Neuropsychologia 69 (2015) 77–84

Contents lists available at ScienceDirect

Neuropsychologia

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

Creativity and sensory gating indexed by the P50: Selective versus leaky sensory gating in divergent thinkers and creative achievers

Darya L. Zabelina*, Daniel O'Leary, Narun Pornpattananangkul, Robin Nusslock, Mark Beeman

Northwestern University, 104 Cresap Hall, 2029 Sheridan Road, Evanston, IL 60208, USA

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form
20 January 2015
Accepted 22 January 2015
Available online 23 January 2015

Keywords:
Creativity
Divergent thinking
Creative achievement
P50
Sensory gating
Attention

ABSTRACT

Creativity has previously been linked with atypical attention, but it is not clear what aspects of attention, or what types of creativity are associated. Here we investigated specific neural markers of a very early form of attention, namely sensory gating, indexed by the P50 ERP, and how it relates to two measures of creativity: divergent thinking and real-world creative achievement. Data from 84 participants revealed that divergent thinking (assessed with the Torrance Test of Creative Thinking) was associated with selective sensory gating, whereas real-world creative achievement was associated with "leaky" sensory gating, both in zero-order correlations and when controlling for academic test scores in a regression. Thus both creativity measures related to sensory gating, but in opposite directions. Additionally, divergent thinking and real-world creative achievement did not interact in predicting P50 sensory gating, suggesting that these two creativity measures orthogonally relate to P50 sensory gating. Finally, the ERP effect was specific to the P50 – neither divergent thinking nor creative achievement were related to later components, such as the N100 and P200. Overall results suggest that leaky sensory gating may help people integrate ideas that are outside of focus of attention, leading to creativity in the real world; whereas divergent thinking, measured by divergent thinking tests which emphasize numerous responses within a limited time, may require selective sensory processing more than previously thought.

1. Introduction

Although numerous papers have claimed that creative thinking is linked with atypical attention, it remains unresolved which types of creativity and which aspects of attention are associated. There are at least two seemingly contradictory proposals, but it is possible that both operate, each on different aspects of creativity.

The first proposal suggests that creative people may have particularly broad or "leaky" attention, or a propensity to deploy attention over a wider focus or a larger range of stimuli at once. Anecdotes indicate that numerous eminent creators, including Richard Wagner, Marcel Proust, and Charles Darwin strongly lamented the distracting nature of noise (Kasof, 1997). More importantly, some empirical evidence supports this putative association between creativity and leaky attention, particularly in dual task situations. For instance, when asked to repeat information presented to one ear, while attempting to remember information presented to the other ear, creative people (creativity assessed with the Pattern Meaning and Similarities subtests from Wallach and Kogan's (1965) battery of creativity tests) make more errors of intrusion from the non-shadowed ear (Rawlings, 1985). Moreover, creative people are more likely to incorporate seemingly irrelevant cues when solving anagrams (creativity assessed with Mednick's (1962) Remote Associate's Test (RAT; Mendelsohn and Griswold, 1964), recalling words and phrases (creativity assessed via RAT; Russell, 1976), and performing auditory discrimination tasks (creativity assessed with a Creative Achievement Questionnaire (CAQ; Carson et al., 2005); Carson et al., 2003).

Leaky attention is akin to reduced latent inhibition, or a reduced ability to screen or inhibit from conscious awareness stimuli previously experienced as irrelevant (Lubow, 1973). Reduced latent inhibition 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 (Carson et al., 2003). Therefore leaky attention may underlie both costs and benefits of creative cognition; noise and other environmental stimuli can serve as distractors for creative people, and lead them to make errors on some tasks. 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.

---

* Corresponding author.
E-mail address: darya.zabelina@u.northwestern.edu (D.L. Zabelina).

http://dx.doi.org/10.1016/j.neuropsychologia.2015.01.034

An alternative proposal of how attention relates to creativity suggests that creativity depends on the ability to focus and shift attention, supporting cognitive flexibility. More generally, creativity may rely heavily on executive functions (De Dreu et al., 2012; Gilhooly et al., 2007; Nusbaum and Silvia, 2011; Wiley and Jarosz, 2012), i.e., general-purpose control mechanisms such as the ability of the cognitive system to configure itself for the performance of specific task goals (Botvinick et al., 2001; Miyake and Friedman, 2012). Indeed, in order to create a highly original thought or product, people have to focus and persist on the task at hand. For instance, the preparation stage of creativity involves information gathering, mastering a knowledge base, and identifying the problem (Wallas, 1926). These behaviors surely benefit from focus and persistence. Leonardo da Vinci, for example, one of the most recognized creative polymaths, was said to have “obsessive attention to detail” (Lester, 2012, p. 191). Marie Currie described her focus during schoolwork as “allowing no lapses of attention (p. 72),” as well as concentrating her attention “without even hearing the mounting roar of chatter” (p. 97; Curie and Sheean, 2001).

Emerging neuroscientific literature provides support for cognitive inhibition involved in creative thinking. Inferior frontal gyrus (IFG), a region associated with interference resolution in the left hemisphere (Thomspon-Schill et al., 1999), and cognitive inhibition in the right hemisphere (Aron, 2007), has been implicated in divergent thinking tasks (Abraham et al., 2012; Chrysikou and Thompson-Schill, 2011; Kleibeuker et al., 2013; Vartanian et al., 2013; for review, see Gonen-Yaacovi et al., 2013), which measure the ability to generate many original responses to a given problem within a limited time (Guilford, 1950; Torrance, 1974), and are often used as measures of creative cognition.

The assertion that creative cognition requires focused and persistent attention seems to directly contradict the first hypothesis, that creative thinking is associated with leaky attention. These ideas, however, may not be mutually exclusive. It may be that different measures of creativity are associated with different forms of attention. Our recent series of experiments, using a model task in which people attend to either local or global aspects of attention (e.g., a large S constructed of small Es), suggest that there are distinct attentional components that independently relate to two different measures of creativity: divergent thinking versus real-world creative achievement. We find that divergent thinkers show selective focus and rapid inhibition of attention, thus exhibiting flexible attention: they easily switch their attention from an incorrect attentional focus to a correct one (Zabelina et al., 2015).

