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Creativity and cognitive control: Behavioral and ERP evidence that divergent thinking, but not real-life creative achievement, relates to better cognitive control.

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Abstract

Two studies used event-related potentials (ERPs) to examine whether and how divergent thinking and creative achievement are linked to attentional flexibility and cognitive control as indexed by response times and by the amplitude of the anterior N2 ERP component. Both experiments used an oddball paradigm in which participants viewed hierarchical letter stimuli and identified target letters in frequent and rare target trials. The successful identification of targets required attentional flexibility when switching levels of attention (from the frequent global to the rare local attentional level, or vice-versa). Divergent thinkers showed smaller switching times on rare target trials, indicating higher levels of attentional flexibility. Furthermore, divergent thinkers engaged cognitive control processes more strongly at the moment of the attentional switch (and before the response), as indicated by a larger N2 difference between frequent and rare targets. In contrast, creative achievement was associated with neither the switching times on rare target trials, nor with a larger N2 difference between frequent and rare targets. All results held when controlling for general intelligence. Results from these studies provide evidence that divergent thinking is associated with higher attentional flexibility and that such attentional flexibility relies on cognitive control processes required when disengaging from one level of attention (e.g., global), and shifting to the other level of attention (e.g., local).

Keywords: creativity, divergent thinking, attention, cognitive control, ERP, N2

1. Introduction

Creativity, like many mental activities, requires attention, but what form of attention is most conducive to creativity remains unresolved. The existing literature provides contradictory accounts on the link between creativity and attention, suggesting that creativity is linked with broad attention (Ansburg & Hill, 2003), “leaky” attention, i.e., attention that allows “irrelevant” information to be noticed (Kasof, 1997; Zabelina, Saporta, & Beeman, 2016), attentional flexibility (Vartanian, Martindale, & Kwiatkowski, 2007; Zabelina & Robinson, 2010), and executive control, which relies heavily on the ability to focus attention (Nusbaum & Silvia, 2011). Recent advances in the field, however, are beginning to elucidate these seemingly contradictory accounts by pointing to the crucial importance of distinguishing between the various operational definitions of creativity.

One of the most common ways of operationally defining creativity is through the performance on the Alternate Uses (Wallach & Kogan, 1965) or divergent thinking tests (Goff & Torrance, 2002; Torrance, 1974). Both alternate uses and divergent thinking tests are aimed at assessing people’s ability to generate multiple original uses for a common object or novel solutions to a stated problem within a limited amount of time in a laboratory setting (although the nature of the tests and instructions can vary). Participants are typically instructed to be creative, and are given 2-3 minutes to generate their creative ideas, with responses scored for fluency (i.e., number of pertinent responses within the allotted time), and originality of responses (i.e., how novel or original the participant’s responses are compared to the responses within the experimental sample or compared to the established norms). Divergent thinking thus requires overcoming prepotent, uncreative response tendencies and involves cognitive strategies to arrive at novel ideas (Gilhooly, Fioratou, Anthony, & Wynn, 2007).

An increasing body of research suggests that creativity, operationalized with divergent thinking tests, tends to involve top-down control of attention (sometimes in combination with more spontaneous, undirected cognitive processes; Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014). Most of this evidence comes from latent variable studies showing effects of higher-order cognitive abilities, such as working memory capacity (Lee & Therriault, 2013; Süβ, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), verbal fluency (Benedek, Bergner, Könen, Fink, & Neubauer, 2011; Silvia, Beaty, & Nusbaum, 2013), and fluid intelligence (Beaty, et al., 2014; Nusbaum & Silvia, 2011). Such abilities are hypothesized to support thinking in a divergent manner by providing the executive control needed to guide memory retrieval and inhibit salient, but unoriginal ideas (Beaty & Silvia, 2012).

Behavioral evidence for the role of executive processes in performance on the divergent thinking tasks has also received support from electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) research. Studies report task-related activation in brain regions associated with interference resolution, response selection, and cognitive control in the inferior frontal gyrus (IFG) and inferior parietal cortex (Abraham, Beudt, Ott, & Cramon, 2012; Chrysikou & Thompson-Schill, 2011; Fink et al., 2009; Fink & Benedek, 2014). Divergent thinking has also been linked with more selective (in contrast to “leaky”) sensory filters that are reflected in the P50 ERP (Zabelina, Leary, Pornpattananangkul, Nusslock, & Beeman, 2015).

Our prior work suggests that divergent thinking is linked with flexible attention, the mechanism for which may indeed be the ability to focus, inhibit, and switch attention, i.e., higher levels of cognitive control (Zabelina et al., 2016). In this study, participants were asked to identify target letters (*S* or *H*) within classic hierarchical stimuli (global letters made of local letters; Navon, 1977). On most trials, participants were correctly cued to the level of the target (80% valid trials) but, critically, they were given invalid cues on a subset of trials (20% invalid trials). Thus, we were able to operationalize attentional flexibility by using well-established stimuli in attention research. Results showed that people with higher divergent thinking scores were quicker to overcome the invalid cues to correctly identify the target, thus showing more attentional flexibility.

We further investigated the mechanism for attentional flexibility in divergent thinkers, by suggesting that there are at least two competing mechanisms through which attentional flexibility can be achieved. One proposed mechanism is “leaky attention,” such that when cued to one level of a stimulus, some information is still processed, or “leaks in,” from the non-cued level. Thus we designed an experiment in which we again presented participants with the hierarchical letters, however in this case the cued stimulus level always contained a target, and the non-cued level was congruent, neutral, or incongruent with the target. Participants were asked to identify the target at the cued level, and the cue was always valid. The congruency effect (response times on incongruent compared to the congruent trials) was the measure of “leaky” attention. We found that divergent thinking did not relate to the congruency effect, suggesting that “leaky” attention is not the mechanism for attentional flexibility in divergent thinkers. We proposed that an alternate mechanism, that of the ability to focus, inhibit, and shift attention, or higher levels of cognitive control, is likely the mechanism by which divergent thinkers achieve attentional flexibility while switching levels of attention. The present study directly examined this hypothesis by investigating whether cognitive control is the mechanism by which divergent thinkers achieve attentional flexibility when switching levels of attention.

In contrast to operationally defining creativity with the laboratory tests of divergent thinking, a more ecologically valid way of assessing people's creativity is by asking them about their real-life creative accomplishments. Admittedly, the creative process of writing a piece of literature or engineering a novel design is distinct from and occurs on a longer timeline than a 2-3-minute laboratory test of divergent thinking. Indeed, correlations between divergent thinking and real-world creativity generally vary considerably, suggesting that they involve some unique processes (Runco & Acar, 2012; Torrance, 1969). While real-world creativity may indeed rely on the ability to think in a divergent manner, it may also reflect other factors, such as incubation of ideas (the opportunity that is severely limited on the divergent thinking tests), as well as persistence, opportunity, personality, and resources.

Unlike the link between divergent thinking and attentional flexibility, real-life creativity tends to be associated with “leaky” attention. For example, latent inhibition, or a reduced ability to screen or inhibit from conscious awareness stimuli previously experienced as irrelevant, relates to creative achievement (Carson, Peterson, & Higgins, 2003). Similarly, people with higher number of real-life creative accomplishments tend to exhibit higher levels of “leaky” attention when asked to identify target letters within hierarchical stimuli (Zabelina et al., 2016), as well as “leaky” sensory filters, as indexed by the P50 ERP (Zabelina et al., 2015). Such perceptual openness, or “open-mindedness” as the literature suggests (Feist, 1998), may enhance creativity by enlarging the range of unfiltered stimuli available in conscious awareness, thereby increasing the possibility that novel and useful combinations of stimuli will be synthesized. It is possible, however, that leaky attention underlies both costs and benefits of creative cognition: noise and other environmental stimuli can serve as distractors for creative people, leading to heightened distractibility, as well as to predisposition for attention disorders and various forms of psychopathology (Boot, Nevicka, & Baas, 2917; Zabelina, Condon, & Beeman, 2014). At the same time, leaky attention may help people integrate ideas that are outside the focus of attention into their current information processing, leading to creative thinking.

In summary, creativity assessed with divergent thinking tests or through a survey of people’s real-life creative accomplishments tends to relate to distinct forms of attention. People who perform well on laboratory tests of divergent thinking exhibit more attentional flexibility, while people with more real-life creative accomplishments show more “leaky” attention. Although we have previously noted that cognitive control is likely the mechanism through which divergent thinkers achieve attentional flexibility (Zabelina et al., 2016), the evidence for it remains to be examined. Moreover, while real-life creativity does not appear to relate to attentional flexibility, it is possible that creative achievement is also linked with higher levels of cognitive control, as it has been posited that “leaky” attention, in combination with higher levels of cognitive control, leads to the highest levels of real-life creative accomplishments (Carson, 2011; Zabelina, in press). Here cognitive control may serve as a protective mechanism, shielding creative achievers from becoming overwhelmed by the incoming sensory information, while helping them funnel it in appropriate ways.

