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# TOWARDS A NEURO-SCIENTIFIC THEORY OF DESIGN PROCESSES

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TO MY PARENTS, FOR THEIR NEVER-ENDING LOVE AND SUPPORT

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# 1. INTRODUCTION

Design is a multifaceted and complex phenomenon that has been studied over the years by researchers of various disciplines. This consequently lead to varying philosophies and methods to approach the subject. From only being studied as a phenomenon and as a science over the past several decades, researchers have recently started approaching this subject from a neuroscientific point of view.

This thesis is an attempt to lay down the foundations of studying the design process from a neuroscientific perspective. The first step to achieve that goal was to carry out a review and establish a state of the art in existing design research that employed neuroscientific tools. A feasibility study was then carried out to evaluate the pros and cons of existing neuroscientific tools and their applicability to design research. In the end an experiment was designed and conducted, and the results were compiled to evaluate if such techniques are feasible in taking the first step towards developing a neuroscientific theory of the design process.

Chapter 2 starts of by touching on the different definitions and fields of Design, Neuroscience, Creativity and Divergent thinking. The first part explains design science, the design process and outlines the several research methods that have been adopted in order to study the design process. The second part applies the same approach on creativity, divergent thinking and their possible connection to neuroscience. A state of the art in neuroscientific research in design is then established and comparison is provided among the results of the existing research and potential directions that can be adopted for future researcher. Finally, the choice of tool for the experiment is discussed and a research question is proposed.

Chapter 3 explains the design of the experiment. It discussed the process of selecting participants, EEG apparatus, experiment procedures, the tasks and the raw data collected.

The first part of Chapter 4 explains step by step the data preparation and cleaning process in the form of a guide that can be used for similar purposes in future researches. It concludes by explaining the algorithms that were used for carrying out the final analysis.

Chapter 5 compares the findings of our analysis to look for patterns in EEG data and to check if our results are concurrent with existing research. We then conclude with what we learnt from our experiment and how future researches can be designed to obtain more accurate results.

## 2. NEUROSCIENCE AND DESIGN

### 2.1 Design Science and the Design Process

A generic definition of design is essential before moving towards a discussion of design science. As described by Professor John S Gero, design is the process by which man changes the physical and virtual world they inhabit (Gero, 2013). Herbert Simon, a pioneer in the existing understanding of design, also defines it as any purposeful activity that aims at changing existing situations into preferred ones (Simon H.A., 1969). Generic definitions like these are vital to encompass the many generic, yet essential, features of design. Essential to the act of designing is, as pointed out by Herbert's definition, is the clear distinction between desirable and undesirable states. Design is used as both, a noun, as well as a verb. The act being implied by the verb 'designing' while the result implied by the noun 'design' (Gero, 2013).

Simon H.A touches on a much broader view of design in his book "The Sciences of the Artificial" (1969). He incorporates a very wide variety of artefacts that aren't essentially related to technology as was the preceding view. To attract intellectuals towards the development of methods and tools for supporting design, he encouraged to study design from a scientific viewpoint. He stimulated the development of systematic and formalized techniques of research that could be applied across various design disciplines, the most obvious ones being architecture, engineering, computer science and management studies.

Paul Johanesson, provides a comparison of design science to other similar discipline to fully understand its nature. Examples include Medicine and Economics as a science; they develop models to study the working of organisms and economy, respectively, and improve their health in the preferred direction. Though there are similarity among these different fields of science, design science is distinctive by being focused on the design phenomena (Johannesson, 2014:13). Johannesson elaborates further in his book "An introduction to Design Science" that design science also wants to change the world and improve it and not only describe, explain or predict it.

A distinction must be made between the "science of design" which views design as a phenomenon to be studied and "design science" which aims to develop scientifically based methods and tools to improve design action with a normative approach (Cantamessa, 2016:15). Nigel Cross, in his book "Designerly ways of Knowing" makes a further clarification as follows.

