Neural Oscillatory Signature of Original Problem Solving

Henk J. Haarmann[1,*], Polly O'Rourke[1], Timothy George[1], Alexei Smaliy[2], Kristin Grunewald[1], and Joseph Dien[1]

[1] Center for the Advance Study of Language, University of Maryland, College Park, MD, USA
{hhaarmann,porourke,tgeorge,kgrunewald,jdien}@casl.umd.edu
[2] Maryland Neuroimaging Center, University of Maryland, College Park, MD, USA
asmaliy@umd.edu

Abstract. The goal of the present research was to increase understanding of the neural oscillatory signature of originality in verbal divergent thinking by determining if event-related synchronization (ERS) in frequency bands other than alpha predicts originality. EEG was recorded while participants performed the insight task in which they were presented with a brief scenario and asked to generate as many explanations as possible during a three minute period. After the EEG session, participants were asked to rate the originality of each idea they produced. Analyses revealed that high originality was associated with decreases in the high beta ERS and with hemispheric asymmetry in the low beta band, immediately prior to idea generation. These results suggest the neural signature of originality extends beyond hemispheric asymmetries in the alpha band and provide important insights into the neural underpinnings of verbal creativity.

Keywords: Divergent thinking, originality, EEG, ERS, alpha, beta.

1 Introduction

Divergent thinking is a type of creative problem solving which involves the generation of multiple, distinct solutions to open-ended problems. These solutions will vary in their level of originality such that some will be highly unique, unusual ideas while others will reflect more standard approaches. One commonly used task is the insight task (IS) in which participants are presented with a brief scenario ("a light in the darkness") and asked to provide as many explanations as possible within a specified time period. A standard, fairly unoriginal response would be "headlights on a car", while "jelly fish in the ocean" is an example of a highly original solution. There is a substantial literature examining the neural oscillatory signature of divergent thinking [1] which suggests that original divergent thinking is associated with increases in spectral power in the alpha band (8-12 Hz). Alpha power is inversely related to neural activation such that greater alpha power indicates reduced activation and vice versa.

* Corresponding author.

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One standard view of alpha is that it reflects cortical idling [2]. It is believed that this disengagement is what enables the formation of atypical conceptual combinations between weakly related or unrelated concepts. Increases alpha power have also been found during cognitive activity as a function of task demand [3-4]. The dominant theory is that alpha reflects a top-down process that inhibits the intrusion of sensory information or conflicting operations [3], [5-7]. In the case of verbal creativity tasks, such as the remote associates test (RAT), the increased alpha power is thought to inhibit the activation of words and concepts that are strongly associated with the cue thus reducing the difficulty of selecting weak associates in the face of competition [8].

One focus of research on the neural basis of divergent thinking is to determine what distinguishes highly original and less original ideas at the neural level. A recent study by Grabner, et al. [5] found that (self-rated) originality of ideas generated during divergent thinking is predicted by event-related synchrony (ERS) in the alpha band over the right hemisphere during idea generation. In their study, highly original ideas were associated with increased alpha ERS in the right hemisphere relative to less original ideas. Their study did not, however, report analyses of whether power in other frequency bands, such as the beta band, predicts originality. The goal of the present study was to fill that gap by determining if other frequency bands are sensitive to originality level during idea generation, and examine how any effects interact with hemisphere given that, though the literature is not unambiguous, there is a strong suggestion of greater engagement of the right hemisphere during the generation of highly original ideas [5], [9].

2 Methods

The current analysis includes data from two experiments, both of which employed the IS as the divergent thinking task.

2.1 Participants

Data from a total of 41 neurologically normal participants were included in this analysis. 21 (7 male; mean age 21.1, S.D. 2.3) from Experiment 1 and 20 (10 male; mean age 21.0, S.D. 1.5) from Experiment 2. All participants were right handed native speakers of English.

