



# THE NEUROSCIENCE OF DIVERGENT THINKING

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## Abstract

Creativity plays a role in innovation, development, and health. Recent research has used neuroscientific methods to study originality, novelty, insight, divergent thinking, and other processes related to creative mental activity. Findings indicate that both hemispheres are involved in divergent thinking, which is accompanied by both event-related increases and decreases in the neural activation. Divergent thinking seems to be associated with high neural activation in the central, temporal, and parietal regions, indications of semantic processing and re-combination of semantically related information. Most of the research in this area has been done in the last 10 years, and very likely refining and standardizing DT testing and scoring will lead to additional insights about creativity.

Key words: *Consciousness; Creativity; Divergent Thinking; Neural Correlates*

## 1. INTRODUCTION

The benefits of creativity have been recognized for many years (Guilford, 1950) but are broader and more widely-recognized now than ever before. Creativity is now discussed in education and business, as well as academic psychology. Indeed, there are discussions of creativity in virtually every field of study and every domain of performance (Runco, 2013). Benefits reflect the role of creativity in innovation, development and learning, society progress, and health (Runco & Richards, 1998).

One of the most recent fields to join in the investigation of creativity is that of neuroscience (for reviews see Sawyer, 2011, or Weisberg, 2013). Once fMRI and other advanced neuroscientific methods could be used to study more than just medical issues, attention quickly turned to creativity. The neuroscientific research on creativity has already challenged some common misconceptions, such as creativity being strictly a right brain function.

The application of advanced neuroscientific methods to creativity may have been slightly delayed by controversies in the measurement of originality and the other indicators of creative talent. Originality is a vital aspect of all creativity (Runco & Jaeger, 2012), but by definition it involves novelty, which can make measurement a challenge. Most tests and measures present a task or ask a question and compare the answer to norms or expectations. This is not possible when the test is designed to measure originality or novelty. Still, several reliable instruments do exist, including the Remote Associates Test (Mednick, 1962; Bowden & Jung-Beeman, 2003;

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Received May 13, 2014; accepted May 24, 2014; *Act Nerv Super* 56(1-2), 1-16; ISSN-1802-9698

Gupta, Jang, Mednick, & Huber, 2012) and various insight (Dow & Mayer, 2004) and divergent thinking tests (Guilford, 1968; Runco, 1991, 2013; Torrance, 1995). Neuroscientific research has employed each of these, with results reviewed by Heilman (2003), Sawyer (2011), and Weisberg (2012).

The Remote Associates Test (RAT) is based on a theory that original ideas are the result of ideational associative processes. The most original ideas are thought to be the most remote and far down the associative pathway. Ideas early in an associative chain tend to be rote, conventional, and unoriginal (Mednick, 1962; Milgram & Rabkin, 1980; Runco & Okuda, 1991). Insight tasks, on the other hand, assess an individual's success when faced with problems that require cognitive restructuring. Insightful solutions appear to be quick, as in an "ah-ha" moment, though in fact the insight may be protracted, even if the processing is not always conscious (Gruber, 1981). Importantly, insightful problem solving may lead to very few, or even just one, solution. There is a problem, and after incubation, one effective solution may come to mind in an "ah-ha!"

This is very different from what is assessed with divergent thinking (DT) tasks. DT tasks are open-ended and often ill-defined. This allows the respondent to generate a number of ideas and, most importantly, to explore original alternatives. They are usually scored for originality (i.e., the number of unique or uncommon ideas), as well as ideational fluency (i.e., the total number of ideas), and ideational flexibility (i.e., the number of conceptual categories in the ideas produced). DT tests are reliable and have quite acceptable predictive validity (Runco, 2013; Torrance, 1995). One fairly recent investigation reported that DT was significantly related to (and predictive of) certain creative activities over a 50 year period (Runco et al., 2011).

There are a number of methodological concerns when using DT tests. These tests should not be timed, for example, for when examinees think they are being timed, they do not find as many original ideas. No doubt they are thinking about the time allotted rather than allowing their thinking to move freely and divergently. Also, they may not have enough time to exhaust obvious ideas and to move to remote associates. Interestingly, DT tasks are most likely to lead to original ideas when examinees are told that the tasks are not tests. If DT tasks are treated as tests, examinees give mostly common ideas that they think will earn high grades or high scores. If they are told that the tasks are not tests but games instead, they tend to be playful and usually find many more original ideas.

Scoring DT tests is also an issue. Some research has relied on fluency alone. The reasoning is that fluency is correlated with originality and flexibility. Fluency should not be used alone, however. That is because originality is more important for creativity than fluency (Runco & Jaeger, 2012). Also, originality has reliable variance, even when the overlap with fluency is statistically controlled (Runco & Albert, 1985). It really makes no sense at all to rely on fluency and ignore originality and flexibility, especially when you take the theory supporting DT into account (Guilford, 1968; Runco, 2013; Torrance, 1995). Recall also the "standard definition" of creativity, with originality necessary (though not sufficient) and fluency not included.

