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Inner Speech as a Brain Mechanism for Preconditioning Creativity Process

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Abstract. The current domain of creativity studies is characterized by a high diversity of psychological and neuroscience techniques and methods researchers use. However, the role of verbal processes, especially inner speech, remains underrepresented in this area. Existing studies point to the heterogeneity of inner speech brain mechanisms involved in creative thinking. While consciously controlled verbalized thoughts are associated with the activity of task-dependent brain networks (TPN), especially lateral-frontoparietal network (L-FPN), non-voluntary, mind-wandering thoughts are supposed to correlate with default-mode networks (DMN) activity. While DMN activity leads to an increased number of creative ideas, L-FPN activity results in fewer ideas but increased idea originality. From this point, rest state and state of getting prepared (preconditioning) to task completion, when both mind-wandering and control thoughts occur, are of specific interest. In our study, 49 volunteers completed divergent thinking tasks with rest state and preconditioning state preceded. We later divided all participants into two groups – with low and high creativity levels based on their performance during divergent tasks. EEG was recorded during rest state and preconditioning state and analyzed based on power spectrum and sLORETA data. Our results show an essential role of preconditioning alpha-2 EEG subband in creative thinking performance. The originality of the task solution correlates with the activity of L-FPN structures, while DMN activity does not differ significantly between the two groups.

Keywords: *creativity, divergent thinking, rest state, preconditioning, EEG, default-mode network, latera-frontoparietal network, inner speech.*

Кузнецов Ілля, Козачук Наталія, Качинська Тетяна, Журавльов Олександр, Журавльова Олена, Раковець Оксана. Внутрішня мова як механізм налаштування мозкових процесів на інтелектуальну творчість.

Анотація. Сучасні дослідження креативності характеризує велике різноманіття психологічних та нейрофізіологічних підходів та методів, які використовують дослідники. Утім, вивчення ролі вербальних процесів, насамперед, внутрішнього мовлення, залишається мало представленою в галузі досліджень креативності. Сучасні публікації вказують на гетерогенність механізмів внутрішнього мовлення залучених до креативного мислення. Так,

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вербалізовані думки, які контролюються свідомо, асоціюються з активністю мозкових мереж, орієнтованих на завдання (task-dependent brain networks, TPN), насамперед, латерально-фронтопарієтальної мережі (L-FPN). Виникнення мимовільних думок корелює із активністю мереж пасивного режими роботи мозку (default-mode network, DMN). Якщо активність DMN призводить до збільшення кількості креативних ідей, активність L-FPN проявляється у меншій кількості креативних ідей, але при цьому підвищує оригінальність ідей. З цього погляду, викликає значну увагу стан спокою та стан підготовки до виконання завдання, коли виникнення мимовільних думок чергується із виникненням контрольованих думок. У нашому дослідженні взяло участь 49 осіб, які спочатку знаходились в стані спокою та стані підготовки до виконання завдання, а потім вирішували дивергентні завдання. Усі учасники в подальшому було поділено на дві групи, з високим та низьким рівнем креативності, залежно від ефективності виконання дивергентного завдання. ЕЕГ реєстрували протягом стану спокою та стану підготовки до виконання завдання, а потім аналізували із визначенням показників спектральної потужності ЕЕГ та активності структур мозку за методикою sLORETA. Наші результати показують важливий зв'язок показників альфа-2 піддіапазону ЕЕГ під час підготовки до виконання завдання із показниками креативності. За даними sLORETA, оригінальність розв'язання завдання корелює із активністю структур L-FPN, а активність DMN не має достовірних відмінностей між групами з різним рівнем креативності.

Ключові слова: *креативність, дивергентне мислення, стан спокою, підготовка до виконання завдання, ЕЕГ, мережа пасивного режиму роботи мозку, латерально-фронтопарієтальна мережа, внутрішня мова.*

Introduction

Current state of neuroscience of creativity is characterized by the complexity of approaches used in this area (Benedek et al., 2011; Fink et al., 2009; Fink & Benedek, 2014; Gruzelier, 2014; Guilford, 1982; Luo & Knoblich, 2007). Even advanced neurovisualization methods are limited in identifying subtle neural mechanisms associated with divergent thinking. Hence, studying brain electrical activity under specific creativity-related conditions is a promising approach for detecting associated neural processes. We suppose that inner speech, as an integral component of thinking, can be the mechanism that preconditions brain for fruitful creative process.

Existing studies show the heterogeneity of inner speech processes involved in the implementation of creative thinking. Critical thinking has been shown to lead to decrease in creativity (Hirsch et al., 2015; Rooij, 2022). The results of the studies on the influence of monological or dialogical inner speech on convergent and divergent thinking are contradictory, implying no specific correlation between the type of inner speech and creativity (Rooij, 2022). At the same time, neuroimaging studies show the difference between voluntary verbal thoughts and spontaneous mind-wandering speech (Perrone-Bertolotti et al., 2014). Voluntary verbal thoughts associated with the activity of task-positive networks (TPN) do not correlate with the results of creativity tests. However, default-mode network (DMN) may play important role in the creativity-related mind wandering and episodic memory activity (Kim, 2010;

Wirth et al., 2011). The data from episodic memory are further processed in semantic memory (Ramey & Zabelina, 2021; Thakral et al., 2020, 2021) implying that DMN activation during divergent thinking is correlated with the processes of episodic memory involving spontaneous mind-wandering speech. The latter is a condition for the further activation of various TPNs involving semantic memory and mechanisms of controlled inner speech. Analysis of EEG microstates confirms the idea of DMN activation during idea generation, while self-controlled speech is related to idea evaluation stage and relies on the control network activity (CN, also known as the lateral-frontoparietal network, L-FPN) (Beaty et al., 2016; Jia & Zeng, 2021; Wu et al., 2020).

