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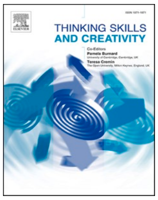

Two sides of the same coin? How are neural mechanisms of cognitive control, attentional difficulties and creativity related?

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ABSTRACT

Creativity has been associated with increased distractibility, but at the same time - and seemingly paradoxically- also with increased focused attention. Therefore, this study focused on the attentional processes involved in creativity and attentional difficulties. Healthy primary school children ($N = 62$) between 9 and 13 years old performed a selective attention paradigm while electrophysiological measures were recorded that measured the neural mechanisms of cognitive control (P300), conflict monitoring (N200), and subconscious attentional shifts (Mismatch Negativity). Attentional difficulties were measured with a parental questionnaire and creativity was measured with a divergent mathematical creativity task and a creative drawing task. We found that more creativity was related to decreased neural mechanisms of cognitive control and conflict monitoring (i.e. less negative N200 and smaller P300 amplitudes), however without affecting task performance. In addition, attentional difficulties were related to less negative N200 amplitudes on the attended and non-attended standard trials of the selective attention paradigm, as well as reduced task performance. Tentatively, the current findings suggest that original responses are associated with decreased cognitive control, possibly by promoting remote associations. Furthermore, our data shows that attentional difficulties are associated with a lack of selective attention and impaired information processing. Hence, although less cognitive control is often referred to in a negative way, it might facilitate certain aspects of creative thinking without affecting task performance.

1. Introduction

As first described by Eysenck (1967) and later supported by findings from Chakravarty (2010), the disinhibition hypothesis states that a creative, excitatory state stems from low levels of cortical arousal in frontal brain regions. This dispersed attentional state may be positively related to creativity, which can be defined as making something novel and useful based on the situation (Plucker, Beghetto & Dow, 2004). Creative individuals have been associated with distractibility, atypical attention, ADHD, and schizotypy (Brandau et al., 2007; Carson, Peterson & Higgins, 2003; Gonzalez-Carpio, Serrano & Nieto, 2017; Hoogman, Stolte, Baas & Kroesbergen, 2020; Nettle, 2006; Stolte et al., 2022). However, accounts that creativity is related to the ability to focus attention also exist (Chrysikou, 2019; Fink

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& Benedek, 2014). Since creativity has been proposed as one of the skills to thrive in the 21st century (Piirto, 2011), it is important to understand the underlying psychophysiological mechanisms. Therefore, the current study investigated these underlying neurocognitive mechanisms of creativity, divergent thinking, and attentional difficulties by examining the electrophysiological measures Mismatch Negativity (MMN), N200, and P300 event related potentials (ERPs) of healthy primary school children during a selective attention paradigm.

When a deviant, rare stimulus is perceived in a sequence of standard stimuli, a subconscious, pre-attentive response is elicited in the brain 100–200 ms afterwards, called MMN (Näätänen, 1995; Umbricht & Krljes, 2005). It is visible as a negative deflection in frontal and temporal areas of the brain Giard, Perrin, Pernier and Bouchet (1990) and linked to attentional shifts (Winkler, 2007). There are numerous studies in literature reporting reduced MMN amplitude in patients with schizophrenia (Avissar et al., 2018; Brenner et al., 2009; Morris, Griffiths, Le Pelley & Weickert, 2012; Oranje, Aggernæs, Rasmussen, Ebdrup & Glenthøj, 2017; Rydkjær et al., 2017; Umbricht & Krljes, 2005) and, although less often reported, also in patients with ADHD compared to healthy controls (Rothenberger et al., 2000; Rydkjær et al., 2017; Sawada, Negoro, Iida & Kishimoto, 2008). Furthermore, these reports on reduced MMN amplitude in patients with ADHD and schizophrenia together with recent reports that individuals with more ADHD symptoms are regularly better at creative tasks (Hoogman et al., 2020) and that creativity and schizophrenia appear positively related (Power et al., 2015), suggest that MMN amplitude might be associated to creativity.

The N200 ERP appears slightly later than MMN in the attentional process. It is a negative peak, that occurs in the frontocentral regions of the brain approximately 200 ms after stimulus presentation in response to conflict and conflict monitoring or mismatch detection even when no response is required (Nieuwenhuis, Yeung, Van den Wildenberg & Ridderinkhof, 2003; Yeung, Botvinick & Cohen, 2004). Given its location and description, the N200 amplitude has been assumed to reflect a neural mechanism of cognitive control (Nieuwenhuis et al., 2003). Moreover, researchers have observed a significantly later latency of N200 amplitude in children with ADHD compared to healthy controls, indicating decreased cognitive control (Tsai, Hung & Lu, 2012). However, as the stimulus discrimination process matures, this relation appears to fade (Barry, Johnstone & Clarke, 2003).