When the testing is done right and recognizes these things (time allotted, instructions, and scores justified by theory), DT tasks provide very useful information. DT is certainly not synonymous with creative talent. Instead, DT tests provide reliable *estimates* of the *potential* for creative thinking. No wonder a large number of investigations have used DT test. No wonder neuroscientific studies of creative potential often rely on DT test.

The neuroscientific research on creativity has been reviewed by Sawyer (2011) and Weisberg (2012). Neither of them focused on DT, however. Fink and Benedek (2013) focused on DT, but they only examined EEG research. None of the previous reviews took the special considerations noted above (timed testing, game-like vs. test-like instructions) into account. Here we include EEG, as well as fMRI, and the research on the neuropsychology of DT is examined by taking all of the special considerations into account. In addition, although this review covers a number of articles that were cited by Finke and Benedek (2013), Sawyer

(2011), and Weisberg (2012), the present paper is obviously more recent, and thus includes several papers that were not in those earlier reviews.

The focus on DT means that the interpretations are not diluted by data from research on the RAT or insight or some other (non-DT) test of creative potential. This is very important. Recall what was said above about DT tests allowing originality, while insight tasks tend to allow one effective solution. Certainly the importance of the present review is that it will say something about creative potential, but what it says may not be in perfect agreement with earlier reviews simply because of the focus on DT. DT tests provide reliable estimates of the potential for creative thinking, so the conclusions of the present review will contribute to an understanding of the neuroscience of creativity. Our own believe is that DT is also meaningful in and of itself, given that ideas are important, even if not related to creative performances (Runco, 2013). After all, ideas are involved in all mindful activity and independent thinking (Langer, 1989), and both of these are adaptive skills, even if they are not related to creativity. We begin by examining the research using EEG.

## 2. EEG AND DIVERGENT THINKING

EEGs detect the electrical signals that constitute the information flow within the brain. A set of electrodes is placed on the human skull and allows active neuron networks to be monitored. This enables EEG machines to provide data instantly. The downside is that the EEG technique has poor spatial resolution. It can be difficult to detect the exact location of the observed neural activity and in majority of studies the electrodes are on the scalp and not implanted.

A few concepts are needed to interpret the EEG research on DT. These include *event related activity*. Before an individual is given a DT task, the individual's basal neural activation level is recorded. This activation level is referred as the resting brain state and is used to calculate event-related changes that occur after the individual is given a DT task. Event-related changes can be caused by both internal neural activity or an external stimulation (Kalcher & Pfurtscheller, 1995), but the interest here is in event-related power changes in neural activity detected by the EEG after an individual's neural system reacts to an external source. Two types of event-related power changes are relevant: Event-related Synchronization (ERS) and Event-related Desynchronization (ERD).

ERS refers to the power increases relative to the resting brain state that are observed after an individual's neural system is induced (Pfurtscheller & Lopes da Silva, 1999). There is evidence that ERS is the reflection of low excitability of neurons and neural inhibition (Klimesch, Sauseng & Hanslmayr, 2007). This neural inhibition is thought to hinder task-irrelevant neural activity in order to allow task-related memory retrieval to be conducted more efficiently (Klimesch et al., 2007). ERD, on the other hand, is the opposite of ERS. ERD refers to the power decreases relative to the resting brain state that are observed after an individual's neural system is induced (Pfurtscheller, 2001). As opposed to ERS, ERD is thought to indicate activation of neurons and enhanced information processing and memory retrieval that are related to the activity being worked on at that moment (Klimesch et al., 2007; Pfurtscheller, 2001).

EEG apparatus monitors neural activity in five different *signal wave patterns*: delta, theta, alpha, beta, and gamma. Frequently, neuroscientists focus on alpha waves. The origins of alpha wave are thought to be caused by rhythmic fluctuations of inhibitory neurons (Klimesch et al., 2007). In many study settings, alpha waves are divided into two levels: lower and upper. Lower alpha wave is associated with attentional processing whereas upper alpha wave is associated with semantic processing (Klimesch et al., 2007). Beta wave is monitored in some studies. Beta wave is thought to indicate cognitive and emotional processing (Ray & Cole, 1985).

*Coherence* is an indication of the phase and amplitude consistency between pairs of signals (Bendat & Piersol, 2000). As long as the phase and amplitude difference maintains its

consistency, two signals that have coherence can have different activation patterns (Srinivasan, Winter, Ding, & Nunez, 2007). As opposed to coherence, decoupling of brain areas indicates inconsistency between pairs of signals in terms of the phase and amplitude differences.

### 3. FINDINGS OF EEG STUDIES

#### 3.1. Event-Related Activity in Overall Analyses

The first EEG studies on DT were conducted by Martindale and Hines (1975) and Martindale and Hasenfus (1978). Both reported that participants exhibited ERS during idea generation. Martindale (1999) described ERS during DT in terms of *low cortical arousal*. EEG studies of DT tend to support this theory.

