



# EEG alpha synchronization is related to top-down processing in convergent and divergent thinking

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## ABSTRACT

Synchronization of EEG alpha activity has been referred to as being indicative of cortical idling, but according to more recent evidence it has also been associated with active internal processing and creative thinking. The main objective of this study was to investigate to what extent EEG alpha synchronization is related to internal processing demands and to specific cognitive process involved in creative thinking. To this end, EEG was measured during a convergent and a divergent thinking task (i.e., creativity-related task) which once were processed involving low and once involving high internal processing demands. High internal processing demands were established by masking the stimulus (after encoding) and thus preventing further bottom-up processing. Frontal alpha synchronization was observed during convergent and divergent thinking only under exclusive top-down control (high internal processing demands), but not when bottom-up processing was allowed (low internal processing demands). We conclude that frontal alpha synchronization is related to top-down control rather than to specific creativity-related cognitive processes. Frontal alpha synchronization, which has been observed in a variety of different creativity tasks, thus may not reflect a brain state that is specific for creative cognition but can probably be attributed to high internal processing demands which are typically involved in creative thinking.

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## 1. Introduction

Changes of activity in different EEG frequency bands have long been observed to reflect various aspects of cognitive activity (e.g. Neuper & Klimesch, 2006). In periods of rest, EEG frequencies in the range of the alpha band (usually defined in the range of about 8–12 Hz) become dominant in the EEG spectrum. This phenomenon of increased alpha power has been labeled synchronization of EEG. In contrast, during tasks involving cognitive demands the power in the alpha band usually decreases, often in return of increases of other frequencies in the EEG spectrum. In contrast to synchronization, this phenomenon is called desynchronization of the EEG. This clear and robust relationship led to the widely accepted notion that EEG desynchronization serves as an indicator of cortical activity or arousal. The amount of event-related (de-)synchronization (ERD/S) or change in task-related power (TRP) is usually assessed by contrasting the alpha power during a cognitive task with a preceding reference interval (this reference interval is commonly realized by requesting participants to simply keep looking at a fixation cross or point). The terms “event-” or “task-related” thus suggest that brain activity in response to a particular event (e.g., performance of

a cognitive task) is related to brain activity during a pre-stimulus reference interval during which no task is performed (Neuper & Klimesch, 2006; Pfurtscheller & Aranibar, 1977; Pfurtscheller & Lopes da Silva, 2005).

To date, the ERD/S method has been employed in a variety of studies covering a broad range of different cognitive task demands (for reviews see Klimesch, 1999; Klimesch, Sauseng, & Hanslmayr, 2007; Neuper & Klimesch, 2006). For instance, Jaušovec, Jaušovec, and Gerlič (2006) measured ERD during spatial rotation, Karrasch, Krause, Laine, Lang, and Lehto (1998) during the performance of auditory lexical matching tasks, or Bastiaansen and Hagoort (2006) investigated ERD effects during language processing or comprehension. In other studies the ERD/S method was applied to the study of visual information processing (Pfurtscheller, Neuper, & Mohl, 1994), reasoning (Fink & Neubauer, 2004; Neubauer & Fink, 2003), or in the context of memory processing (Doppelmayr, Klimesch, Hödlmoser, Sauseng, & Gruber, 2005; Grabner, Fink, Stipacek, Neuper, & Neubauer, 2004; Krause, Sillanmäki, Häggqvist, & Heino, 2001). It appears to be particularly worth mentioning that ERD measures display re-test reliability and internal consistency of about .80 (cf. Burgess & Gruzelier, 1996; Neuper, Grabner, Fink, & Neubauer, 2005), which indicates “excellent” reliability according to common biostatistical classifications (Cicchetti & Sparrow, 1981), and therewith substantiates their valuable role in the context of

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neuroscientific research on individual differences (Neubauer, Fink, & Grabner).

Research using ERD/S revealed evidence that different patterns of alpha desynchronization can be observed when the broad alpha frequency band is subdivided into different alpha sub-bands. These sub-bands commonly comprise one or two lower-alpha bands and an upper alpha band, each with a more constrained frequency range of about 2 Hz. This procedure has been established by Klimesch and colleagues' extensive work in this research field which is comprehensively described in Klimesch (1999). Klimesch and colleagues found evidence that the lower alpha ERD is more likely to reflect general task demands such as attentional processes (basic alertness, vigilance, or arousal), whereas ERD in the upper alpha band has been observed to reflect specific task requirements (e.g., semantic memory processes; see e.g., Doppelmayr, Klimesch, Stadler, Pöllhuber, & Heine, 2002; Doppelmayr et al., 2005; Klimesch, Doppelmayr, Röhm, Pöllhuber, & Stadler, 2000; for review see Klimesch, 1999). Similarly, the upper alpha frequency band turned out to be most sensitive to intelligence-related demands (see Doppelmayr et al., 2002; Grabner et al., 2004; Grabner, Neubauer, & Stern, 2006; Neubauer & Fink, 2003; Neubauer & Fink, 2009; Neubauer, Fink, & Schrausser, 2002; Neubauer, Grabner, Fink, & Neuper, 2005).