The P300 amplitude is a positive deflection in an ERP related to stimulus discrimination. It relates to memory-driven and attentional aspects of stimulus processing (Friedman, Cycowicz & Gaeta, 2001; Polich, 2007). The P300 amplitude has an early, more frontally oriented subcomponent, the P3A amplitude, and a later, more parietal oriented subcomponent, the P3B amplitude. The P3A amplitude is elicited when a distractor stimulus is presented and signals stimulus-driven, involuntary monitoring or switching of frontal attentional resources (Berti, 2016). The later P3B component has been named as a neural component of attentional and cognitive control, necessary for task switching and is triggered when memory evaluation of a stimulus takes place because task relevant information is detected (Gajewski, Kleinsorge & Falkenstein, 2010; Lange, Seer & Kopp, 2017; Polich & Criado, 2006).

Although evidence is scarce, the P300 amplitude has been associated with one or more of the following characteristics: ADHD, task-set shifting, schizophrenia, and cognitive flexibility (Bramon, Rabe-Hesketh, Murray & Frangou, 2004; Gow et al., 2012; Lange et al., 2017; Oja et al., 2016; Polich, 2007; Tsai et al., 2012). First, neurocognitive studies reported that the reduced P300 amplitude of individuals with ADHD compared to healthy controls was associated with inhibitory and executive processes (Gow et al., 2012; Oja et al., 2016; Tsai et al., 2012). It has been suggested that this explains why individuals with ADHD have more difficulty focussing their attention again after a distraction (Oja et al., 2016; Tsai et al., 2012). Second, meta-analyses found a significant decrease in P3a amplitude in patients with schizophrenia compared to healthy controls (Bramon et al., 2004; Jeon & Polich, 2003. Moreover, P3b amplitude was also reduced in patients with schizophrenia (Giordano et al., 2021). These decreases were found to be indicative of deficits in cognitive and psychosocial functioning related to the disorder presumably by overprocessing of irrelevant and under processing of relevant stimuli (Hermens et al., 2010). Third, in relation to cognitive flexibility, the P300 amplitude has been related to how efficient an individual can orient their attention after a task-relevant stimulus and when stimuli are related to a shift (Lange et al., 2017; Ocklenburg, Güntürkün & Beste, 2012). As such, the P300 amplitude reflects an individual's attentional shift towards a relevant, novel stimulus that needs to be identified, compared, and processed (Polich, 2007).

Next to this association between cognitive flexibility and the P300 amplitude, cognitive flexibility has also been associated with the prefrontal cortex, and creativity in some (Barceló, Periáñez & Knight, 2002; De Dreu, Nijstad & Baas, 2011) but not all research (Zabelina & Ganis, 2018). Hence, previous research seems to indicate that creative people are more adept at flexibly controlling their conscious attentional processes (Martindale, 2007; Zabelina & Ganis, 2018). This would allow them to narrow their cognitive and attentional filter when necessary, perhaps at different phases of the creative process (Daikoku, Fang, Hamada, Handa & Nagai, 2021) or based on the complexity and type of task (Benedek & Jauk, 2019; Zabelina, 2018).

There are multiple possibilities to increase the number of associations or creativity of responses (e.g., Miroshnik, Forthmann, Karwowski & Benedek, 2023). In accordance with the dual-pathway approach for creativity, the current study focused on two of those possibilities, namely the increase of the number of stimuli being processed and altered cognitive control of the association areas in the brain (Benedek & Fink, 2019; Nijstad, De Dreu, Rietzschel & Baas, 2010). Hypothetically, on a pre-attentional level creative individuals may have altered sensitivity to changes in their environment, which would allow a greater number of environmental stimuli to be processed. In addition, creative individuals might also have advanced cognitive control enabling them to focus their attention on task relevant stimuli later in the attentional process, resulting in larger N200 and P300 amplitudes (Bott et al., 2014; Conzelmann et al., 2010; Hawk, Yartz, Pelham & Lock, 2003; Zabelina & Ganis, 2018; Zabelina, Saporta & Beeman, 2016). Moreover, results suggest that creative individuals are more adapt at flexibly shifting between different patterns of brain connectivity (Beaty, Seli & Schacter, 2019). This combination might enable creative individuals to select task-relevant stimuli from a larger pool of environmental input in comparison to others.

