MODAL SHIFTS IN CONCENTRATION INDICATE CREATIVITY

Nguyen, Philon; Zeng, Yong
Concordia University, Canada

Abstract

Modal shifts are said to indicate heightened creativity in the conceptual design process. These modal shifts are traditionally detected using concurrent verbal protocols. However, it is known that verbal protocols fail in some situations such as when dealing with creativity, insight, nonverbalizable and nonconscious processes. It is an open debate in the design literature on verbal protocols whether nonconscious (nonverbalizable) processing is significant or not. We used EEG signals recorded on subjects who were asked to solve design problems on a sketch pad to detect modal shifts in concentration. We found that modal shifts in concentration were often occurring when subjects were erasing completely their previous solution and restarting a new solution from scratch (i.e. tabula rasa event), indicating heightened creativity. From EEG segments where modal shifts in concentration were deemed to be high, we performed source localization using the LORETA algorithm. Cross-checking with the physiology literature on the neurology of creativity, we found that regions of the brains associated with creativity (e.g. prefrontal lobe) were activated during modal shifts.

Keywords: Design cognition, Creativity, Human behaviour in design

Contact:
Philon Nguyen
Concordia University
Concordia Institute for Information Systems Engineering
Canada
philon.nguyen@gmail.com

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1 INTRODUCTION

Modal shifts (Cross *et al.*, 1994) were proposed as a model for detecting creativity bursts in the study of the conceptual design process. Modal shifts are episodes where "especially during creative periods of conceptual design, designers alternate rapidly in shifts of attention between different aspects of their task, or between different modes of activity", or different design strategies (Cross, 2001). Traditionally, these modal shifts are detected using verbal protocol (Ericsson & Simon, 1984). A subject concurrently verbalizes his thoughts while solving a design problem. The recordings of these verbal protocols are then encoded and segmented. When a large number of segments related to ideation and solution generation occurs in a given short time period, modal shifts are said to occur. These modal shifts were found to indicate creativity (Cross, 2001). However, verbal protocols are known to have weaknesses. They are known to fail when faced with nonreportable processes (Chiu and Shu, 2010) such as: creative tasks, insight (e.g. Aha! experience, gestalt), affective judgment, task parallelism or automated tasks (e.g. facial recognition, visual recognition tasks) (Kuusela and Paul, 2000).

While verbal protocols may fail in particular situations, electroencephalograms (EEG) excel at measuring states of mind (e.g. mental effort, concentration, fatigue). It is an open debate whether nonconscious (insight) processing is significant (Ericsson and Simon, 1984). Using source localization techniques, regions of the brain that are activated at a given time can be approximately identified and cross-referenced with the physiology literature. If creativity is said to occur, the prefrontal cortex is most likely to be activated and, if an insight solution (Jung-Beeman, 2004) is said to occur, the right prefrontal cortex and the right anterior superior temporal gyrus are most likely to be activated.

In (Nguyen *et al*., 2015), a method to segment design protocols based on mental effort (measured using EEG transient microstate percentages) was discussed. More specifically, variations in mental effort were used as a heuristic to segment a design protocol into time points. These segments could emulate basic segmentations performed by domain experts while providing insight into hidden cognitive structures that are not easily visible. Following this line of research, we segmented our design protocols using an EEG metric for concentration (i.e. beta band). Concentration "means a work state where cognitive resources are assigned to target work" (Shimoda *et al.*, 2013). In EEG analysis, concentration is associated to the beta band (Baumeister *et al*., 2008). We found that periods of high concentration followed a modal shift model. More specifically, we found that periods of heightened concentration were associated with higher variability of the beta band segmentation of an EEG signal. That is, heightened concentration produced more short duration time segments indicating modal shifts in concentration. These periods of heightened concentration were associated with segments in the design protocols where subjects were rethinking completely their sketched solutions and erasing their previous solution to sketch a new solution (we term those sequences *tabula rasa* events).