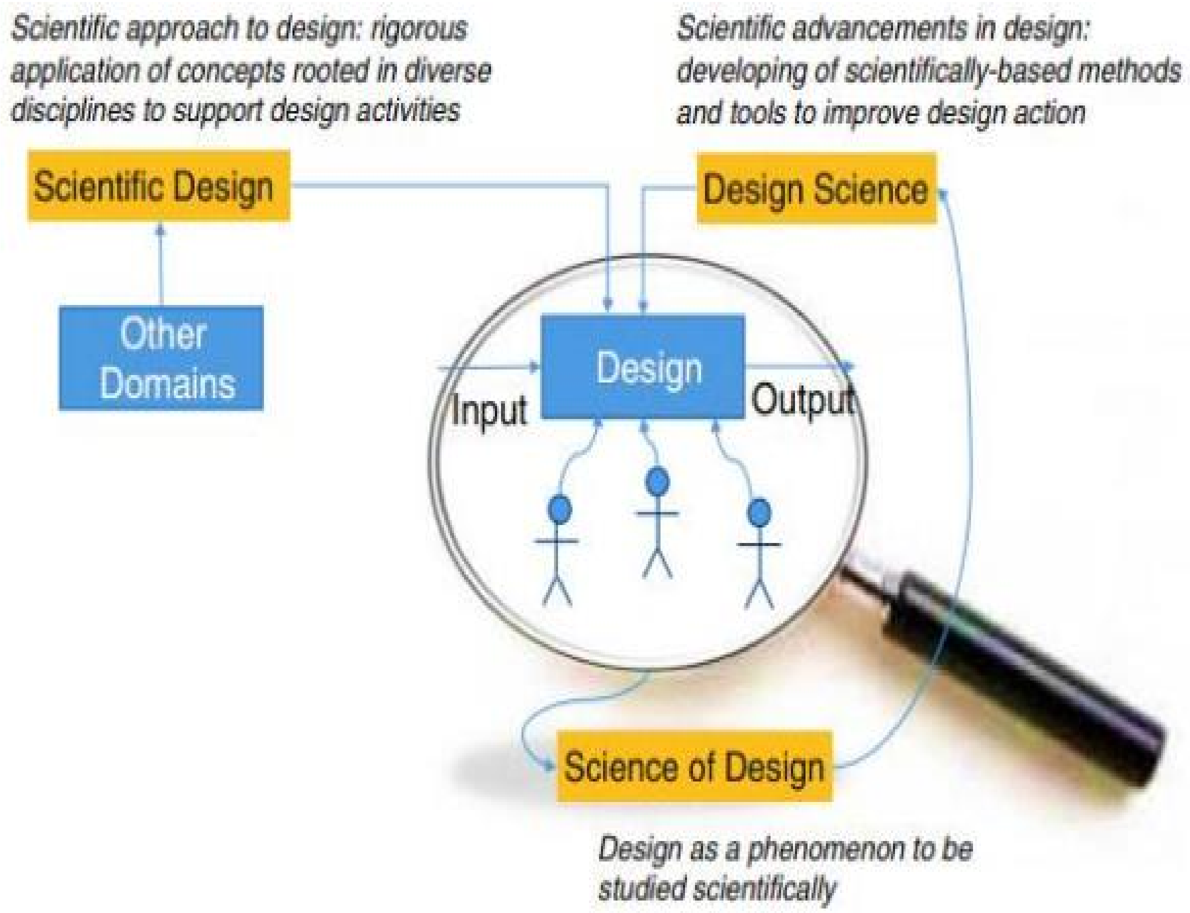



*Figure 1 - The relationships between design and science (Cross, 2001)*

Both design and design science may seem similar by focusing on the development of artefacts and aiming at novelty. Their differences lie in their purpose with respect to their generalizability and contribution to knowledge.

The design process is also described as tackling a problem by following a rigid series of pre-defined steps. These steps mainly involve defining the problem, deducing the requirement specifications, selecting, prototyping and testing along with the development of the testing criteria. The focus of this thesis is on the cognitive process of design. Since a major part of design cognition is visual and not verbal; the cognitive process of designing can be quite complex. Even expert designer can find it challenging to explain the thought process behind their decisions (Suwa, Purcell, and Gero 1998). Professor John S. Gero proposed the Function Behavior Structure ontology of design object, which is often used to model the design process.