Previous research found that P3a amplitude decreases across adolescence, while MMN amplitude remains consistent (Mahajan & McArthur, 2015). Furthermore, P3b latency was found to be earlier in adults while its amplitude remained unaltered (Sussman &

Steinschneider, 2009). Between the ages of 7 and 10 children become better at ignoring irrelevant stimuli and focusing their attention. After they turn 12 this development is completed (Werner, 2007). Due to these differences in psychophysiological processing, it is important to investigate this in a child sample. Early screening for children with different psychophysiological processing can be useful as an indicator of creativity. It can provide relevant information for parents and teachers when explaining tasks and strategies, or even contain useful information on how to adjust the child's environment, because attention is closely related to learning and performing complex tasks, such as creative tasks. Therefore, in the current study we exploratively investigated the association between early information processing, attentional difficulties, and creativity, by studying how these aspects are related to MMN, N200, and P300 amplitudes in a population of healthy children in the age of 9 to 13. We previously presented results of this same group of participants on the association between pre-attentional measures of information processing and creativity showing no significant associations between any of our assessed measures of creativity or attention and sensory or sensorimotor gating, except for an association between higher scores on fluency and flexibility and higher scores on P50 amplitude to testing stimuli (Stolte, Oranje, et al., 2022). In the current paper we present the results on selective attention. Given the literature cited above, we first hypothesized that higher levels of creativity and/or attentional difficulties are related to altered MMN amplitudes. Second, we hypothesized that higher levels of creativity would be related to increased N200 and P300 amplitudes on deviant trials (when increased attentional cognitive control is required) whereas more attentional difficulties would be related to decreased N200 and P300 amplitudes, during the selective attention paradigm. Third, we examined task performance of the selective attention paradigm and compared it to the severity of attentional difficulties that parents reported their children to have in order to validate these measures. Hence, we expected a negative relation between attentional difficulties and task performance.

2. Materials and method

2.1. Participants

70 participants that previously participated in a largescale behavioral study ($N = 360$) about creativity, mathematics, and executive functioning (Stolte et al., 2020) agreed to participate in the current study. Five participants did not perform the selective attention task caused by physical discomfort given that this task was at the end of our electrophysiological test battery. Parents of seven participants reported that their children had ADHD, which were included in the study in order to investigate the full range of attentional difficulties. In addition, we excluded three participants from the analyses because of a suspicion or diagnosis of an autism spectrum disorder. Hence, 62 children were included in the final analysis. The sample included 33 boys (M_{age}=10.76, SD_{age}=0.78, Range = 9.42 – 12.47) and 29 girls (M_{age}=10.89, SD_{age}=0.87, Range = 9.52 – 12.72). Furthermore, of these 62 included children, three had missing data on the attentional questionnaire, two participants had missing data on the mathematical creativity test and one participant on the Test for Creative Thinking Drawing Production (Urban, 2004). This resulted in them not being included in those analyses.

2.2. Procedure

Participants performed The Copenhagen Psychophysiological Testbattery, which contains paradigms to measure P50 suppression, prepulse inhibition of the startle reflex, MMN, and selective attention (e.g. Oranje et al., 2017; Rydkjær et al., 2017). Participants completed the tests in a dimly lit and soundproof room after informed consent was obtained from a parent. Additionally, a test designed to detect possible hearing deficits was assessed by randomly presenting pure tones of 500, 1000, and 6000 Hz at an intensity of 40 dB for 40 ms across both ears. None of the participants failed this test. The test session lasted approximately two hours, of which 70 min was spend assessing the test battery. The remaining time was spent explaining the study and EEG procedure to the participant, attaching the EEG electrodes and removing the electrodes after the tests. All study-procedures were approved by the Medical Ethical Committee of the Utrecht Medical Centre (NWMO18–849) and the Faculty Ethics Review Board (FETC18-018) prior to data collection.

2.3. Behavioral instruments

2.3.1. Mathematical creativity task

Creativity was measured with a divergent mathematical multiple solution task. This task is based on the test described in previous research (Schoevers, Kroesbergen & Kattou, 2018). In short, it contained three questions from an adapted and translated mathematical creativity test (Kattou, Kontoyianni, Pitta-Pantazi & Christou, 2013; Schoevers et al., 2018) and one additional question from a different study (Hershikovitz, Peled & Littler, 2009). For example, one of the questions the participants had to answer was *"Look closely to the following numbers: 23, 20, 15, 25. Which number does not belong to this group of numbers? Explain your answer. Is there more than one possible answer? If so, please write down as many possible answers."* To obtain a holistic measure of divergent thinking, questions were scored on originality, flexibility, and fluency (Leikin & Lev, 2013). The task has an acceptable internal consistency (Cronbach's α = 0.78; Kattou et al., 2013). Fluency refers to the total answers correct, flexibility to the different answer-categories, and originality to the uniqueness of an answer. To correct for the confounding effect of fluency on originality, we predicted originality from fluency and saved the residuals. Increases on any of these measures refers to more creative, divergent thinking in the domain of mathematics.