2.2 Materials

In both experiments, participants performed the insight (IS) task, in which they were presented with situations and asked to produce different explanations. The following are the test items:

- “a light in the darkness”
- “Person A is lying down, person B is sitting and person C is standing”
- “a cloth in the air”
- “Person A walks, Person B jumps”

Items 1 and 2 are the English translations of the items used in [5]. Items 3 and 4 were added in order to increase the power of the design.

2.3 Procedure

After signing a consent form and electrode application, participants were tested individually in a sound-attenuating room with the lights turned off. Participants were seated in a comfortable chair in front of a computer monitor and asked to use a chin rest in order to minimize movement artifacts. Prior to the task, two one-minute base baselines were recorded, one with eyes open and the other with eyes closed. Each of the four task items consisted of the presentation of a fixation cross for 15 seconds, followed by the presentation of the item. Participants were instructed to generate as many solutions as possible and to be creative in their responses. When participants had an idea, they pressed a button on the response box. They then vocalized their idea and pressed the button again to indicate when they were done. The response period for each item lasted 3 minutes. The testing session lasted approximately 30 minutes. At the conclusion of the EEG session, participants were presented with the transcription of the ideas they produced for each item and were asked to rate the originality of each response on a scale of 1 to 5. In Experiment 1, participants were exposed to pink noise during task performance while in Experiment 2 there were no auditory stimuli. Also, in Experiment 2, participants had a one minute rest between the IS task items.

2.4 EEG Recording

Electroencephalographic (EEG) data were acquired with a 128-channel HydroCel Geodesic Sensor Net using the Electrical Geodesics Inc. (EGI) NetStation system. The EEG signal was sampled at 250 Hz. The signal was high-pass filtered online at 0.1 Hz, low-pass filtered at 100 Hz, and notch filtered at 60 Hz. Impedances were kept below 50 KΩ where possible per manufacturer recommendation, and otherwise under 100 KΩ.

2.5 EEG Analysis

EEG data were artifact-corrected using the EP toolkit for MATLAB [10]. Spectral power was obtained through Fast Fourier Transform averaged across 1-second epochs within a period. By-subject averages of EEG spectral power were obtained for every cell in our design and then log-transformed, except for power values that were entered into the ERS analyses [cf. 5]. ERS was calculated using the following formula [11]: %ERS = [(Activation-Reference)/Reference] x 100. The 1000 ms period terminating 250 ms prior to first button press (indicating an idea) served as the activation interval. Reference was the pre-task eyes-open baseline.

The design for the data analysis was the following: Originality (High, Low) x Hemisphere (Left, Right) x Lobe (frontal, temporal, parietal, occipital). This repeated measures ANOVA was performed for each frequency band with Experiment as a between subjects factor. The lobe by hemisphere division of the scalp electrodes was accomplished via Brain Voyager QX 2.4 (Brain Innovation, Maastricht, The Netherlands) which mapped the 10/20 sensor positions, using the coordinates set forth in [12] on to brain lobes. The frequency bands were defined as follows: delta (1-4 Hz), theta (4-8 Hz), lower alpha (8-10 Hz), upper alpha (10-12 Hz), overall alpha (8-12 Hz), low beta (12-16 Hz), mid beta (16-20), high beta (20-28 Hz) and gamma (28-70 Hz). The EEG data for each response in the Insight Task was categorized as high or low originality (as per the median split performed on the originality ratings). The degrees of freedom in all analyses were Greenhouse-Geisser corrected when appropriate.

In addition, a correlational analysis, using Pearson product-moment correlations, was run using an index of hemispheric asymmetry (right minus left hemisphere) for the alpha and beta sub-bands in order to assess the impact of hemispheric asymmetry on divergent thinking performance (fluency and originality). Fluency was defined as the number of distinct ideas and originality as a rating from 1 (least original) to 5 (most original). The analysis was run on both the pooled data from the two experiments and on each experiment separately.