Using these beta band segmentations, we isolated segments in the EEG signals where heightened concentration occurs. We then used Low Resolution Electromagnetic Tomography (LORETA) as a method to perform source localization on the associated scalp field data (Pascual-Marqui *et al.*, 1994). Creativity is often associated to the prefrontal cortex. Based on the left/right hemisphere model of brain function, it is known that the right hemisphere is associated with insight (e.g. Aha! experience, not easily verbalizable solutions) while the left hemisphere is associated with logic and language (e.g. verbalizable solutions). Using source localization, we were then able to distinguish insight solutions from verbalizable solutions.

The rest of this paper is organized as follows. Section 2 provides background and a literature review on the limitations of verbal protocols and the neurology of creativity. Section 3 provides information on the EEG analysis methods we used in our experiments. Section 4 describes our experimental setup. Section 5 provides an analysis of our results. Section 6 provides a short conclusion.

2 BACKGROUND AND LITERATURE REVIEW

2.1 Limitations of Verbal Protocols

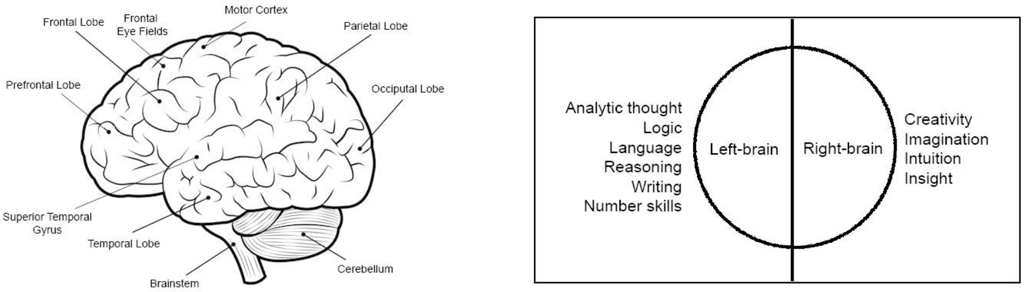

Figure 1. (left) Regions of the brain. (right) Functions of the left/right hemispheres.

Verbal protocols are known to have some limitations. (Wilson, 1984; Kuusela and Paul, 2000) argue that verbal protocol ignore cognitive processes that do not reach the verbalization process. Furthermore, (Wilson, 1984) argues that concurrent verbalization changes the sequence of thought processes (i.e. “the reactive effects of verbal protocol”). In (Schooler et al., 1993), four sets of experiments are performed to show that verbalization impacts problem solving: subjects asked to verbalize their problem solving strategies were significantly less successful than control subjects. Verbalization is shown to affect performance in (Wilson et al., 2013; Schooler et al., 1993; Fallshore and Schooler, 1993; Wilson and Schooler, 1991; Schooler et al., 1991; Schooler and Engstler-Schooler, 1993). (Schooler et al., 1993) states that “certain thoughts have a distinctly nonverbal character” such as creative thoughts and insights (i.e. unexpected problem solutions that just happen, Aha! experience, gestalt). Furthermore, facial recognition is discussed as an example of task that requires large amounts of information that cannot be easily verbalized (Schooler et al., 1993). Creativity and insight are then said to “have occurred in the absence of words” (Schooler et al., 1993). (Wilson and Schooler, 1991) discusses how verbalization distorts the salience of verbal attributes and “overshadows” nonverbal attributes (e.g. cognitive processes such as affective judgment are often ignored using verbalization). Verbal overshadowing happens when a subject’s focus on verbally relevant information against information that is not easily verbalized. Subjectivity of verbal protocols (e.g. self-presentational concerns) is also discussed in (Wilson, 1984). (Smagorinsky, 1989) further reports that subjects have a hard time verbalizing while manipulating objects. (Chiu and Shu, 2010) shows that verbal protocols were faced with limitations in their experiments by contradicting the assumption that stimuli increase concept creativity. In (Chiu and Shu, 2010), three concerns are raised in relation to verbal protocols: time and resource intensiveness (i.e. the technical setup of verbal protocols), data validity and the fact that some tasks are not conducive to verbalization (e.g. task parallelism impacts verbalization that is inherently sequential and automaticity (Rasmussen and Jensen, 1991; Gordon, 1992)). (Schooler et al., 1993; Metcalfe, 1986) note that, in the context of insight problem solving, “subjects who believe that a solution is imminent are engaging in a ‘gradual rationalization process’ that focuses them on an inaccurate yet reportable approach”. (Schooler et al., 1993) lists of few types of insight problem solving tasks as follows: memory retrieval tasks, spreading activation tasks (i.e. how the brain navigates in a network of thoughts), constraint relaxation (i.e. how we remove a constraint on a problem that is false) and perceptual reorganization (e.g. Necker cube illusion). They form a group of “difficult-to-report perceptual and memory processes” (Schooler et al., 1993). Two opposing views about verbal protocols then arise: (Ericsson and Simon, 1984) argues that concurrent verbalization is qualitatively correct while only decreasing the overall performance of problem solving while (Schooler et al., 1993) argues that in the case of insight problem solving, verbalization impedes cognitive processes as it “overshadows” nonreportable processes.

