Intelligence 49 (2015) 171–178

Contents lists available at ScienceDirect

Intelligence

Intelligence in creative processes: An EEG study

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ARTICLE INFO

Article history:
Received 14 July 2014
Received in revised form 16 January 2015
Accepted 20 January 2015
Available online xxxx

Keywords:
Intelligence
Creativity
EEG-Alpha synchronization
Complex problem solving
Ill-defined problem space

ABSTRACT

Intelligence and creativity are usually studied as two separate cognitive faculties assessed with standard problems having well- or ill-defined problem spaces; intelligence primarily focuses on finding the correct solution, creativity on generating new approaches. The view emerges, however, that they play complementary roles and may be more related than research recognizes. In the present study, participants ($N = 52$) created their own intelligence tasks: 3×3 matrices featuring relations between geometrical components. Using task related alpha synchronization, we demonstrated that intelligence integrates with creativity in a problem solving process evolving in open problem space. Activity was especially visible at prefrontal and frontal sites when information processing was most demanding, i.e., at the start of the creative process due to multiplicity of ideas, and at the end due to narrowing down alternatives. This research could open the way to an approach to cognition where intelligence-related abilities are studied in open problem spaces.

Traditionally, intelligence is studied with tests that reflect cognitive processes evolving in a certain problem space. Problem spaces represent abstract spaces that contain all possible pathways and stages toward a solution. They also contain the allowed rules (algorithms and heuristics) that one must apply to move from one step to the next. Problem spaces can be characterized along the range from well- to ill-defined according to the measure of description of the problem's constraints (Simon, 1973).

Clearly formulated problem constraints serve as helpful guidelines when searching for the correct solution. They state which features a solution should accommodate, thereby making the solving process more synoptic. Here, we find no reinterpretation of rules such as one might find in a game of chess, for example, where changing the rules yields a different situation and solutions no longer apply. Intelligence test items contain clearly stated constraints. For instance, in the Raven Progressive Matrices (RPM, Raven, Raven, & Court, 1998), relations among geometric components form the explicit constraints and only one of eight alternatives completes the matrix correctly. Hence, solving these items evolves in well-defined problem spaces.

Less clearly stated constraints leave room for a multitude of ideas. Creativity tests ask for elaborations on incomplete information, drawing from episodic and semantic memory resources (Cacciari, Levorato, & Cicogna, 1997). Items on the Torrance Test of Creative Thinking (TTCT, 1966), for example, invite, with the instruction that one can do nothing wrong, the completion of figures or the generation of multiple uses for a tin can. Creative ideation generates ideas and responses that cannot be matched to clear constraints. Instead, cognition complements the less clearly stated constraints with idiosyncratic interpretations and associations (Karmiloff-Smitt, 1990) that involves uncovering implicit requirements and making trade-offs among conflicting constraints (Yamamoto, Nakakoji, & Takada, 2000).

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http://dx.doi.org/10.1016/j.intell.2015.01.012
0160-2896/

Responses on creativity test items are scored on quantity (fluency), variety (flexibility), and exceptionality (originality or relative frequency), but not appropriateness. Cognitive abilities that yield this latter variable can only be scored when tests present problems that ask for original and appropriate solutions, such as preventing a fire from spreading (Kanazawa, 2004, in Jung, 2014) or inventing a Raven-like matrix (Jaarsveld, Lachmann, Hamel, & van Leeuwen, 2010). Solving such problems require *creative reasoning*, which is defined as cognition applying reasoning abilities in ill-defined problem spaces, yielding a thinking process in which intelligent and creative abilities play complementary roles (Jaarsveld, Lachmann, & van Leeuwen, 2013, Jaarsveld et al., 2010). This mechanism evolved when human survival depended on finding effective solutions to both common and novel problem situations (Jung, 2014). Situations differ in their constraints along the range from common to novel. Aside from the ability to apply both intelligent and creative thinking, cognition also requires the ability to adjust both modes of thought to match the demands of the problem situation (Gabora, 2002).

Tests are developed according to the definitions of the construct they are intended to measure. Definitions of the constructs of intelligence and creativity, however, vary in the degree to which they include abilities that are generally considered to belong to the other construct (Jaarsveld, Lachmann, & van Leeuwen, 2012; Runco, 2003; Sternberg, 2005). The ability to *evaluate*, for example, which is considered to belong to the construct of intelligence and gauges the match between a proposed solution and task constraints, also plays a role in creative processes that goes beyond the mere generation of a series of ideas (Geneplore model; Finke, Ward, & Smith, 1992). In addition to phases in which objects were merely generated, these authors included phases in which an object's utility was explored in their creativity tasks. They have shown that the ability of evaluation, which is considered to belong to the construct of intelligence, is also functional in creative processes.