Whereas divergent thinking tests are timed laboratory measures of creative cognition, real-world creative achievement is a survey of people's creative achievements over their lifetime. Unlike the flexible attention observed in divergent thinking, we find that real-world creative achievers show leaky attention; when asked to identify a target that competes or is facilitated by other information presented concurrently with the target, real-world creative achievers are more likely to be affected by the competing information (Zabelina et al., 2015).

Here we examine how early in the processing stream these attentional differences between divergent thinkers and real-world creative achievement occur. Specifically, we examine whether different measures of creativity relate to sensory gating (sensory inhibition) of meaningless stimuli, in the absence of task goals. Thus we examine specific neural markers of sensory gating, namely the P50 event-related potential (ERP), a neurophysiological response that occurs 50 ms after stimulus onset (for review, Patterson et al., 2008). In this paradigm two auditory clicks are presented to a participant, and the extent to which the second click is inhibited compared to the first click (P50 of the second click/P50 of the first click) is seen as a marker of sensory gating (Patterson et al., 2008). P50 is a very early, automatic, form of sensory gating, influencing which stimuli capture attention (Banich, 2004; Gjini et al., 2011). Some view the P50 marker of sensory gating as a marker to some psychopathology, particularly schizophrenia (Olincy et al., 2010).

With respect to P50 and cognitive functioning, studies have reported inconsistent outcomes. Associations between increased P50 sensory gating and better attention, motor speed, and learning, have been observed, mostly in small samples of patients with schizophrenia (Cullum et al., 1993; Erwin et al., 1998; Hsieh et al., 2004), and in Alzheimer's patients or healthy elderly controls (Thomas et al., 2010). These studies are consistent with reports of the associations between better P50 sensory gating and better orienting of attention, better inhibition of conflicting information (Wan et al., 2008), and fewer commission errors on the Delayed Memory Task (Lijffijt et al., 2009) in healthy participants. However, some studies have failed to find such associations (Cullum et al., 1993; Thoma et al., 2006).

Sensory gating, as measured by the P50, varies in the general population (Patterson et al., 2008). We predicted different relations between sensory gating and the two distinct measures of creativity.

First, given that divergent thinking is associated with the ability for selective focus and rapid inhibition of attention, supporting attenional flexibility (Zabelina et al., 2015; Nusbaum and Silvia, 2011), as well as with neural regions implicated in cognitive inhibition (Gonen-Yaacovi et al., 2013), we predict that divergent thinking will relate to more selective sensory gating.

Second, given that real-world creative achievement is associated with reduced latent inhibition (Carson et al., 2003), and with leaky attention on behavioral tasks (Zabelina et al., 2015), we predict that real-world creative achievement will be related to reduced, or leaky sensory gating.

Thirdly, hypothetically the two measures of creativity combined could better predict sensory gating. However, based on prior research suggesting that divergent thinking and creative achievement are only modestly related (Runco and Acar, 2012; Zabelina et al., 2015), and that only creative achievement related to our behavioral measure of leaky attention (Zabelina et al., 2015), we did not expect divergent thinking and creative achievement to interact in predicting sensory gating.

We also considered academic achievement scores as a proxy for general intelligence and as a control variable, given that academic achievement may relate to divergent thinking through the common component of performance on a cognitive measure, and may relate to creative achievement through the common component of achievement. Additionally, we assessed the specificity of the association between the P50 sensory gating and divergent thinking and creative achievement by examining later attentional ERP components, namely N100 and P200.

2. Method

2.1. Participants

One hundred participants were recruited to participate in the present study. Because data collection failed for 3 participants, we were left with 97 participants ages 18–30 (mean age=20.55, SD=2.51, male/female=32/65). Participants were pre-screened to ensure they had no hearing or head injuries. None of the participants abused alcohol or drugs, and none smoked. None of the participants had been hospitalized for psychiatric or neurologic reasons. Four participants had history of depression or mild anxiety (three in the past, but in remission at the time of the study and not taking medication; one current, treated with Zoloft). All subjects were Caucasian, and right-handed, as assessed by the Chapman Handedness Questionnaire (Chapman and Chapman, 1987). Participants completed an informed consent prior to participating in the study, and received $20 for their participation. The study was approved by the Institutional Review Board of Northwestern University.

2.2. Procedure

Participants were tested individually, with each session lasting up to two hours. Participants completed a timed laboratory test of divergent thinking, and completed a questionnaire surveying their creative achievements in the real world, before undergoing the sensory gating paradigm.

2.3. Measures

2.3.1. Abbreviated Torrance Test for Adults (ATTA; Goff and 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 are 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 normative data), with scores summed across the three activities (Goff and Torrance, 2002). The total divergent thinking score reflects a weighted score of fluency plus two times originality, to equally weight the two scores, since the average fluency score (14.1) was approximately double the average originality score (7.2) (see Runco and Acar, 2012 for suggestions on scoring divergent thinking tests). Two participants did not follow task instructions, thus we were not able to score their tests. The average divergent thinking score was 29.00 ($SD=7.98$, range 15–50). Given that recent approaches often focus on ideational creativity (Fink and Benedek, 2014; Runco and Mraz, 1992), we also separately considered only the ATTA originality score in our analyses.

2.3.2. Creative Achievement Questionnaire (CAQ: Carson et al., 2005)

We assessed real-world creative behavior with the Creative Achievement Questionnaire, a survey on which participants cataloged any 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. One participant's total creative achievement score was more than 6 *SDs* above the mean (possibly due to an error), and was therefore removed from further analyses. The mean creative achievement score was 12.95 ($SD=9.77$, range 0–48). CAQ scores were positively skewed, therefore we used the signed log transformation to normalize the CAQ distribution.

2.3.3. Academic achievement scores

As a proxy for general intelligence, participants provided their academic achievement test scores (Scholastic Assessment Test (SAT) or American College Testing (ACT); College Board, 2012; ACT Inc., 2014), which we converted into percentile scores based on the national statistics for all test-takers in 2012 ($M=98.01$, $SD=2.20$, range 87–100). In prior studies in our lab, self-reported scores were confirmed with actual scores through the admissions office, and the two correlated $r=.97$ (Wegbreit et al., 2012). Fourteen people did not provide their academic test scores (therefore degrees of freedom will be different when academic test scores are included in the analyses). The range of scores was very narrow, so this measure should be interpreted cautiously.