When dealing with hidden cognitive processes, (Wilson, 1984) concludes that verbal protocols cannot be “taken on faith”. There are some tasks where verbal protocols yield poor quality results such as creative tasks, insight (e.g. the ”Aha” experience, gestalt psychology), affective judgment, memory retrieval tasks, task parallelism or automated tasks (e.g. facial recognition, visual recognition tasks). These tasks are sometimes termed as nonreportable processes (Schooler et al., 1993). More specifically, (Wilson, 1984) argues that while verbal protocols are not “completely invalid”, they do not provide “a perfect window into the mind" and by doing so, challenges the positions long held in (Ericsson and Simon, 1984) where it is believed that research has "overestimated the extent of nonconscious processing".

2.2 Neurology of Creativity

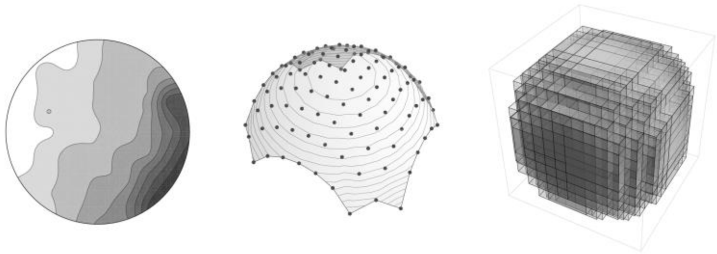

Figure 2. (left) 2-D scalp field map. (center) Interpolated 3D scalp field map using 107 points. (right) Voxels representing the brain using 452 voxels.

The left/right brain paradigm was pioneered by Robert Sperry using the so-called "split brain" experiment (Gazzaniga, 1967). "Split brain" experiments are cognitive experiments on subjects whose corpus callosi (the neurological structure that connects the left and right hemisphere of the brain) has been severed surgically notably as a treatment for epilepsy. More specifically, when such subjects were presented with a visual stimulus to their left brain, they were unable to verbalize it as information was not transferred to their right hemisphere which is known to process visual information. Using these type of experiments, it was found (cf. Figure 1(right)) that the left hemisphere is responsible for analytic though, logic, language, reasoning and writing whereas the right hemisphere is responsible for creativity, imagination, intuition, insight, holistic thought, music and form recognition (Ornstein, 1977). Also, the left hemisphere controls the sensory functions of the right side of the body while the right hemisphere controls the sensory functions of the left side of the body.
In recent functional imaging experiments, it is found that the prefrontal cortex (PFC) plays a crucial role in creative tasks (de Souza *et al*., 2014; Gonen-Yaacovi *et al*., 2013). In these assessments, creativity was often measured using standardized tests of divergent thinking or the Torrance Test of Creative Thinking (Torrance, 2004). Subjects affected with neurodegenerative diseases of the frontal lobes often saw a decrease in their Torrance test score although some notable exceptions to the rule were reported (perhaps due to neuroplasticity). (Jung *et al*., 2010) correlates cortical thickness to higher performance in Creative Achievement Questionnaire (CAQ) tests. Furthermore, it was found that activation of subregions in the lingual gyrus correlated negatively with the Composite Creativity Index (CCI) while the right posterior cingulate correlated positively. (Heilman, 2003; Dietrich, 2004) discuss whether creativity engages predominantly the frontal lobes or posterior brain regions and subcortical structures (basal ganglia).
Evidence that creativity is hard to verbalize can be found in such the concepts that go as far back as the Wechsler Intelligence Scale (Wechsler, 1944), insight (Aha! experience) (Jung-Beeman, 2004) and creative "flow" (the feeling of being fully immersed and focused in an activity (Csikszentmihalyi, 1996)). More specifically, the Wechsler Intelligence Scale also emphasizes non-verbal performance in contrast to other scales such as the Binet test which overly emphasizes on language and verbal skills. In an fMRI study, (Jung-Beeman, 2004) finds that subjects solving problem using insight solutions (Aha! experience) had increased sudden flashes of activity in the right hemisphere anterior superior temporal gyrus. In another fMRI study, (Liu, 2012) shows that improvising musicians (i.e. nonverbalizable and insight task) saw lower activity in their dorsolateral prefrontal cortex and increased activity in their medial prefrontal cortex (cf. Figure 1(left)).