2.3.2. Test for creative thinking-drawing production (TCT-DP)

A creative drawing test was administered to assess creative thinking. The drawing template contains six figural fragments (see Fig. 1) and participants had 15 min to finish the drawing. Drawings were scored on fourteen creativity aspects, which were summed to one score. Hence, a higher score on the TCT-DP signals more creativity. Previous research has shown a high interrater reliability (r = 0.87) with an additional high differential reliability ($\chi^2 = 33.45$, $C_{(corr.)} = 0.92$; Urban, 2004). In the current study, inter-rater reliability was r = 0.96.

2.3.3. *Strengths and difficulties questionnaire*

We assessed whether children had attentional difficulties by letting parents complete the Strengths and Difficulties Questionnaire (SDQ). Answering options to the 25 questions were: “No”, “A little”, and “A lot”. More attentional difficulties is related to a higher score on the subscale hyperactivity which contains statements such as “*Constantly fidgeting or squirming*” and “*Easily distracted, concentration wanders*”. A report on the internal consistency and validity showed satisfactory levels (Cronbach α between 0.65 – 0.88; Goodman, 2001; Mieloo et al., 2013).

2.3.4. *Selective attention paradigm*

The selective attention task contained 400 randomly presented stimuli. Stimulus presentation was randomized across the right and left ear. Stimuli were either standard stimuli (1000 Hz), which were presented in 80% of all cases or deviant stimuli (1200 Hz). The intensity of all stimuli was 75 dB for 50 ms with an ISI randomized between 700 and 900 ms. The participants were instructed to push a button as fast as possible when hearing a deviant stimulus in a previously designated ear. False alarms were scored for each of an individual’s button press to a non-target stimulus. Likely because all children were healthy, they reached such a high percentage of accuracy (M = 99.45 SD = 0.42) that statistical analyses of accuracy were pointless. The task was performed twice, for monitoring in the left and right ear, lasting approximately 11 min. The amplitudes for MMN, N200, and P300 gave an overview of selective attention. That is, a less negative MMN amplitude is related to an attenuated automatic response to deviant trials. In addition, more positive values on P300 amplitudes as well as more negative values of N200 amplitude indicate increased processing of that trial type.

2.4. *Data processing*

Electroencephalography (EEG) recordings were made with BioSemi ® hardware (BioSemi, The Netherlands) containing 64 Active Two electrodes arranged according to the (extended) 10–20 system (Jasper, 1958). Signals were digitized at 2 kHz by a computer. We used BESA software (version 6.0, MEGIS Software, Gräfelfing, Germany) to process the data. We resampled the data from 2 kHz to 250 Hz and corrected the data for eye-artifacts with the adaptive method from BESA (Ille, Berg & Scherg, 2002). Additionally, we removed any non-paradigm related artifacts, i.e. by removing trials where the difference in minimum and maximum amplitude exceeded 150μV in the relevant scoring window of 0 to 900 ms post-stimulus. Hereafter, data were epoched and averaged for each trial type from 100 ms pre-stimulus to 900 ms post-stimulus and band-pass filtered (between 0.5 and 40 Hz). Last, we scored our EEG measures at the electrodes where they reached maximum or minimum amplitude, with average reference; minimum N200 amplitude was scored at Fz between 200 – 300 ms, and maximum P300 amplitude at Pz between 200 and 450 ms, all separately for each trial type (i.e. attended deviant (=target), non-attended deviant, attended standard and non-attended standard). The time window in which the EEG components were scored were based on when the relevant component occurred in the grand-average wave forms (see Fig. 2). We expressed MMN as the most negative difference between the averaged ERPs to the deviant stimuli subtracted by the averaged ERPs to the standard stimuli in the unattended ear, at electrode Fz between 250 and 350 ms. We did not assess the P3A component of the P300 amplitude as this component is overshadowed by the P3B component in our specific paradigm. In addition to the usual scoring of ERPs (see Fig. 2), we also included scoring of difference waves of the trials, much similar as is done for MMN, i.e. we subtracted an

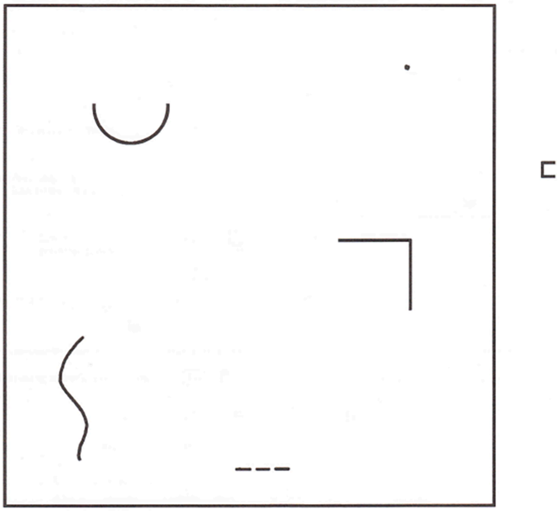

Fig. 1. Test for Creative Thinking Drawing Production (Urban, 2004).