As outlined in Neuper and Pfurtscheller (2001), the ERD of EEG activity in the alpha band presumably reflects an increased excitability level of neurons in the involved cortical areas, which could be related to an enhanced information transfer in thalamo-cortical circuits (see also Pfurtscheller & Lopes da Silva, 2005). In contrast, event-related synchronization (ERS) of alpha activity (i.e., increases in alpha activity from the pre-stimulus reference to the task performance interval) is thought to reflect a reduced state of active information processing in the underlying neuronal networks (Pfurtscheller & Lopes da Silva, 2005) or 'cortical idling' (Pfurtscheller, 1999; Pfurtscheller, Stancak, & Neuper, 1996). However, recent evidence in this field of research also suggests that synchronization of alpha activity can be viewed as a functional correlate of active cognitive task performance presumably involving cognitive inhibition processes (for a review see Klimesch et al., 2007). Contrary to the usual finding that alpha power decreases when individuals become engaged in the performance of cognitively demanding tasks, Klimesch, Doppelmayr, Schwaiger, Auinger, and Winkler (1999) reported a 'paradoxical' synchronization of alpha activity during the retention period in a short term memory task. Moreover, the amount of alpha activity has been shown to increase with memory load (Jensen, Gelfand, Kounios, & Lisman, 2002) and during manipulation of memory content as compared to simple retention of information (Sauseng et al., 2005). Cooper, Croft, Dominey, Burgess, and Gruzelier (2003) showed that alpha synchronization is also related to internally versus externally directed attention. They presented sequences of stimuli in the visual, acoustic and haptic domain and then trained participants to imagine these stimulus sequences. They found that alpha activity was consistently higher during the imagination of stimulus sequences (i.e., internally directed attention) than during their presentation (i.e., externally directed attention). In these studies the observed synchronization of alpha activity has been interpreted to reflect selective inhibition of task irrelevant brain areas or inhibition of interfering external input (Klimesch et al., 2000, 2007; Rihs, Michel, & Thut, 2007), and to reflect internal information processing involving top-down control on internally represented information (e.g., Sauseng et al., 2005; Von Stein & Sarnthein, 2000).

EEG alpha activity has also been found to be sensitive to creative cognition in a series of studies employing a variety of methodological approaches (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Fink, Benedek, Grabner, Staudt, & Neubauer, 2007). These studies include the investigation of ERD/S

in divergent thinking tasks (i.e., task commonly employed in the assessment of creativity), which require participants to generate many original ideas to open problems (e.g., a typical example is the alternate uses task, which asks to think of many unusual uses of everyday objects such as a brick). Taken together, there is evidence that alpha synchronization especially in frontal and posterior parietal brain regions of the right hemisphere is related to (1) creative task demands (more creativity-related tasks are accompanied by more alpha activity than convergent or intelligence-related tasks; e.g., Fink et al., 2007; Jaušovec, 2000; Jaušovec & Jaušovec, 2000; Martindale & Hasenfus, 1978; Razumnikova, 2000), (2) inter-individual level of creativity (more creative individuals show higher alpha activity; e.g. Fink, Grabner, et al., 2009; Fink, Graif, & Neubauer, 2009; Jaušovec, 2000; Martindale & Hines, 1975), (3) originality of ideas (the generation of more original ideas is accompanied by higher alpha activity; Fink & Neubauer, 2006, 2008; Grabner, Fink, & Neubauer, 2007), (4) the subjective experience of insight (more alpha activity in insight vs. non-insight solutions; Jung-Beeman et al., 2004; Sandkühler & Bhattacharya, 2008; see also Bowden, Jung-Beeman, Fleck, & Kounios, 2005), and (5) to training and stimulation of creativity (enhancement of creativity is related to higher alpha activity; Fink, Grabner, Benedek, & Neubauer, 2006; Fink, Schwab, & Papousek, in press-b). These alpha effects associated with creativity were sometimes interpreted in terms of low cortical arousal reflecting states of defocused attention and highly associative thinking (Martindale, 1999). Another line of interpretation stresses that alpha synchronization during creative task performance probably indicates high internal processing demands and states of heightened internal attention facilitating the (re-)combination of distantly related semantic information (e.g. Fink et al., 2007; Fink, Grabner, et al., 2009; Fink, Graif, et al., 2009).