3 EEG ANALYSIS

3.1 Beta Band and Concentration

Beta bands are computed using power spectral densities (PSD) over the beta frequency ranges of an EEG signal (12.5Hz – 30Hz). Many techniques exist to approximate PSD such as correlogram and periodograms. Here we use the modulus of the Discrete Fourier Transform (DFT) of a given sample x within the beta frequency range. This effectively yields the power of the beta wave within the beta frequency range. The PSD is a widely used feature of EEG signals, if not the most widely used. It is effectively used to detect eye-blinking artifacts, sensorimotor artifacts, sleep cycles and other states of mind such as fatigue, concentration and relaxation. The PSD is usually computed on a given electrode of a multichannel EEG such as FP1 (left frontal area).

Following its computation and since such beta power curves are often too high frequency to analyse, we clustered the beta band power curves into 5 clusters and using the cluster segments. From the clustering, we extracted time segments which regrouped samples with similar beta powers. Periods of heightened concentration were determined to be periods that generated many time segments, indicating a high variability in the beta power curves.

3.2 Source Localization

Source localization is an indeterminate inverse problem for which may exist an infinity of approximations. Effectively, the associated forward problem is to map densities in a 3D model of the brain (of *M* voxels – cf. Figure 2(right)) to a 2D scalp field map (of *N* electrodes – cf. Figure 2(left)) - Equation (1):

$$\Phi = KJ \tag{1}$$

where Φ is the N-by-1 vector representing the 2D scalp field map, K is a transfer matrix and J are the *M* densities associated with the *M* voxels model of the brain. Since *M* is usually much greater than *N*, solving Equation 1 for *J* is indeterminate. The approximation for the inverse equation is given by Equation (2):

$$\hat{J} = T\Phi \tag{2}$$

where $\hat{J}$ is an approximation of the densities associated with the 3D voxel model of the brain and *T* is a resolution matrix. Using the LORETA technique (Pascual-Marqui *et al.*, 1994), the resolution matrix is given by Equation (3):

$$T = W^{-1}K^{T}\left[KW^{-1}K^{T}\right]^{+} \tag{3}$$

where *K* is a lead field matrix (in our experiments, for simplicity, we used the lead field of a homogeneous conducting sphere in air with conductivity 0.185 S/m – grey matter conductivity), *W* is a positive definite matrix and + denotes the Moore-Penrose pseudo-inverse. The LORETA solution is said to yield the "smoothest solution capable of explaining the data" (Pascual-Marqui *et al.*, 1994). Since we did not have access to MRI data, we interpolated 2D scalp field maps (Figure 2(left)) to an intermediate 3D scalp representation (Figure 2(center)) using a radial basis interpolating function for scattered data. Furthermore, our brain topology was simplified by using a voxelized sphere (Figure 2(right)).