ERS was more prominent than ERD in many studies during DT. Fink et al. (2009), for instance, found that ERS was greater during Alternative Uses (AU) DT task in both alpha waves. Grabner, Fink, and Neubauer (2007) observed the same. In this study, EEG activity was recorded when the participants were generating ideas to explain possible causes of two Insight Problems (IS). The problems were light in darkness, and Person A is lying, Person B is sitting, and Person C is standing, respectively. During the tasks, ERS was recorded in both alpha waves. Fink and Neubauer (2006) recorded EEG activity while the participants were working on a series DT tasks (e.g., AU and IS). In overall analyses, ERS was recorded to be stronger during the tasks.

ERS recorded during DT tasks has different magnitudes in the two hemispheres and across different brain regions. The right hemisphere usually displays stronger ERS than the left. ERS observed when working on a Uses DT task was stronger in the right hemisphere in both alpha waves (Fink, Graif, & Neubauer, 2009; Fink et al., 2009). Stronger right hemispheric ERS was also recorded while the participants were working on IS (Fink & Neubauer, 2008; Grabner, Fink, & Neubauer, 2007). In terms of ERS magnitude differences across different brain regions, it was observed that the prefrontal regions exhibited stronger ERS than the central, temporal, and parietal regions (Fink & Neubauer, 2006; Fink, Graif, & Neubauer, 2009; Fink et al., 2009).

While ERS is observed to be more prominent most of the time, ERD was also a part of the process and reported to be stronger during DT by Jausovec and Jausovec (2000). They also used a Uses DT test, as well as a figural DT task (picture completion). The figural task presents an ambiguous line drawing and examinees are asked to list everything it represents. Jausovec and Jausovec found that ERD was greater in the lower alpha wave in both types of tasks with the figural DT task generating the highest ERD. The ERD difference between the verbal and figural DT tasks was the largest in the bilateral occipital and left frontal regions.

Razoumnikova (2000) asked participants to generate ideas to measure a poisonous snake's length. ERD in both alpha waves was recorded during the task. This ERD was most prominent in the central regions. In the upper beta wave, however, participants exhibited ERS. Similar findings were obtained by Jauk, Benedek and Neubauer (2012) where the participants worked on Uses DT test. Here ERD was recorded in the prefrontal and posterior regions. ERD was stronger in the left hemisphere than the right hemisphere especially in the centrotemporal and parietooccipital regions.

There is also research conducted with other types of DT tasks, such as Name Invention (NI), sentence generating, and sentence completing. These tasks are slightly different from the DT tasks mentioned above because they are correlated with verbal intelligence (Staudt & Neubauer, 2006). Still, even with this correlation with verbal intelligence, similar results have been reported. Danko, Shemyakina, Nagornova and Starchenko (2009), for instance, asked the participants to complete Russian proverbs creatively. In the study ERS was recorded in the upper beta wave. Benedek, Bergner, Konen, Fink and Neubauer (2011) had the participants generate sentences by using four initial letters (e.g., CAKE). ERS was detected in the alpha wave in frontal lobes and in right-hemispheric parietotemporal brain regions during the task.

As opposed to ERS, ERD was recorded by Fink et al. (2009) where the participants were generating names by using two-letter initials. ERD observed during task was most prominent in the posterior regions in both alpha waves.

In sum, when no comparison among groups or conditions is made, ERS usually appears to be more dominant during DT; however, ERD is apparently also a part of DT process. Overall, it can be concluded that the neural activation level usually tends to decrease during DT in the entire brain, but this decrease is more prominent in the right hemisphere and in the frontal regions. When activity level increases, the effect of this increase is still greater in the left hemisphere and in the temporal, central, and parietal regions.

### **3.2. EEG-Related Activity and Group Differences**

When attempting to make a general comparison between any two groups in terms of the brain activity observed during DT, a high number of variables may confound or even contaminate the results. This may be why the findings of different studies often contradict each other. There is not firm conclusion about whether or not group differences in fact exist or observed differences are due to variations in DT tasks.

Particularly important is to consider gender. We cannot conclude that there is a particular way of thinking for males or females when working on a DT task, but studies indicate that males and females have different activation patterns during DT. Fink and Neubauer (2006) found that males displayed higher ERS in the right hemisphere compared to females. In addition, females with high verbal intelligence exhibited stronger ERS than females with average verbal intelligence whereas males with high verbal intelligence exhibited less ERS than males with average verbal intelligence. When not verbal intelligence, but creativity skills are taken into account, relatively opposite results were obtained by Razumnikova (2004). In the study, the participants were asked to generate ideas on how to measure a poisonous snake's length. Average creative males and females exhibited similar brain activity in the lower alpha wave which was ERD in the frontal cortex. Highly creative males displayed more ERS in the upper beta waves than average creative males whereas highly creative females displayed less ERS in the upper beta wave than average creative females.

When gender is controlled, group differences are relatively easy to identify. Jausovec (2000) compared activity differences among gifted (with high IQ and high creativity), creative (high creativity and average IQ), intelligent (high IQ and average creativity) and average (average IQ and average creativity) participants during verbal and figural DT tasks. The tasks were things making noise, AU, how radio and telephone are alike, and 3 unfinished pictures respectively. It was found that gifted and creative participants exhibited higher ERS than intelligent and average participants in both alpha waves. In addition, the gifted group displayed the highest ERS among all groups.