The available evidence on alpha synchronization during active cognitive task performance can thus suggest that alpha synchronization generally reflects high internal processing demands; or, in considering the extensive evidence on alpha synchronization and creativity, it could also be assumed that alpha synchronization indicates cognitive or neural processes specifically related to creative cognition. As these two conceptions may not be fully unrelated, the present study addressed the research question to what extent alpha synchronization is related either to internal processing demands in general and/or specifically to creative (or divergent) thinking. To this end, a convergent and a divergent task were adopted, which had to be completed either involving low internal processing demands (i.e., requiring bottom-up stimulus-driven processing) or involving high internal processing demands (i.e., preventing stimulus-driven processing). Specifically, we presented single meaningful words consisting of four letters each, for which in the convergent task version a correct anagram solution had to be found, and in the divergent task version an original four-word sentence had to be generated using the given characters as initial letters. Pilot tests suggested that these tasks can not only be solved by external bottom-up stimulus processing (i.e., working on the visible stimulus), but also by internal processing (i.e., working on an internal representation of the stimulus). By contrasting these experimental conditions, we would be able to decide whether alpha activity independently increases either with the amount of internal processing demands, or with the amount of creative task demands. This design hence is expected to further elucidate the meaning of EEG alpha synchronization.

## 2. Methods

### 2.1. Participants

36 students (18 female) participated in this study. Due to an insufficient number of valid trials six participants were excluded from further analyses (exclusion criteria are presented below). The final sample thus comprised 30 participants (15 female).

On average, study participants were 21.8 years old ( $SD = 2.64$ ). All participants were right-handed, had normal or corrected-to-normal vision and reported no medical or psychological disorders. Participants gave written informed consent prior to the EEG recording session and were allocated quasi-randomized to the experimental sequences. The procedure was approved by the Ethics Committee of the University of Graz.

## 2.2. Experimental tasks and conditions

A convergent and a divergent thinking task were employed, both of which were presented in two experimental conditions involving either low or high internal processing demands ( $2 \times 2$ -within-subject design). The tasks were based on a stimulus set of 20 meaningful four-character words. In the *convergent* task participants were asked to find an anagram solution of the given stimulus word (e.g., for the stimulus word "POST" the solution would be "STOP"). The word class of the anagram was irrelevant, but participants had to use all four letters exactly once (e.g., "TOP" as solution for "POST" was incorrect). This task can be considered a convergent thinking task as there exists only a limited number of known correct solutions (usually just one per item; Guilford, 1967). In the *divergent* thinking task, participants were required to create an original but meaningful four-word sentence using the given four characters as initial letters (e.g., for the item "POST" a possible response would be "Oliver teaches Portuguese students"). As shown in the example, the order of the initial letters in the sentence could differ from the order of characters in the stimulus word, but every character had to be used exactly once. This task was derived from a well-known German creativity test (VKT, Schoppe, 1975) and can be considered as divergent thinking task since there are nearly unlimited possible solutions for every stimulus (Guilford, 1967).

Both tasks were presented in two experimental conditions: In the low internal processing (LIP) condition, the stimuli were kept visible on screen thus allowing the participants to process the stimulus characters during the entire task in a bottom-up manner. In contrast, in the high internal processing (HIP) condition, stimuli were presented for 500 ms and then masked by "XXXX". This supraliminal stimulus presentation is sufficiently long to allow for encoding of the meaningful stimulus word, but it was found to be too short for solving the task, as shown in a pre-experimental pilot test with 18 students who did not take part in the EEG study. The latter experimental condition is assumed to require comparatively high internal processing demands, as the problem has to be solved without further bottom-up processing of the stimulus. As soon as the participants came up with a response they had to press a button and then were prompted to vocalize the response. Responses were recorded, and after each EEG session transliterated. The timeout duration per trial was set to 30 s (see Fig. 1). Both tasks used exactly the same stimulus set, with half of the items (10 items) being randomly assigned to the LIP and the other half to the HIP condition. The tasks thus did not differ in stimulus complexity.