2.3.4. Sensory gating paradigm

Consistent with literature on P50, auditory modality was used to measure sensory gating (e.g., Cadenhead et al., 2000; Chang et al., 2012; Olincy et al., 2010). The sensory gating measure occurred within a sound-attenuated, electrically-insulated booth, and was presented through the headphones using Presentation 16.1 software (Neurobehavioral Systems). The task consisted of passively listening to two auditory clicks per trial, each a flat broadband square wave of 1 ms duration, with an average intensity of 89 dB. The two clicks were presented with an intra-pair interval of 500 ms, and a pseudo-randomized inter-pair interval of 6, 8, or 10 s.

Participants were instructed to sit in an upright but relaxed position, with eyes open and focused on a fixation cross located on a computer screen approximately 1 m away. Participants were asked to remain relaxed and to refrain from blinking during presentation of the clicks, but to otherwise blink naturally in between trials. These parameters were set to minimize muscle tension and movement artifact. The EEG activity of each participant was recorded continuously during 5 blocks of 20 trials each, for a total of 100 click pairs. Participants were offered self-timed breaks between each block (breaks generally lasted less than 30 s). The testers, in an adjacent room, observed the participant via camera, and interacted with the participant during the inter-block intervals to ensure that all participants remained comfortable and alert.

2.3.5. Electrophysiological recordings

EEG data were recorded from 14 tin electrodes attached inside an Electro-Cap with Electrogel (Electro-Cap Intl., Eaton, Ohio) as the conductance agent. Using the 10/20 system, electrodes were positioned at FP1, FZ, FP2, F3, F4, F7, F8, C3, CZ, C4, P3, PZ, P4, and mastoid locations M1 and M2 (see Bak et al., 2011; Lijffijt et al., 2009). Impedance for all electrodes was less than 5 kΩ. Data were collected using the Acquire module of Scan 4.5 (NeuroScan Labs, El Paso, Texas). Signals were continuously sampled at 1000 Hz, and filtered online between .05 and 100 Hz (AC mode). The ground electrode was fixed inside the cap between the FPz and Fz electrodes. The left mastoid electrode (M1) was used as an online reference electrode.

2.3.6. ERP waveform and component analysis

The Edit module of Scan 4.5 and Curry 7 software (NeuroScan Labs, El Paso, Texas) were used to conduct offline EEG analyses. Following methodology reported in prior P50 ERP investigations (Cadenhead et al., 2000; Chang et al., 2012; Olincy et al., 2010), the continuous EEG data for each participant were first re-referenced off-line from the left mastoid (M1) to the linked mastoids (mean of M1 and M2), which was appropriate given our focus on the midline (Luck, 2014). Data were digitally high-pass filtered at 1 Hz (12 dB). Trials contaminated with artifacts (amplitude values exceeding -75 to 75 μV, blinks during clicks – rejected based on FP1 and FP2 electrodes, excessive muscle related activity) were all visually inspected and excluded from further analysis. Trials containing artifacts were not included in final waveform averaging, leaving an average of 71 trials per participant ($SD=22$, range 23–

100; all results were maintained when controlling for the number of epochs in a multiple regression, see Section 3). Following artifact rejection, we segmented the EEG data into event-locked epochs for both the first and second click, with epoch durations spanning 100 ms pre-stimulus to 499 ms post-stimulus. Non-rejected segments were baseline corrected using the pre-stimulus interval (−100 to 0 ms), as is typical in the literature (see Gumenyuk et al., 2013; Lijffijt et al., 2009), low-pass filtered at 70 Hz (dB), and averaged to create ERP waveforms for both clicks. P50 amplitudes and latencies were scored at Cz using the trough-to-peak method, following prior P50 methodology (Cadenhead et al., 2000; Chang et al., 2012; Olincy et al., 2010). This technique first identifies the actual P50 response as the most positive peak, in μV, on the ERP waveform within the 35–75 ms time window immediately following the first click onset. The value of the most negative trough, immediately preceding the P50 peak of this component within the 35–75 ms time window, was then located and subtracted from the previously designated peak to generate the P50 amplitude value for each click (amplitude of P50 peak minus amplitude of preceding trough). The P50 peak response to the second click was always within 10 ms of the peak response to the first click, and the P50 amplitude for the second click was calculated using the same technique as described above. All waveforms were visually inspected to verify the integrity of the data.

After averaging across all trials, no P50 peak could be detected for either Click 1 or Click 2 for ten of the 97 participants. These participants' data were excluded. Together with the 3 participants for whom data collection failed, the sample resulted in the total of 84 participants (27 males) who were included in the final analysis (mean age=20.54, $SD=2.45$).

For each participant, we computed the final P50 ratio by dividing the trough-to-peak amplitude value for the averaged second click by the corresponding trough-to-peak amplitude value for the averaged first click (Cadenhead et al., 2000; Chang et al., 2012; Olincy et al., 2010). A participant who demonstrates selective sensory gating would manifest a smaller P50 response to the second click, and thus a smaller Click 2/Click 1 ratio, typically less than 1.0. A participant with leaky sensory gating would manifest a P50 response to the second click that is approximately as large as, or larger than that to the first click, and thus a Click 2/Click 1 ratio approaching, or lager than, 1.0.

Data from trials contaminated either with sound artifacts from the headphones or with electrocardiography (EKG) signal were corrected using event-locked and template-matching principal component analysis (PCA) in Curry 7. For participants whose data required PCA correction, the mean P50 sensory gating ratios did not change following the artifact reduction procedure: before PCA mean=.84, $SD=.68$, after PCA mean=.73, $SD=.63$, $t(17)=-1.69$, and $p=.11$. Moreover, no significant differences existed between the mean ratios of the participants whose data did versus those whose data did not undergo PCA artifact correction (no PCA mean=.71, $SD=.64$, with PCA mean=.73, $SD=.63$, $t(82)=.50$, and $p=.49$. Overall results were also not altered when non-corrected PCA data were used (see Supplementary materials).