4 EXPERIMENTAL SETUP

The Design Lab gathered over that past few years datasets of subjects performing various design tasks while having their EEGs monitored and their actions recorded on a touchpad. We used a subset of 8 datasets recorded on 8 different subjects to perform our experiments. We chose these datasets because the quality of the EEG recordings was higher. The questions that the subjects were asked to solve on the touchpad were the following:

- **Problem 1:** Make a birthday cake for a five year old kid. How should it look like?
- **Problem 2:** Sometimes, we don't know which items should be recycled. Create a recycle bin that helps people recycle correctly.
- **Problem 3:** Create a toothbrush that incorporates toothpaste.
- **Problem 4:** In many cities, people on wheelchair cannot use the metro safely because most metros only have stairs or escalators. Elevators are not an option because they are costly. You are asked to create an efficient solution to solve this problem.
- **Problem 5:** Employees in IT companies sit too much. The company wants their employees to stay healthy and work efficiently at the same time. You are asked to create a workspace that can help employees to work and exercise at the same time.
- **Problem 6:** There are two problems with standard drinking fountains: a) filling up water bottles is not easy, b) people too short cannot use the fountain and people too tall have to bend over. Create a new drinking fountain that solves these problems.

After each question, the subjects were asked to sketch a solution. Following the sketch, they were also asked to answer a multiple choice question in relation to the question. They were basically asked to choose the best solution among two proposed solutions. After the multiple choice segment, they were asked to rate subjectively the hardness of each question.
The length of each design session varied between 30 minutes and 2 hours gathering EEG signals samples of length between 1, 000, 000 and 4, 000, 000 points.
Our experimental protocol was approved by the Human Research Ethics and Compliance Department of our university. Subjects volunteered to participate in the experiments. All of them were graduate students from the Quality System Engineering program at our university. The ages of subjects ranged from 25 to 35. Every subject was compensated with a gift card.

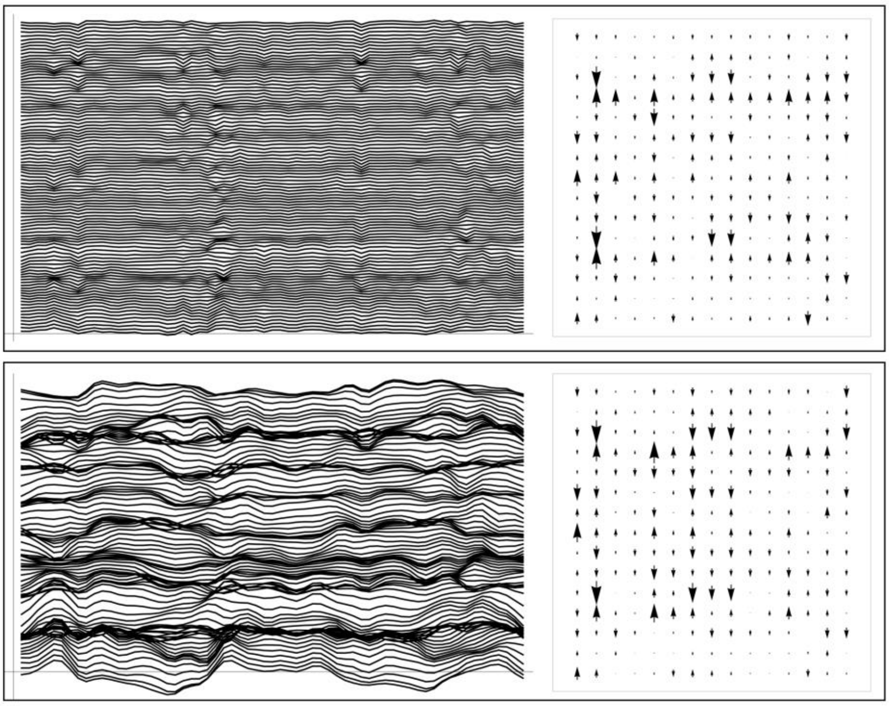

Figure 3. (top-left) Plot of a 100-sample multichannel EEG signal – x-axis displays electrode labels (1-64) and y-axis shows time. (top-right) Gradient field in the time direction. (bottom-left) Plot of a 100-sample multichannel EEG signal that in bandpassed in the beta range. (bottom-right) Gradient field in the time direction. Peaks and changes indicate concentration is high.

5 ANALYSIS

We have found evidence supporting the following:

- Modal shifts in concentration indicate creativity (they often happen when a *tabula rasa* event is under way).
- During modal shifts in concentration, the left and right prefrontal lobes are activated with, as pattern, an alternation between insight (nonconscious, right lobe) solutions and verbalizable (conscious, left lobe) solutions.
- During modal shifts in concentration, dominance of the left and right upper frontal area occured in circa 25% of the samples each.