Of particular interest is the role salience brain network regions (bilateral insula). These areas are involved in brain function of switching between DMN and TPN. Bilateral insula activity strongly correlates with the divergent task performance (Beaty et al., 2015). Another explanation for the insula activity is supporting intensified idea generation by both the CN and the DMN (Heinonen et al., 2016). There’s an active discussion regarding whether inner speech is a manifestation of metacognitive control, consuming brain resources during problem-solving, decreasing the intensity of decision-making, filtering out extra solutions, and decreasing the divergent tasks productivity (Perrone-Bertolotti et al., 2014; Vicente & Manrique, 2011). This metacognitive control is associated with the simultaneous activation of the dorsolateral prefrontal cortex (dlPFC) and temporal cortex speech centers (Perrone-Bertolotti et al., 2014; Shi et al., 2019). Wu and colleagues (Wu et al., 2015) suggest that left dlPFC activity is associated with the selection of loosely and distantly related concepts and their organization into creative ideas; in turn, anterior cingulate cortex (ACC) activity is associated with tracking and forming distant semantic associations when solving divergent tasks. Another brain area showing high involvement in creative process is the left inferior frontal gyrus (IFG), which increased activity is associated with more flexible semantic associative networks in highly creative subjects (Cogdell-Brooke et al., 2020; Perrone-Bertolotti et al., 2014; Shi et al., 2019). Another significant IFG function may also be supporting metacontrol processes (Zhang et al., 2020).

Different modalities information integration is crucial for generating creative ideas, and language may be considered a method of such integration (Benedek et al., 2011; Carruthers, 2002; 2006; Fink et al., 2009; Spelke, 2003; Wu et al., 2015). Our previous studies showed that the level of integration of activity in the frontal cortex positively correlates with the divergent thinking originality (Kotsan et al., 2016).

Interestingly, inner speech is associated with a stronger lateralization of brain activity compared to external speech condition. Furthermore, the activity in the cerebellum structures related to the process of generating ideas, mainly during visual divergent thinking tasks (Cogdell-Brooke et al., 2020; Gao et al., 2020; Heinonen et al., 2016).

Summing up, the literature analysis shows an active but different role of inner-speech-related brain networks in creative thinking. The activity of DMN is necessary for processes of spontaneous inner speech for making remote associations. This results in the increase of the number of ideas during divergent task. In turn, the activity of the L-FPN leads to more controlled inner speech process, allowing selection and rearrangement of weakly associated ideas, increasing the originality during divergent task. Stronger inner control lowers the number of generated ideas. Finally, insula-guided switching between DMN and L-FPN, results in the flexibility of associative thinking and higher originality.

Based on the literature data, we proposed the following working hypotheses.

Working hypothesis 1. During both the resting state and preparing to mental activity, brain regions associated with the inner speech will be more active in individuals with higher divergent task productivity.

Working hypothesis 2. During the resting state DMN speech-associated regions will show higher activity in subjects with high productivity.

Working hypothesis 3. During the state of preparing to mental activity, the L-FPN speech-associated regions, will show higher activity in high-productivity subjects.

Working hypothesis 4. The main differences in the activity of speech-related brain regions will be observed in the alpha-3 EEG subband.

Method

49 females aged 18-21 years took part in the study. The study was conducted in accordance with generally accepted bioethical standards in compliance with the relevant international regulations for conducting experimental and clinical studies. All participants gave their voluntary written consent to participate in the study. All subjects participated in the study during the follicular phase of the menstrual cycle. Subjects were divided into two groups based on the results of the creative thinking test: subjects with high (29 subjects) and low (20 subjects) productivity of creative thinking.

The divergent type task was selected from the testbook (Altshuller, 2008) by a group of independent experts: "13 million date palms are growing in Bangladesh. During the season, each palm tree can produce 240 liters of juice, from which palm sugar is then made. But to collect this juice, one has to make an incision on the stem under the crown at a height of 20 m. Suggest as many ways as possible to make this incision." The task text was presented on the computer monitor. Each task was given 2 minutes to complete. Tasks were performed mentally. Solutions were registered at the end of EEG acquisition. No instruction for originality was given. The number of suggested responses indicated performance level. The 25th and 75th persentiles were determined for all subjects as typical performance (2-3 responses). The number of responses, lower or higher than these limits were rated as low and high performance, respectively.

Brain electrical activity was registered for 3 conditions: eyes closed rest-state, eyes open, preparing for mental activity with eyes open.

EEGs were registered in the laboratory of aging neurophysiology of Lesya Ukrainka Eastern European National University, Ukraine. The subject was sitting at a distance of 1.5 m from the stimuli-presenting computer monitor. EEGs were registered using 19 active monopolar electrodes positioned according to the 10/20 system using "Neurocom" EEG equipment. Linked ear electrodes were used as reference. EEG intervals of 60 seconds per condition were recorded. The sampling rate was 500 Hz; the input impedance for the common – mode signal was more than 100 Mohm. High-pass filters were set to .1 Hz, low-pass – to 50 Hz. The ICA analysis procedure was used to detect EEG artifacts, the artifact ICA components were rejected and non-artifact ICA components were used for resulting EEG composition. In case when artifact activity could not be filtered out using ICA processing, the artifact EEG segments were rejected manually.

