á., **Kóbor, A.**, Honbolygó, F., & Csépe, V. (2012). Interference control on different levels of required effort and motivation in impulsivity. *1st Conference of the European Society for Cognitive and Affective Neuroscience*, Marseille (poster).

6.3. Other publications (Journal articles)

Takács, Á., **Kóbor, A.**, Tárnok, Zs., & Csépe, V. (2014). Verbal fluency in children with ADHD: Strategy using and temporal properties. *Child Neuropsychology, 20*(4), 415-429.

Font O., **Kóbor A.**, Takács Á. (2013). A nem verbális fluencia fejlődési mintázata 3. és 5. osztály között. *Gyógypedagógiai Szemle, 41*(4), 275-288.

Kóbor, A., Takács, Á., & Urbán, R. (2013). The Bifactor Model of the Strengths and Difficulties Questionnaire. *European Journal of Psychological Assessment, 29*(4), 229-307.

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