## 2.3. Data acquisition and analysis

The EEG was recorded by means of a customary EEG amplifier (BrainAmp and Vision Recorder 1.20; Brain Products, Gilching, Germany) and sampled at a frequency of 500 Hz. Gold electrodes (9 mm diameter) were located in an electrode cap in 33 positions (according to the international 10–20 system with interspaced positions), a ground electrode was located on the forehead, the reference electrode was placed on the nose. To register eye movements, an electrooculogram (EOG) was recorded bipolarly between two gold electrodes diagonally placed above and below the inner respectively the outer canthus of the right eye. The EEG signals were filtered between 0.1 Hz and 100 Hz; an additional 50 Hz notch filter was applied to avoid power line contamination. Electrode impedances were kept below 5 k $\Omega$  for the EEG and below 10 k $\Omega$  for the EOG. The EEG signal was corrected for ocular artifacts by means of an automated regression-based method (Gratton, Coles, & Donchin, 1983; Vision Analyzer 1.05, Brain Products, Gilching, Germany), and by means of a subsequent visual inspection of possible remaining artifacts caused by eye blinks, eye movements or muscle tension, which were marked and excluded from further analysis. In a next step, the band power of the EEG signal was computed by means of a time-frequency analysis employing a standard FFT applied to time windows of 1000 ms with 900 ms overlap. From this, the power in the upper alpha frequency band (10.5–12.5 Hz) was extracted; for complementary analyses also the power in the lower alpha band (8.5–10.5 Hz) was computed.

Brain activity during the performance of experimental tasks was quantified by means of task-related power (TRP) changes in the EEG (Pfurtscheller, 1999). Task-related power at an electrode  $i$  was obtained by subtracting the log-transformed power during prestimulus reference intervals ( $Pow_{i,reference}$ ) from the log-transformed power during the activation intervals ( $Pow_{i,activation}$ ) according to the formula:  $TRP(i) = \log(Pow_{i,activation}) - \log(Pow_{i,reference})$ . Therefore, decreases in power from the reference to the activation interval are expressed as negative values (i.e., desynchronization), while task-related increases in power (synchronization) are expressed as positive values. As shown in Fig. 1, a 4-s time interval during presentation of the fixation cross (500–4500 ms after onset of the fixation cross) served as pre-stimulus reference interval for TRP calculation. In both tasks (convergent and divergent) and both experimental conditions (LIP and HIP) the whole time period of idea generation was used as activation interval (from 1000 ms after stimulus onset to 500 ms before the pressing of the idea button; see Fig. 1). By defining the activation

period to start not until 1000 ms after stimulus onset (or 500 ms after stimulus masking in the HIP condition), the TRP is thought to reflect task performance but not initial stimulus encoding. Only trials with correct responses before timeout, and consisting of artifact-free data of more than 500 ms in the reference and the activation periods were included in further analyses. Participants who failed to show a minimum of three valid trials in all tasks and conditions were excluded from the analysis.

For statistical analyses, electrode positions were topographically aggregated as following: anteriofrontal (AF) left (FP1, AF3), frontal (F) left (F3, F7), frontocentral (FC) left (FC1, FC5), centrottemporal (CT) left (C3, T3), centroparietal (CP) left (CP1, CP5), parietotemporal (PT) left (P3, T5), parietooccipital (PO) left (PO3, PO5, O1), and analogously for the right hemisphere. The midline electrodes (FZ, CZ, PZ) were not included in the analyses as we were also interested in hemispheric differences.

## 2.4. Procedure

The participants were seated comfortably in the darkened sound-attenuating EEG recording room, electrodes were mounted and impedances checked. In the beginning of the experiment two 2-min EEG sequences under resting conditions were recorded, the first one with eyes closed, the second one with eyes open. Then the four EEG tasks (convergent and divergent, once in the LIP and once in the HIP condition) were presented. Prior to each task, participants were familiarized with task requirements and response mode by two exercise trials. The presentation of tasks followed a quasi-randomized sequence plan, which varied the order of experimental tasks and conditions but ensured that for each experimental task both experimental conditions were realized one after the other, and that this sequence of experimental conditions was kept constant for both experimental tasks. The EEG session lasted about 1 h in total.