Evidence gathered through our experiments shows that the importance of nonconscious and nonverbalizable processing should not be ignored and that insight (nonreportable) solutions do effectively occur in the conceptual design process.
As a first step in our analysis, we extracted from the design protocol data available sequences where we determined that concentration was high. High concentration was determined to happen when modal shifts in the beta feature curves occurred. More specifically, we segmented the design protocols using the beta values and when, on short time lapses, many time segments were produced, we determined that a modal shift in concentration occurred. Figure 3 shows an EEG signal and its beta filtering for such a

sequence where concentration was high. Interestingly, we found that such modal shifts in concentration often occurred when subjects were in a *tabula rasa* event. Figure 5 shows a beta segmentation of a design protocol excerpt.

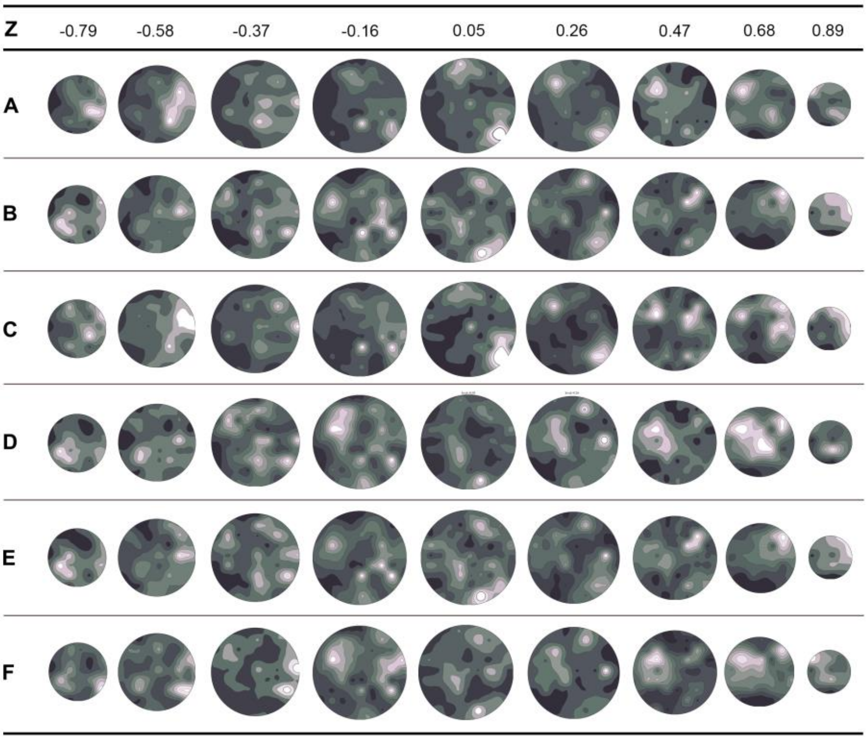

Figure 4. Slices of the spherical 3D model of the brain we used at different z values (-0.79, -0.58, -0.37, -0.16, 0.05, 0.26, 0.47, 0.68, 0.89) which also corresponded to the location of the voxel slices. White denotes high density magnitudes while black denotes low density magnitudes.

Table 1. Approximate regions of the brain activated related to creativity. Timestamps are relative to the beginning of the sequence (with high levels of concentration) excerpted from a design episode. The sequence occurs while a subject is solving Problem 4 and is in a tabula rasa event.