Spectral power (μV^2) was calculated using the discrete Fast Fourier Transform for the following frequency ranges: Δ, θ, $\alpha 1$, $\alpha 2$, $\alpha 3$, β, γ.

The frequency boundaries were determined based on the individual frequency of the α-rhythm of each subject (Klimesch, 2012) using the following principle: the lower limit of alpha-1 is the value of the individual frequency minus 4, the upper limit of alpha-1 is the individual frequency minus 2; the upper limit of alpha-3 is the individual frequency plus 2. Resulting boundaries were used as the upper for theta rhythm boundary and lower beta rhythm boundary correspondingly.

Analysis of the EEG activity sources was implemented using LORETA-KEY software, sLORETA mode (Pascual-Marqui et al., 2011). Complete EEG recordings with previously rejected artifacts were analyzed. Activity analysis and analysis of statistically significant differences were performed using the LORETA-KEY built-in methods, for 5 EEG bands – theta, alpha-1, alpha-2, alpha-3, and beta, with the boundaries based on standard LORETA-KEY settings.

The significance of intra-group differences was calculated using the Student's t-test (in the case of normal distribution), the Wilcoxon test (in the case of non-normal distribution); inter-group differences were calculated using the Student's t-test and the Mann-Whitney test, $p \leq .05$ as significance level. Power analysis was performed for the following conditions: analysis type – post-hoc for the average differences for two independent groups, two-tailed, effect value = .5 (average level), alpha – .05. The level of statistical significance of the t-test for selected conditions was 2.01 with a test power of .4. Statistical processing and graphical design of the obtained data was conducted using the following software: "Microsoft Office Excel 2003", "Statistica-5.5", "GPower 3.1", "CorelDRAW X3".

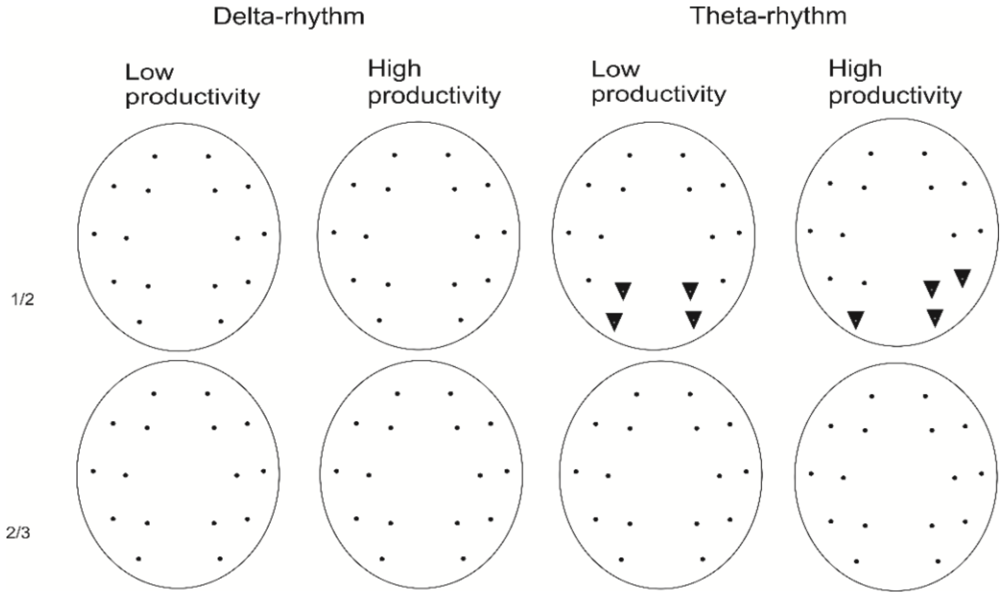
At the end of the experiment, all subjects participated in the survey reporting the way they prepared for mental activity. Subjects reported that they tried to calm down, thought about something pleasant, imagined possible future tasks, recalled numbers and dates, and so on. Thus, subjects were focused on their inner thoughts, implying their mental activity contained inner speech.

Analysis of the EEG Spectrum Indices

Analysis of obtained results for low-frequency EEG showed no statistically significant (Figure 1).

Figure 1

Changes (p<.05) in EEG Power in the Delta and Theta Frequency Ranges in Study Groups