## 3. Results

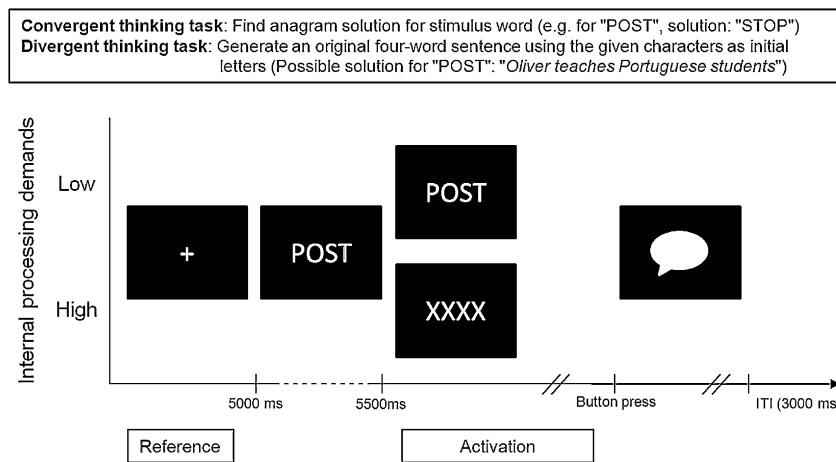
### 3.1. Behavioral results

Task performance was analyzed with respect to the solution rate (i.e., relative amount of correct responses) and the response time (i.e., time until pressing of the idea-button in correct trials) by means of ANOVAs for repeated measures (within-subject factor TASK: convergent vs. divergent, and within-subject factor CONDITION: low vs. high internal processing demands [LIP vs. HIP]). Considering the solution rate, the ANOVA yielded a significant main effect CONDITION ( $F[1,29] = 6.37, p < .05, \text{partial-}\eta^2 = .18$ ) indicating that the solution rate in the LIP condition ( $M = 83.8\%$ ,  $SEM = 1.6\%$ ) was significantly higher than in the HIP condition ( $M = 78.2\%$ ,  $SEM = 2.9\%$ ); there were no significant effects related to TASK. The analysis of response times showed that responses were generally faster in the convergent task ( $M = 8.4$  s,  $SEM = 0.5$  s) than in the divergent task ( $M = 15.9$  s,  $SEM = 0.7$  s; main effect TASK:  $F[1,29] = 123.42, p < .001, \text{partial-}\eta^2 = .81$ ). Moreover, the significant interaction TASK  $\times$  CONDITION ( $F[1,29] = 10.96, p < .01, \text{partial-}\eta^2 = .27$ ) suggested that the response times in the convergent task were shorter under low ( $M = 7.8$  s,  $SEM = 0.5$  s) as compared to high internal processing demands to ( $M = 9.0$  s,  $0.7$  s), while there was an opposite trend in the divergent task ( $M = 16.7$  s,  $SEM = 0.7$  s, and  $M = 15.1$  s,  $SEM = 0.8$  s, for LIP and HIP, respectively).

### 3.2. EEG results

Task-related power (TRP) changes in the upper alpha band were analyzed by means of an ANOVA for repeated measures using the within-subject factors TASK (convergent vs. divergent), CONDITION (LIP vs. HIP), HEMISPHERE (left vs. right) and AREA (anteriofrontal, frontal, frontocentral, centrottemporal, centroparietal, parietotemporal, and parietooccipital). Generally, a multivariate analysis approach (Pillai's trace) was employed which is known to be robust in face of violations of sphericity (Vasey & Thayer, 1987). The probability of a Type I error was maintained at 0.05.

There was a significant effect of AREA ( $F[6,24] = 10.83, p < .001, \text{partial-}\eta^2 = .73$ ), indicating that task-related desynchronization is generally stronger in posterior as compared to frontal brain



**Fig. 1.** Above: Task description of the convergent and divergent thinking task. Below: Trial sequence for the two experimental conditions, where the stimulus once becomes masked after 500 ms (high internal processing demands) and once remains visible throughout the task (low internal processing demands).

areas. A significant  $TASK \times HEMISPHERE$  effect ( $F[1,29] = 5.29$ ,  $p < .05$ ,  $\text{partial-}\eta^2 = .15$ ) suggests that in the convergent task alpha-desynchronization was somewhat lower (or alpha synchronization was higher, respectively) in the left as compared to the right hemisphere.