In contrast, the ability of *flexibility*, which is considered to belong to the construct of creativity and ensures the generation of ideas from different domains, showed a relationship with intelligence (Silvia, 2008) and plays an important role in intelligent behavior, enabling us to do novel things smartly in new situations (Colunga & Smith, 2008). These authors studied children's generalizations of novel nouns and concluded that if we are to understand human intelligence, we must understand the processes that make inventiveness. They propose to include the construct of flexibility within that of intelligence. Hence, intelligent processes such as hypothesis testing, evaluation, inhibition of alternative responses, and creating mental images of new actions or plans could also be considered to be involved in creative thinking (Colom et al., 2009; cf. Fuster, 1997, p. 215). This overlap between definitions of the constructs of intelligence and creativity yields a test diversity that "makes it impossible to interpret the different findings across studies with any confidence" (Arden, Chavez, Grazioplene, & Jung, 2010).

The literature is moving towards the view that in cognitive processes, intelligence and creativity play complementary roles (Dietrich, 2007; Jung, 2014; Ward, 2007) and that through retrieval activities, intelligence and creativity are more related than creativity research has yet recognized (Silvia, Beaty, & Nusbaum, 2013). When both types of thinking are considered as complex information processing abilities evolving in tasks that are not immediately solvable (Freund, Holling, & Preckel, 2007), they can be placed within one model (Guilford, 1956; Kaufmann, 2003). In that case, cognitive activities ensuing from an ill-defined task can be categorized as convergent thinking (which is associated with intelligence) and divergent thinking (which is associated with creativity), establishing that creative processes contain both modes of thinking intertwined (Cropley, 2006; Jaarsveld & van Leeuwen, 2005). In the creative process, on the other hand, convergent thinking assesses, evaluates, and integrates generated information. Instead of comparing different tasks, such as an alternate use task (Christensen, Guilford, Merrifield, & Wilson, 1960) versus an arithmetic task, it could be more informative to study divergent and convergent thinking processes within the same type of task (Arden et al., 2010; Jauk, Benedek, & Neubauer, 2012).

In accordance with the conclusions of cognition research about the interaction between intelligence and creativity in ill-defined problem spaces, neuroscientific studies have shown that abilities associated with the construct of intelligence, such as making choices, analysis, and evaluation, and those abilities associated with creativity such as the integration of complex, original, and creative behavior, all have their basis in the prefrontal cortex (Fuster, 1997, pp. 163–217). Increased EEG alpha synchronization at prefrontal sites is considered to be an indication of the cognitive processes implicated in ill-defined problem spaces (Fink & Benedek, 2014; Fink et al., 2009a). Alpha synchronization is understood as top down control that is often observed in states of high internal processing demands (Benedek, Bergner, Konen, Fink, & Neubauer, 2011; Benedek, Schickel, Jauk, Fink, & Neubauer, 2014; Cooper, Croft, Dominey, Burgess, & Gruzelier, 2003), including mental activities such as memory, perception, and attention. It was observed in frontal areas in convergent and divergent thinking tasks (Benedek et al., 2011), especially for gifted persons (Jaušovec, 1996) and was found to be more related to divergent thinking than convergent processing (Fink & Benedek, 2014; Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Jauk et al., 2012). That divergent processing can include high internal processing demands was shown by the registration of higher event-related synchronization in the EEG alpha rhythm for individuals engaged in creative ideation tasks compared to intelligence related tasks (Fink et al., 2007). As indicated by EEG data, divergent processing also includes stronger cooperation between brain areas in creative individuals compared to gifted ones when solving ill-defined problems (Jaušovec, 2000).

In this work we studied intelligence operating in open problem space using a test for Creative Reasoning (CRT, Jaarsveld et al., 2010). The task is not, however, to generate a multitude of ideas on simple or incomplete information within this open problem space, but to *produce* a well-defined problem. This task presents a problem space in which intelligence and creativity both play a role. Jaarsveld et al. (2012) demonstrated that the CRT sub scores for intelligence and creativity correlated significantly with the Raven Progressive Matrices test (RPM, Raven et al., 1998) and the Test for Creative Thinking-Drawing Production (TCT-DP, Urban & Jellen, 1995), respectively. Importantly, the sub scores of the CRT did not show a relationship, although correlations between scores of RPM and TCT-DP were observed (Jaarsveld et al., 2012; Urban, 2005; Urban & Jellen, 1995). In addition to the above reported contrast, we note that intelligence in the CRT and RPM operates on an identical knowledge domain, namely, relationships among geometric components, but that intelligence in RPM and creativity in TCT-DP operate in different knowledge domains. These observations together highlight the role of intelligence in ill-defined problem situations.