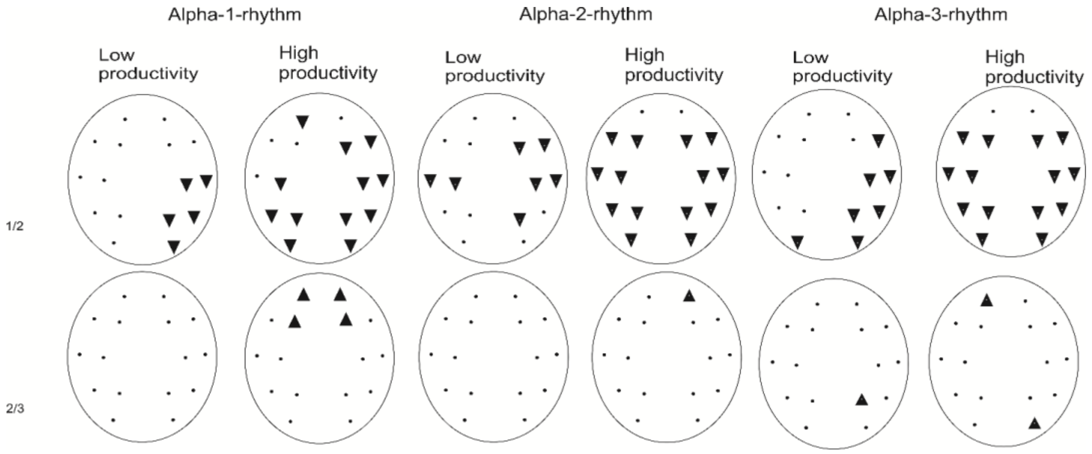
1/2 – changes in the eyes open rest state compared to eyes closed rest state, 2/3 – changes in the mental activity preconditioning state compared to the eyes open rest state. A top-directed triangle indicates an increase of the EEG range power, bottom-directed triangle indicates a decrease.

In the EEG alpha-range, different levels of cortical activation were observed as response to the open eyes condition in studied groups. In the high-level creative productivity group, a decrease in the power of Alpha-1,2,3-rhythms was widely distributed over the scalp. In the low creative productivity group, the decrease in EEG power was expressed mainly in the right hemisphere.

As for statistically significant changes in EEG power during mental activity preconditioning compared to open eyes rest state, they were sparse and more expressed in the high creative productivity group. The most significant changes were observed in the alpha-1 range. During mental activity preconditioning, an increase in the EEG power was observed in the frontal anterior and frontal posterior sites of both hemispheres (Figure 2).

Figure 2

Changes (p<.05) in EEG Power in the Alpha Frequency Sub-ranges in Study Groups

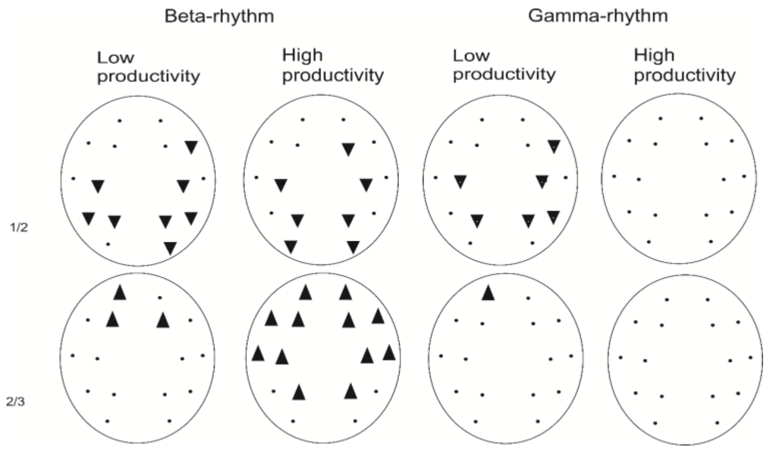


1/2 – changes in the eyes open rest state compared to eyes closed rest state, 2/3 – changes in the mental activity preconditioning state compared to the eyes open rest state. A top-directed triangle indicates an increase of the EEG range power, bottom-directed triangle indicates a decrease.

In the EEG beta-range the high creative productivity group showed the increase in the EEG power in all areas except for the posterior temporal and occipital regions. The low level productivity group showed the increase of gamma-range spectral power in both the posterior-frontal regions of the cortex and the left anterior-frontal region (Figure 3).

Figure 3

Changes (p<.05) in EEG Power in the EEG Beta and Gamma Frequency Ranges in Study Groups



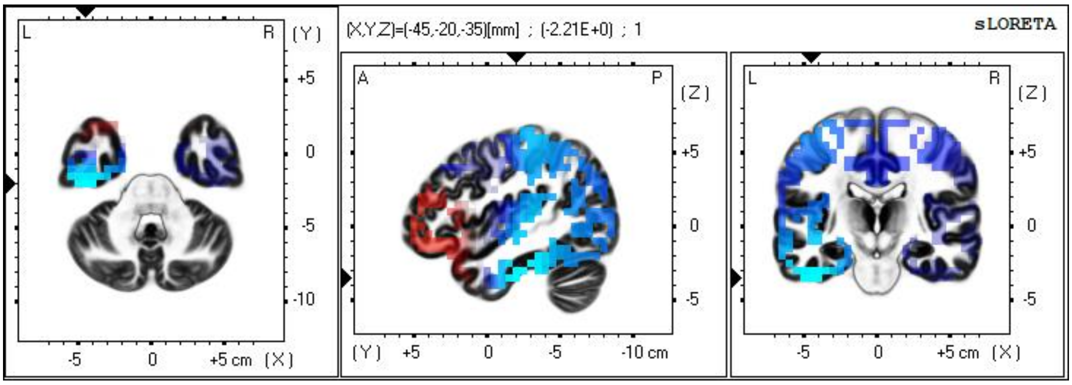
1/2 – changes in the eyes open rest state compared to eyes closed rest state, 2/3 – changes in the mental activity preconditioning state compared to the eyes open rest state. A top-directed triangle indicates an increase of the EEG range power, bottom-directed triangle indicates a decrease

Analysis of the Brain Electrical Activity Sources

Analysis of the EEG sources during rest state showed that main differences between the groups are expressed in alpha-1 EEG range. Subjects with low productivity have higher brain activity in the lower left temporal region, Brodmann field 20 (Figure 4).