Most interestingly, there was a highly significant main effect  $CONDITION$  ( $F[1,29] = 26.27$ ,  $p < .001$ ,  $\text{partial-}\eta^2 = .48$ ), revealing generally stronger alpha-synchronization (or lower alpha-desynchronization, respectively) during task performance under high as compared to low internal processing demands (see Fig. 2). This condition effect was found to be significantly moderated by  $AREA$  ( $CONDITION \times AREA$ :  $F[6,24] = 5.02$ ,  $p < .01$ ,  $\text{partial-}\eta^2 = .56$ ), suggesting that the TRP difference between conditions was stronger in parietal and occipital brain areas than in frontal regions of the brain. More specifically, in the LIP condition there was a gradual increase of task-related alpha desynchronization from anterior to posterior brain regions, whereas in the HIP condition alpha synchronization also decreased from anteroventral to frontocentral brain areas but the TRP did not further decrease with increasing posteriority but stayed close to zero in parietal and occipital brain regions. This interaction was further moderated by  $HEMISPHERE$  ( $CONDITION \times AREA \times HEMISPHERE$ :  $F[6,24] = 2.83$ ,  $p < .05$ ,  $\text{partial-}\eta^2 = .41$ ) indicating that the TRP difference between conditions was most pronounced in parietotemporal areas of the right hemisphere. This was especially evident for the divergent thinking task, for which alpha-synchronization was not only observed in frontal but also in right-hemispheric parietotemporal brain regions (see Fig. 2). While the four-way interaction (additionally involving  $TASK$ ), however, failed to reach statistical significance ( $p = .66$ ), a follow-up univariate analysis (Greenhouse-Geisser corrected dfs) per task revealed a significant  $CONDITION \times AREA \times HEMISPHERE$  interaction only for the divergent task ( $F[2.23,64.63] = 7.27$ ,  $p < .001$ ,  $\text{partial-}\eta^2 = .20$ ) but not for the convergent task ( $F[3.17,91.83] = 1.15$ , *ns.*,  $\text{partial-}\eta^2 = .04$ ).

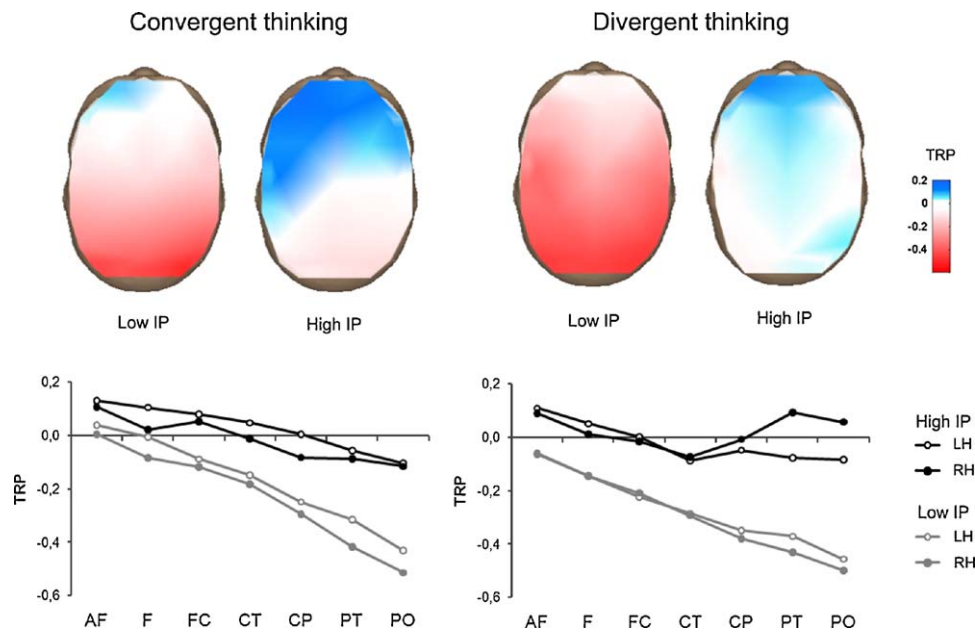
In a complementary analysis, ANOVAs were also performed for the lower alpha band. Results indicate that the major effects obtained for the upper alpha band were largely replicated in the lower alpha band ( $AREA$ :  $F[6,24] = 11.20$ ,  $p < .001$ ,  $\text{partial-}\eta^2 = .74$ ;  $TASK \times HEMISPHERE$ :  $F[1,29] = 8.25$ ,  $p < .01$ ,  $\text{partial-}\eta^2 = .22$ ;  $CONDITION$ :  $F[1,29] = 13.31$ ,  $p < .001$ ,  $\text{partial-}\eta^2 = .32$ ;  $CONDITION \times AREA \times HEMISPHERE$ :  $F[4,26] = 4.45$ ,  $p < .01$ ,  $\text{partial-}\eta^2 = .53$ ; the  $CONDITION \times AREA$  effect however no longer was significant:  $F[6,24] = 0.80$ , *ns.*) showing essentially the same neurophysiological pattern.

#### 4. Discussion

The aim of this study was to investigate to what extent EEG alpha synchronization is related to internal processing demands in general and/or to specific cognitive processes involved in creative thinking. To this end, a convergent and a divergent thinking task (i.e., creativity-related task) were employed which once were processed with low and once with high internal processing demands. High internal processing demands were established by masking the stimulus (after encoding) and thus preventing participants' further bottom-up processing. This experimental condition is therefore conceived to require exclusively top-down processing. In contrast, the low internal processing condition allowed for steady bottom-up processing as the stimulus remained visible throughout the task.