To understand cognition it is critical to study its information processing (Arden et al., 2010). EEG/ERP designs are an appropriate method to gain insight in the temporal evolution of cognitive processes (Srinivasan, 2007). Within a neurocognitive approach, we expect to confirm the findings of Jaarsveld et al. (2010, 2012). These authors showed that, unlike the classical approach where intelligence is studied in defined problem spaces, the application of intelligence related abilities can be reliably studied in ill-defined problem spaces. In the present study we used an approach of EEG registration in which the idea for the end product is elaborated and realized through alternate phases of *thinking* and *drawing*. This approach is originally based on a procedure in which participants are requested to indicate the occurrence of a creative idea to a given stimulus in a self-paced manner by pressing the so-called "Idea button" and subsequently to verbalize or reproduce the idea (Fink et al., 2007), thereby facilitating the separation of the imagination and realization phases during the process of creative thinking. With differences in alpha activation within and between thinking stages of the task, we expect to demonstrate that intelligence related abilities play a role in the creative process.

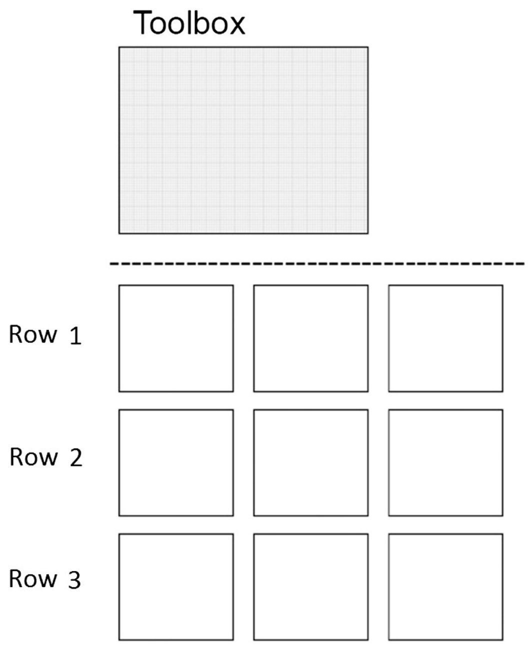

Fig. 1. Answering form of the Creative Reasoning Task (CRT) with the four stages of the creative problem solving process added to it, namely, Toolbox, Row 1, Row 2, and Row 3. Stages contained a thinking phase in which EEG activity was registered and a drawing phase in which the outcome of the preceding thinking stage was realized.

1. Methods

1.1. Participants

Our sample comprised 55 university students from multiple disciplines. Due to technical problems associated with the implementation of the CRT in the EEG environment, the first three persons had to be excluded from analyses, the final sample thus comprised 52 participants (31 females) in the age range between 19 and 42 years ($M = 24.33$, $SD = 4.25$). All participants were healthy and reported no history of substance abuse or other medical, psychiatric or neurological disorders. They had normal or corrected-to-normal vision, gave written informed consent, and most were right-handed (two participants were left-handed, as determined by self-report). This study was approved by the ethics committee of the University of Graz.

1.2. Materials and procedure

We used the Creative Reasoning Task (CRT, Jaarsveld et al., 2010, 2012) in which participants are asked to create a 3 × 3 matrix containing self-generated logical relationships among similarly self-generated geometrical components. For this study we adapted the instructions and the test form (see Fig. 1). The most important modification of this task was that we separated performance into so-called thinking and drawing phases to obtain reliable EEG data. Instructions throughout the task appeared on a computer screen and informed participants that each of the four stages, namely, Toolbox, Row 1, Row 2, and Row 3, consisted of one thinking phase and one drawing phase.

EEG was recorded in the thinking phases while participants pondered possible solutions; in the subsequent drawing phase, they sketched their ideas on the test form. Ten CRT trials were performed. Each trial started with the so-called *Toolbox* in which participants were asked to imagine the components they wanted to work with, followed by Rows 1 through 3 when they had to imagine and picture the relationships that would connect the components (see Fig. 1). By pressing keys on the PC keyboard, participants could indicate the end of a thinking phase or a drawing phase. We asked participants to work creatively, to design matrices featuring as many different and original components and relationships as possible, and to keep in mind that another person should, in principle, be able to infer what relationship(s) were contained in their matrices.