Figure 4

Differences in the Level of Brain Structures Activity Between Study Groups in the Alpha-1 EEG Sub-Band During Eyes Closed Rest State

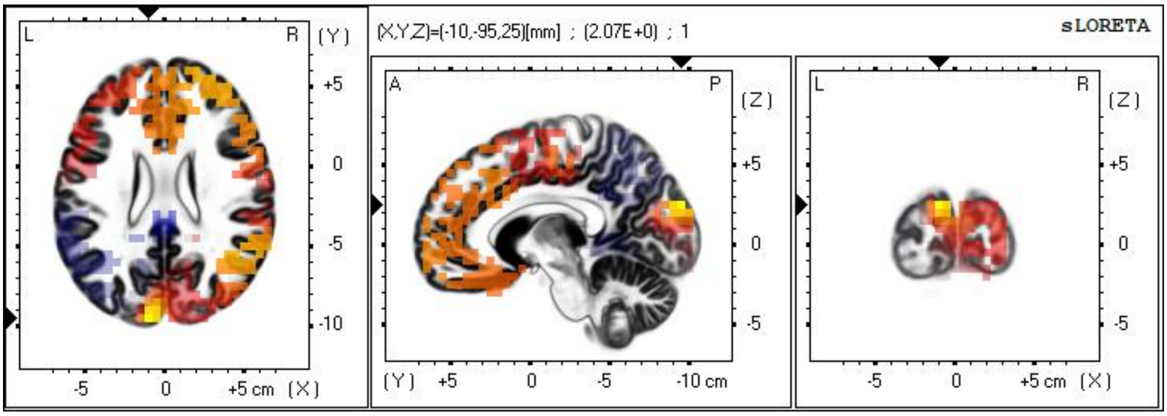


t = 2.21, red indicates higher activity in the group with high performance level, blue- in the group with a low performance level

During mental activity preconditioning, the main differences between the studied groups are observed in the theta range. Higher brain activity in the left cuneus area was registered specific for high creative productivity group (Figure 5).

Figure 5

Differences in the Level of Brain Structures Activity Between Study Groups in the Theta EEG Band During Mental Activity Preconditioning State

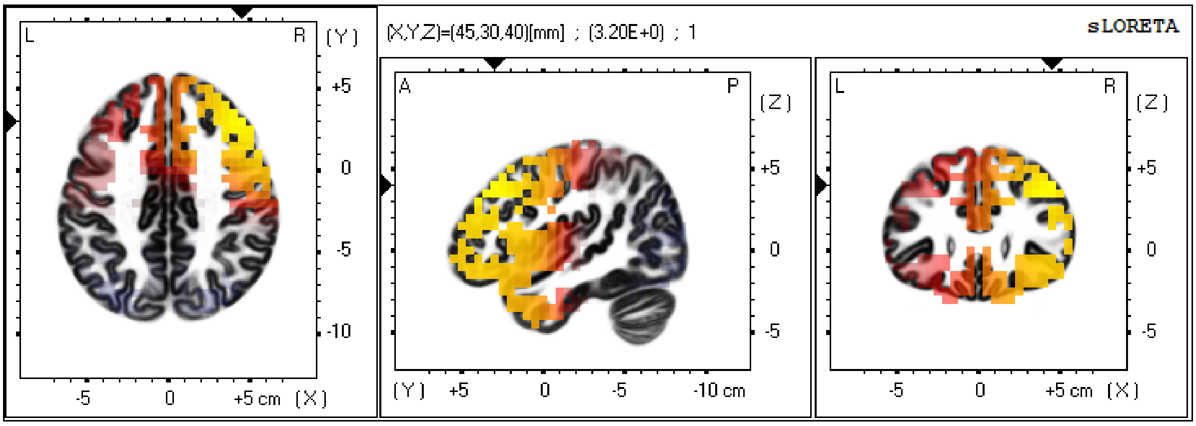


in the group with a low performance level

During mental activity preconditioning, a higher level of brain cortex activity in the EEG alpha-1 sub-band was shown for high creative productivity group in the right middle frontal gyrus (Figure 6).

Figure 6

Differences in the Level of Brain Structures Activity Between Study Groups in the EEG Alpha-1 Sub-Band During Mental Activity Preconditioning