The goal of the present work was to investigate the role of attention and cognitive control in creativity.

We examined whether and how divergent thinking and creative achievement relate to attentional flexibility as indexed by response times, and to cognitive control as indexed by the N2 event–related potential (ERP) in an *oddball paradigm*. In this paradigm, rare (and thus unexpected) changes in a stream of otherwise uniform stimuli require one to update internal representations of the ongoing stimulus sequence and to reorient attention, providing a way to assess attentional flexibility. A number of studies using variants of this paradigm have indicated that a family of frontocentral N2 components (which we will refer to as “N2 components” hereafter, for simplicity) is related, among other things, to cognitive control– namely, response inhibition, response conflict, and error monitoring (for review, see Folstein & Van Patten, 2008).

It has been debated whether the N2 component reflects inhibition (Falkenstein, Hoormann, & Hohnsbein, 1999) or conflict monitoring processes (Nieuwenhuis, Yeung, Van Den Wildenberg, & Ridderinkhof, 2003), but both of these interpretations are consistent with the N2 serving as an index of cognitive control processes. In line with this interpretation, dipole-modeling work suggests that the N2 can be localized to the anterior cingulate cortex (ACC), a neural structure known to play a key role in cognitive control (Nieuwenhuis et al, 2003; Yeung, Botvinick, & Cohen, 2004).

In oddball paradigms, anterior N2 components to targets are often observed in combination with the P3b component, which has often been interpreted as reflecting contextual and memory updating processes, such as the revising of working memory templates (Debener, Makeig, Delorme, & Engel, 2005; Spencer, Dien, & Donchin, 1999, 2001). The P3b is a task-relevant potential elicited during target stimulus processing (Snyder & Hillyard, 1976), and is distinguished from a P3a task-irrelevant potential (Polich, 1988). Although we examined the P3b, because the goal of this paper was to investigate the relationship between creativity and cognitive control, we did not have any predictions regarding the link between creativity and this component.

While a number of studies have used electroencephalogram (EEG) methodology to investigate creative cognition (for review, see Dietrich & Kanso, 2010; Srinivasa, 2007), few have attempted to link any component related to ERPs with creative thinking. Exceptions include studies on insight problem solving (e.g., Lang Kanngieser, Jaśkowski, Haider, Rose, & Verleger, 2006; Lavric, Frostmerier, & Rippon, 2000; Luo et al., 2011; Qiu et al., 2008), and an examination of conceptual expansion (Rutter, Kröger, Hill, Windmann, Herman, & Abraham, 2012). To our knowledge this is the first investigation linking creativity to the N2 ERP.

Experiment 1 was preliminary in nature, and was conducted in order to evaluate the feasibility of the proposed project, and confirm the time windows and electrode sites of interests for the ERP analyses. We assessed divergent thinkers' attentional flexibility by comparing their response times on rare and frequent target trials (that is, response time when switching attention from the local to the global attentional level, or vice versa), and by determining whether such attentional flexibility is accompanied by increased recruitment of cognitive control as indexed by ERP measures. Experiment 2 improved on

Experiment 1 by using a larger sample and by also measuring real-life creative achievement and intelligence scores.

In both experiments people viewed hierarchical letter stimuli (global-local letters, Navon, 1977) in blocks of trials, and they had to detect a target letter provided at the beginning of each block. Eighty percent of the trials (frequent target trials) occurred at one attention level (e.g., global), 10% of the trials (rare target trials) occurred at the other level (e.g., local), and the remaining 10% contained no target and were used as control. Thus, when performing this task, participants pay attention to target letters that appear at the most frequent level (.e.g., global), but occasionally, they need to detect letters that appear at the other level (e.g., local). This feature of the oddball task is what enabled us to assess attentional flexibility, that is, the ability to switch between different attentional levels. As done in our previous work (Zabelina et al., 2016), we assessed each person’s capacity for attentional flexibility by computing their behavioral *oddball effect*: how much longer they took to respond to the rare compared to the frequent targets. Cognitive control is one of the mechanisms by which attentional flexibility may be achieved, and so we assessed each person’s levels of cognitive control engagement by computing the same measure for N2 amplitude (N2 oddball effect), as suggested by prior ERP work (Folstein & Van Patten, 2008). Finally, we assessed the engagement of contextual and memory updating processes by computing the same measure for P3b amplitude (P3b oddball effect).

Given prior literature, we expected that people with higher divergent thinking scores would show a smaller behavioral oddball effect, indicating better attentional flexibility. Further, if cognitive control is the mechanism by which divergent thinkers achieve attentional flexibility when switching levels of attention, we also expected to see a larger N2 oddball effect (as increased cognitive control engagement is reflected in larger N2 amplitudes). Alternatively, if cognitive control is not the mechanism by which divergent thinkers achieve attentional flexibility, we should see no relationship between divergent thinking and the N2 oddball effect.

Experiment 1

2. Methods

2.1. Participants and design

Participants included 15 (5 male, 10 female, mean age = 19.4, *SD* = 1.0) University of Plymouth students who took part in the study for course credit. Two participants were not included in the analyses because of incomplete datasets due to technical issues. None of the participants had a history of epilepsy, neurological, psychiatric, or psychological disorders, learning disability, current or history of drug, alcohol, or substance abuse, head trauma, concussion, or loss of consciousness of substantial duration (minutes or more). None of the participants were taking any potentially psychoactive medication, or had an untreated health problems that may affect cognitive function (e.g., high blood pressure, diabetes). All participants were either fluent English speakers or learned English before 5 years of age, and all had normal or corrected-to-normal vision. The study was approved by the University of Plymouth Ethics Board and all participants reviewed and signed a consent form.

The study was correlational in nature, with divergent thinking, attentional flexibility (RT), and cognitive control (N2) as the variables of interest.

2.2. Materials

2.2.1. Abbreviated Torrance Test for Adults (ATTA; Goff &Torrance, 2002)

To assess divergent thinking, participants completed the ATTA – a shortened form of the Torrance Test of Creative Thinking (Torrance, 1974). The ATTA consists of three activities (3 min each), one involving verbal (written) responses (e.g., generating problems that may arise from being able to walk on air or fly without being in an airplane or a similar vehicle), and two involving figural responses (e.g., using incomplete figures to make pictures). Responses were scored for fluency (i.e., a count of the number of pertinent responses), and originality (i.e., the number of responses that are not typically produced, according to the normative data), with scores summed across the three activities (Goff & Torrance, 2002). The total divergent thinking score reflects a weighted score of fluency plus two times originality, to equally weigh the two scores, since the average fluency score (14.5) was approximately double the average of the originality score (8.4), similar to the norms reported by the test developers (Goff & Torrance, 2002; see Runco & Acar, 2012 for suggestions on scoring divergent thinking tests). The ATTA reports good reliability (KR-21 = .84; Goff & Torrance, 2002). The average divergent thinking score was 31.4 (*SD* = 11.35, range 14-50).

2.2.3. Oddball task

We adapted the Local-Global letter task (Navon, 1977) to optimally test for the oddball effect. The stimuli were Navon figures (Navon, 1977), and were designed so that global and local stimuli would elicit approximately equal response speed and accuracy based on a previous study (Bultitude, Rafal, & List, 2009). The stimuli consisted of twelve composite letters (Figure 1A). The local letters (subtending 0.3 by 0.5 degrees of visual angle) were arranged within an invisible 5 x 4 rectangular grid to form the global letters (subtending approximately 1.5 by 3 degrees of visual angle).

Participants were instructed to press one of two keys on a button box with their dominant hand to indicate whether a target letter was present or not. Participants were asked to respond as quickly and as accurately as possible. After 9 practice trials there were 8 blocks of experimental trials, each with 60 stimuli presented in pseudo-random order. Before each block, a single red letter (twice in size as the local letters) in the center of the screen indicated the target letter to be detected in the upcoming block. Each stimulus was presented in the center of the screen for 700 ms, with an average inter-stimulus interval (ISI) of 2500 ms, randomly varying between 2400 and 2600 ms (to minimize effects of temporal expectation). Targets could occur at either the local or the global attentional level. In each block, 80 % of trials (48 trials) contained targets at one attentional level (frequent), 10% (6 trials) contained a target at the other attentional level (rare), and the remaining 10% (6 trials) contained no target (Figure 1B).

2.2.4. Electrophysiological recordings

The EEG was sampled at 8192 Hz using a Biosemi Active Two system. EEG data were collected from 32 active Ag/AgCl electrodes arranged according to the 10–20 system, and loose lead electrodes (Ultra Flat Active electrodes, Biosemi) below the right eye, to monitor eye blinks and vertical eye movements, and on the left and right mastoids. Horizontal eye movements were monitored using 2 loose electrodes placed on the outer canthi of the right and left eyes. The data were downsampled off-line to 512 Hz before further processing. Data were re-referenced off-line to the average of the two mastoids for consistency with key literature on the topic.