1.3. EEG recording and quantification

The EEG was measured with a BrainVision BrainAmp Research Amplifier (Brain Products) with Ag/AgCl electrodes and a stretchable electrode cap from the following 19 positions: FP1, FP2, F3, F7, FZ, F4, F8, T7, C3, CZ, C4, T8, P7, P3, PZ, P4, P8, O1, and O2. The midline electrodes (FZ, CZ, PZ) were not included in the statistical analyses as we were also interested in potential hemispheric differences. The ground electrode was located at FPZ and the reference electrode was placed on the nose. To register eye movements, an electro-oculogram (EOG) was recorded bipolarly between two electrodes placed diagonally above and below the inner and 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. Electrode impedances were kept below 5 kΩ for the EEG and below 10 kΩ for the EOG. All signals were sampled at a frequency of 500 Hz.

EEG data were preprocessed by removing drifts and low pass filtering (50 Hz). The data were visually checked for artifacts, and artifactual epochs caused by muscle tension, eye blinks or eye movements were excluded from further analysis. In a next step, EEG signals were filtered by applying an FFT filter for the upper alpha frequency band (10 and 12 Hz). Power estimates were obtained by squaring filtered EEG signals, and then band power values (μV^2) were (horizontally) averaged for each single trial.

As in previous studies (e.g., Benedek et al., 2011, 2014; Fink, Grabner, et al., 2009a; Fink, Graif, & Neubauer, 2009b; Fink, Schwab, & Papousek, 2011), we quantified task-related power (TRP) changes in the alpha band during creative ideation. We focused on the alpha frequency range because task-related power changes in this frequency band have been found to be particularly sensitive to different creativity-related task demands, and empirical findings on the relationship between alpha power and creativity could be considered as being among the most consistent findings in the neuroscientific study of creativity (Fink & Benedek, 2014). Specifically, TRP was investigated in the lower (8–10 Hz) and in the upper alpha band (10–12 Hz). In accordance with previous findings (for an overview see Fink & Benedek, 2014), both alpha bands yielded highly similar results. Thus, to increase the paper's readability and to avoid redundancy and problems associated with multiple testing, we decided to present only the findings of the upper alpha band. This band is also thought to be more sensitive to specific task-related requirements, while the lower alpha band is more associated with attention processes such as vigilance and alertness (Klimesch, 1999).

Each CRT trial started with the presentation of a fixation cross for a time period of 15 s, which served for the assessment of pre-stimulus reference power (specifically, 10 s time segments out of the 15 s reference periods, starting 2.5 s after the onset of the fixation cross were used for the quantification of pre-stimulus reference power). The thinking phases of the respective CRT stages (i.e., Toolbox, Row 1, Row 2, and Row 3) were used as activation periods in quantifying task-related power changes. The TRP for each electrode position (i) was computed according to the formula: $TRP(i) = \log[Pow_{i,\,activation}] - \log[Pow_{i,\,reference}]$. Hence, increases in alpha power from the reference to the activation period are reflected in positive values (hereinafter referred to as *alpha synchronization*), whereas negative values indicate decreases in power (i.e., *alpha desynchronization*).

Given that the different stages of the CRT differed considerably with respect to length (both inter- and intra-individually), only trials that did not exceed a specified maximum length were considered in statistical analyses (Toolbox: <3 min; Row 1 to 3: <2 min) to avoid extreme outliers in our EEG data. The choice of these time limits was based on an inspection of the RTs of each individual CRT stage. The mean time on task (in seconds) for Toolbox was $M = 36.34$ ($SD = 19.32$), for Row 1 $M = 18.52$ ($SD = 10.60$), Row 2 $M = 16.04$ ($SD = 9.33$) and Row 3 $M = 11.39$ ($SD = 6.90$). To investigate the time-course of creative problem solving within each stage of CRT task performance (i.e., Toolbox and Row 1 through 3), the trials of each stage were divided into four isochronous time intervals (individually adjusted for each trial and stage) and the obtained band power estimates for these four time segments were aggregated across trials. The analysis of EEG data in individually adjusted time segments could be considered as a powerful approach for the study of time-course effects because it accounts for inter- and intraindividual differences in response intervals.

2. Results

The matrices created by our participants (see Fig. 2) showed features not contained in the RPM, e.g., the original intertwining of relationships (see Matrix A, combination of components within a succession of components; Matrix B, succession of size of components that change over row), components that are not exclusively geometrical (see Matrix C, resistors; Matrix D, wheels), and three-dimensionality (Matrices B and D). To assess the creative output during the performance of the CRT, we computed a total score that involves two sub scores, one for the reasoning component of the task and one for the creativity component. Participants' CRT scores ranged between 26.6 and 83.4 ($M = 54.49$, $SD = 10.53$).

An ANOVA for repeated measures was performed on the task-related power changes (TRP) in the upper alpha band in considering the STAGE of creative problem solving (Toolbox, Rows 1 to 3), TIME (4) within each stage, AREA (8) and HEMISPHERE (2) as within subjects variables. In case of violations of sphericity assumptions, Greenhouse–Geisser-Correction was applied. For post-hoc comparisons of means, Tukey Honestly Significance Difference (HSD) tests were used.