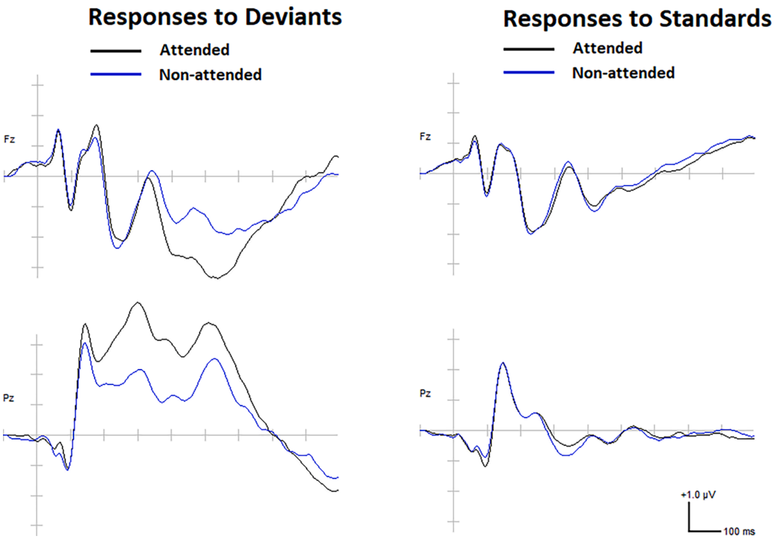

Fig. 2. Grand average responses to the 4 different types of trials.

individuals' average response to the non-attended stimuli from those of the attended stimuli (both for deviants and standards separately), and subtracted an individuals' average response to the standard stimuli from those of the deviant stimuli (both for attended and non-attended stimuli separately); after which the maximum or minimum amplitudes were scored in the same time window and at the same electrode as scored for the ERPs in question (e.g. maximum P3B amplitude difference was scored at Pz between 200 and 450 ms). Please note that MMN is identical to 1 of these 4 difference waves (see also Supplementary materials Fig. 1A).

2.5. Analysis

We analysed the data in IBM SPSS Statistics 24. First, we performed Kolmogorov Smirnov tests to inspect the distribution of the data. Second, the potential relation between the EEG measures and behavioral responses on the selective attention task (hits, misses, and false alarms), creativity and attention was determined with Spearman correlations. Third, we inspected if age and sex were significant covariates. If this was not the case, they were omitted. Because of the explorative nature of this research, we did not correct for multiple comparisons with Bonferroni.

3. Results

Descriptive information on the amplitude of MMN to non-attended stimuli, creativity and attentional measures is shown in Table 1. The amplitudes of the auditory N200 and P300 amplitudes are presented in Table 2. Since all creativity and attentional measures were non-normally distributed (Kolmogorov Smirnov test), we proceeded with Spearman correlations to test our hypotheses.

The relations between creativity, attention difficulties, and N200/P300 amplitudes are displayed in Fig. 3. A significant negative correlation was found between the TCTDP and N200 amplitude to the non-attended deviant trials ($r_s = -.258$, $p = .045$). Additional significant correlations were found between originality and P300 amplitude on the attended ($r_s = -.291$, $p = .025$) and non-attended deviant trials ($r_s = -.325$, $p = .011$). Furthermore, the scores on the SDQ and N200 amplitude were positively correlated on attended ($r_s = 0.393$, p 0.002) and non-attended standard trials ($r_s = 0.291$, $p = .025$). We found no significant correlations between MMN amplitude and any of the creativity or attentional measures ($r_s \langle\ 0.193, p \rangle\ .136$) or between N200 and P300 amplitude and flexibility ($r_s \langle\ -0.171, p \rangle\ .191$) or fluency ($r_s > -0.182$, $p > .165$). For a full overview of all correlations see Table S1 and Table S2 in the Supplementary materials.

To account for the individual differences in N200 and P300 amplitudes we also analyzed the relation between creativity,

Table 1
Mean and standard error of mismatch negativity (MMN), creativity, and attentional outcome measures.

Measure	Mean	SE
TCTDP	22.42	1.34
Fluency	15.26	.95
Flexibility	7.52	.28
Originality	1.80	.08
SDQ hyperactivity/inattention subscale	3.96	.33
MMN amplitude (µV)	−1.55	.15

Table 2
Mean and standard error of the ERP amplitudes (uV) per stimulus type.