2.2.5. ERP waveform and component analysis

EEGLab and ERPLab were used to conduct offline EEG analyses (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014). ERPs were averaged off-line for an epoch of 1000 ms, including a 200 ms baseline. Trials contaminated by blinks, eye movements, muscle activity or amplifier blocking were rejected off-line. Although the figures show data low-pass filtered at 30Hz (to avoid visually distracting high frequency noise in the plots), all analyses were conducted on unfiltered data.

As with fMRI, with ERP analyses there is the risk of circularity if one uses a dataset to define time windows and scalp sites to measure the amplitude of ERP components in that same dataset. Thus, we used information about the frontal N2 and the P3b from the literature and from visual inspection of these components in Experiment 1 to define the time windows and sites of interest. These temporal and spatial parameters were then also used to measure the amplitude of these components in the independent dataset for Experiment 2. N2 and P3b amplitudes were measured at sites Fz/Cz (mean value between 350 and 450 ms) and Pz (mean value between 500 and 700 ms), respectively, where they usually are maximal (Folstein & Van Patten, 2008 for N2; Polich, 2009 for P3b). For the N2, data from sites Fz and Cz were combined to provide more robust single-subject averages.

For each participant, we computed the final N2 (P3b) oddball effect by subtracting N2 (P3b) amplitudes on the frequent target trials from the N2 (P3b) amplitudes on the rare target trials. Since the N2 is a negative-going potential, larger negative values for the difference indicate an N2 with greater amplitude on rare than frequent target trials. Conversely, since the P3b is a positive-going potential, larger positive values of the difference indicate a P3b with greater amplitude.

2.3. Procedure

Participants were tested individually during a session lasting approximately 90 minutes. During this session, participants were administered a divergent thinking test and an oddball task using the Navon figures during which the EEG was recorded continuously. For the oddball task, after setting up the EEG cap and electrodes, participants were seated on a comfortable chair, 115 cm from a computer screen in a dark room. They were asked to relax and to refrain from blinking during the presentation of the stimuli, but otherwise blink naturally in between trials.

2.4. Analytical strategy

First, differences in RTs for rare target, frequent target, and no target trials were examined with an ANOVA and follow-up t-tests. Next, t-tests were conducted to compare the amplitude of the N2 and P3b components to rare and frequent targets (oddball effect). Finally, linear regressions were carried out to determine whether divergent thinking scores (total scores, as well as fluency and originality scores separately) predicted the RT, N2, or P3b oddball effects.

3. Results

Two participants were outliers with average RTs larger than 2.5 standard deviation of the mean in at least one trial type, and so they were excluded from the analyses. Normality checks were carried out on residuals, which were approximately normally distributed. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 3.25$, $p = .20$.

A repeated measure ANOVA on the 11 participants with complete datasets showed that mean RT differed between the three types of trials [*F*(2,20) = 119.69, p < .001]. Post hoc analysis using Bonferroni correction revealed that participants responded faster to frequent target (*M* = 524 ms, *SE* = 20.41) than to rare target trials (*M* = 697 ms, *SE* = 40.60, *p* < .001). Participants also responded faster to frequent target (*M* = 524 ms, *SE* = 20.41) than to no targets trials (*M* = 848, *SE* = 42.14, *p* < .001). Finally, they also responded faster to rare target than to no target trials (*p* < .001, Figure 2). Because in a typical two-stimulus oddball paradigm rare and frequent trials are compared (see Folstein & Van Patten, 2008), further analyses focused on the oddball effect calculated as the difference between the rare and frequent targets (for RTs, N2, and P3b amplitudes).

The ERPs elicited by the rare targets included a frontocentral N2 followed by a parietal P3b (Figure 3). No obvious P3a component was observed in this dataset (for review, see Polich, 2007). The N2 was 1.1 μV larger (i.e., more negative) for rare than for frequent targets [*t(10)* = 3.24, *p* = .009]. There was a positive but non-significant correlation between the RT and N2 oddball effects (*r* = .45, *p* = .16). The P3b was 3.9 μV larger (i.e., more positive) for rare than for frequent targets [*t(11)* = 4.11, *p* = .002] (Figure 3).

3.1. Divergent thinking, attention, and cognitive control

Our primary hypothesis was that people with higher divergent thinking scores (as measured by the ATTA) would exhibit more attentional flexibility, as indexed by a smaller RT oddball effect, accompanied by increased cognitive control engagement, indicated by a larger N2 oddball effect.

As predicted, higher total divergent thinking scores were associated with a smaller RT oddball effect (*r* = -.64, *p* = .034, Figure 4). This effect was significant for fluency (*r* = -.61, *p* = .046), and there was a trend towards significance for originality (*r* = -.54, *p* = .09) of divergent thinking.

Further, higher total divergent thinking was associated with a larger N2 oddball effect (*r* = -.67, *p* = .024). This effect was significant for originality (*r* = -.68, *p* =.021), but not for fluency (*r* = -38, *p* =.25) of divergent thinking.

There was no significant correlation between divergent thinking and the P3b oddball effect (*r* = -.31, *p* = .35).

4. Discussion

These results indicate that people with higher divergent thinking scores were more flexible when switching levels of attention, as evident by the smaller RT oddball effect. Flexible switching was accompanied by the larger N2 oddball effects in divergent thinkers, indicating increased cognitive control engagement at the moment of the attentional switch.

Experiment 1 was exploratory in nature, and although the sample size was small, it provided preliminary evidence that cognitive control may be the mechanism for attentional flexibility in divergent thinking. Experiment 2 included a larger scale replication of Experiment 1, and also examined the link between cognitive control and real-life creative achievement. Because of the potential link between intelligence and creativity (Silvia, 2015 for review), we included a test of general intelligence (WASI; Wechsler, 1999) as a covariate (FSIQ-4 scores). To be specific, intelligence measures are generally found to be associated with laboratory tests of creativity, such as alternate uses or divergent thinking tests (e.g., Nusbaum & Silvia, 2011), but not with real-life creativity.

Experiment 2

Experiment 2 tested the relationship between divergent thinking, real-life creative achievement, attentional flexibility, and cognitive control. Participants completed the same oddball task as in Experiment 1, as well as a divergent thinking test, a survey about their real-life creative accomplishments, and an intelligence test. Considering the results of Experiment 1, we expected that people with higher divergent thinking scores would be more flexible in their attention, as indexed by a smaller RT oddball effect. Additionally, we expected that higher divergent thinking would be associated with increased levels of cognitive control, indicated by a larger N2 oddball effect.

As for creativity operationalized with a more ecologically-valid survey of people’s real-life creative accomplishments, there are two alternate hypotheses. If creative achievement is indeed linked with higher levels of cognitive control, we should see a positive association between creative achievement and the size of the N2 oddball effect. Alternately, if real-life creative achievement is not associated with cognitive control, we should see no relationship between creative achievement and the size of the N2 oddball effect.

5. Methods

5.1. Participants

Participants included 39 (10 male, 29 female, mean age = 20.2, *SD* = 1.8) University of Plymouth students who took part in the study for course credits. Four participants were not included in the analyses because of incomplete datasets due to technical issues. All participation criteria were identical to the participation criteria in Experiment 1. The study was approved by the University of Plymouth Ethics Board, and all participants gave informed consent.

5.2. Materials

5.2.1. Abbreviated Torrance Test for Adults (ATTA; Goff & Torrance, 2002)

Divergent thinking was assessed with the ATTA with the same instructions and scoring procedures as in Experiment 1. Mean divergent thinking score was 26.14 (*SD* = 8.20, range 14-51). One participant's score was larger than 3 SD, and was Winsorized from 51 to the next largest value of 43.

5.2.2. Creative Achievement Questionnaire (CAQ; Carson, Peterson, & Higgins, 2005)

Real-world creative behavior was assessed with the Creative Achievement Questionnaire in which participants catalogued their prior creative achievements across ten creative domains (visual art, music, dance, architectural design, creative writing, humor, inventions, scientific discovery, theater and film, and culinary arts). In the music domain, for example, questions range from "I have no training or recognized talent in this area" (score of 0) to "my compositions have been critiqued in a national publication" (score of 7). In the scientific discovery subset, scores vary from "I have no training or recognized ability in this field" (score of 0) to "my work has been cited by other scientists in national publications" (score of 7). Separate domain scores were then combined to form a single index of creative achievement. The CAQ has excellent psychometric properties, including test-retest reliability (r = .81, p < .0001), internal consistency (α = .96), as well as good predictive, convergent, and discriminant validity (Carson et al., 2005). The mean creative achievement score was 9.34 (*SD* = 7.65, range 1-28). CAQ scores were positively skewed, and so we used the signed log transformation to normalize the CAQ distribution.