3 Results

When analyzed separately, the data from the two experiments showed effects of originality in the alpha and beta bands only. These two bands will, therefore, be the focus of this analysis. In the lower alpha band, there was a four-way interaction of Originality, Lobe, Hemisphere and Experiment ($F(3,117) = 3.24$, $p < .05$, $\eta_p^2 = .077$). Splitting across the factor Experiment revealed a significant Originality x Hem x Lobe interaction ($F(3,57) = 2.935$, $p = .050$, $\eta_p^2 = .134$) in Experiment 2 only. Separate analysis of the levels of the Lobe factor reveals an interaction of Originality and Hemisphere in the frontal lobe ($F(1,19) = 7.431$, $p < .05$, $\eta_p^2 = .281$) such that high originality responses had greater ERS in the left hemisphere while ERS for low originality responses was greater in the right. Simple comparisons revealed no significant effects. In the high alpha band, there was also a significant four-way interaction ($F(3,117) = 4.14$, $p < .05$, $\eta_p^2 = .096$). This was driven by a marginally significant Originality x Hem x Lobe interaction ($F(3,60) = 3.183$, $p = .059$, $\eta_p^2 = .137$) in Experiment 1 only. Splitting across the factor lobe revealed a marginal interaction of originality and hemisphere in frontal sites ($F(1,20) = 4.038$, $p = .058$, $\eta_p^2 = .168$). Simple comparisons showed a main effect of hemisphere for high originality responses in the frontal lobe ($F(1,20) = 4.899$, $p = .039$, $\eta_p^2 = .197$) such that ERS was greater in the right hemisphere than the left. Finally, in the high beta band there was a main effect of Originality in the high beta band ($F(1,39) = .7863$, $p = .008$, $\eta_p^2 = .185$), such that ERS was greater for low originality responses pooled across both experiments. When the data from each experiment were analyzed separately, the effects of originality on the high beta band were marginal (Experiment 1, $F(1,20) = 4.129$, $p = .058$, $\eta_p^2 = .171$; Experiment 2, $F(1,19) = 4.320$, $p = .051$, $\eta_p^2 = .185$) but in the same direction as the pooled analysis.

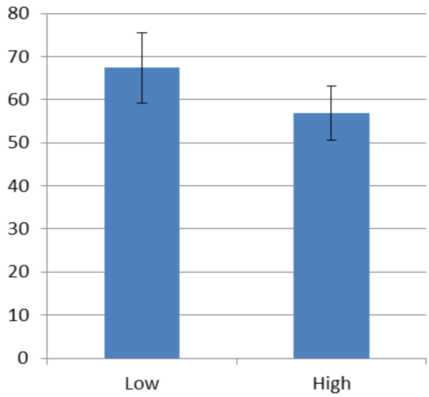

Fig. 1. Percentage of ERS for low and high originality responses in the high beta band with standard error bars

The correlational analysis ran between the index of hemispheric asymmetry and the behavioral measures. In Experiment 1, there was a positive correlation between hemispheric asymmetry and fluency in the high alpha band (r = .545, p < .05). In Experiment 2, there was a positive correlation between asymmetry in the low beta band and originality (r = .488, p < .05). The pooled analysis did not yield any significant correlations.

4 Discussion

The results of the current experiment provide a more nuanced view of the neural signature of originality. While confirming the association between alpha power and originality (albeit only significant in Experiment 1), the finding that the beta band is also sensitive to originality level is a novel finding. Similarly, the suggestion that hemispheric asymmetry in not only the alpha but also the beta band during idea generation predicts performance underlines the contribution of beta to divergent thinking.

The findings for the ERS in the alpha band in the two experiments are somewhat contradictory in terms of sub-band and hemispheric distribution. In Experiment 1 the ANOVA results showed that highly original responses had increased high alpha ERS in the right compared to left frontal areas. In experiment 2, a marginal interaction of originality and hemisphere in frontal areas for the low alpha band suggested that highly original responses elicited increased ERS in the left hemisphere. It is possible that the presence or absence of pink noise contributed to this difference but not likely given that the pattern exhibited in Experiment 1 is very similar to that found by Grabner et al. [5] in an experiment that contained no auditory stimuli. The discrepancy is, however, not surprising as in the wider literature findings for the topographical distribution of alpha tend to be inconsistent [1]. It must be recognized that both experiments did show evidence of an association between originality and frontal alpha ERS which generally does replicate previous experiments using the IS task [9], [13].