ERP	Attended				Non-attended			
	Standard		Deviant		Standard		Deviant	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
N200	−2.80	.15	−3.57	.27	−2.82	.15	−3.44	.22
P300	1.40	.12	4.45	.23	1.42	.12	3.31	.19

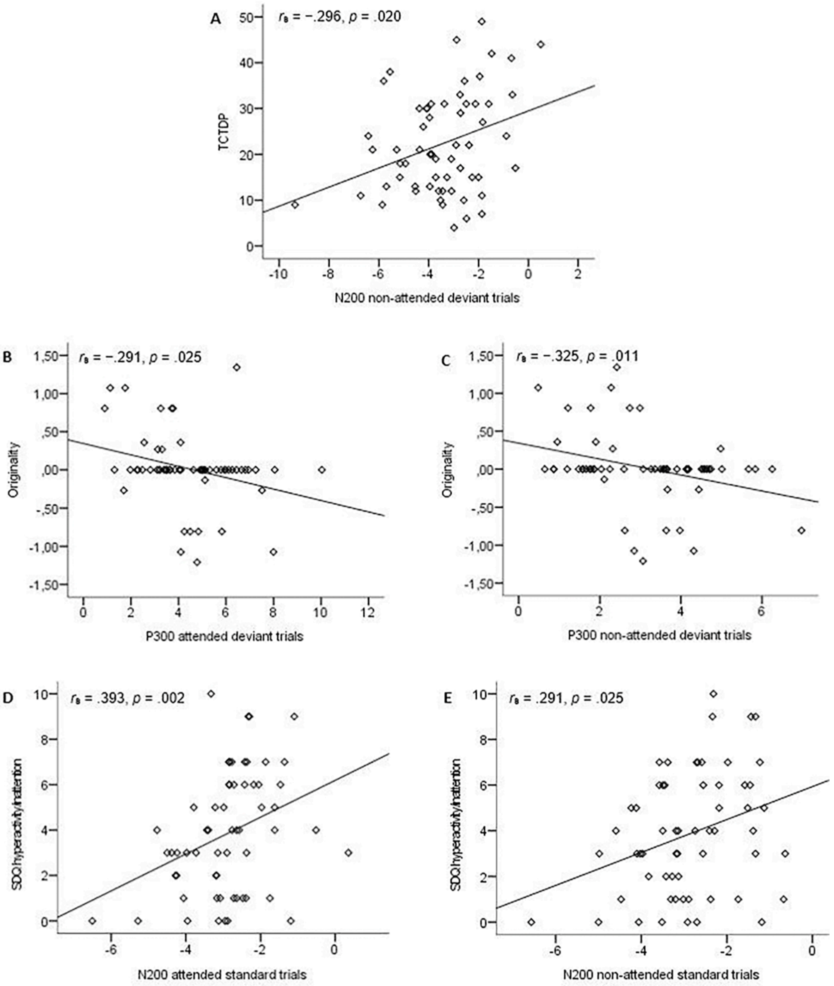

Fig. 3. Scatterplots of the main significant Spearman correlations between the N200 & P300 amplitudes, creativity, and attentional measures ($p < .05$). Panel A: TCTDP x N200 amplitude to non-attended deviant trials. Panel B: Originality x P300 amplitude to attended deviant trials. Panel C: Originality x P300 amplitude to non-attended deviant trials. Panel D: SDQ hyperactivity/inattention subscale x N200 amplitude to attended standard trials. Panel E: SDQ hyperactivity/inattention subscale x N200 amplitude to non-attended standard trials.

attentional difficulties and the difference between ERP responses to standard and deviant responses which yielded one significant correlation between originality and the attentional difference in N200 amplitude ($r_s = -.351, p = .006$). A complete overview of these results can be found in Table S4 of the Supplementary materials.

Since sex had a significant positive association with originality ($r_s = 0.266$, $p = .032$, $n = 65$), we inspected the relation between P300 amplitude and originality for boys and girls separately. Here, we only found a significant negative correlation between P300 amplitude to the attended deviant trials and the score on originality for boys ($r_s = -.397$, $p = .027$, $n = 31$) and not for the non-attended deviant trials ($r_s = -0.076$, $p = .616$). For girls, we found neither a significant relation between P300 amplitude to the attended deviant trials and the score on originality ($r_s = -0.186, p = .334, n = 29$) nor for the non-attended deviant trials ($r_s = -0.346$, $p = .066$).

Behavioral performance on the selective attention paradigm was assessed with number of hits, false alarms and incorrect responses on deviant trials. It was tested how these measures were related to attention difficulties (SDQ hyperactivity/inattention subscale) and the creativity measures. No significant associations were found between any of the creativity measures and these performance measures. However, children who scored high on the SDQ hyperactivity/inattention subscale, had significantly more false alarms ($r_s = 0.314$, $p = .016$). In addition, a negative correlation was found for severity of attentional difficulties and hits to target (= attended deviant) trials ($r_s = -.444$, $p < .001$). For a full overview of all correlations see Table S3 Supplementary materials.