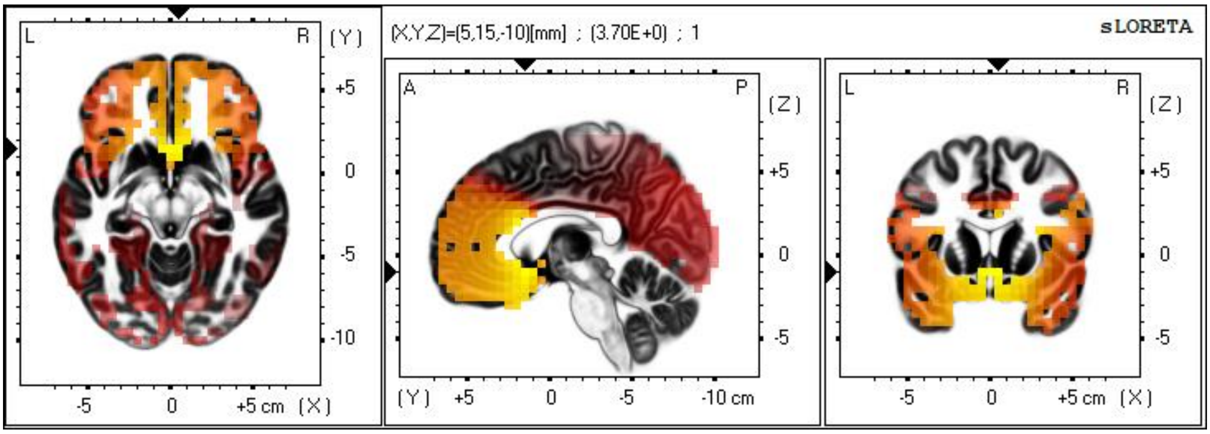


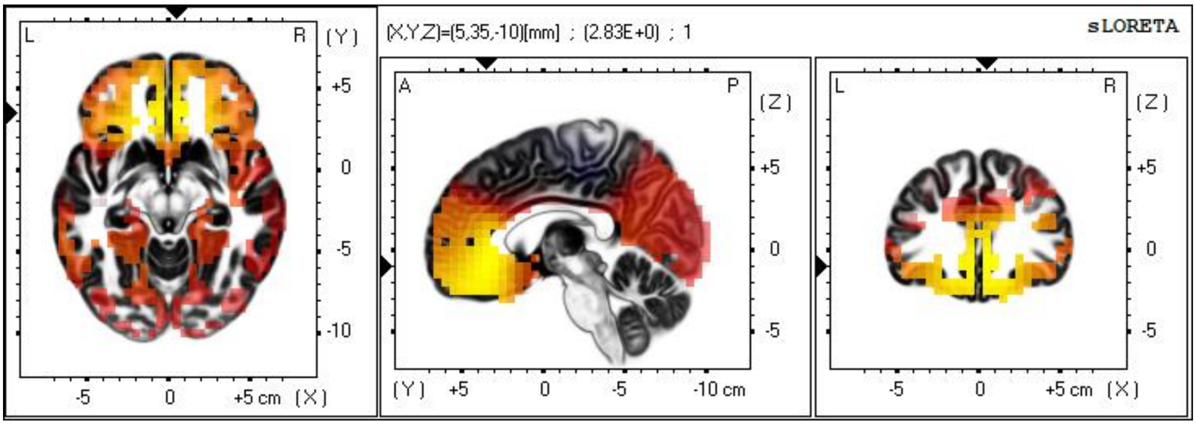
t = 3.2, red indicates higher activity in the group with high performance level, blue-in the group with a low performance level

In the alpha-2 and alpha-3 EEG sub-bands, higher levels of brain cortex activity were recorded in high-productivity subjects in the anterior cingulate gyrus bilaterally (Figure 7).

Figure 7

Differences in the Brain Structures Activity Between Study Groups in Alpha-2 (Top) and Alpha-3 (Bottom) EEG Sub-Bands During Mental Activity Preconditioning