Segment	Timestamp	Activation
A	1 sec.	left frontal and prefrontal lobe, right temporal lobe
B	3 sec.	right frontal and prefrontal lobe, basal ganglia
C	28 sec.	right frontal and prefrontal lobe, left prefrontal lobe, right temporal lobe
D	36 sec.	left/right frontal lobe, left prefrontal lobe, left superior temporal gyrus
E	52 sec.	right frontal lobe
F	58 sec.	left/right frontal and prefrontal lobe, right superior temporal gyrus

We then performed source localization on the samples (scalp field maps) of these excerpts where it was determined that concentration was high. The goal was to determine if these sequences were indicative of higher levels of creativity. If such was the case, modal shifts in concentration would then be indicative of creativity. To determine this, we crosschecked with the physiology literature where creativity is said occur when the prefrontal lobe is activated. Some work shows that creativity also occurs when the right posterior cingulate and the basal ganglia are activated. Furthermore, two types of creativity occur: insight creativity (e.g. Aha! experience and gestalt) and verbalizable creativity (e.g. logic and language). Insight creativity is said to occur when the right prefrontal lobe or the right anterior superior temporal gyrus (right upper temporal lobe) are activated. Verbalizable creativity is said to occur when the left prefrontal lobe is activated. Table 1 shows that activation regions were found to be the left and right prefrontal and frontal lobes, the right temporal lobe and other regions associated with creativity. Activation of the left and right frontal lobe (motor cortex) was most likely due to voluntary movement control (subjects were sketching on a sketchpad). During the segment of the design protocol we analysed, we found that there was an alternation between left prefrontal lobe activation and right prefrontal lobe activation indicating alternation between insight and logical solution finding.

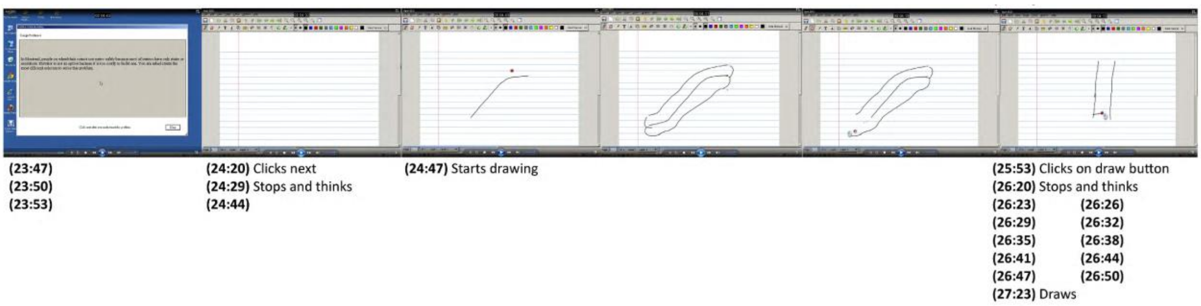

Figure 5. Excerpt from the design protocol data of a subject solving Problem 4. Below are timestamps generated by the segmentation algorithm. At screenshot 6, a large quantity of timestamps are generated. This indicates a modal shift in concentration. In this case, the modal shift occurs while the subject is erasing his previous design and redrawing from scratch a new one (tabula rasa event).

Figure 6. Source localization of a scalp field map of a subject at rest with eyes closed. No significant frontal and prefrontal lobe activation patterns. Left hemisphere of the brain is mostly non-active. Activation can be found mostly in the right parietal lobe and to a lesser degree in the right occipital lobe.

Figure 7. Source localization of a scalp field map of a subject subjectively rating the hardness of a problem (non-creative task). Regions are mostly non-activated (dark gray patches) with activation of the left frontal lobe (speech center activated due to subject reading the rating form). Right temporal lobe and left frontal lobe is slightly activated which may indicate that rating requires insight processing.

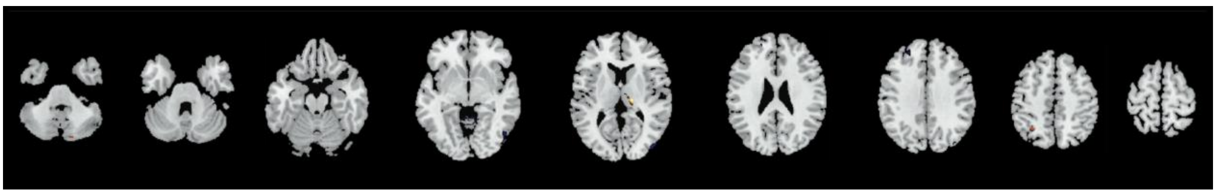

Figure 8. The weakness of the LORETA method is that the lead field matrix assumes the brain model is a sphere with homogeneous conductivity. The brain is actually non-homogeneous and non-spherical. The results of LORETA source localization are therefore only an approximation. Precision is only limited to hemisphere and sometimes lobe information.