Fink and Neubauer (2008) studied neural activity differences between extraverts and introverts. Results showed that extraverts displayed higher ERS than introverts. Staudt and Neubauer (2006) compared the brain activity differences between achievers and underachievers. The participants were divided into two groups based on their grades. While working on AU, underachievers exhibited lower ERD in the anteriofrontal, frontocentral and centrotemporal regions than achievers. Achievers, on the other hand, displayed lower ERD in the centroparietal, parietotemporal and parietooccipital brain regions than underachievers. Fink, Graif and Neubauer (2009) studied EEG performance differences between professionals and novice dancers during AU. After the analyses, it was found that professional dancers exhibited higher ERS in the frontal regions than posterior regions whereas novice dancers displayed no significant ERS differences among brain areas. Overall, the magnitude of ERS was higher in professional dancers.

Finally, Fink, Grabner, Benedek and Neubauer (2006) studied the effects of DT training delivered via software on neural activity. The participants were given a series DT tasks (e.g., IS, AU and NI). Overall, ERS was detected during DT with the right hemisphere displaying

higher ERS. It was found in the post test that the training group exhibited stronger ERS in the frontal regions than the control group.

In summary, there is evidence to suggest that males and females use different strategies and exhibit different activation patterns while working on a DT task. However, it is not possible to pinpoint specific brain regions or event-related activity changes for either gender. When gender is controlled, it becomes clearer that highly creative individuals, extraverts, those who are experts in a field (e.g., dancing), those who receive DT training and those who have poor focused attention skills (e.g., underachievers) display lower levels of neural activation (i.e., higher ERS), especially in the frontal regions.

### **3.3. EEG-Related Activity Related to Manipulation of the Process**

Findings from studies show that manipulating the DT process through instruction influences brain activity. Jauk, Benedek and Neubauer (2012) studied the effects of instruction on DT. The participants were given Word Association (WA) task and AU, and told to generate common and original responses respectively. When being instructed to generate common ideas in both tasks, the participants exhibited higher ERD than when being instructed to generate original ideas. During the original idea generation condition, lower ERD was recorded during WA whereas ERS was recorded during AU. Razumnikova, Volf and Tarasova (2009) compared neural activity between two instruction conditions: when the participants were just told to generate ideas and when the participants were told to generate original ideas. In the study, the participants were given a verbal task (sentence generating with 3 words) and a figural task (picture completion). When the participants were just told to generate ideas, ERD in both alpha waves increased compared to the other instruction condition where the participants were asked to generate original ideas. In the upper beta wave, on the other hand, ERS increased when participants were just told to generate ideas compared to the other instruction condition.

In another study, Fink, Schwab and Papousek (2011) compared neural activity among three conditions during AU task: one with being exposed to others' ideas, one with positive affective stimulation via video clips and one with no intervention. Overall, ERS in the right hemisphere, especially in prefrontal regions in the alpha wave was recorded. In addition, ERD was observed in the parietal, occipital and temporal regions of the left hemisphere in the same wave. Among all conditions, the highest ERS in the alpha wave was obtained during exposure to others' ideas and the lowest was obtained during the no-intervention condition. ERS in the alpha wave increased significantly in the dorsolateral prefrontal cortex when participants were exposed to others' ideas and given a video clip. In the no-intervention condition small ERD was recorded in the temporal areas.

Volf and Tarasova (2014) studied the effects of monetary reward on figural DT. The participants were given incomplete pictures and asked to draw pictures under two conditions: with no reward and with a monetary reward. In the monetary reward condition, ERD in the lower alpha wave was observed. In the monetary reward condition, females displayed left hemispheric ERS in the lower alpha wave whereas males did not exhibit any hemispheric activation difference. In both beta waves, neural activation increased significantly in the temporal and temporooccipital cortices in the monetary reward condition. It should be noted that in the monetary reward condition, the participants generated fewer ideas compared to no-reward condition.

Benedek, Schickel, Jauk, Fink, and Neubauer (2014) studied neural activity while the participants were working on two types of DT task under two conditions. The participants were given AU and four-word sentence (FS) generation task. The same stimuli used for both tasks. In the first condition, a stimulus was reflected on a screen until the next one came on. In the second condition, a stimulus disappeared after 500ms. Overall, the participants exhibited ERS in AU in the posterior regions whereas ERD was detected in FS in the same regions. When the stimuli disappeared after 500ms in FS, the magnitude of ERD decreased in the right

parietal and occipital regions. The two conditions did not have a significant impact on the neural activity related to AU. The posterior regions of the right hemisphere displayed higher ERS than the left hemisphere in both conditions.

Findings of different studies show that the overall neural activation level may either increase or decrease when an individual is told to generate common or original responses. These indicate that for some ideas an individual may actively evaluate whether an idea is common or original when being told to generate common or original ideas. This evaluation process in turn, increases neural activation level. Expecting a monetary reward also has the same effect. Individuals most likely exhibit lower levels of neural activation, especially in the prefrontal cortex when they are exposed to others' ideas. This may be because an individual does not need to give extra effort to initiate activation in certain neural structures to find a new association for an idea because the idea and the association have already been given to him or her. The reason why lower levels of neural activation occurs during a video clip inducing positive emotions is most likely because an individual gives into a more relaxed state of mind and can use defocused attention skills more efficiently.