### 2.1.1 Function – Behavior – Structure (FBS) Ontology and the FBS Framework

During the 60's and 70's it was difficult to understand if the terms used by different researcher were describing similar or different phenomenon. Looking for regularities in the design process was one way to address this problem. This lead to a proposal of an axiom:

*The foundations of designing are independent of the designer, their situation and what is being designed.*

The Function-Behavior-Structure (FBS) ontology addresses this issue by describing all design no matter what discipline of design it belonged to. The thee fundamental constructs of the FBS ontology, namely, Function (F), Behavior (B) and Structure (S), are defined as follows: Function is the teleology of the artefact ("what the artefact is for"). It is ascribed to the artefact by establishing a connection between one's goals and the artefact's measurable effects. Behavior is defined as the artefact's attributes that can be derived from its structure ("what the artefact does"). Behavior provides measurable performance criteria for comparing different artefacts. Structure is defined as its components and their relationships ("what the artefact consists of").

| | Dwelling | Editing software | Manufacturing process | Team |
|---|---|---|---|---|
| Function (F) | Provide safety, provide comfort, provide affordability | Be time efficient, provide affordability | Be safe, be time efficient, provide sustainability, provide affordability | Be time efficient, provide affordability |
| Behaviour (B) | Strength, weight, heat absorption, cost | Response times, cost | Throughput, accuracy, speed, waste rate, cost | Working speed, success rate, cost |
| Structure (S) | Geometrically interconnected walls, floors, roof, windows, doors, pipes, electrical systems | Computationally interconnected program components | Logically and physically interconnected operations and flows of material and information | Socially interconnected individuals |

*Figure 2 - FBS Examples (Gero, 2004)*

Professor John S. Gero further developed an extension to the FBS ontology in the form of the FBS framework (Gero 1990). The framework basically represents the design process as various transformations between the three FBS constructs (Function, Behavior and Structure). Transformations from function to behavior and vice versa can be considered as the most basic view of designing. Behavior, in this regard can be interpreted as the expected performance to achieve the desired function. Upon producing a structure, it is still important to verify whether the "actual" performance (based on operating environment and structure) match the "expected behavior". Behavior is therefore separated into two different classes by the FBS framework: namely, expected behavior (Be) and behavior derived from structure (Bs).

The FBS framework is characterized by eight fundamental transformations or processes:

| | |
|---|---|
| 1. Formulation | R → F, and F → Be |
| 2. Synthesis | Be → S |
| 3. Analysis | S → Bs |
| 4. Evaluation | Be ↔ Bs |
| 5. Documentation | S → D |
| 6. Reformulation type 1 | S → S′ |
| 7. Reformulation type 2 | S → Be |
| 8. Reformulation type 3 | S → F (via Be) |