4. Discussion

The current study reports on the psychophysiological underpinnings of attentional difficulties and creativity in healthy primary school children. We investigated the association between neural markers of cognitive control, creativity, and attentional difficulties. We found that originality and performance on our creative drawing task were related to some decreased neural markers of cognitive control during a selective attention task, as measured by less negative N200 and smaller P300 amplitudes on the attended or non-attended deviant trials for higher values of creativity, contradicting our hypotheses. In addition, we found that lower neural markers of cognitive control, as indicated by less negative N200 amplitude on standard trial types, was related to more attentional difficulties as indicated by a higher score on the SDQ subscale hyperactivity/inattention. Contrary to our predictions, there was no significant relation between MMN amplitude and creativity or attentional difficulties. Our behavioral results revealed that although creativity was not related to scores of hits or false alarms on the selective attention task, the presence of attentional difficulties was related to these scores.

In contrast to previous research, we found that higher levels of originality and performance on our creative drawing task were related to electrophysiological indicators of less focused attention and diminished cognitive control, to deviant, rare stimuli (Barceló et al., 2002; Zabelina & Ganis, 2018). However, in spite of this, no association was found between task performance (scores of hits and false alarms) and the creativity measures, indicating that children performed equally well on the selective attention task, regardless of creativity. Hence, it appears that more creative children do not appeal to their cognitive control processes as much as less creative children when they encounter stimuli that require their attention, while still performing equally well as less creative children. This agrees with the above-mentioned disinhibition hypothesis by Eysenck (1967), probably by less cortical suppression of remote associations (Radel, Davranche, Fournier & Dietrich, 2015). Perhaps an explanation for differences in results is that time pressure leads to a different utilization of cognitive control processes since we allowed our participants more time to complete the creative tasks in comparison to previous research that found contradicting results (Zabelina & Ganis, 2018). In addition, creative achievements in daily life, that are less confined in terms of time, also seem to benefit from distractibility (Zabelina et al., 2016).

These results could not be replicated in the additional analyses containing difference ERP responses to standard and deviant stimuli, although the negative correlation between originality and N200 amplitude can be explained in the same way as the results from our original analyses (i.e., diminished cognitive control is advantageous to originality). Moreover, the inability to replicate the results based on raw amplitude data with results on difference waves is likely due to (intra-)individual aspects.

Creative, divergent thinking requires making numerous associations in order to increase the number of responses (diversification based on fluency and flexibility). Two options exist to increase the number of associations. First, by increasing the number of environmental stimuli that reach the association areas of the brain by opening up the sensory filters. Second, by inhibiting areas that exert cognitive control in the brain, resulting in the brain's sensory filters opening up, and thus blocking less environmental stimuli. In turn, this increase in environmental stimuli results in an increase in available information that can be combined in the associative areas of the brain. We found no evidence for a relation between less stringent sensory filters and creativity, as indicated by our current finding that MMN amplitude did not correlate with creativity. Furthermore, in our previous study on this same group of children we found no relation between sensory-and sensorimotor gating, originality, or creative drawing but only a minor association between sensory gating and flexibility and fluency (Stolte, Oranje, Van Luit & Kroesbergen, 2022). Instead, our current finding that creative drawing and originality appear related to less focused attention and diminished neural markers of cognitive control, points toward the idea that less cognitive control might make it easier to make associations and think of original responses. In addition, in the absence of a relation between cognitive control and other aspects of creativity (fluency and flexibility), these aspects may rely on some aspects of sensory filtering, in which perceiving more input based on less sensory gating benefits these aspects of creativity.

Based on these results, there seems to be some kind of quantitative route where we go for bulk answers (fluency and flexibility) that also requires bulk input (because of a less stringent sensory filter). This route therefore relies on the amount of input but does not seem to depend on cognitive control because it is a way of responding, which depends on making close and common associations. However, if the answers need to be original something else is needed, namely a qualitative route which enables people to come up with something outside the norm that is original. Our results seem to indicate that this route is related to reduced cognitive control in that it possibly makes it easier to make associations because it allows the associative areas of the brain to make more loose and distant associations, increasing the chance of an original association and response.

However, other factors must be involved because making loose and distant associations may produce original responses but not all those original responses will be 'correct'. An original response can also be a completely nonsensical response. Presumably, the assessment of responses also plays a role and might depend on factors such as intelligence or domain specific knowledge. Investigating this was outside the scope of this study but we recommend future studies to take this into account.

Interestingly, patients with schizophrenia are known for their so-called "loose associations" (DSM-5; American Psychiatric Association, 2013). Besides this, there are studies linking (subclinical levels of) schizophrenia with creativity (Acar, Chen & Cayirdag, 2018; Kyaga et al., 2013), as well as numerous reports indicating both reduced sensory filtering and diminished N200 and P300 amplitudes (e.g. Bramon et al., 2004; Kim, Kwon, Kang, Youn & Kang, 2004; Oranje & Glenthøj, 2013). This suggests that patients suffering from schizophrenia are flooded by sensory stimuli and have overactive association areas that try to make sense of all these stimuli, hence resulting in loose associations which in later stages of schizophrenia develop into hallucinations and delusions (Perry, Geyer & Braff, 1999). In other words: schizophrenia patients may suffer from pathological levels of creativity or originality.