2.3.7. *Analytical strategy*

We first computed zero-order correlations between P50 sensory gating and divergent thinking, and P50 sensory gating and creative achievement, and tested whether these correlations differed from each other. Next we performed two multiple linear regressions: The first regression used three scores – divergent thinking, creative achievement, and academic achievement scores, to predict P50 sensory gating. The second regression specifically tested the interactive effects of divergent thinking and creative achievement in predicting P50 sensory gating. Finally we tested the specificity of the associations by examining how divergent thinking and creative achievement related to later attentional ERP components, the N100 and P200.

3. Results

The grand average of the ERPs at Cz is presented in Fig. 1. There was no reliable correlation between the Creative Achievement Questionnaire (CAQ) and either the Abbreviated Torrance Test for Adults (ATTA) total divergent thinking (fluency+originality) scores, nor with ATTA originality only, (both $ps>.16$), indicating no association between divergent thinking and real-world creative achievement in our sample. This is consistent with our previous investigations (Zabelina et al., 2014), although other studies have observed modest correlations between divergent thinking and creative achievement (see Plucker and Renzulli, 1999). Scoring methods could alter the extent of such associations.

Divergent thinking was reliably correlated with academic achievement scores, $r(68)=.27$, $p=.03$, suggesting an overlap in the performance on the divergent thinking and academic achievement tests (no association if ATTA originality is considered, $p>.15$). Creative achievement and academic achievement were unrelated, $p>.78$. We additionally examined the associations between age and divergent thinking, creative achievement, and sensory gating, given that age can be associated with creative achievement, in particular. We found no reliable associations in our sample, all $ps>.12$.

3.1. *Divergent thinking and sensory gating*

Divergent thinking was negatively associated with the sensory gating P50 ratio, $r(80)=-.30$, $p=.006$ ($r(80)=-.29$, $p=.01$ if only the ATTA originality score is considered). Thus, as predicted, increased divergent thinking was associated with more *selective*

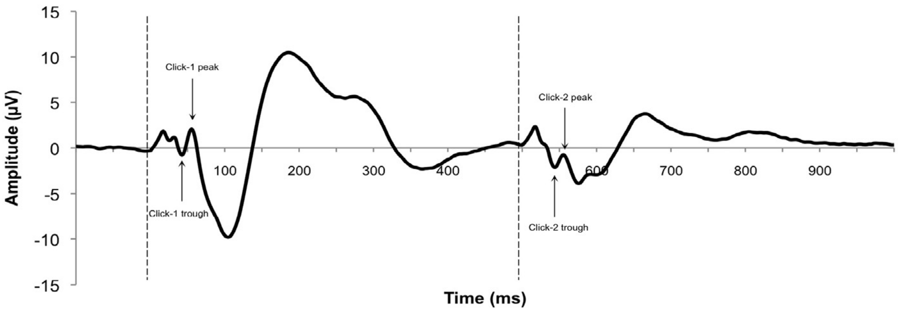

Fig. 1. Grand averages of the ERPs at Cz. Vertical dashed lines at 0 ms mark onset of Click 1, and at 500 ms mark the onset of Click 2. The P50 ratio is calculated as the P50 peak to trough difference of Click 2 over the P50 peak to trough difference of Click 1. Thus larger difference in the wave-forms would result in a smaller ratio. Smaller ratios represent more selective sensory gating, while larger ratios represent leakier sensory gating.

sensory gating, i.e., a reduced response to Click 2 compared to Click 1. This result suggests that divergent thinkers show more selective sensory gating very early (50 ms after stimulus onset) in the processing stream, with no task goals and meaningless stimuli.

3.2. Creative achievement and sensory gating

Real-world creative achievement was marginally positively associated with the P50 ratio, $r(81)=.20$, $p=.07$. Thus, the more creative achievements people reported, the *leakier* was their sensory gating, early in the processing stream with meaningless stimuli and no task goals.

3.3. Does P50 relate differently to divergent thinking and creative achievement?

Although the correlation between the P50 sensory gating and each creativity measure was only modest, the two creativity measures related to sensory gating in opposite directions, and the two correlations strongly differed from each other, Fisher's $z=-3.23$, $p<.001$.

3.4. Controlling for academic achievement scores

To test for independent associations between divergent thinking, creative achievement, and P50 sensory gating we performed a multiple linear regression, with divergent thinking, real-world creative achievement, and academic test scores as predictors of P50 sensory gating. All variable were normally distributed, meeting the linearity assumptions underlying multiple linear regression, Shapiro–Wilk, $ps>.05$. As can be seen from Table 1, divergent thinking remained a significant predictor of the P50 sensory gating, such that higher divergent thinking scores were linked with *more selective* sensory gating. Creative achievement, on the other hand, was a significant predictor of P50 sensory gating in the opposite direction, such that higher creative achievement scores were linked with *leakier* sensory gating. Interestingly, controlling for the creativity variables, academic achievement scores reliably predicted P50 sensory gating, such that higher academic achievement was associated with more selective sensory gating. This effect was in the same direction as divergent thinking, indicating that selective sensory processing may be common to successful performance on both tests of divergent thinking and academic achievement tests.

Partial regression plots, depicting partial correlations between divergent thinking and P50 sensory gating, and creative achievement and P50 sensory gating, are presented in Figs. 2 and 3, respectively. All results were maintained when the number of EEG epochs was entered into the regression model as a control variable. The number of epochs was not associated with P50 sensory gating, $r(82)=-.11$, $p>.32$.

Table 1
P50 sensory gating as a function of divergent thinking, creative achievement, and academic achievement scores.

Variable	*B*	SE *B*	β	*t*	*p*
Divergent Thinking	−.02	.01	−.25	−2.20	.03
Creative Achievement	.58	.17	.38	3.39	.001
Academic Achievement	−.07	.03	−.26	−2.31	.02

$p<.05$.