The ANOVA revealed significant main effects of STAGE ($F_{1.87,95.50} = 24.60$, $p < .01$, $^2p = .33$), TIME ($F_{2.25,114.66} = 69.64$, $p < .01$, $^2p = .58$) and AREA ($F_{2.93,149.28} = 34.97$, $p < .01$, $^2p = .41$), but not of HEMISPHERE. The main effect of AREA indicates that performance of the CRT task was generally accompanied by comparatively strong alpha increases (i.e., alpha synchronization) at frontal sites ($FP_{1,2}$, $F_{7,8}$, $F_{3,4}$), while over the posterior cortex, alpha power desynchronized slightly. The main effect of STAGE indicates that the Toolbox was associated with task-related decreases of alpha power as did Row 1 to a minor extent, while Row 2 and particularly Row 3 showed alpha synchronization. Post-hoc Tukey HSD tests revealed significant differences between the Toolbox and Rows 2 and 3 ($p < .01$); Row 3 also elicited significantly stronger alpha synchronization than the preceding Rows 1 and 2 ($p < .01$). Finally, the significant main effect TIME indicates that within a stage, the time-course of alpha power during the process of creative problem solving seems to follow a U-shaped function, with the strongest increases in alpha power at the beginning of the creative process (i.e., T1, first time interval of a thinking phase), followed by the final interval (i.e., T4, at the end of a thinking phase prior to responding and entering a subsequent drawing phase), and finally by both intermediate time intervals, T2 and T3, which even displayed decreases in alpha (i.e., alpha desynchronization). Tukey post-hoc tests revealed significant mean differences between all time intervals ($p < .01$), except the mean differences between both intermediate time intervals.

The ANOVA further revealed significant interactions between STAGE and AREA ($F_{6.37,324.79} = 7.95$, $p < .01$, $^2p = .14$), TIME and AREA ($F_{6.56,334.40} = 16.51$, $p < .01$, $^2p = .24$), and STAGE and TIME ($F_{6.41,327.06} = 8.31$, $p < .01$, $^2p = .14$), which were further specified by a significant three-way interaction between STAGE,