5.2.3. *Wechsler Abbreviated Scale of Intelligence (WASI;* Wechsler, 1999)

Because factors related to intelligence likely influence scores on the divergent thinking test (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Nusbaum & Silvia, 2011), we included WASI composite test scores as a variable in linear regression analyses predicting divergent thinking. The WASI is aimed at estimating intelligence scores rapidly, and it consists of four sub-tests, block design, vocabulary, matrix reasoning, and similarities, resulting in FSIQ-4 scores. The mean FSIQ-4 score was 119 (*SD* = 8.1, range 104-140).

5.2.4. Oddball Task

The oddball task was identical to the oddball task used in Experiment 1, including the same stimuli as depicted in Figure 1.

5.2.5. Electrophysiological recordings and analyses

The details of EEG recording and analyses were the same as for Experiment 1.

5.3. Procedure

Participants were tested individually during a session lasting approximately 90 minutes. During this session, participants were administered a divergent thinking test (ATTA), the Creative Achievement Questionnaire, and the oddball task, during which the EEG was recorded continuously. After the EEG session, participants were also administered the Wechsler Abbreviated Scale of Intelligence.

5.4. Analytical strategy

First, differences in RTs for rare target, frequent target, and no target trials were examined with an ANOVA and follow-up t-tests. Second, t-tests were conducted to compare the amplitude of the N2 and P3b components to rare and frequent targets (oddball effect). Next, simple linear regression analyses were carried out to determine whether divergent thinking and creative achievement scores predicted the size of the oddball effects for RTs, the N2, and the P3b. Finally, corresponding multiple linear regression analyses were conducted to control for intelligence scores by also including FSIQ-4 scores as a predictor.

6. Results

Four participants had excessive eye movement artifacts and so they were not included in the ERP analyses (N = 31). However, they were included in the behavioral analyses (N = 35). Figure 5 shows the response time results. Normality checks were carried out on residuals, which were approximately normally distributed. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 1.97$, $p = .37$.

A repeated measure ANOVA indicated that RTs differed between the three types of trials [$F(2,68) = 195.23$, p < .001]. Post hoc tests using Bonferroni correction revealed that participants responded faster to the frequent targets (*M* = 445 ms, *SE* = 9.62) compared to the rare targets (*M* = 596 ms, *SE* = 18.52, *p* < .001). Participants also responded faster to the frequent targets (*M* = 445 ms, *SE* = 9.62) compared to the trials with no target (*M* = 703, *SE* = 17.29, *p* < .001). Similarly, participants responded faster to the rare targets compared to the trials with no targets (*p* < .001).

The ERPs were similar to those found in Experiment 1 and they showed a prominent frontal N2 followed by a parietal P3b (Figure 6). The N2 was 1.66 μV larger for rare than frequent targets [$t(30) = 1.66$, $p = .005$]. There was a trend for a positive correlation between the RT and N2 oddball effects ($r = .32$, $p = .08$). The P3b was 6.3 μV larger for rare than for frequent targets [$t(30) = 8.14$, $p < .0001$].

6.1. Divergent thinking, attention, and cognitive control

Our primary hypothesis was that people with higher divergent thinking scores (as measured by the ATTA) would exhibit higher levels of attentional flexibility as indexed by the smaller RT oddball effect, as well as higher cognitive control engagement, as indexed by the larger N2 oddball effect. As predicted, and replicating the results of Experiment 1, higher divergent thinking was associated with a smaller RT oddball effect ($r = -.34$, $p = .047$; Figure 6), with a trend towards significance for the association between the RT oddball effect and fluency ($r = -.32$, $p = .06$), but not originality ($r = -.24$, $p = .16$) of divergent thinking. Higher divergent thinking was still associated with a larger RT oddball effect after including FSIQ-4 scores in a multiple linear regression ($r = -.35$, $p = .039$). In this analysis, FSIQ-4 scores were not reliably associated with the RT oddball effect ($r = .22$, $p = .18$).

Likewise, and replicating the results of Experiment 1, higher divergent thinking was associated with a larger N2 oddball effect ($r = -.50$, $p = .004$; Figure 7). This was true for both fluency ($r = -.37$, $p = .04$), and originality ($r = -.44$, $p = .01$) of divergent thinking. There was no correlation between divergent thinking and the P3b oddball effect ($r = .03$, $p = .87$). Higher divergent thinking was still associated with a larger N2 oddball effect after including FSIQ-4 scores in a multiple linear regression (*r* = -.45, *p* = .005). In this analysis, FSIQ-4 scores were also associated with a larger N2 oddball effect (*r* = -.36, *p* = .024). Table 1 shows the Pearson correlation matrix between the ATTA (originality, fluency, and total), FSIQ-4, and CAQ scores.

6.2. Creative achievement, attention, and cognitive control

In contrast to divergent thinking, real-life creative achievement was associated with neither the RT oddball effect (*r* = .15, *p* = .40), nor the N2 oddball effect (*r* = -.29, *p* = .11), indicating no reliable link between creative achievement, attentional flexibility, or cognitive control. Furthermore, there was no correlation between real-life creative achievement and the P3b oddball effect (*r* = .03, *p* = .86).

7. General Discussion

The purpose of this investigation was to examine the role of cognitive control in creativity. We examined whether and how divergent thinking and creative achievement relate to attentional flexibility and cognitive control as indexed by the response times and by the N2 ERP amplitude in an oddball paradigm. Results from Experiment 1 and Experiment 2 demonstrate that people who perform better on the divergent thinking tests also exhibit more attentional flexibility, which is accompanied by increased cognitive control engagement at the moment of the attentional switch.

In both experiments, people viewed hierarchical letter stimuli and identified target letters in frequent (80%) and rare (10%) trials. Successful identification of targets required attentional flexibility when switching levels of attention (from global to local attentional level, and vice-versa). Results showed that people with higher divergent thinking scores exhibited a smaller RT oddball effect, even when controlling for overall intelligence, indicating higher levels of attentional flexibility in divergent thinkers. This result is in line with our previous findings in a similar paradigm (Zabelina et al., 2016), where divergent thinking was also linked with attentional flexibility when switching levels of attention. We have suggested that cognitive control, or the ability to focus, inhibit, and switch attention, may be the mechanism for attentional flexibility in divergent thinkers. The results from both experiments confirm that divergent thinking is linked with higher levels of cognitive control at the moment of an attentional switch (and before the response), indicated by the larger N2 oddball effect, even when controlling for general intelligence. In other words, divergent thinkers recruit cognitive control processes more strongly when an attentional switch is required.

To our knowledge this is the first account presenting neurophysiological evidence for the link between divergent thinking and the N2 oddball effect. Although no prior studies have investigated the N2 and its relationship with divergent thinking, insight studies have examined how N2 relates to insight in problem solving. Specifically, successful solutions of insight problems elicited a stronger N2 over left frontal areas (Qiu et al., 2008). The authors concluded that the higher N2 amplitude was critical for breaking mental set and to form new associations. Successful performance on divergent thinking tests arguably requires breaking of mental sets in order to abandon salient ideas and forming new associations in the service of identifying more original ideas. Further, considering the manner in which divergent thinking tests are administered (limited time, laboratory setting), higher levels of cognitive control appear to facilitate successful performance on divergent thinking tests. Our results corroborate prior findings and provide support for the claim that thinking in a divergent manner relies on executive control more than previously thought (Benedek et al., 2014; Nusbaum & Silvia, 2011).

Further, we found a positive association between general intelligence as assessed with the WASI test and the N2 oddball effect. This in itself is a novel finding, and is consistent with a large body of literature reporting that the efficiency of cognitive control is the most likely determinant of intelligence (Chuderski & Nęcka, 2010 for review).

Although some capacity for divergent thinking may be involved in real-life creativity, the two measures do not appear to relate to similar attentional or cognitive processes. Experiment 2 provided evidence that, in contrast to divergent thinking, real-life creativity is not linked with either attentional flexibility (RT oddball effect) or cognitive control (N2 oddball effect) when switching levels of attention. Further, and contrary to prior reports, there was no association between general intelligence and creativity as assessed with the ATTA or the CAQ measures.

Prior empirical investigations have suggested that creative achievement, rather than being associated with attentional flexibility, is linked with leaky attention (Carson et al., 2003; Zabelina et al., 2015; Zabelina et al., 2016). Because real-life creativity occurs on a longer time-scale than time-limited divergent thinking tests, attentional flexibility in some cases may even undermine real-life creative accomplishments. Indeed, since the time of Wallas (1926), *immersion*, i.e., extended preparation and thought, has been considered a critical stage of the creative process. Too much attentional flexibility may be harmful to the immersion stage of the creative process. Indeed, deep thinking has been found to increase task shielding, and reduce shifting flexibility (Fischer & Hommel, 2012). And while prior studies suggested that flexible switching between global and local modes of processing may promote successful creative problem solving (Wiley & Jarosz, 2012), it appears that real-world creative acts may require a different form of attention.