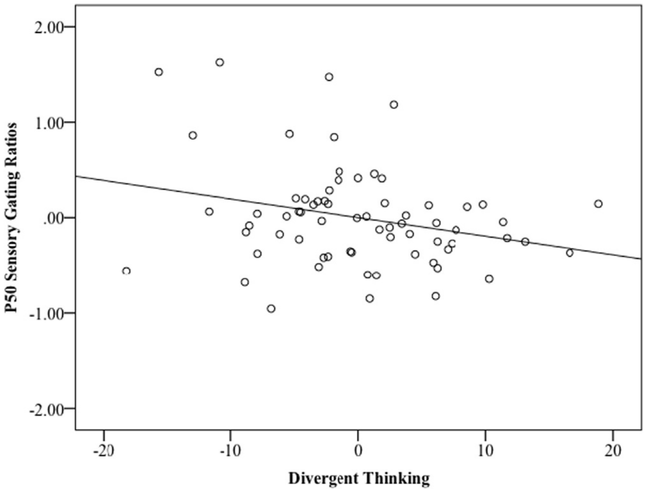

Fig. 2. Partial regression plot depicting partial correlations between divergent thinking (centered) and P50 sensory gating. This plot demonstrates that higher divergent thinking scores are associated with smaller P50 ratios, i.e., more selective sensory gating.

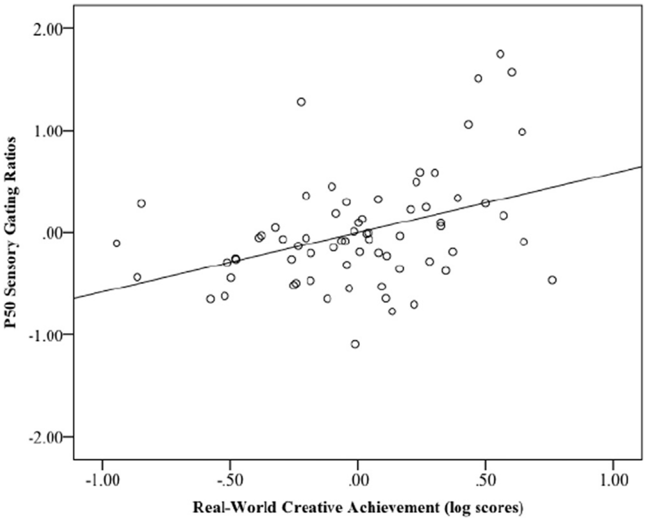

Fig. 3. Partial regression plot depicting partial correlations between creative achievement (centered) and P50 sensory gating. This plot demonstrates that higher creative achievement is associated with larger P50 ratios, i.e., leakier sensory gating.

3.5. Do divergent thinking and creative achievement interact in predicting P50 sensory gating?

With the P50 sensory gating ratios as the dependent variable, we performed a multiple regression examining a potential interactive effect of divergent thinking and creative achievement. In a multiple regression, divergent thinking and creative achievement were *z*-scored, and an interaction term was calculated by multiplying the two predictors (Aiken and West, 1991). All three predictors – both main effects and the interaction variable – were then entered as simultaneous predictors of P50 sensory gating. As expected, the interactive predictor (divergent thinking × creative achievement) was not associated with P50 sensory gating, $\beta=-.05$, $t(80)=-.42$, $p=.68$. The main effects, on the other hand, were both reliable, but in opposite directions, such that divergent thinking was a significant negative predictor of leaky sensory gating (i.e., predicted more selective sensory gating), $\beta=-.36$, $t(80)=-3.29$, $p=.002$, while creative achievement was a significant positive predictor of leaky sensory gating, $\beta=.27$, $t(80)=2.43$, $p=.02$. These results suggest that divergent thinking and creative achievement are additive rather than interactive predictors of sensory gating.

3.6. Is the effect specific to P50?

To test the specificity of the association of the P50 components with divergent thinking and creative achievement, we performed additional analyses with the N100 and P200 ERP components (as computed in Lijffijt et al., 2009). N100 ratio (Click 2/Click 1) did not reliably relate to divergent thinking ($r(80)=-.10$, $p=.40$), nor to creative achievement ($r(81)=.13$, $p=.28$). Similarly, P200 ratio (Click 2/Click 1) was not associated with divergent thinking ($r(80)=-.05$, $p=.71$), nor with creative achievement ($r(81)=-.01$, $p=.97$). These results suggest that exclusively very early sensory gating, as indexed by the P50 ERP, is differentially associated with divergent thinking and creative achievement.

3.7. Analyses excluding family history of psychiatric disorder

Although not a focus of this paper, we collected information on participants' personal history and relatives' history of psychiatric disorders, because some view the P50 marker of sensory gating as a marker to some psychopathology (Cadenhead et al., 2000; Olincy et al., 2010), and putative associations between psychopathology and creativity have been reported in the literature (Folley and Park, 2005; Kinney et al., 2001; Kyaga et al., 2012). Seven participants had first-degree relatives with diagnosed psychiatric illnesses, and four participants had personal history of psychiatric disorders (see Section 2). The association between divergent thinking and P50 sensory gating was maintained when excluding participants with history of psychiatric disorders ($r(75)=-.30$, $p=.008$), and when excluding participants who had relatives diagnosed with psychiatric illness ($r(71)=-.31$, $p=.007$). Likewise, the association between creative achievement and P50 sensory gating was maintained when participants with psychiatric disorders ($r(75)=.23$, $p=.04$) or those who had relatives diagnosed with psychiatric illness ($r(71)=.22$, $p=.05$) were excluded. Moreover, after excluding people with personal and family history of psychiatric disorders, and controlling for academic achievement scores within a multiple regression, divergent thinking remained a significant predictor of P50 sensory gating, $\beta=-.24$, $t(61)=-2.04$, $p=.04$, while creative achievement also remained a significant predictor of P50 sensory gating, in the opposite direction, $\beta=-.37$, $t(61)=3.19$, $p=.002$.