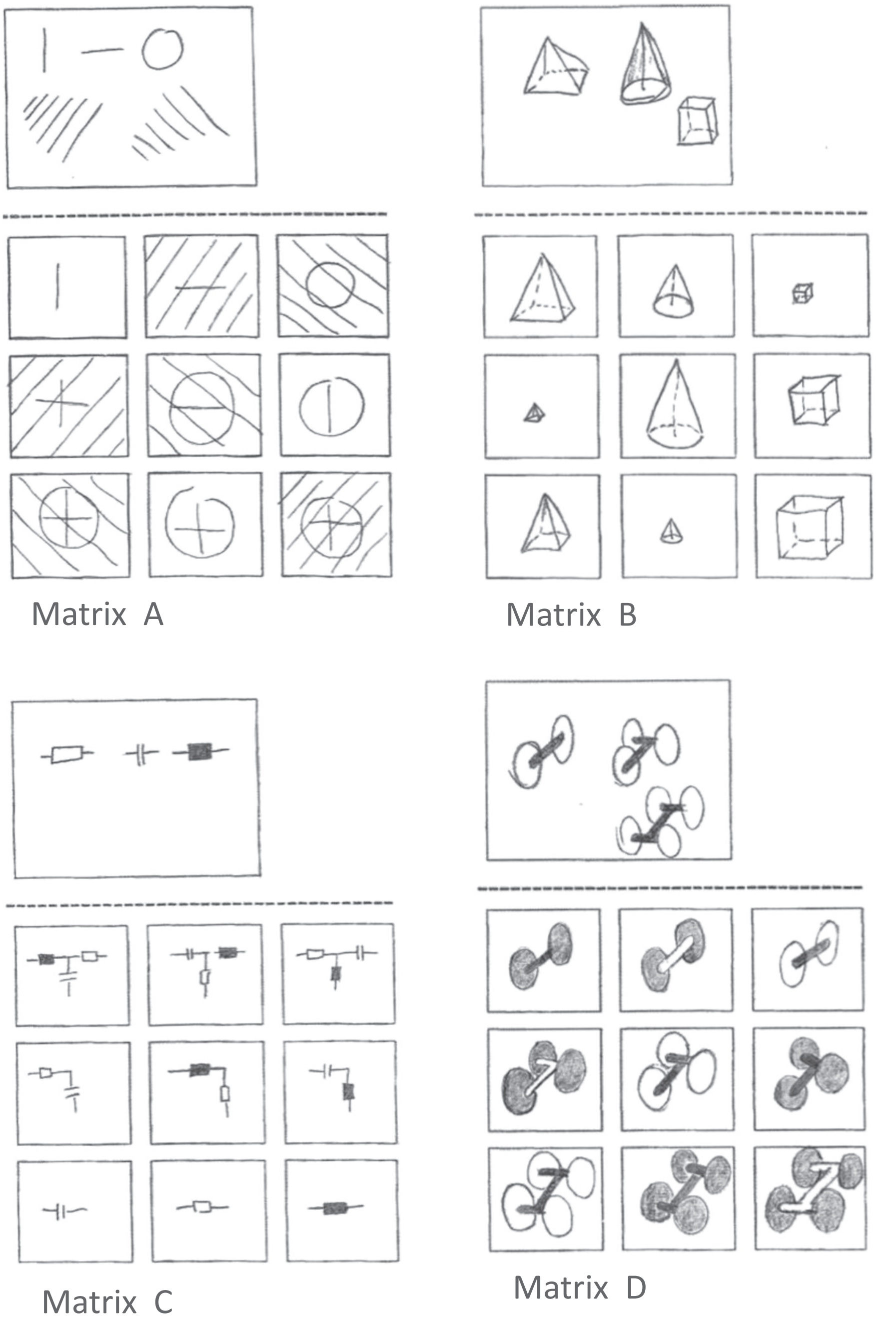

Fig. 2. Examples of created matrices in the CRT. Matrices are created in four thinking stages (Toolbox and Rows 1–3) in which EEG activation is registered, followed by four drawing stages. Generating ideas for the Toolbox (upper rectangle) involves more divergent than convergent thinking (more creativity than intelligence related thinking abilities) because relationships still must be realized. Towards the completion of the matrix, convergent thinking becomes more important as ideas have to fit into a narrowing space of possibilities. Due to ideas realized in preceding stages, the problem space becomes more defined with each row, making intelligence related abilities such as assessing, evaluating, and integrating more applicable.

TIME and AREA ($F_{19.57,997.82} = 2.24, p < .01, {}^{2}p = .04$). As shown in Fig. 3, the Toolbox was mostly associated with alpha desynchronization, except in the first and last time interval, which both showed slight increases in alpha power at prefrontal sites. With subsequent stages of the creative problem solving process (i.e., from Toolbox through Row 1, 2, and 3), alpha power tends to increase, particularly over the prefrontal cortex (see Fig. 3). This was most pronounced for the first time interval, followed by the last one and finally by both intermediate time intervals, which mostly showed decreases in alpha power. Tukey post-hoc tests corroborate this finding pattern: Alpha power during the first time interval increases significantly ($p < .01$) as a function of STAGE (at $FP_{1/2}$ and $F_{7/8}$ alpha power significantly increases with subsequent STAGE, except between Rows 1 and