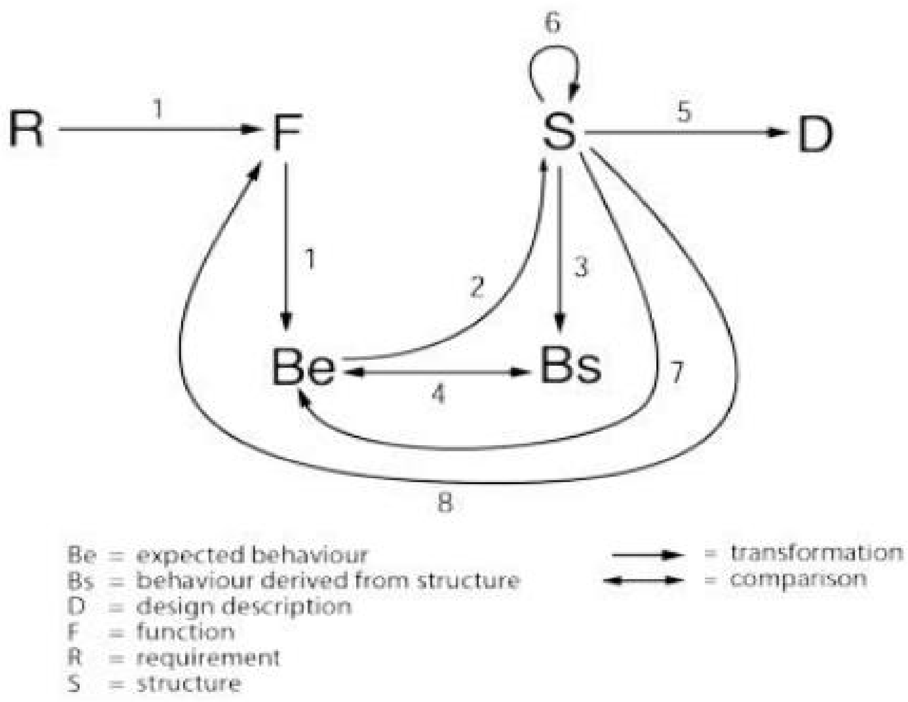



*Figure 3 - The FBS Framework (Gero, 2004)*

The ability of the framework to describe any instance of designing, irrespective of a specific domain or method makes one of the foundations for theory of designing. Experiments to be carried out in this research are focused on investigating the cognitive processes of Analysis (how designers analyze the "behavior derived from structure") and Synthesis (how they come up with a "structure" for the "expected behavior").

### 2.1.2 Design Science – A Brief Modern History

The period from 1920's to 1960's was a period of emergence of understanding design as a scientific, objective and rational activity. The establishment of Staatliches Bauhaus in 1919 (Weimar, Germany), as the first school with a design curriculum, is amongst the most significant milestones in the field of understanding design. Although it was closed due to the Nazi regime in 1933, it eventually led to the establishment of the 'New Bauhaus' in US in 1937. The 'New Bauhaus' then eventually became the foundation of the Institure of Design at Illinois Institute of Technology. The following figure shows the chronology of what was considered design in research alongside the development in science / industry.

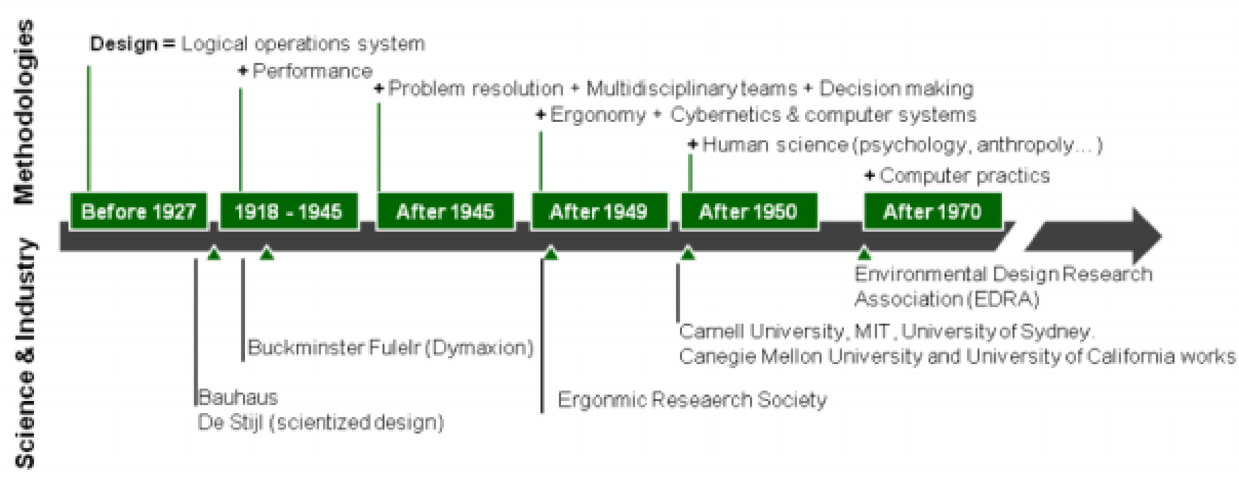



*Figure 4 - Design Research Chronology (Bayazit, 2010)*

Richard Fuller, a technologist from the 60's believed that problems that could not be addressed by politics or economics should be addressed by science, technology and rationalism. For this purpose, he christened the 'design science revolution' and considered the 60's as the decade for design science. TRIZ (Altshuller's Theory of inventive problem solving), a forecasting and problem-solving tool is perfect example of early design science [8]. The tool was founded in Russia during the 1940's. Eventually in the 1960s, the decade culminated with Herbet Simon's 'The sciences of the artificial' and his strong plea for the development of a science of design in universities. With significant shifts in the field of this research the focus moved to creating a design discipline and using design cognition to understand the design process (Cross, 2007; Bayazit, 2010).