### **3.4. Hemispheric Coherence and Divergent Thinking**

There is reasonable consistency in findings about event-related activity changes and overall DT process, but coherence findings on DT vary. Jausovec and Jausovec (2000), for example, reported that when working on the figural DT problem, participants displayed more of an intra-hemispheric decoupling between the temporal electrodes and frontal electrodes in both hemispheres. In overall analyses, inter-hemispheric decoupling was greater in the figural task. This inter-hemispheric decoupling was observed between the right frontal electrode and the left parietal electrode. In the upper alpha wave, however, decoupling between frontal and parietal, temporal and parietal, and prefrontal and temporal electrodes as well as greater inter-hemispheric cooperation between the frontal electrodes were observed. Razoumnikova (2000) compared Convergent Thinking (CT) related coherence with DT related coherence. Inter-hemispheric coherence was increased during both CT task and DT task in both alpha waves and the upper beta wave. Compared to CT and the resting state, the right hemispheric coherence increased in the upper beta wave during DT and was greater than the left hemispheric coherence. Inter-hemispheric coherence was greater between the central-caudal regions.

### **3.5. Hemispheric Coherence and Group Differences**

As it is the case for event-related activity changes, findings on coherence also indicate that males and females use different strategies and exhibit different activation patterns during DT. Razoumnikova, Volf, and Tarasova (2009) found in overall analyses that when both genders were told to generate original ideas in a figural task, they exhibited lower intra-hemispheric coherence in the upper beta wave in both hemispheres compared to the baseline. However, only females displayed greater intra-hemispheric coherence in the upper alpha wave in the right hemisphere when being told to generate original ideas. In addition, in the upper beta wave, females displayed greater right-hemispheric coherence when just being told to generate ideas. When participants were told to generate original ideas in the verbal task, they displayed greater intra-hemispheric coherence in the lower and upper alpha waves. In males, however, inter-hemispheric coherence was greater during the figural task and lower during the verbal task compare to the baseline. Razoumnikova (2004) compared coherence differences between highly creative and average creative participants. In overall analyses, the right hemispheric coherence increased in highly creative individuals, but decreased in average creative individuals compared to the baseline. Highly creative males displayed increase in the inter-hemispheric coherence in the lower alpha and upper beta wave. Highly creative females, on

the other hand, displayed decrease in the inter-hemispheric coherence in the lower alpha and upper beta waves.

Coherence differences between highly creative and average creative individuals are clearer when gender differences are controlled. Razoumnikova (2000) found that highly creative individuals had greater right intra-hemispheric coherence and greater inter-hemispheric coherence than average creative individuals especially in the upper alpha waves. This right intra-hemispheric coherence of highly creative individuals was most prominent between the central and parietal regions. In addition, highly creative individuals exhibited greater long-distance inter-hemispheric coherence between the left occipital and right frontal regions. Along the same lines, Jausovec (2000) found that highly creative individuals exhibited greater inter- and intra-hemispheric coherence. High IQ individuals, however, displayed greater decoupling of brain areas than average IQ individuals. During DT problems highly creative individuals showed more cooperation in the lower alpha wave. In the upper alpha wave, however, highly creative individuals displayed more decoupling of brain areas. In the upper alpha wave, again, high IQ individuals showed more cooperation between brain regions in the right hemisphere during DT tasks. High IQ individuals displayed more decoupling of brain regions in the lower alpha wave during DT tasks.

Results indicate that there is no single coherence pattern observed during DT. It seems that DT benefits almost equally from hemispheric coherence and decoupling. The fluctuation in hemispheric coherence is understood better when event-related activity changes are taken into account. Previously, we showed that individuals exhibit different event-related activity patterns in both hemispheres and across various regions. Some brain regions exhibit activation increases whereas some other brain regions exhibit activation decreases. In light of this, coherence results indicate that event-related activity changes across brain regions sometimes maintain amplitude differences and sometimes these amplitude differences increase or decrease due to an unexpected neural activity. This unexpected neural activity can be caused by a new association an individual has just activated. This may increase neural activation levels in the central, temporal and parietal regions. Another possibility is related to the neural activity caused by attentional skills. In this case, the frontal regions most likely exhibit small increases in neural activity, but other brain regions do not have the same increase to maintain coherence.

#### **4. fMRI AND DIVERGENT THINKING**

When a group of neurons is activated, they use more oxygen, and as a result, the oxygen flow towards that particular neuron group increases compared to the resting brain state. The amount of oxygen used by the active neurons creates a ratio between the resting and active brain state (Heeger & Ress, 2002). This ratio is called *Blood Oxygen Level Dependent* (BOLD) signal and fMRI technique depends on this chemical process to report neural activation. The BOLD signals can be caused by oxygen carried by larger vessels as well as smaller capillaries (Heeger & Ress, 2002). These blood vessels and capillaries also carry oxygen to adjacent neuron groups that are not activated, but close to active neurons (Huettel, Song & McCarthy, 2009). It should also be noted here that BOLD signals may vary across the brain and are affected by individual differences (Kalbfleisch, 2008). These points need to be kept in mind when interpreting fMRI results. Unlike EEG machines, fMRI machines are good at detecting the location of the observed activity; however, fMRI technique does not provide data as instantly as EEG technique does.