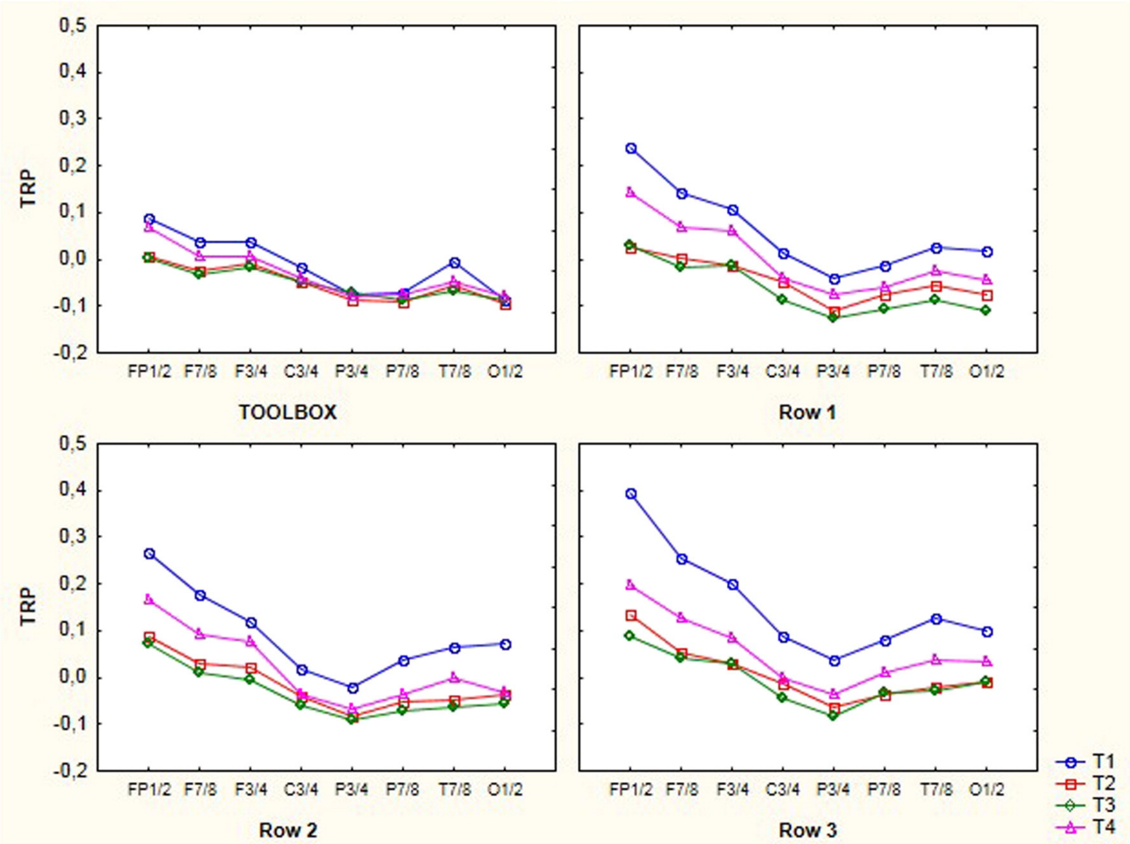

Fig. 3. Task-related power (TRP) changes in the upper alpha band over eight brain areas for the four time intervals (T1 to T4) defined within the four stages (Toolbox, Row 1 to Row 3) of the creative problem solving process. The brain area relates to electrode placement $Fp_{1,2}$ (fronto polar), $F_{3,4}$, $F_{7,8}$ (frontal), $C_{3,4}$ (central), $P_{3,4}$, $P_{7,8}$ (parietal), and $O_{1,2}$ (occipital), where odd and even numbers indicate the left and right hemisphere, respectively.

2), and similarly, prefrontal alpha power during the last time interval was significantly ($p < .01$) lower in the Toolbox than in Rows 1, 2, and 3.

Although less pronounced, alpha power also tends to increase over posterior cortical sites ($P_{7,8}$, $T_{7,8}$, $O_{1,2}$) with subsequent STAGE, especially in the first time interval (T1, see Fig. 1): Here, Tukey HSD tests revealed significant differences at $O_{1,2}$ between the Toolbox and Rows 1 through 3 ($p < .01$), and between Row 1 vs. Rows 2 and 3 ($p < .05$). Quite similarly, alpha power at $P_{7,8}$ was significantly lower during the Toolbox than during Rows 1 to 3 ($p < .01$).

3. Discussion

In the present study we demonstrated the evolving operation of intelligent abilities in a creative process relative to task-related changes in EEG alpha power. Research has shown that the process invoked by the Creative Reasoning Test (CRT) is indeed a process evolving in an ill-defined problem space activating creative ideation. Intelligence related abilities yielded responses that differed quantitatively and qualitatively between the well-defined Raven Progressive Matrices (RPM) and the ill-defined CRT (Jaarsveld et al., 2010). The CRT represents an ill-defined problem space because of the underspecified nature of its constraints and the underspecified methods of realizing the end product. The evolving thinking processes are by definition creative (Goel & Pirolli, 1992). Moreover, the relationships between the scores of the RPM and the CRT-Intelligence sub score and between the scores of the Test of Creative Thinking (TCT) and the CRT-Creativity sub score revealed not only that intelligence related abilities played a role but also that creative ideation took place in the CRT (Jaarsveld et al., 2012).

EEG alpha power was measured in an upper (10–12 Hz) and a lower (8–10 Hz) alpha band. We assessed alpha power in four thinking stages when participants pictured components and their features for three subsequent rows of a 3 × 3 matrix. In four drawing stages, the outcome of the preceding thinking stage was realized on a test form. Alpha power changes per stage were analyzed in four equally long, individually adjusted time intervals. We found alpha synchronization in temporal and occipital areas and over (pre)frontal sites that are associated with visualization processes and complex information processing, respectively.