## 2.2 Studying Design Behavior – A Comparison of Different Research Strategies

The question that fascinates researchers the most is trying to know what is it that designers do when trying to solve design problems? The focus is this section is to give a brief description of some the most commonly used strategies that have been used by researchers to answer the above question. The four strategies that we discuss are the following:

- Think-aloud Protocols
- Content Analysis
- Process Isolation
- Situated studies

This will give us a better understanding of how to evaluate neuroscientific experiments, like the one carried out in the following chapter. The key similarity among these four strategies is that they all consider design as a distinct type of behavior, while they differ on assumptions made regarding design.

| Research Strategy | Theoretical Bias / Assumption |
|---|---|
| Think-aloud Protocols | Design can be described as search |
| Content Analysis | The structure and content of internal representations is critical to understanding design behavior |
| Process Isolation | Design can be cognitively decomposed |
| Situated Studies | Studying designers and their environments in an integrated way is critical to understanding design |

*Table 1- Research strategies and their theoretical bias*

### 2.2.1 Think-aloud Protocols

Think-aloud protocols, as the name suggests, involves participants to think out loud as they are performing a set of specified tasks. Participants are asked to say whatever comes into their mind as they complete the task. To observe the processes as explicitly as possible, and not only the final product, the subjects are required to speak out loud what they are thinking, doing, feeling or looking at.

In a formal research protocol, all verbalizations are transcribed and then analyzed. In a usability testing context, observers are asked to take notes of what participants say and do, without attempting to interpret their actions and words, and especially noting places where they encounter difficulty. Audio and video records of these test sessions are often kept so they can be referred to later by the researchers.

Such strategies are ideal for problems that offer little space for possible solutions. Thus, "whenever verbalizations correspond to plausible intermediate states in a processing model for the problem-solving activity, we can plausibly infer that this information is actually used in generating the problem solution" (Ericsson and Simon, 1993:171). A common difficulty faces in this kind of strategy is regarding the interpretation of utterances. Newell and Simon conducted several protocol studies [7] to map out plausible problem spaces that participants might transverse while performing a task. The problem spaces help identify some concepts that can used as a dictionary to interpret these utterances. Another major criticism of this strategy is that verbal data may not be adequate for tracking sequential thought process. Think-aloud protocols may misrepresent underlying processes to the extent that subjects "sometimes cannot report on the existence of critical stimuli, sometimes cannot report on the existence of their responses, and sometimes cannot even report that an inferential process of any kind has occurred" (Nisbett and Wilson, 1977:233).

2.2.2 Content Analysis

Another widely used research technique is content analysis. There are three major approaches for such analysis, namely, conventional, directed and summated. The three approaches differ in coding schemes, origins of codes and threats to trustworthiness, while similar in that they all use text data content for interpretation. Conventional content analysis derives coding categories directly from text data, direct approach uses theories or relevant researches as a guide of the codes, while summative analysis uses counting and comparison of keywords, followed by interpretation [Hsiu-Fang and Shannon, 2005].

The basic idea here is that different concepts get their meaning through links with other concepts often inheriting or sharing meanings with other domains. Content analysis aims to overcome the limitations of the think-aloud protocols by focusing on the content of the thought, particularly on the kind of knowledge representations used in design (Eastman, 2001:28). The aim is to understand the structure and content of representations often heavily relying on qualitative analysis of external reports e.g. verbal data.  Hence content analysis may also involve participants saying out loud what they're thinking as they perform a task. Researchers may still do some kind of probing since the idea is to unveil the internal representation. So, this kind of strategy also depends on theories for coding, similar to think-aloud protocols. This also suggests that it would be ideal to use content analysis as complementary layer on top of think-aloud protocols instead of using it as a stand-alone technique. Both the approaches depend on theoretical models that help us understand of what can be considered as a representation and what not. Though content analysis includes the measurement of quantitative performance, researchers are still required to make assumption, mainly regarding the variables that would be measured (independent/dependent or significant/insignificant).