Although the ATTA and CAQ are accepted measures, their use leads to certain limitations in terms of the conclusions that can be drawn. The CAQ is a well-established measure, with high predictive validity against artist ratings of a creative product, and high convergent validity with other measures of creative potential (Carson et al., 2005), but it may not encompass some creative achievements that may be important to an individual (e.g., sports). In contrast, the ATTA is a more narrowly defined performance measure that theoretically contributes in part to creativity, and there is some evidence of the association between the ATTA and CAQ, though it is weak in our studies. Interpretations of the current work need to bear these caveats in mind when interpreting the results. Furthermore, the effect size in Experiment 1 should be interpreted with caution, as smaller sample sizes are likely to overestimate the size of the correlations. Given that our samples consisted of young psychology students, future studies will need to investigate the role of attention and cognitive control in creative professionals in various creative fields. Finally, our study was correlational in nature, and future studies will need to examine the causal role of attention and cognitive control in creativity.

4.1. Conclusion

We replicate previous behavioral findings that divergent thinking, but not real-world creative achievement, is associated with greater attentional flexibility. Critically, we provide novel electrophysiological evidence that such greater attentional flexibility may rely on increased engagement of cognitive control processes indexed by the N2, even when controlling for intelligence measures. In contrast, no association with cognitive control engagement was found for creative achievement. These results confirm that these two creativity measures rely on different neural mechanisms and provide evidence for one of the mechanisms underlying divergent thinking.

Acknowledgements

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Table 1

Correlations Between ATTA (Ffluency, Originality, and Total), WASI, and CAQ Scores.

In Parenthesis Are the p Values.

	ATTA ORI	**ATTA TOT**	**FSIQ-4**	**CAQ**
ATTA FLU	.21 (.23)	.64 (< .001)	.23 (.18)	.19 (.26)
ATTA ORI		.87 (< .001)	-.06 (.75)	.27 (.12)
ATTA TOT			.05 (.79)	.27 (.12)
FSIQ-4				.15 (.42)

Figure Caption

Figure 1. A): Stimuli consisted of twelve composite letters: an *A* made of *e*s, *s*s, or *h*s; an *E* made of *a*s, *s*s, or *h*s; an *H* made of *e*s, *s*s, or *a*s; and an *S* made of *e*s, *h*s, or *a*s. B): Trial structure in the oddball task. In this example, participants were instructed to determine if the letter H was present (either at the global or local level, 80% and 10% of trials, respectively), or not (10% of trials).

Figure 2. Response times for frequent, rare, and no target trials in Experiment 1.

Figure 3. The left side of the figure shows grand-averaged ERPs (-200ms – 1000ms) to frequent and rare targets at central sites Fz, Cz, and Pz in Experiment 1 (N = 11). The N2 and P3b components are indicated with arrows (left). The right side of the figure shows topographic maps for the N2 and P3b component (rare target condition). The topographic map for the N2 is relative to the preceding positive component (150 – 250 ms baseline) to emphasize that it is a negative-going component. Note that the biphasic potentials visible around 850 ms are due to stimulus offset.

Figure 4. Correlation between divergent thinking and the behavioral oddball effect in Experiment 1 (the RT difference between rare and frequent targets), showing that people with higher divergent thinking scores have more flexible attention.

Figure 5. Response times for frequent target, rare target, and no target trials in Experiment 2.

Figure 6. The left side of the figure shows grand-averaged ERPs (-200ms – 800ms) to frequent and rare targets at central sites Fz, Cz, and Pz in Experiment 2 (N = 31). The N2 and P3b components are indicated with arrows (left). The right side of the figure shows topographic maps for the N2 and P3b component (rare target condition). The topographic map of the N2 is relative to the preceding positive component (150 – 250 ms baseline), to emphasize that it is a negative-going component.

Figure 7. Correlation between divergent thinking and the RT oddball effect in Experiment 2 (the RT difference between rare and frequent targets), showing that people with higher divergent thinking scores have more flexible attention.

*Figure 8***.** Correlation between divergent thinking and the N2 oddball effect (N2 for rare targets minus frequent targets combining sites Fz and Cz within the 350-450 ms time window) in Experiment 2, showing that people with higher divergent thinking scores have better cognitive control (a more negative N2 oddball effect indicates better cognitive control).

Figure 1

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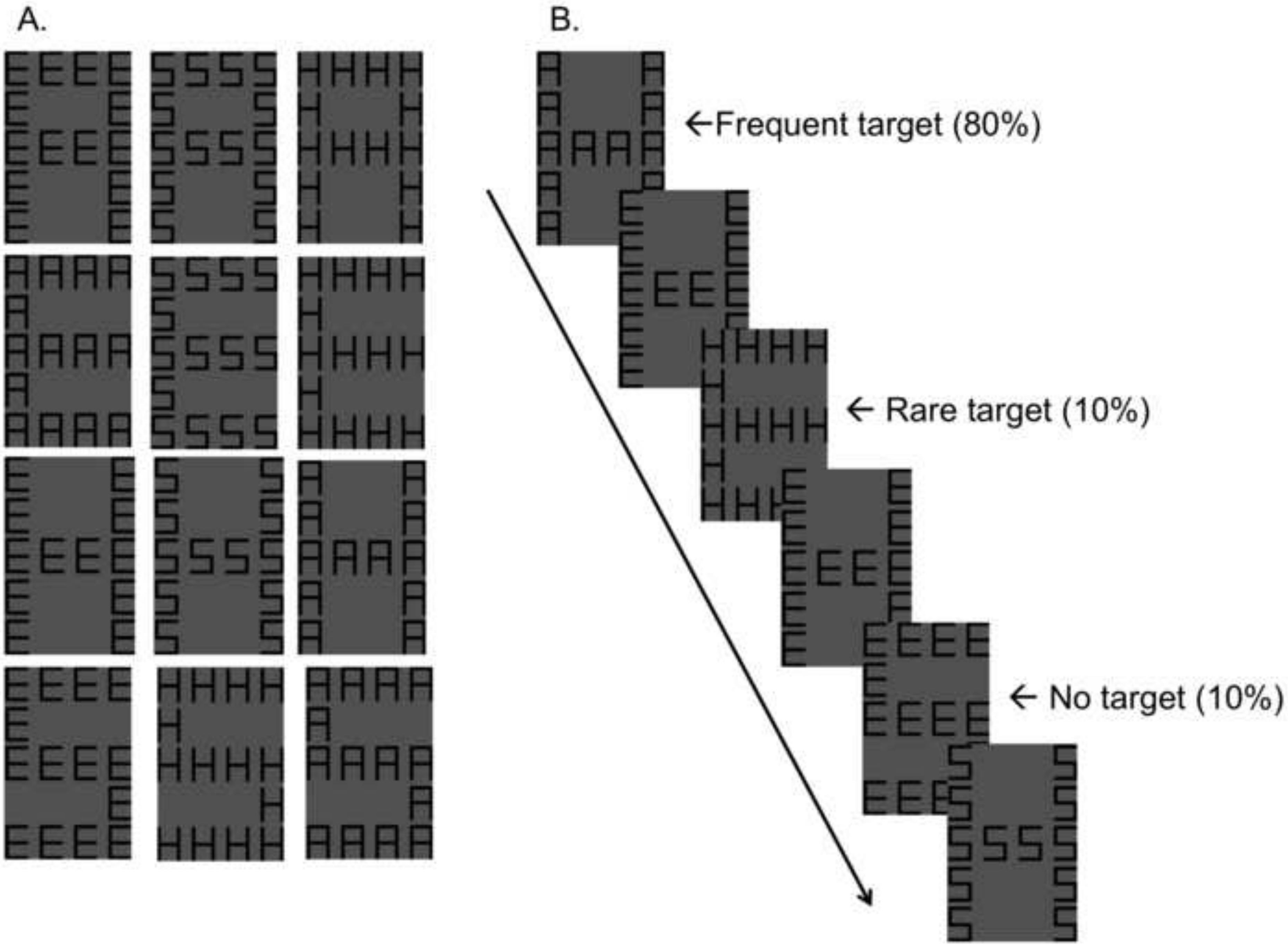