Behavioral analysis revealed that the solution rate was found to be somewhat lower when high internal processing demands were imposed. This small but significant difference in solution rate might be attributable to differences in memory load between the two experimental conditions. In the high internal processing condition the stimulus characters had to be maintained and processed in memory throughout the task, whereas in the control condition the stimulus characters could be retrieved externally at any time. The high internal processing condition thus probably involved a higher load of working memory, which may have resulted in a somewhat poorer overall task performance. This result may be also considered as some sort of validation of the experimental manipulation, as task performance under exclusive top-down processing can be generally conceived as being more challenging, which could eventually have affected task performance.

Considering the EEG results, task-related frontal alpha synchronization was observed during convergent and divergent thinking only when the tasks posed high internal processing demands (i.e., top-down processing). In contrast, task processing under low internal processing demands (i.e., involving bottom-up processing) did not result in alpha synchronization but in strong desynchronization especially in posterior brain regions, which could reflect stronger demands on the visual system during this type of information processing. Taken together, the results suggest that alpha synchronization may be considered as an indicator of top-down information processing, whereas bottom-up processes (or stimulus-driven processing) are rather accompanied by a decrease of alpha desynchronization. In this vein, the findings of this study are in agreement with functional imaging and cellular data highlighting the particular role of frontal brain regions for top-down attention (e.g., Buschman & Miller, 2007; Engel, Fries, & Singer,



**Fig. 2.** Task-related power (TRP) changes in the upper alpha band during convergent and divergent thinking under low vs. high internal processing (IP) demands. Positive TRP indicates task-related alpha synchronization, negative values indicate desynchronization (AF = anteriofrontal, F = frontal, FC = frontocentral, CT = centrotemporal, CP = centroparietal, PT = parietotemporal, PO = parietooccipital, LH = left hemisphere, RH = right hemisphere).

2001). Moreover, there is increasing evidence that frontal brain regions may exert top-down control by means of temporal synchrony of lower frequencies (especially alpha but also theta) with parietal brain regions (Buschman & Miller, 2007; Klimesch et al., 2007; Sarnthein, Rappelsberger, Shaw, & Von Stein, 1998; Sauseng et al., 2005; Von Stein & Sarnthein, 2000).

The findings are also consistent with relevant studies in this field such as that of Cooper et al. (2003), who found that internally driven attention (imagination of stimulus sequences) resulted in higher alpha activity than externally driven attention (presentation of stimulus sequences). Task performance in the present study required active processing towards a (convergent or divergent) solution, which can be considered to involve working memory (e.g., for maintenance and recombination of characters) but also long-term memory (e.g., for retrieval and examination of adequate solution words). As mentioned above, the high internal processing condition may have taxed working more strongly memory than the control condition. The results thus are also in line with previous findings that alpha activity is related to higher memory load (Jensen et al., 2002; Klimesch et al., 1999) or stronger involvement of working memory (Sauseng et al., 2005). These findings may, however, also be seen at odds with evidence for alpha activity to decrease with higher memory load or task complexity (Gevins, Smith, McEvoy, & Yu, 1997; Neubauer & Fink, 2003). A possible explanation for this apparent discrepancy may again be found in the processing mode related to the employed tasks: Increasing alpha desynchronization for higher memory load or task complexity was found for tasks such as the n-back task or the triplet number test (Stankov, 2000) which require constant externally directed attention, while findings for increasing alpha synchronization for higher memory load (or task complexity) have been obtained in tasks and time periods which relate to retention and manipulation of internally represented information (i.e., top-down processing).

A particular aim of this study was to examine the role of alpha synchronization in the context of creative cognition. This was motivated by recent evidence in this field showing that tasks with high creative demands result in larger alpha synchronization in frontal cortex (Fink et al., 2006; Fink, Grabner, et al., 2009; Grabner et al., 2007) and in right-hemispheric posterior