## **5. FINDINGS OF fMRI STUDIES**

### **5.1. fMRI and Overall Analyses**

Various brain regions exhibit higher activation during DT compared to the resting state. These regions are not restricted in one brain lobe or few certain brain areas. Instead, the active brain regions are located all over the brain and display bilateral as well as unilateral activation patterns. These are supported by fMRI studies.

Fink et al., (2009) studied brain activity during a series of DT tasks (e.g., NI and AU). Overall, it was found that the frontal gyrus, precentral gyrus, anterior cingulate cortex, inferior parietal gyrus, superior parietal gyrus, and inferior temporal gyrus of the left hemisphere displayed the higher activation during the tasks. Bilateral hippocampus, left angular gyrus and the left thalamus were more active during AU whereas the right middle frontal gyrus, inferior occipital gyrus and the inferior temporal gyrus were active in NI task. In another verbal DT task, generating words from a single letter, Badzakova-Trajkov, Häberling and Corballis (2011) found that the participants displayed neural activation in the inferior frontal gyrus, precentral gyrus, inferior parietal lobule and bilateral inferior occipital gyri.

Ellamil, Dobson, Beeman, and Christoff (2012) recorded neural activity during idea generation and idea evaluation processes of DT which was creating a book cover based on a description. Compared to the baseline, greater activation in bilateral inferior parietal lobule, the left inferior frontal gyrus, bilateral superior parietal lobule, bilateral middle temporal gyrus and left cerebellum was observed during idea generation. During idea evaluation, on the other hand, anterior cingulate cortices, dorsolateral prefrontal cortices, medial prefrontal cortices and posterior cingulate cortices in both hemispheres were more active compared to the baseline.

Shah et al. (2013) studied neural activity during brainstorming for creative writing. During brainstorming the participants displayed bilateral activation, but the activation in the left hemisphere was stronger than the activation in the right hemisphere. The strongest activation patterns during brainstorming was observed in the left inferior frontal gyrus, left parieto-temporal regions, anterior temporal regions and right inferior frontal gyrus.

Benedek et al. (2014) studied neural activity related to two kinds of ideas when the participants were working on AU. Specifically, they compared neural activity when original ideas were retrieved from long term memory with neural activity when original ideas were generated. Overall, DT was associated with neural activation in the left inferior frontal gyrus, superior frontal gyrus, inferior temporal gyrus, superior temporal gyrus and bilateral precentral gyrus. In addition, brain activation in the right temporoparietal junction, precuneus and posterior cingulate gyrus decreased in overall DT. When new ideas were generated, significant activation was observed in the left inferior parietal cortex. No significant activation was detected when old ideas were retrieved from memory. Based on the findings, it can be concluded that new and old idea generation is affected by episodic memory.

Huang et al. (2013) studied neural activity in non-artists. The participants were given figural DT task. Moreover, they also were asked to generate non-original ideas. The left middle prefrontal cortex, the left inferior frontal gyrus and the right middle occipital lobe exhibited greater neural activation during DT compared to unoriginal idea generation. Neural activation in the left parietal lobe was lower during the DT task compared to unoriginal idea generation. While working on a DT task, neural activation in the left middle prefrontal cortex and inferior frontal gyrus increased whereas neural activity in the right middle prefrontal cortex and the left inferior parietal lobe decreased.

### **5.2. fMRI Findings Related to Idea Sharing**

Similar with EEG findings on idea sharing, fMRI studies also support that idea sharing influences neural activation during DT. Fink et al. (2010) studied the effects of idea sharing

during AU. When participants were exposed to others' ideas, stronger activation was detected in the cingulate gyrus, bilateral superior parietal cortex, the right temporo-parietal cortex and the medial orbitofrontal gyrus compared to no stimulation condition. Fink et al. (2012) studied the effects of exposure to others' ideas during DT. When participants were exposed to common ideas, middle temporal and superior frontal brain regions of the left hemisphere exhibited stronger neural activation compared to no-stimulation condition. When participants were exposed to original ideas, stronger neural activation in the middle and superior temporal gyri in the left hemisphere was detected compared to no-stimulation condition. During exposure to original ideas neural activation in the bilateral superior parietal cortices and right supramarginal gyrus decreased. Neural activation differences were observed in the left-hemispheric hippocampus and in the parahippocampal gyrus as well as in the inferior temporal cortex, fusiform gyrus, mid temporal, and inferior occipital brain regions between the two conditions. These brain regions were more active during exposure to original ideas.