4. Discussion

We examined whether sensory gating – an early, automatic form of attention, is associated with individual differences in creativity as measured by divergent thinking tests or by an index of real-world creative achievements. As predicted, given prior results on selective attention, increased divergent thinking, as assessed by the standard time-limited divergent thinking test, was associated with *selective* sensory gating. This finding indicates that divergent thinking is associated with selective sensory processing very early in the processing stream. Given that the stimuli were meaningless and there were no task requirements, increased sensory gating may indicate that selective sensory gating is a general neural processing characteristic related to divergent thinking.

The divergent thinking measure we used emphasizes producing many responses in a short period of time (3 min). Doing so may benefit from the ability to selectively focus on relevant information while inhibiting irrelevant information, then rapidly switching to a new response. This may rely heavily on executive functions in a similar manner to standard academic achievement tests (St Clair-Thompson and Gathercole, 2006). Indeed, in our study divergent thinking correlated with academic test scores, as well as both academic achievement and divergent thinking test scores reliably predicted selective sensory gating. The association between divergent thinking and selective sensory gating is in line with previous studies showing a positive association between individual differences in divergent thinking and cognitive inhibition (Benedek et al., 2014; Zabelina et al., 2012). In other studies, short initial time limits on a divergent thinking test lead to faster rates of performance, but also to lower creativity, than did longer time limits (Kelly and Karau, 1993), indicating that fast responses may not necessarily be the most creative responses.

In direct contrast to divergent thinking, creative achievement in our study was associated with *leaky* sensory gating. This physiological effect concords with our prior behavioral evidence that creative achievement is associated with leaky attention (Zabelina et al., 2015), and demonstrates that it happens early in the processing stream. Given that there were no task requirements and stimuli were meaningless, this reduced sensory gating may indicate that a leaky sensory filter is a general neural processing characteristic related to real-world creative achievement.

Thus, real-world creative achievers appear to have reduced filtering of information, which may be the mechanism for their wider focus on a larger range of stimuli (Mendelsohn and Griswold, 1964; Russell, 1976), and their ability to make connections between distantly related concepts or ideas (Ansburg and Hill, 2003). In conjunction with other protective factors, such as cognitive control, reduced sensory gating may be what is needed for real-world creative achievements. In the absence of strong cognitive control (or other protective factors), leaky sensory gating may be a risk factor for attention disorders and/or psychopathology.

Highlighting the fact that divergent thinking and creative achievement address different aspects of creativity, the relations for the two creativity measures and the P50 sensory gating were in opposite directions, strongly differed from each other, and did not interact. The results suggest that these two creativity measures are orthogonally associated with sensory processing, and, in fact, involve different neural mechanisms. Finally, the ERP effect was specific to the P50 – a very early attentional component unaffected by attentional demands (Gjini et al., 2011). Neither divergent thinking nor creative achievement were related to later components, such as the N100 and P200, which are sensitive to manipulations of attention (Gjini et al., 2011). Additionally, the experimental paradigm involved no task demands – if task demands were introduced, perhaps we would find different associations between creativity measures and later ERP components.

It is not clear whether reduced sensory gating is a stable trait, or whether creative achievers can modulate their sensory processing depending on task demands. In other words, they may be particularly good at narrowing and widening their sensory filters depending on task demands. Indeed, flexible cognitive control (Zabelina and Robinson, 2010), and variable attention (Vartanian et al., 2007) have been suggested to facilitate creativity. Because our sensory gating paradigm lacked goals or meaningful stimuli, participants may not focus on the first click nor filter the second. If we changed instructions to require participants to attend, or included task goals or meaningful stimuli, sensory gating could relate differently to divergent thinking, to creative achievement, or to both.

The link between reduced sensory gating and creative achievement is particularly intriguing given that the P50 is viewed as a marker of vulnerability to some psychopathology, particularly schizophrenia (Cadenhead et al., 2000; Olincy et al., 2010), and a rather debated view that creativity and psychopathology may be related (Folley and Park, 2005; Kinney et al., 2001; Kyaga et al., 2012). Indeed, our recent investigations report that real-world creative achievement is associated with several dimentional psychopathology measures, namely psychoticism and hypomania, while divergent thinking is not associated with any psychopathology measures (Zabelina et al., 2014). Thus it is possible that some risk factors that are associated with elevated psychopathology, such as leaky sensory gating, might also, in combination with other factors, be a "risk" factor for increased creative achievement, as previously suggested (Carson, 2011; Richards et al., 1988). Therefore for some prominent creative achievers who complained about noise as a source of distraction, the same leaky filters may have facilitated their creativity.

Additionally, it is important to examine whether people with creative achievements are particularly those who have increased cognitive control paired with leaky sensory gating. Investigations of how creative people modulate their attention will also provide further insight into how different components of attention are associated with different aspects of creativity.

5. Conclusion

We report a novel association between creativity and sensory gating. We provide clear evidence that divergent thinking and real-world creative achievement have reliably different neural mechanisms of sensory gating. Specifically, divergent thinking is associated with selective sensory gating, whereas creative achievement is associated with leaky sensory gating, both in terms of zero-order correlations, or within a linear regression controlling for academic achievement scores. The relations between the two creativity measures and P50 sensory gating strongly differ from each other, and do not interact in predicting P50 sensory gating. Finally, the association is specific to P50, as there are no associations between creativity measures and N100 or P200. The results suggest that these two creativity measures involve different neural mechanisms of sensory processing.

Acknowledgements

We thank everyone who contributed to this paper, with special thanks to William J. Gavin and Ken A. Paller for their valuable feedback regarding the manuscript. This research was supported by the NSF Graduate Student Fellowship and Northwestern University Graduate Research Grant to DLZ, and the John Templeton Foundation Grant to MB (Grant no. 24467).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2015.01.034.

References

Aron, A.R., 2007. The neural basis of inhibition in cognitive control. Neuroscientist 13, 214–228.

Abraham, A., Beudt, S., Ott, D.V.M., von Cramon, D.R., 2012. Creative cognition and the brain: dissociations between frontal, parietal-temporal and basal ganglia groups. Brain Res. (1482), 55–70.

ACT Inc., 2014. National Ranks for Test Scores and Composite Score. Available online at: ⟨http://www.actstudent.org/scores/norms1.html⟩. (accessed 03.08.14).