Figure 2

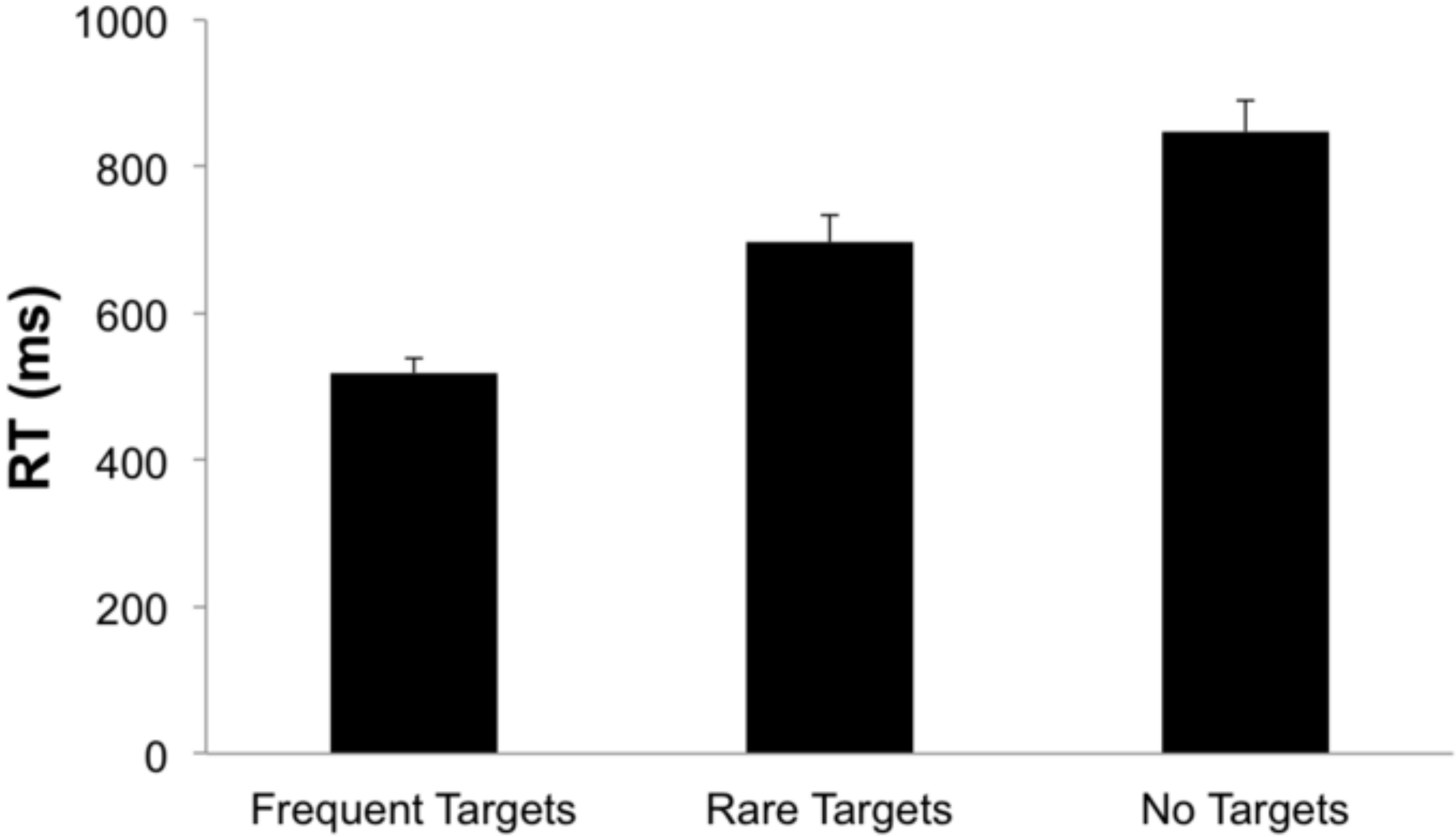
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Figure 3

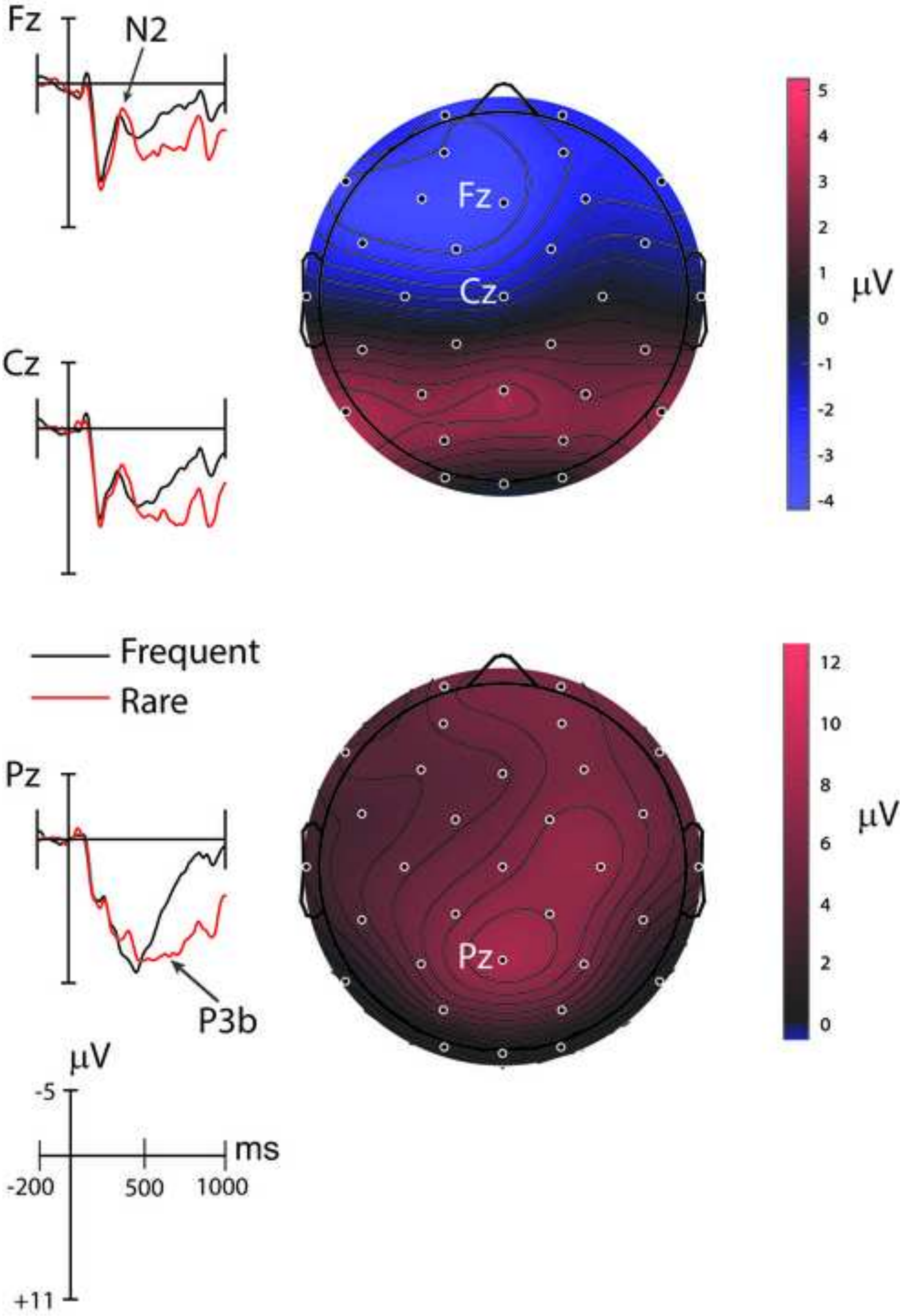
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Figure 4