### **5.3. fMRI Findings Related to Group Differences**

When looking at the fMRI studies of DT, it is again apparent that males and females activate different parts of their brains when working on a DT task. Abraham, Thybusch, Pieritz and Hermann (2013) studied gender differences during two DT tasks (AU and object location). Overall, in both DT tasks males showed stronger activation in the hippocampal formation, amygdala, retrosplenial cortex, orbitofrontal cortex, and the inferior frontal gyrus. Females, on the other hand, activated the dorsal and ventral medial prefrontal cortex of the right hemisphere, temporal poles and temporoparietal junction of the left hemisphere, and the right posterior cingulate cortex. Compared to object location task, more activity in the left hemisphere in both genders was detected in the AU task. Males displayed stronger activity in the left inferior frontal gyrus, right orbitofrontal cortex, inferior temporal gyrus and inferior parietal lobule compared to females in AU. Females, on the other hand, exhibited stronger activation in the anterior and posterior superior temporal gyri, superior parietal lobule than males in AU.

Kleibecker, Koolschijn, Jolles, DeDreu, and Crone (2013) studied neural activity differences between adolescents and adults while the participants were working on AU and object characteristics task. It was found in AU that left supramarginal gyrus, bilateral middle temporal gyri, left angular gyrus, left medial frontal cortex, inferior frontal gyrus and middle frontal gyrus displayed neural activation. While working on the object characteristics task, the participants displayed activation in the bilateral posterior supramarginal gyri and anterior angular gyri. Analyses showed that adults exhibited more activation in the left inferior frontal gyrus and middle frontal gyrus than adolescents while working on AU.

Vartanian et al. (2013) studied the effects of working memory training on DT. All participants received training delivered via software. One group of participants worked on n-back task as a part of the training whereas other group of participants worked on 4-choice reaction time task. Overall, activation in the left dorsolateral prefrontal cortex and anterior prefrontal cortex was detected when the participants were working on AU. Participants who received n-back training exhibited lower neural activation in the right ventrolateral and dorsolateral prefrontal cortex than the participants who received 4-choice reaction time training. There was no performance difference between the two groups.

## **6. DISCUSSION**

EEG and fMRI studies often report different activation patterns, but there is some agreement between EEG and fMRI findings on DT. Both EEG and fMRI studies show that when an individual is involved in DT, he or she displays bilateral neural activation. Although increased neural activation is also a part of DT process, during DT the neural activation levels most

likely decrease compared to the baseline and the brain enters a low excitability state. This point has especially been supported by EEG studies reporting stronger ERS. In this low excitability state the left hemisphere usually exhibits stronger neural activation than the right hemisphere. In addition, the neural activation level in the frontal regions tends to decrease, and in turn, relatively stronger neural activation in the temporal, central, and parietal regions becomes more prominent.

Because an individual does not need to process information which is thought to take place in the prefrontal regions (Fakhri, Sikaroodi, Maleki, Oghabian, & Ghanaati, 2012; Klimesch et al., 2007), neural activation in the prefrontal regions while DT most likely decreases. This indicates that focused attention skills are not strongly needed during DT. Quite the contrary, defocused attention is essential. Defocused attention allows individuals not only to process different aspects of a situation, but also to activate additional neural structures in long term memory and find new associations (Gabora, 2010; Mednick, 1962; Mendelsohn, 1976). In fact, study showed that hyperactive children, who had poor focused attention skills and had working memory impairments, were more original in their responses compared to those with no attention disorder (Shaw, 1992). Similarly, Takeuchi et al., (2011) found that working memory performances and DT were not correlated with each other.

The reason why the left hemisphere and the temporal, central, and parietal regions exhibit more activation is most likely related to long term memory, especially semantic memory. The general view on long term memory is that long term memory representations are kept in the frontal, temporal, and parietal cortex (Dietrich, 2004). In addition, verbal memory is thought to depend more on the left hemisphere and non-verbal memory is thought to depend more on the right hemisphere (Eichenbaum, 2002). Simmons, Hamann, Harenski, Hu, and Barsalou (2008) hypothesized that certain neural structures in the left hemisphere (e.g., inferior frontal gyrus) contain superficial memory representations whereas bilateral parietal and temporal cortices are involved in more complex long term memory representations (e.g., spatial context, episodic memory and emotions). In their meta-analyses Binder, Desai, Graves and Conant (2009) focused on semantic memory only and identified seven key brain regions that are responsible for semantic memory. These brain regions are posterior inferior parietal lobe, temporal cortex, ventral temporal cortex, dorsal medial prefrontal cortex, inferior frontal gyrus, ventromedial prefrontal cortex of the left hemisphere, and bilateral posterior cingulate cortices.

Results show that the left inferior parietal lobe, the left inferior frontal gyrus and bilateral posterior cingulate cortices usually display activation during DT. There might be two reasons why the left hemisphere exhibits more activation during DT. The first reason is because most of the semantic memory traces are kept in the left hemisphere and an individual uses these traces when working on a DT problem. However, the semantic memory traces in the left hemisphere most likely include primary associations. These primary associations can be thought of as the basic features and superficial representations of a concept or an object. For example, some primary associations for a tin can might be related to its material, use or size, such as aluminum, and its being a container and round. When an individual needs to generate alternative uses for a tin can, he or she activates these primary associations first which usually happen to be common ideas.