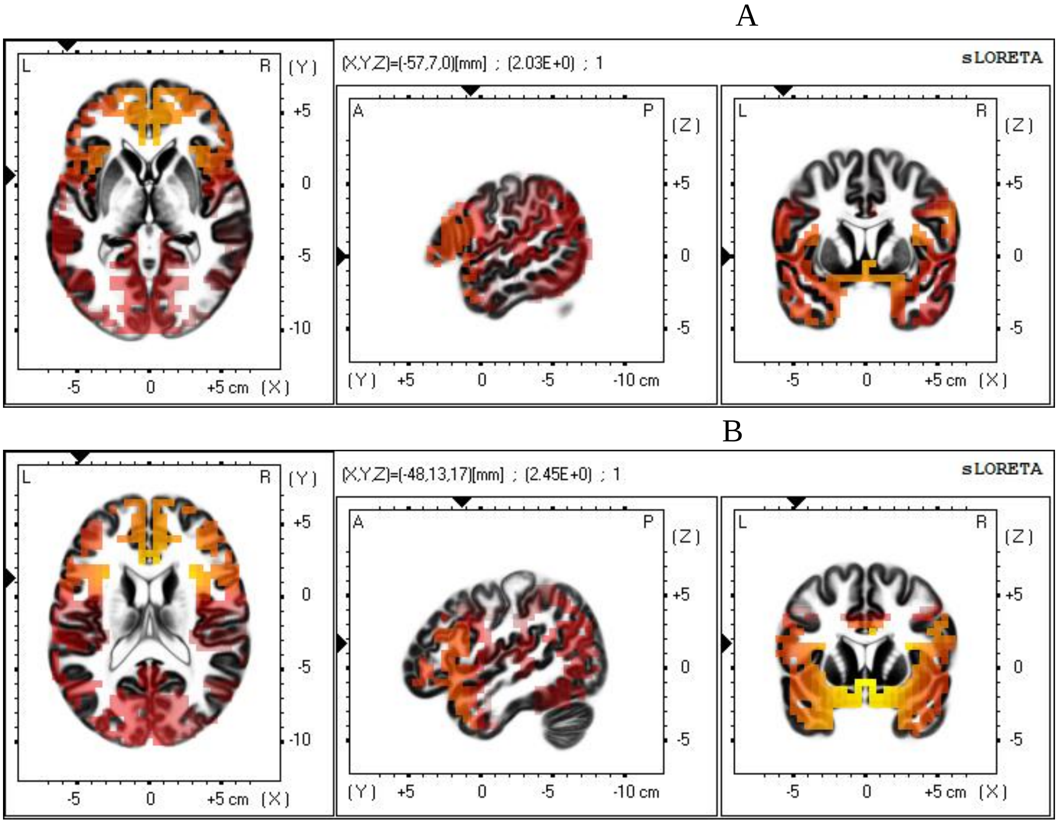


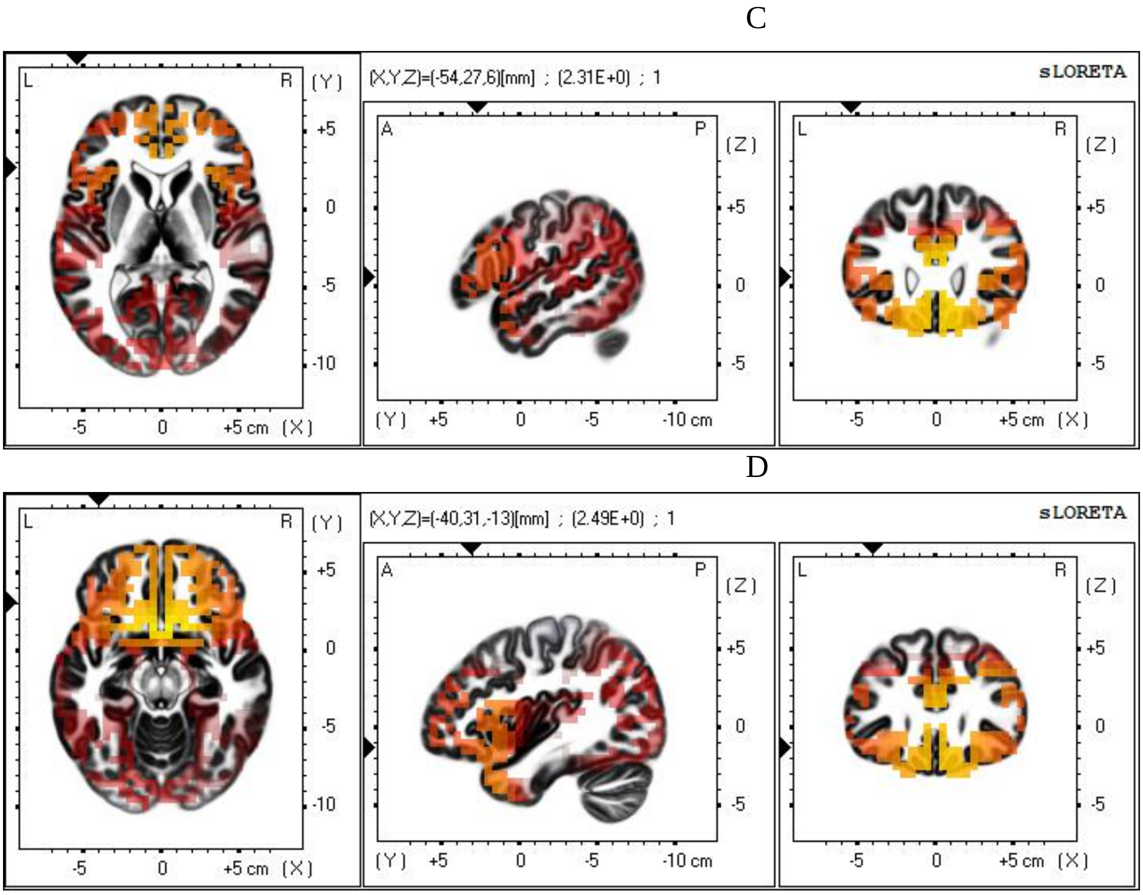
t = 3.7, red indicates higher activity in the group with high performance level, blue-in the group with a low performance level

According to the existing literature data, the main brain regions supporting inner speech processes are: 22 (Wernicke's), 44, 45 (Broca's), 44, 45, 47 (IFG), 40 (supramarginal gyrus, SMG) Brodmann areas (Li et al., 2020; Perrone-Bertolotti et al., 2014). Analysis of brain activity differences showed the higher activity of these areas being specific for the high-performance subjects (Figure 8). A higher level of activity is typical for this group in the alpha-2 EEG sub-band in Brodmann areas 22 (t = 3.7), 44 (t = 2.45), 45 (t = 2.31), 47 (t = 2.49).

Figure 8

Differences in the Activity Level of Brodmann Areas 22 (A, t = 3.7), 44 (B, t = 2.45), 45 (C, t = 2.31), 47 (D, T = 2.49) Between Study Groups in the Alpha-2 EEG Sub-bands During Mental Activity Preconditioning