The finding of an association between decreased spectral power in the high beta band and generation of high originality responses was more robust and has not been previously reported. Dietrich and Kanso indicate that "the single most common finding in this literature is the absence of significant changes to the beta frequency" [1 p. 825]. They are also surprising as oscillations in the beta frequencies are associated with motor processes. The execution of movements is associated with desynchrony in the beta band [2], as is observing movements [14] or imagining them [15]. While the production of both high and low originality ideas involve movements and, therefore motoric processes, high originality responses involve retrieving and producing words that are not strongly primed by the cue and may, as a result, involve more effortful production and, therefore, distinct (and perhaps increased) motoric demands, evidenced by increased beta desynchrony. However, while lexical-semantic priming affects the time course of lexical access, it does not necessarily affect subsequent speech motor planning and execution.

The notion that distinct linguistic demands are reflected in power changes in the beta band is supported by recent research in semantic processing [16]. Luo, et al. [17] and Wang, et al. [18] have found decreases in power in the mid beta band (16-19 Hz in [17]. and 16-20 in [18]) for semantically incongruent words in a sentence compared to congruent words. These studies examined brain activity during language perception while we looked at activity during idea generation (preceding speech production) so it is difficult to make direct comparisons with confidence. Nevertheless, as the generation/production of highly original ideas involves accessing and integrating lexical items that are normally not considered related, there is a parallel. [16] and [17] found that unprimed words (semantically incongruent) elicited reductions in beta synchrony, as did the highly original (i.e. unprimed) ideas in our experiments, albeit in the high but not mid beta band. The sensitivity of the beta band to the semantic features of words found in the sentence processing studies listed above implies that our effect may reflect the differing linguistic and cognitive demands of high and low originality ideas.

How specific properties of these demands reflect different sub-bands within the overall beta band remains to be determined. One possibility is that the decreased power associated with high originality in the high beta band reflects decreased demands in active, controlled semantic processing needed for the generation of more original ideas. For example, reducing this type of processing may facilitate access to implicit semantic memory without top-down bias from explicit semantic memory, thus resulting in more original ideas. This explanation is admittedly post-hoc and it does not rule out the possibility that there are conditions under which an increase in active, controlled semantic processing results in greater originality. The latter type of processing can help to resolve the competition between dominant and weak associations in favor of weak ones, thereby contributing to greater originality. This analysis, while speculative, implies that divergent thinking can be achieved with different modes of thinking, which need to be experimentally controlled.

The correlational analysis revealed that in Experiment 1, hemispheric asymmetry (increased ERS on the right compared to the left) in the high alpha band predicted fluency (but not originality), but in Experiment 2 asymmetry in the low beta band predicted originality (and not fluency). Though the correlations differed across experiments, they do emphasize the importance of hemispheric asymmetry during divergent thinking and provide evidence that fluency and originality are underpinned by distinct neural mechanisms. The relationship between alpha and fluency found in Experiment 1 is novel but generally consistent with Jung-Beeman et al.'s account [8] such that individuals with greater right hemispheric alpha are able to inhibit standard associations in favor of weakly associated concepts while those without the greater right hemispheric alpha may become fixated on standard, unoriginal associations and generate fewer overall responses. The lack of correlation between alpha asymmetry and originality is somewhat surprising. But, as mentioned above, the mode of thinking induced by the experimental context may influence whether increased alpha asymmetry is associated with increased originality. With respect to beta, the correlational analysis of Experiment 2 provides additional evidence for the relationship between beta and generating original responses and suggests that a greater increase in low beta power in the right than left hemisphere may be a key component.

Taken together, these results suggest the neural signature of originality extends beyond the alpha band. The findings that both activity in the high beta band and hemispheric asymmetry in the low beta band predict originality provide new and important insights into the neural underpinnings of verbal creativity. Future research will further elucidate the role of beta in the generation of original ideas. Of particular interest is the question of whether original divergent thinking can arise from different modes of thinking and their associated neurophysiological mechanisms. In this paper, the focus was on the association between neural oscillatory activity and originality. Frequency-specific experimental manipulation of this activity will be crucial for moving beyond association and establishing its causal role in cognitive creativity.