Specifically, the different stages of creative problem solving in the CRT (Toolbox, Row 1 to 3) were associated with distinct patterns of task-related alpha power changes. Alpha desynchronization was mostly found while participants thought of possible components and features they wished to use in the subsequent 3 × 3 matrix (i.e., thinking phase of Toolbox stage). We could argue that divergent thinking operates in a purely generative mode in this stage, i.e., branching out over different domains without the intertwining of convergent thinking. Then, participants started to work on the 3 × 3 matrix, row by row. In doing so, components of the Toolbox and possible logical relationships between them must be temporarily held in mind to be explored in light of the task constraints in such a way that they result in a "correct" 3 × 3 matrix. Here, divergent thinking becomes intertwined with convergent thinking (Jaarsveld & van Leeuwen, 2005; Jaarsveld et al., 2012) because abilities such as hypothesis testing, evaluation, and selection must be applied to arrive at an applicable creation, namely, a solvable matrix.

Moreover, subsequent stages of the CRT require the consideration of an increasing number of relationships and rules as introduced by previous stages. As the findings of this study suggest, alpha power tends to increase with each subsequent row of the CRT, especially at prefrontal sites. Increases in prefrontal alpha have been interpreted as reflecting high internal processing demands or the inhibition of task-irrelevant processes enfolding within ill-defined problem spaces (Fink & Benedek, 2014). Increases in parietal alpha synchronization as were found in T1 of Stage 3 and 4 may indicate attention for mental arithmetic (Ray & Cole, 1985), which could be expected towards the end of this type of task. Alpha synchronization in this particular context may reflect the process of task shielding and thus indicate an executive mechanism that supports active maintenance of relevant information in memory. Translated to our findings, a possible interpretation would be that increases in frontal alpha synchronization at later task stages reflect increasing working memory load involved in those stages.

Another interesting finding in this context is that, within each stage of the CRT, task-related alpha power increases were most pronounced at the beginning of the creative problem solving process (i.e., first time interval of a thinking phase), followed by the last time interval (at the end of a thinking phase, prior to responding to and entering a subsequent drawing phase) and finally by both intermediate intervals. This U-shaped function of task-related alpha power (Schwab, Benedek, Papousek, Weiss, & Fink, 2014) seems to reflect distinct stages of the creative thinking process. As in other creativity tasks, each CRT stage began with a step in which the problem is defined that involved the retrieval of relevant knowledge from memory. The process of controlled memory retrieval is known to induce bilateral alpha synchronization (Klimesch, 2012). After this initial step, we assume that possible task solutions were examined in a trial and error manner. Finally, finding an adequate solution that fulfills all the criteria of the actual CRT stage requires the binding of all involved task features. This binding process is known to be achieved through working memory (e.g., Oberauer, Schulze, Wilhelm, & Süß, 2005) and could thus be responsible for re-increases of alpha synchronization towards the end of a stage.

With respect to increases in alpha power at prefrontal sites, performances of the CRT yield quite similar findings as performances of the classic Alternative Uses task (Fink & Benedek, 2014). What is different is that increases of alpha power at posterior cortical sites were not lateralized towards the right hemisphere in the CRT as was sometimes found in typical divergent thinking tasks. This lateralization is thought to be specific to creativity-related demands and to reflect high internal processing demands, aiding the effective search of semantic memory (Benedek et al., 2011, 2014; Fink & Benedek, 2014). This discrepancy could be explained by the differences in task demands: unlike the AU task, the performance of the CRT can be assumed to involve a broader spectrum of intelligence-related demands such as the processing of abstract figures (components of the Toolbox) that are required to be spatially, logically, or mathematically related to each other. In contrast, the AU task involves the retrieval and processing of semantic information. Differences in the nature of task demands (abstract versus semantic), along with differences in task modality (spatial versus verbal) could thus have reduced the lateralization of alpha effects. Moreover, the observed alpha synchronization in occipital areas may point to an increased top-down control of visual areas during the elaborate imagination of the spatial features of the solution right before participants transferred their mental conceptualization into a physical drawing.

Taken together, we showed with EEG data that abilities considered to belong to the construct of intelligence interact with abilities considered to belong to the construct of creativity. Unlike the classical approach of studying intelligence in defined problem spaces, we show that intelligence can be studied operating in ill-defined spaces. We used the Creative Reasoning Test (CRT, Jaarsveld et al., 2010, 2012), which asks participants to create on an empty form an original and most complex 3 × 3 matrix that should, in principle, be solvable by another person. This task involves generating components and the relationship(s) that connect them and yields a cognitive thinking process in which both intelligent and creative abilities play a role.

The findings of this study suggest that alpha synchronization was most pronounced in those episodes of the creative reasoning process in which information processing is most demanding and complex. This occurred at the beginning of each of the thinking phases when participants began picturing ideas for the matrix rows and evaluating them against their own interpretations of the task constraints. It also occurred at the end of the task when possibilities for completing the matrix had been narrowed down due to ideas realized in previous stages. This work proposes an approach to cognition research where intelligence and creativity are considered to intertwine in processes that evolve in ill-defined problem space.

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