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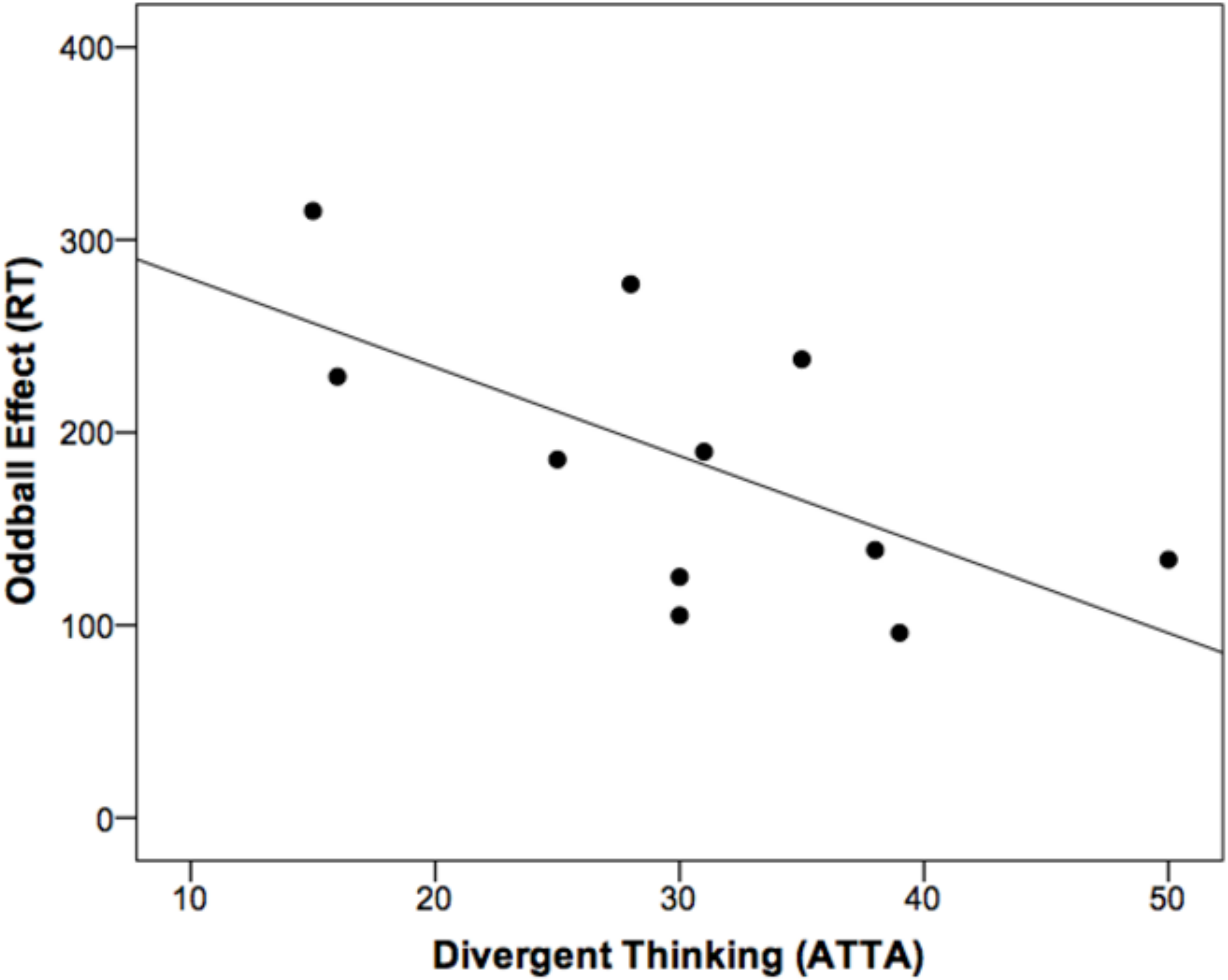

Figure 5

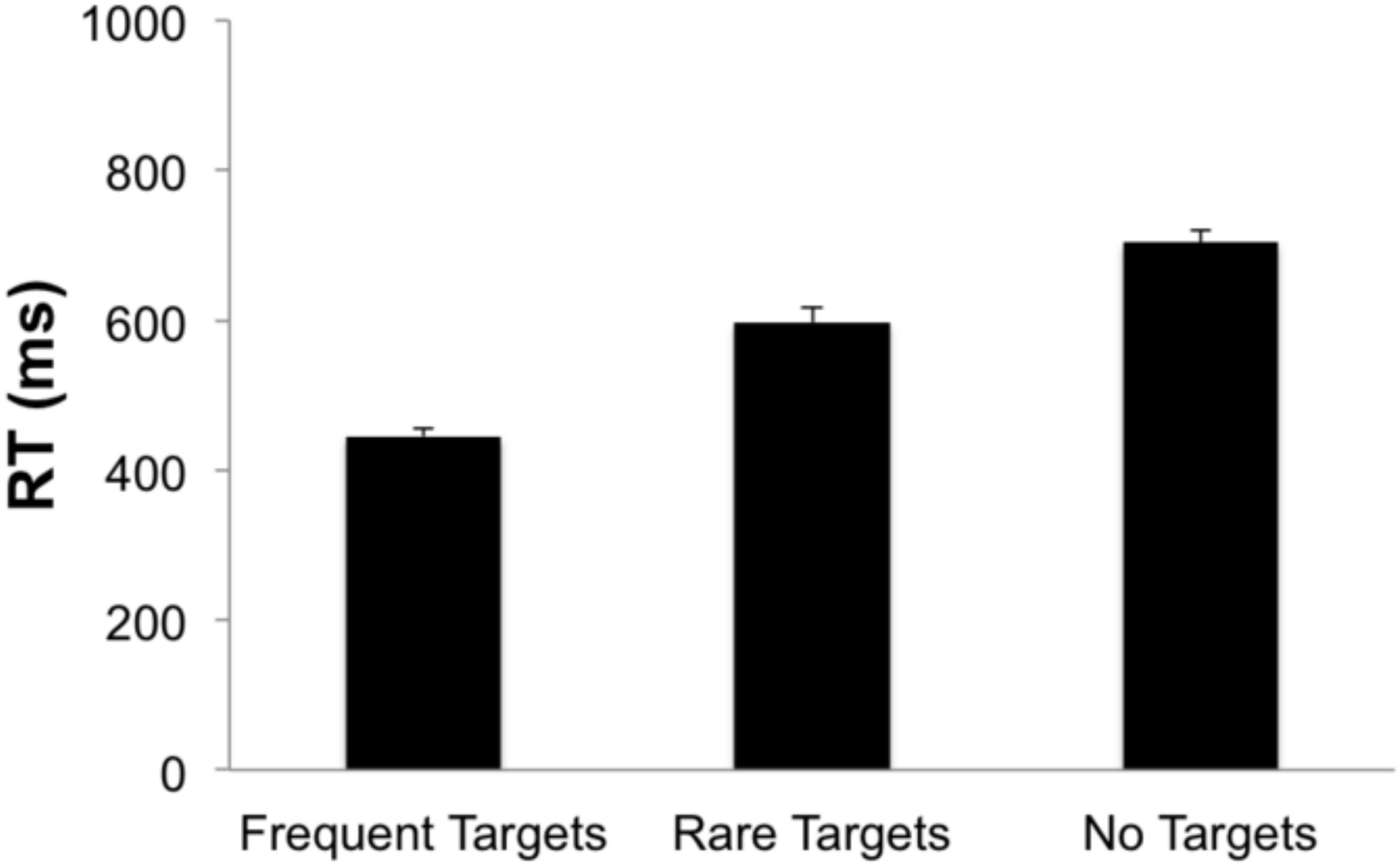
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Figure 6

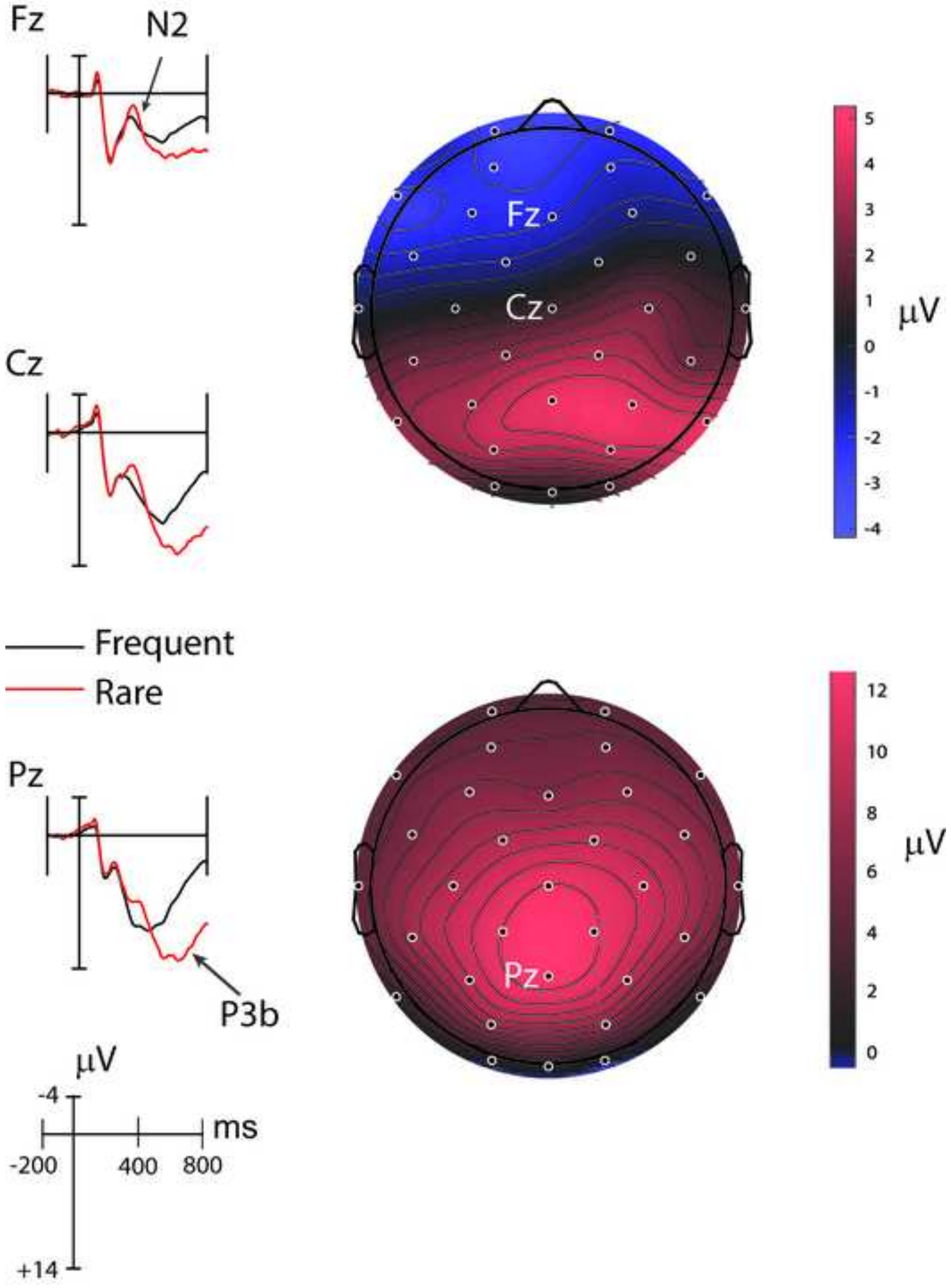
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Figure 7