Aiken, L.S., West, S.G., 1991. Multiple Regression: Testing and Interpreting Interactions. Sage, Thousand Oaks, CA.

Ansburg, P.I., Hill, K., 2003. Creative and analytic thinkers differ in their use of attentional resources. Personal. Individ. Differ. 34, 1141–1152.

Bak, N., Glenthoj, B.Y., Rostrup, E., Larsson, H.B., Oranje, B., 2011. Source localization of sensory gating: a combined EEG and fMRI study in healthy volunteers. NeuroImage 54, 2711–2718.

Banich, M.T., 2004. Cognitive Neuroscience and Neuropsychology. Houghton Mufflin Company, New York, NY.

Benedek, M., Jauk, E., Fink, A., Koschutnig, K., Reishofer, G., Ebner, F., Neubauer, A.C., 2014. To create or to recall? Neural mechanisms underlying the generation of creative new ideas. NeuroImage 88, 125–133.

Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. Psychol. Rev. 108, 624–652.

Cadenhead, K.S., Light, G.A., Geyer, M.A., Braff, D.L., 2000. Sensory gating deficits assessed by the P50 event-related potential in subjects with schizotypal personality disorder. Am. J. Psychiatry 157, 55–59.

Carson, S.H., 2011. Creativity and psychopathology: a shared vulnerability model. Can. J. Psychiatry 56, 144–153.

Carson, S.H., Peterson, J.B., Higgins, D.M., 2003. Decreased latent inhibition is associated with increased creative achievement in high-functioning individuals. J. Personal. Soc. Psychol. 85, 499–506.

Carson, S.H., Peterson, J.B., Higgins, D.M., 2005. Reliability, validity, and factor structure of the creative achievement questionnaire. Creat. Res. J. 17, 37–50.

Chang, W.-P., Gavin, W.J., Davies, P.L., 2012. Bandpass filter settings differentially affect measurement of P50 sensory gating in children and adults. Clin. Neurophysiol. 11, 2264–2272.

Chapman, L.J., Chapman, J.P., 1987. The measurement of handedness. Brain Cognit. 6, 175–183.

Chrysikou, E.G., Thompson- Schill, S.L., 2011. Dissociable brain states linked to common and creative object use. Hum. Brain Mapp. 32, 665–675.

College Board, 2012. College-Bound Seniors Total Group Profile Report New York: The College Board. Available online at: ⟨http://media.collegeboard.com/digitalServices/pdf/research/TotalGroup-2012.pdf⟩ (accessed 03.08.14).

Cullum, C.M., Harris, J.G., Waldo, M.C., Smernoff, E., Madison, A., Nagamoto, H.T., Griffith, J., Adler, L.E., Freedman, R., 1993. Neurophysiological and neuropsychological evidence for attentional dysfunction in schizophrenia. Schizophr. Res. 10, 131–141.

Curie, E., Sheean, V., 2001. Madame Curie: A Biography. Da Capo Press, New York, NY.

De Dreu, C.K.W., Nijstad, B.A., Baas, M., Wosink, I., Roskes, M., 2012. Working memory benefits creative insight, musical improvistion, and original ideation through maintained task-focused attention. Psychol. Sci. 3, 656–669.

Erwin, R.J., Turetsky, B.I., Moberg, P., Gur, R.C., Gur, R.E., 1998. P50 abnormalities in schizophrenia: relationship to clinical and neuropsychological indices of attention. Schizophr. Res. 33, 157–167.

Fink, A., Benedek, M., 2014. EEG alpha power and creative ideation. Neurosci. Behav. Rev. 44, 111–123.

Folley, B.S., Park, S., 2005. Creativity and schizotypal personality in relation to prefrontal hemispheric laterality: a behavioral and near-infrared optical imaging study. Schizophr. Res. 80, 271–282.

Gilhooly, K.J., Fioratou, E., Anthony, S.H., Wynn, V., 2007. Divergent thinking: strategies and executive involvement in generating novel uses for familiar objects. Br. J. Psychol. 98, 611–625.

Gjini, K., Burroughs, S., Boutros, N.N., 2011. Relevance of attention in auditory sensory gating paradigm in schizophrenia. J. Psychophysiol. 25, 60–66.

Goff, K., Torrance, E.P., 2002. Abbreviated Torrance Test for Adults Manual. Scholastic Testing Service, Bensenvill, IL.

Gonen-Yaacovi, G., de Souza, L.C., Levy, R., Urbanski, M., Josse, G., Volle, Emmanulle, 2013. Rostral and caudal prefrontal contributions to creativity: a meta-analysis of functional imaging data. Front. Hum. Neurosci. 7, 465.

Guilford, J.P., 1950. Creativity. Am. Psychol. 5, 444–454.

Gumenyuk, V., Korzyukov, O., Roth, T., Bowyer, S.M., Drake, C.L., 2013. Sleep extension normalizes ERP of waking auditory sensory gating in healthy habitually short sleeping individuals. Plos One 8, e59007.

Hsieh, M.H., Liu, K., Liu, S.K., Chiu, M.J., Hwu, H.G., Chen, A.C., 2004. Memory impairment and auditory evoked potential gating deficit in schizophrenia. Psychiatry Res. 130, 161–169.

Kasof, J., 1997. Creativity and breadth of attention. Creat. Res. J. 10, 303–315.

Kelly, J.R., Karau, S.J., 1993. Entrainment of creativity in small groups. Small Group Res. 24, 179–198.

Kinney, D.K., Richards, R., Lowing, P.A., LeBlanc, D., Zimbalist, M.E., Harlan, P., 2001. Creativity in offspring of schizophrenic and control patients: an adoption study. Creat. Res. J. 13, 17–25.

Kleibeuker, S.W., Koolschijn, P.C.M.P., Jolles, D.D., De Dreu, C.K.W., Crone, E.A., 2013. The neural coding of creative idea generation across adolescence and early adulthood. Front. Hum. Neurosci. 7, 905.

Kyaga, S., Landén, M., Boman, M., Hultman, C.M., Langström, N., Lichtenstein, P., 2012. Mental illness, suicide, and creativity: 40-year prospective total population study. J. Psychiatr. Res. 47, 83–90.