Figure 4 shows a sequence of samples that were source localized and Table 1 summarizes the activation patterns of each source localized sample. While in a *tabula rasa* event, a subject’s mind effectively alternates between insight (nonconscious) solutions and verbalizable (conscious) solutions. Figure 6 shows the source localization of a scalp field map of a subject at rest with eyes closed that can be used as a baseline for comparison. Figure 7 shows the localization of a subject rating a question.

To compare activation patterns in the left-frontal-upper and the right-frontal-upper quadrants of our brain model, we determined the number of times the average magnitude per voxel in any of the 8 quadrants of our 3D model was a maximum value. Following this analysis, we determined that the left-frontal-upper quadrant (which contains the left frontal and prefrontal lobes) dominated in 23.68% of samples whereas the right-frontal-upper quadrant (which contains the right frontal and prefrontal lobes) dominated in 26.66% of samples. Although both values are similar, indicating that insight and intuitive solutions were at par with logical and verbalizable solutions, insight solutions can be seen to have a slight edge in the design protocol excerpt we used, emphasizing the importance of nonconscious processing

Although LORETA is only an approximation of source localization (as the underlying matrix equations are underdetermined), we saw a clear activation pattern in the alternation of right and left frontal and prefrontal lobe activation during the design segment where we found modal shifts in concentration. Furthermore, other structures often associated with creativity, such as the superior temporal lobes, were at moment activated. These activation patterns where stable for subsecond periods and quickly shifted to another stable subsecond pattern.

"Modal shifts" seem to be indicative of designer creativity. "The apparent importance of frequent shifts of attention or activity mode in influencing either the creativity or overall quality of the design concepts produced" is discussed in (Cross, 2001; Cross et al., 1994). (Nguyen and Zeng, 2012) describes creativity as a sequence of iterates that can fall into a chaotic state. More specifically, the iterates $\{P_i,K_i,S_i\}$, $\{P_{i+1},K_{i+1},S_{i+1}\}$, $\{P_{i+2},K_{i+1},S_{i+2}\}$,… where P, K, S are Problem-Knowledge-Solution triplets are considered. In our research, we found that concentration (beta band) was better understood using the concept of "modal shifts" as segments of the protocol data where subjects were experiencing *tabula rasa* events (erasing their prior design and replacing it with a new one) were associated with high levels of short duration segments in the beta feature segmentation. In contrast, segments where the beta features were simply elevated did not describe as completely the subject's state of mind as did modal shifts in beta features. These theories (the theory of modal shifts (Cross, 2001) and the nonlinear dynamic theory of creativity (Nguyen and Zeng, 2012)) fit well with the empirical evidence we have found using EEG frequency domain analysis and source localization (LORETA). Although LORETA is only an approximation, we were still able to find a pattern in the activation loci of the EEG signals we gathered while subjects were performing design tasks, which were in agreement with underlying theories on the neurology of creativity.

6 CONCLUSION

We have described the use of frequency domain features (i.e. beta band) of EEG signals to segment design protocols and extract segments where creativity was visibly high (i.e. *tabula rasa* events). We determined that concentration was high when modal shifts in the beta segmentation were occurring, more specifically, when the beta segmentation generated many time segments for a short lapse of time. After extracting these moments of heightened concentration, we applied source localization (LORETA) techniques to the underlying EEG scalp field maps to determine a pattern of activation. We found that in those moments of heightened concentration, there was an alternation between left frontal and prefrontal activation and right frontal and prefrontal activation. This confirms findings in the related neurology literature which reports that prefrontal activation is related to creativity, left prefrontal activation is related to logic and language related creativity (conscious, verbalizable creativity) and right prefrontal activation is related to insight solutions (nonconscious, nonverbalizable creativity). Other activation patterns, such as the superior temporal lobe, were found in agreement with the related literature. These results confirm that nonconscious processing in creativity studies should not be neglected. Our technique offers a complementary alternative to concurrent verbal protocol techniques, which are known to bear limitations when dealing with creativity, affective judgement and insight.

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