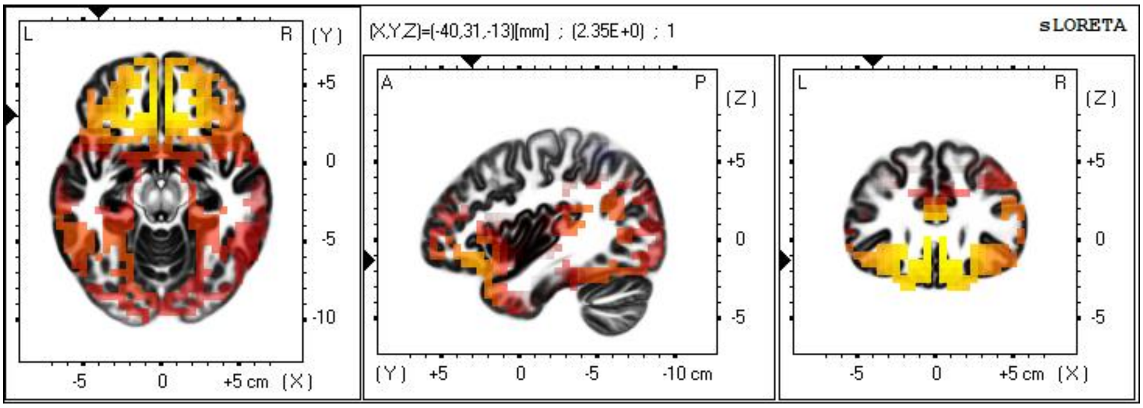




Red indicates higher activity in the group with high performance level, blue-in the group with a low performance level.

During mental activity preconditioning, high-productivity subjects have higher activity of Brodmann 47 area in the alpha-3 EEG sub-band (Figure 9, t = 2.35).

Figure 9
Differences in the Activity of Brodmann 47 Area Between Study Groups in the Alpha-3 EEG Sub-Band During Mental Activity Preconditioning



Red indicates higher activity in the group with high performance level, blue-in the group with a low performance level.

Discussion

In general, the analysis of brain cortex activity shows that the spectral features of the EEG alpha-2 and alpha-3 sub-bands are functionally related to the divergent problem solving performance. First, the brain activity changes while transitioning from rest state to mental activity preconditioning state are similar for these two sub-bands. Group differences in the activation of the anterior cingulate gyrus during mental activity preconditioning are observed in both the alpha-2 and alpha-3 EEG sub-bands. For alpha-1 sub-band, the structures of the middle frontal gyrus are most sensitive to group differences. These results contradict the ideas about the functional role of alpha rhythm sub-bands proposed by Klimesh and co-authors. According to Klimesh (Klimesch, 2012; Klimesch et al., 2007), alpha-1 and alpha-2 sub-bands are associated with the activity of the attention system, while alpha-3 sub-band is considered being sensitive to the processing of semantic information from long-term memory. Since Klimesh interpretation is considered generally accepted and confirmed in other studies (Chikhi et al., 2022), we assume that the evidence we obtained about the functional unity of alpha-2 and alpha-3 EEG sub-bands can be explained by the following reasons: 1) we analyzed complete EEG records, and not spectral changes in EEG areas associated with stimulus onset; 2) we analyzed EEG indices in the absence of external stimulation; 3) our study is focused on analyzing integral indices instead of direct effects. However, the type of differences in the studied groups, especially during mental activity preconditioning, clearly indicates the activation of inner-speech-associated processes, confirmed by self-reports and by prominent alpha-2 EEG sub-band sensitivity to these processes. Accordingly, a less controlled process of inner speech without involving external stimulation is implemented by brain structures activity in the alpha-2 subband. The response to external stimuli, which requires more control of both sensory and associative parts of the brain cortex, results in either switching the same structures to operation at the frequency of alpha-3 sub-band, or in masking their activity by the activity of other brain areas in the alpha-3 sub-band. Indirect first evidence in favor of the latter mechanism is a small number of between-groups differences in the sources of brain activity in the alpha-3 EEG subband. The second indirect evidence is the same type of changes in the beta EEG band during the transition from eyes closed rest state to the state of mental activity preconditioning.

Regarding the role of brain networks in the implementation of inner speech processes, the increased activity of the anterior cingulate gyrus and lower frontal gyrus in the high productivity group should be noted. These structures are considered to be a part of L-FPN and their role in inner speech processes is associated with the activation and involvement of distant associations (Cogdell-Brooke et al., 2020; Perrone-Bertolotti et al., 2014; Shi et al., 2019; Wu et al., 2015; Zhang et al., 2020). Thus, a more effective solution of a divergent problem can be associated with a controlled use of long-term semantic memory, reflected in the EEG parameters during mental activity preconditioning stage. On the other side, subjects with a high level of productivity may be more motivated and more responsible in completing the tasks. Interestingly, the structures associated with DMN do not show differences in brain activity between the study groups. In our opinion, this can be explained by low number of subjects with very high indicators of divergent thinking productivity and originality. In this case, an increase in the level of originality and productivity could be implemented at the expenses of either existing specific experience (Beaty et al., 2016; Madore et al., 2016; Schacter & Madore, 2016) or additional attention to external stimulation (Bitu et al., 2022; Salvi et al., 2016). However, the activity of DMN-related cuneus structures in the theta range was higher in high-productivity group during mental activity preconditioning, probably indicating the involvement of involuntary imagination in creative thinking (Beaty et al., 2015; Heinonen et al., 2016; Wu et al., 2015).

Summing up, the divergent thinking originality feature is highly independent of productivity. The divergent thinking performance depends on the level of inner control of mental processes and on the inner speech type (controlled or spontaneous). The interaction between originality and productivity can be separated into following cases, based on the specific neural mechanisms:

1. High productivity and low originality result from significant inner control of mental processes, supported by L-FPN activity, controlled inner speech, and active usage of semantic memory.
2. High productivity and high originality result from weak inner control, DMN activation, intensive usage of episodic memory and spontaneous, non-controlled inner speech.
3. Finally, low productivity and low originality are observed when L-FPN is active and supports strong inner control, controlled search of distant associations in memory.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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