Lester, T., 2012. Da Vinci's Ghost: Genius, Obsession, and How Leonardo Created the World in his Own Image. Free Press, New York, NY.

Lijffijt, M., Lane, S.D., Meier, S., Boutros, N.N., Burroughs, S., Steinberg, J., Moeller, G., Swann, A.C., 2009. P50, N100, and P200 sensory gating: relationship with behavioral inhibition, attention, and working memory. Psychophysiology 46, 1059–1068.

Luck, S., 2014. An Introduction to the Event-related Potential Technique. Massachusetts Institute of Technology, Boston, MA.

Lubow, R.E., 1973. Latent inhibition. Psychol. Bull. 79, 398–407.

Mednick, S., 1962. The associative basis of the creative process. Psychol. Rev. 69, 220–232.

Mendelsohn, G., Griswold, B., 1964. Differential use of incidental stimuli in problem solving as a function of creativity. J. Abnorm. Soc. Psychol. 68, 431–436.

Miyake, A., Friedman, N., 2012. The nature and organization of individual differences in executive functions: four general conclusions. Curr. Dir. Psychol. Sci. 21, 8–14.

Nusbaum, E.C., Silvia, P.J., 2011. Are intelligence and creativity really so different? Fluid intelligence, executive processes, and strategy use in divergent thinking. Intelligence 39, 36–45.

Olincy, A., Braff, D.L., Adler, L.E., Cadenhead, K.S., Calkins, M.E., Dobie, D.J., Freedman, R., 2010. Inhibition of the P50 cerebral evoked response to repeated auditory stimuli: results from the consortium on genetics of schizophrenia. Schizophr. Res. 119, 175–182.

Patterson, J.V., Hetrick, W.P., Boutros, N.N., Jin, Y., Sandman, C., Stern, H., Bunney Jr., W.E., 2008. P50 sensory gating ratios in schizophrenics and controls: a review and data analysis. Psychiatry Res. 158, 226–247.

Plucker, J.A., Renzulli, J.S., 1999. Psychometric approaches to the study of human creativity. In: Sternberg, R.J. (Ed.), Handbook of creativity. Cambridge University Press, New York, pp. 35–61.

Rawlings, D., 1985. Psychoticism, creativity, and dichotic listening. Personal. Individ. Differ. 6, 737–742.

Richards, R., Kinney, D.K., Lunde, I., Benet, M., Merzel, A.P.C., 1988. Creativity in manic-depressives, cyclothymes, their normal relatives, and control subjects. J. Abnorm. Psychol. 97 (281–288).

Runco, M.A., Acar, S., 2012. Divergent thinking as an indicator of creative achievement. Creat. Res. J. 24, 66–75.

Runco, M., Mraz, W., 1992. Scoring divergent thinking tests using total ideational output and a creativity index. Educ. Psychol. Meas. 52, 213–221.

Russell, J., 1976. Utilization of irrelevant information by high and low creatives. Psychol. Rep. 39, 105–106.

St Clair-Thompson, H., Gathercole, S.E., 2006. Executive functions and achievement in school: shifting, updating, inhibition, and working memory. Q. J. Exp. Psychol. 59, 745–759.

Thoma, R.J., Hanlon, F.M., Miller, G.A., Huang, M., Weisend, M.P., Sanchez, F.P., 2006. Neuropsychological and sensory gating deficits related to remote alcohol abuse history in schizophrenia 12, 34–44.

Thomas, C., vom Berg, I., Rupp, A., Seidl, U., Schröder, J., Roesch-Ely, D., Kreisel, S.H., Mundt, C., Weisbrod, M., 2010. P50 gating deficit in Alzheimer dementia correlates to frontal neuropsychological function. Neurobiol. Aging 31, 416–424.

Thompson-Schill, S.L., Ramscar, M., Chrysikou, E.G., 2009. Cognition without control: when a little frontal lobe goes a long way. Current Directions in Psychological Science 18, 259–263.

Torrance, E.P., 1974. The Torrance Tests of Creative Thinking-Norms – Technical Manual Research Edition, Figural Tests, Forms A and B. Personnel Press, Princeton, NJ.

Vartanian, O., Jobidon, M.-E., Bouak, F., Nakashima, A., Smith, I., Lam, Q., Cheung, B., 2013. Working memory training is associated with lower prefrontal cortex activation in a divergent thinking task. Neuroscience 236, 186–194.

Vartanian, O., Martindale, C., Kwiatkowski, J., 2007. Creative potential, attention, and speed of information processing. Personal. Individ. Differ. 43, 1470–1480.

Wallach, M.A., Kogan, N., 1965. Modes of Thinking in Young Children: A Study of the Creativity–Intelligence Distinction. Holt, Rinehart, & Winston, New York.

Wallas, G., 1926. The Art of Thought. Harcourt Brace, New York.

Wan, L., Friedman, B.H., Boutros, N.N., Crawford, H.J., 2008. P50 sensory gating and attentional performance. Int. J. Psychophysiol. 67, 91–100.

Wegbreit, E., Suzuki, S., Grabowecky, M., Kounios, J., Beeman, M., 2012. Visual attention modulates insight versus analytic solving of verbal problems. J. Problem Solving 4, 94–115.

Wiley, J., Jarosz, A.F., 2012. Working memory capacity, attentinal focus, and problem solving. Curr. Dir. Psychol. Sci. 39, 36–45.

Zabelina, D.L., Condon, D., Beeman, M., 2014. Do dimensional psychopathology measures relate to divergent thinking or creative achievement? Front. Psychol. 5, 1–11.

Zabelina, D.L., Robinson, M.D., 2010. Creativity as flexible cognitive control. Psychol. Aesthet. Creat. Arts 4, 136–143.

Zabelina, D.L., Robinson, M.D., Council, J., Bresin, K., 2012. Patterning and non-patterning in creative cognition: performance in a random number generation task. Psychol. Aesthet. Creat. Arts 6, 137–145.

Zabelina, D.L., Saporta, A.N., Beeman, M., 2015. Broad or flexible attention in creative individuals? Distinct patterns of attention for different types of creative thinking. (submitted for publication).