References

1. Dietrich, A., Kanso, R.: A review of EEG, ERP and Neuroimaging Studies of Creativity and Insight. Psyc. Bul. 136(5), 822–848 (2010)
2. Pfurtscheller, G., Stancák, A., Neuper, C.: ost-movement beta desynchronization. A correlated of idling motor area? Electroencephalography and Clinical Neurophys 98(4), 281–293 (1996)
3. Klimesch, W.: EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res. Rev. 29(2-3), 169–195 (1999)
4. Jensen, O., Gelfand, J., Kounios, J., Lisman, J.E.: Oscillations in the alpha band (9-12 Hz) increase with memory load during retention in a short-term memory task. Cerebral Cortex 12(8), 877–882 (2002)
5. Grabner, R.H., Fink, A., Neubauer, A.C.: Brain Correlates of Self-Rated Originality of Ideas: Evidence From Event-Related Power and Phase-Locking Changes in the EEG. Behav. Neurosci. 121(1), 224–230 (2007)
6. Fink, A., Grabner, R.H., Benedek, M., Neubauer, A.C.: Divergent thinking training is related to frontal electroencephalogram alpha synchronization. Eur. J. of Neurosci. 23, 2241–2246 (2006)

7. Cooper, N.R., Croft, R.J., Dominey, S.J.J., Burgess, A.P., Gruzeiler, J.H.: Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses. Int. J. of Psychophys 47(1), 65–74 (2003)
8. Jung-Beeman, M., Bowden, E.M., Haberman, J., Frymiare, J.L., Arambel-Liu, S., Greenblatt, R.: Neural activity when people solve verbal problems with insight. PLoS Biol. 2(4), 500–510 (2004)
9. Fink, A., Grabner, R.H., Benedek, M., Neubauer, A.C.: The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. Hum. Brain Mapping 30, 734–748 (2009)
10. Dien, J.: The ERP PCA Toolkit: An Open Source Program For Advanced Statistical Analysis of Event Related Potential Data. J. of Neurosci. Methods 187(1), 138–145 (2010)
11. Pfurtscheller, G., Lopes da Silva, F.H.: Event-related EEG/MEG synchronization and desynchronization: basic principles. Clinical Neurophys 110(11), 1842–1857 (1999)
12. Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., Oda, I., Isobe, S., Suzuki, T., Kohyama, K., Dan, I.: Three-dimensional probabalistic anatomical cranio-cerebral correlation via the international 10-20 system oriented for transcranial functional brain mapping. NeuroImage 21, 99–111 (2004)
13. Fink, A., Neubauer, A.C.: EEG alpha oscillations during the performance of verbal creativity tasks: Differential effects of sex and verbal intelligence. Int. J. of Psychophys 62(1), 46–53 (2006)
14. Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., Rizzolatti, G.: Activation of human primary motor cortex during action observation: a neuromagnetic study. Proc. of the Nat. Acad. of Sci. 95, 15061–15065 (1998)
15. Neuper, C., Wortz, M., Pfurtscheller, G.: ERD/ERS patterns reflecting sensorimotor activation and deactivation. Prog. Brain Res 159, 211–222 (2006)
16. Weiss, S., Mueller, H.M.: "Too many betas do not spoil the broth": the role of beta brain oscillations in language processing. Fron. in Psyc. 3, 1–15 (2012)
17. Luo, Y., Zhang, Y., Feng, X., Zhou, X.: Electroencephalogram oscillations differentiate semantic and prosodic processes during sentence reading. Neurosci. 169, 654–664 (2010)
18. Wang, L., Jensen, O., van den Brink, D., Weder, N., Schoffelen, J.M., Magyari, L., Hagoort, P., Bastiaansen, M.: Beta oscillations related to the N400m during language comprehension. Hum. Brain Mapping 33(12), 2898–2912 (2012)