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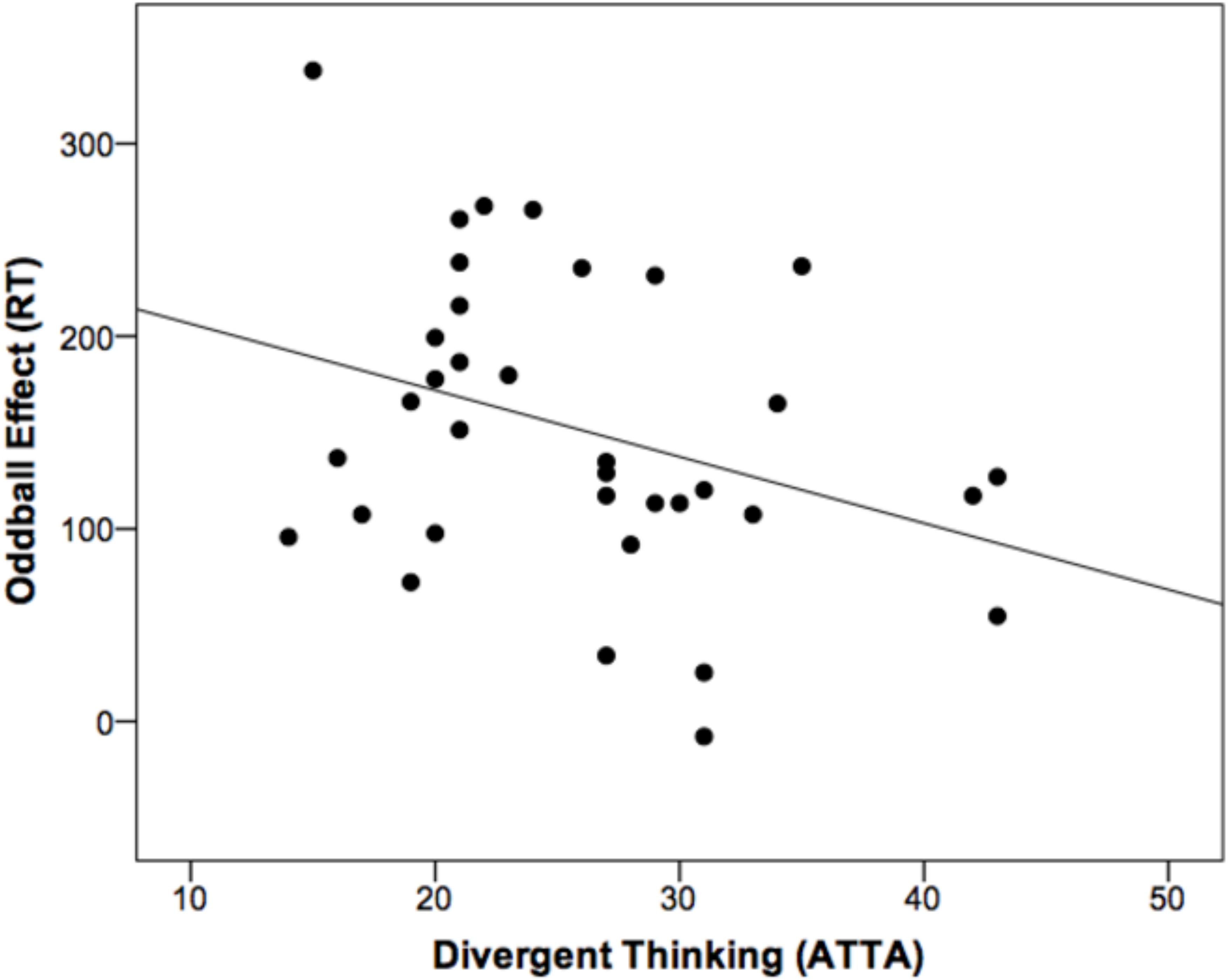
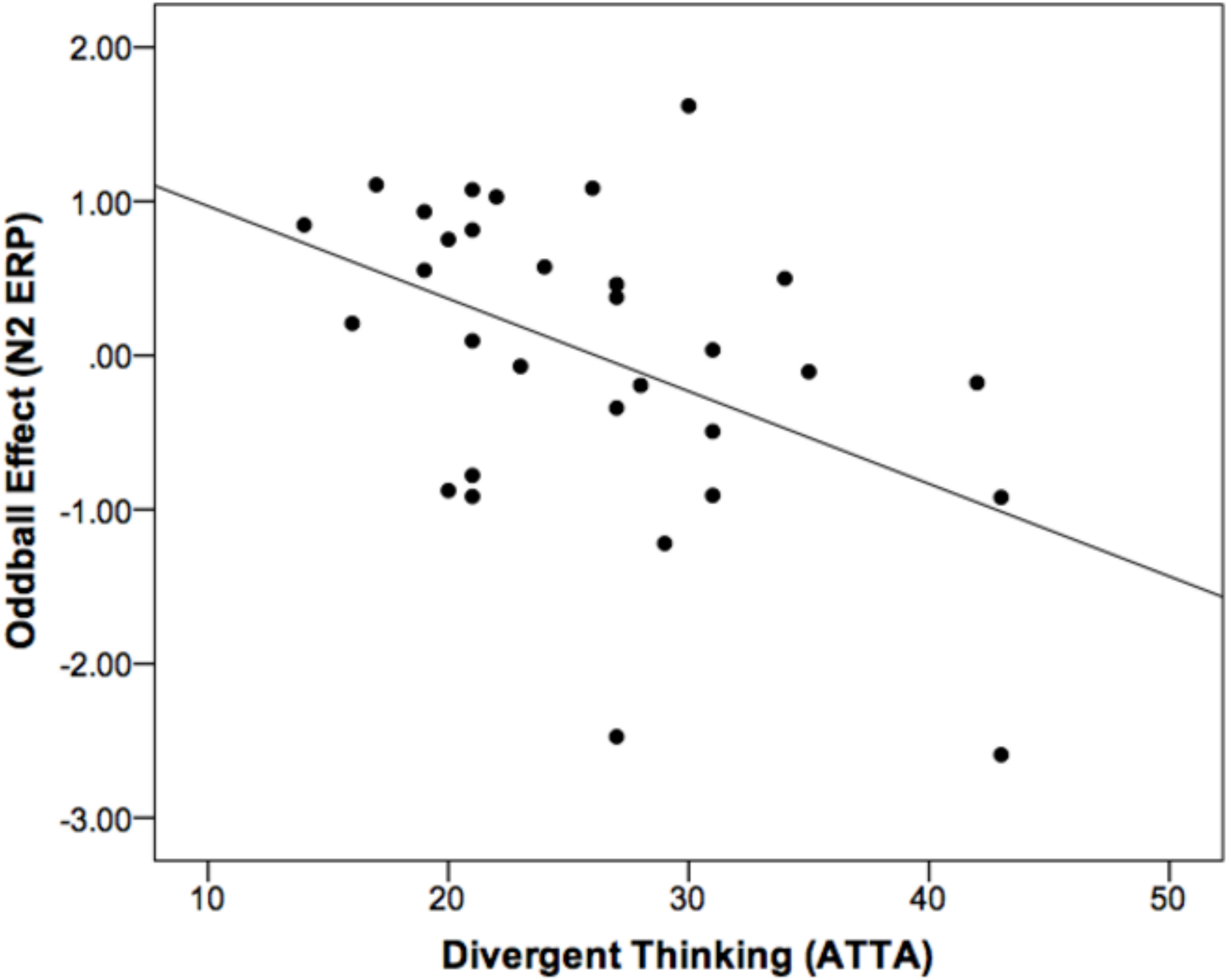


Figure 8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Oddball Effect (N2 ERP)
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Divergent Thinking (ATTA)