Contrary to our hypothesis, we did not find that the presence of mild attentional difficulties was associated with differences in MMN amplitude. Hence, this indicates that the automatic, pre-attentive identification system for deviant or unexpected stimuli is intact in children with mild attention difficulties. In the past, several studies reported relationships between attenuated MMN responses and clinical levels of attentional difficulties, such as present in individuals with ADHD (Kilpeläinen, Partanen & Karhu, 1999; Rothenberger et al., 2000; Sawada et al., 2008). However, similar to our current results, this is not always found, also in previous studies from our lab (Gomes, Duff, Flores & Halperin, 2013; Rydkjær et al., 2017). Some of these discrepancies might be explained by methodological differences such as (frequently) small sample sizes, differences in population (i.e. individuals with subclinical levels of attentional difficulties in comparison to individuals diagnosed with ADHD), differences in ERP time window, and differences in task characteristics such as stimulus duration, frequency, and inter-stimulus interval. Moreover, others claim that pre-attentive measures such as MMN are not the cause of attentional difficulties but that deficits in later attentional processes are the root of such behavioral issues, which may also be true for creativity and would agree with our current results (Gomes et al., 2013; Sergeant, Geurts, Huijbregts, Scheres & Oosterlaan, 2003).

Consistent with this line of thinking, we found that increases in attentional difficulties were indeed accompanied with less negative N200 amplitudes on both attended and non-attended standard trials, indicating less inhibitory processing. Indeed, not only did we find that the presence of attentional difficulties was associated to these electrophysiological measures, it was also related to several measures indicating lower performance on our selective attention paradigm. Similar results have been reported before (Johnstone & Barry, 1996; Stroux et al., 2016), hence providing further evidence that impaired information processing is linked to impaired cognitive control (Cai, Griffiths, Korgaonkar, Williams & Menon, 2019). This link between attentional difficulties and impaired neural mechanisms of cognitive control might correspond to deficits in the executive control network that have been extensively documented in children with ADHD (Francx et al., 2015; Lin, Tseng, Lai, Matsuo & Gau, 2015), because these children usually show similar attentional difficulties.

Our current sample was too small to examine subgroups or the development of associations between creativity and cognitive control, but future studies could focus on gifted and learning-disabled children or investigate the relation between creativity and psychophysiological properties in children of different ages, longitudinally or with ADHD to inspect if the high levels of inattention in a clinically diagnosed sample are associated with reduced cognitive control and how this relates to creativity. Furthermore, we recommend investigating whether our results hold for other measures of creativity, such as creative achievements, since real-life creativity and standardized tests have led to different results in the past (Zabelina & Ganis, 2018). While the current study provides insight into the association between neural markers of cognitive control and creativity in children, it should be noted that the creativity tasks and the selective attention task are separate paradigms. Moreover, given the exploratory nature of this study, we did not account for multiple testing in our analyses. Future studies should therefore confirm our results with more goal directed hypotheses and statistical analyses. Therefore, conclusions should be drawn with care and we recommend future research to investigate (electrophysiological parameters of) cognitive control and creativity simultaneously, i.e., in one paradigm. In addition, future studies should try to replicate our current MMN results with a paradigm without an (selective) attentional component. After all, it is conceivable that the lack of correlations between MMN amplitude and creativity as well as between MMN amplitude and attentional difficulties in the current study was caused by the children concentrating on performing well during our selective attention paradigm, creating a confounding factor of attention. Future research should examine the relation between creativity and neural measures of cognitive control with a longitudinal design as previous research suggests that a stronger attentional element is at play in children in comparison to adults (Sussman & Steinschneider, 2009).

In conclusion, we found that some decreased markers of cognitive control in healthy primary school children were related to higher originality and performance on our creative drawing task but not to differences in the quantitative measures of creativity, fluency and flexibility. In addition, while more attentional difficulties were related to some decreased markers of cognitive control and worse task performance during a selective attention task, task performance was not related to the level of creativity; suggesting that while creative children utilize less cognitive control on a neural level, this does not impair them behaviorally. These new insights into the underlying cognitive component processes of creativity provide important knowledge about how encouraging a more dispersed attentional state can lead to greater creative potential.

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CRediT authorship contribution statement

Marije Stolte: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Evelyn H. Kroesbergen:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Johannes E.H. Van Luit:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Bob Oranje:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tsc.2024.101533.

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