Another reason why the left hemisphere displays more activation during DT is that individuals most likely keep using these primary associations as a gateway to original ideas whenever they have a change or shift in focus. In addition, it is most likely that individuals shift in focus between superficial representations and more complex representations when involved in thinking (Simmons et al., 2008). For example, once an individual activates neural structures related to a tin can's material, he or she activates new neural structures related to that material. These new neural structures may be considered secondary neural structures. These secondary neural structures can be thought of as more complex representations of the object. For example, some secondary associations related to a tin can's material might be recycling, sharpness and durability. These secondary associations most likely activate new

associations as well, such as personal experiences that can be related to tin can and its physical characteristics. The most important thing here is that most of the secondary associations and additional other associations activated through the secondary associations are probably kept in the right hemisphere. This is why the right hemisphere usually exhibits stronger ERS during DT because the task-irrelevant information in the right hemisphere is blocked through ERS in order to increase the amount of task-related associations and semantically related information. To us, this is how the right hemisphere contributes more to DT.

This hypothesis is also supported by the findings of a lesion study conducted by Shamay-Tsoory, Adler, Aharon-Peretz, Perry, and Mayseless (2011). Strong evidence for the relation between the right hemisphere and originality was reported, with both figural and verbal DT tasks administered. These are drawing a picture by using 30 circles and AU respectively. Overall, it was found that lesions in the right hemisphere deflate DT performance and originality whereas lesions in the left hemisphere inflate DT performance and originality. The left inferior frontal and posterior lesions were correlated with higher originality because patients with lesions in the left temporoparietal region, including the inferior parietal lobule, and patients with left inferior frontal gyrus lesions exhibited high originality scores. These results indicate that patients with the right hemispheric lesions are forced to use primary associations in the left hemisphere, so that they cannot generate as many original ideas as healthy individuals. As opposed to this, high originality scores caused by lesion in the left inferior frontal gyrus and the left inferior parietal lobule support the assumption that the patients who had lesion in these two regions were most likely forced to skip primary associations and activate the secondary associations which are kept most likely in the right hemisphere. Similarly, Grabner, Fink and Neubauer (2007) observed greater right hemispheric ERS in the participants who exhibited high originality in their responses whereas the participants with average originality showed no hemispheric differences.

### **6.1. Neural Activity Related to Group Differences**

Both fMRI and EEG findings vary in terms of neural activity when gender is taken into account. Therefore, we cannot pinpoint certain brain regions or event-related activity changes for either males or females. However, males and females do seem to use different brain regions and exhibit different activation patterns. These differences, however, do not appear to be a disadvantage for either group. Usually study results show that there is no significant difference between males and females in terms of DT performance based on the number of ideas in total and the number of original ideas.

Precise conclusions are also not obvious when gender is controlled. Study results indicate that DT may benefit more from lower levels of neural activation, especially in the frontal regions because those receiving DT training and those who are highly creative have higher originality in their ideas and exhibit stronger ERS. However, there is also evidence that stronger ERS and lower neural activation does not bring better DT performance in terms of originality because extraverts, underachievers and professional dancers showed lower neural activation, but no group differences were computed between extraverts and introverts, achievers and underachievers, and professional dancers and novice dancers. These group differences need to be evaluated carefully because when gender is taken into account, males and females appear to have different activation patterns.

### **6.2. Neural Activity Related to Instruction**

Both fMRI and EEG studies show that manipulation of DT processes through instruction changes neural activity. When an individual is told to generate either original or common ideas, the neural activation tends to increase, especially when generating common ideas. This is most likely because an individual evaluates whether or not an idea is common or original and this evaluation processes increases neural activity.

Exposure to others' ideas also affects the neural activation during DT. During exposure to others' ideas, ERS may increase and additional brain regions may exhibit activation increases. The reason why this is observed during exposure to others' ideas is because when an idea is given to an individual, he or she activates neural structures related to this new idea. In addition, as was previously mentioned, this causes ERD when retrieving the idea as well as ERS that dominates the ERD occurring during retrieval. Thus, overall ERS tends to increase when being exposed to others' ideas.

## 7. CONCLUSION

The conclusions just offered parallel those of Sawyer (2011) and Dietrich and Kanso (2010). When all of the findings are taken into account, it appears that both hemispheres are involved in DT, and DT is accompanied by both event-related increases and decreases in the neural activation. There is a hint that the right hemisphere contributes more to DT. This is implied by the relatively high neural activation in the right central, temporal, and parietal regions during DT which is an indication of semantic processing and re-combination of semantically related information.

There is no longer a paucity of data on the neural bases of divergent thinking, but there are still some inconsistencies among different methodologies and investigations. Some of these may be technological, some a reflection of individual differences, and some variations caused by the lack of standardization of DT administration and testing. Still, the progress is encouraging, especially given that recent rate of research. Most of the research in this area has been done in the last 10 years, and very likely, new insights will be offered within the next few years. Great headway is being made towards refining and standardizing DT testing and scoring, and the brain is not quite the mystery it was even a decade ago.

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