parietal brain regions (Fink & Neubauer, 2006; Fink, Grabner, et al., 2009; Fink, Graif, et al., 2009; Jung-Beeman et al., 2004). The results of this study clearly indicate that frontal alpha synchronization may be attributed to internal processing demands in general rather than to cognitive or neural processes specifically involved in creative thinking. But considering posterior brain regions, alpha synchronization in parietal areas of the right hemisphere was observed only during divergent thinking under high internal processing demands but not during convergent thinking (see Fig. 2). The corresponding four-way interaction failed to reach statistical significance, which may also be due to a lack of power of the multivariate approach in multi-factorial designs. Accordingly, in a follow-up analysis performed separately for each task, a significant three-way interaction supporting the effect in right-hemispheric posterior regions was obtained only for the divergent but not for the convergent task. This right-hemispheric synchronization effect has previously been related to a state of heightened internal attention facilitating the recombination of distantly related semantic information (Fink et al., 2006; Fink, Grabner, et al., 2009; Fink, Graif, et al., 2009; Von Stein & Sarnthein, 2000). Moreover, this effect may be also related to recent fMRI findings on creative cognition which suggest that high creativity demands are associated with lower activation of right hemispheric temporo-parietal brain regions including the right precuneus, angular gyrus, and temporo-parietal junction (Berkowitz & Ansari, 2010; Fink et al., 2010, in press-a; Kowatari et al., 2009). These findings have been interpreted in terms of increased focused attention to memory supporting efficient retrieval of existing memory. Taken together, alpha synchronization in temporo-parietal brain regions may reflect increased internal attention related to retrieval processes that may be rather specific for creative idea generation.

One might still wonder why the divergent thinking task in this study did not result in higher frontal alpha synchronization than the convergent thinking task, as it has been found in some earlier studies. In our view, the reason is that unlike in previous studies the two tasks here did not a priori differ with respect to the internal processing demands. Typical convergent thinking tasks usually involve complex abstract stimuli (e.g., Ravens matrices items usually feature eight pictograms with a number of varying

symbolic characteristics each). Therefore, many convergent tasks require continuous bottom-up processing of relevant stimulus features. In contrast, typical divergent thinking tasks (e.g., find alternate uses of a brick) usually involve rather concrete conceptual stimuli (i.e., brick) which can easily be maintained in memory. Successful problem solving in such tasks rather relies on the internal processes of retrieval and recombination of semantic associations of the stimulus concept (Benedek, Könen, & Neubauer, submitted for publication), thereby minimizing the need for further bottom-up processing of the stimulus. Therefore, when typical divergent thinking tasks (usually involving high internal processing demands) are contrasted to typical convergent thinking tasks (often involving higher bottom-up processing) the former are expected to show higher task-related frontal synchronization of alpha activity. In the present study, however, convergent and divergent thinking tasks were selected to show similar internal processing demands, because this variable was intended to be explicitly varied by a separate factor. This may explain why in this study task differences in frontal alpha have not been observed. However, since creative thinking is usually assumed to be linked to internal processing, the findings do not oppose the view that creative cognition is crucially linked to the function and activity of the frontal cortex (cf., Dietrich, 2004; Flaherty, 2005; Goel & Vartanian, 2005; Heilman, Nadeau, & Beversdorf, 2003).

Some limitations of this study should be mentioned. First of all, while it is a central assumption of this study that there was a successful experimental variation of low vs. high internal processing demands, the effect of this variation (i.e., the actual ratio of bottom-up and top-down information processing) could not be directly assessed. As argued above, we assume that the higher solution rate in the low internal processing condition indicates that working memory load was reduced by means of bottom-up stimulus processing. Furthermore, we believe that the experimental manipulation has strong face validity, and that the involved processing mode (top-down vs. bottom-up) thus may provide the most parsimonious explanation for the strong neurophysiological condition effects. In future studies, however, maybe a more direct assessment of bottom-up processing might be obtained by analyzing stimulus-directed fixation times as provided by eye-tracker measurements. As a potential second limitation, the present study did not employ the same divergent thinking tasks used in the ERD/S literature so far, which could limit the generalizability to previous results. More specifically, the employed sentence generation task may have involved lower creativity-related task demands than e.g. the commonly employed alternate uses task (e.g., Fink et al., 2007). As already mentioned, the sentence generation task was employed in order to avoid a priori task differences to the convergent task in internal processing demands. All the same, the employed tasks complied with the most decisive difference between convergent and divergent thinking tasks: in the former a given correct solution had to be found, while in the latter one possible original solution out of a virtually infinite solution space had to be generated. Nevertheless, it is very plausible to assume that a more creativity-related divergent thinking task would have resulted in even stronger and more extended task-related alpha synchronization (cf. Fink et al., 2007; Fink, Graif, et al., 2009, where task-related alpha synchronization was obtained for the whole cortex), which may still be the effect of even stronger internal processing demands.

Summing up, the present study provides straightforward experimental evidence that task-related alpha synchronization in frontal brain regions is related to top-down processing and high internal processing demands. In contrast, task-related desynchronization of alpha activity may rather indicate stimulus driven bottom-up information processing. The present study extends previous findings by demonstrating that alpha synchronization equally applies

to convergent and divergent thinking if both tasks are controlled for equal demands of internal processing.

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