### 2.2.3 Process Isolation

Process isolation offers another alternative to two protocols explained above. They make the use of processes that are isolated from design episodes to understand the underlying cognitive processes as well as the representations [Eastman, 2001:26]. The assumption here is that designers undertake a host of activities that contribute to the transformation of representations in design. These activities include those traditionally studied in cognitive science such as analogy (Holyoak, 1983), mental modelling (Johnson-Laird, 1983), simulation (Barsalou, 1999), conceptual combination (Wisneiwski, 1997) and conceptual blending (Turner, 1998). The major difficulty encountered with this approach is that researchers must construct tasks that are related to design and have well-defined dependent variables, since researchers often try to understand the design behavior by extending existing theories in cognitive science. Creating the right task could be crucial when adopting this approach. In Casakin and Goldschmidt [1999], for example, the dependent variable was the general quality of design as assessed by a panel of experts. Though the quality of design can be of interest, the problem with assessing design quality is that it is not a quantifiable variable. In Casakin and Goldschmidt's study, design quality may be confounded with variables other than those directly related to the analogical processes being studied. Therefore, the study doesn't really lead to clarify underlying cognitive processes, although there is a marked improvement in the quality of design by the presence of visual analogs.

### 2.2.4 Situated Studies

Jesper Simonsen in his book Situated Design Methods claims that "all design is situated – carried out from an embedded position". Situated studies considers designers and their social, cultural and material contexts as 'Intact activity systems' by focusing on activities that relate to these contexts (Greeno, 1998). Proponents of this research claim that working bottom up is insufficient for this approach since for complex behaviors the interactions may differ unpredictably, and hence they require the development and employment of theoretical concepts that are specific to the situated behavior. These studies often focus on one of the following two things: the way meaning is produced in situations or the way social context / material environment regulate behavior. The assumptions made with such studies depends on whether the focus is on the meaning or on the effects of environment on the behavior. In the first case, the assumption is that the meaning is created in particular situations and not carried in symbols, while in the second case the assumption is that the situation or environment will result in specific behavior being exhibited.

The purpose of the descriptions and comparison of the pros and cons of the above approached are intended to give us some context into research methods used for studying design behavior.

## 2.3 Cognitive Neuroscience and Design

Analysis of neurobiological substrates of various cognitive processes is represented by cognitive neuroscience. It puts together the various experimental techniques that are used to study these substrates, mainly focusing on physiology, psychophysics, electrophysiology and functional neuro-imaging. Design research acknowledges the comprehension of design cognition as a significant focus of research since it a very complex activity in nature, even though typical studies focus on very simple and repetitive processes. Notably, the early stages of design are considered to be among the most cognitively intensive in the design process (Nakakoji, 2005), resulting in most of the research studies focusing only on the early stages of the design process. Cognitive psychology researches, on the other hand, have focused more on psychological elements like attention, perception, learning, remembering, speaking and reasoning, being the most common amongst them. In design research community, problem solving has been one of the widest concerns when it comes to research in design cognition. As further justified by Herbert Simon in his book "The Science of the Artificial", "design is inherently computational – a matter of computing the implications of initial assumptions and combinations of them". Hence the consensual notion of design cognitive activity is that designers start with ill-defined or illstructured problems in the early stages of design process; each problem solver (here, the designer) then constructs its mental representations of design problem which are mostly incomplete and imprecise in the beginning (Simon, 1968). It becomes clear that design is not normal "problem solving". Though it was common to use concepts of cognitive science to study design cognition, but as Herbert implies that these could be inaccurate and partial, to fully analyze and study design cognition it is critical to establish the right concepts and structure.

The complexity of design activity raises a further question of how reliably and to what extent do experimental setting allow us to study the relationship between design and brain related functions and hence allowing scientific questions to be answered that address that relationship of cognitive competences and designing. A further hurdle has been the lack of tools that would allow to carry out such researches. Only recently researchers have started to investigate problem solving processes using fMRI (Functional Magnetic Resonance Imaging) and focused on analyzing differences between ill-defined design and well-defined problem solving tasks (Goel & Grafman,2000; Alexiou & al.,2009; Gilbert, & al.,2010). The cognitive neuroscience research community is obviously still not at a point where they could tell what and how a designer thinks when carrying out a task but we can apply it to analyze the brain activity of designers during very specific phases of problem solving.

### 2.3.1 Neuroscience Research in Design – The State of the Art

In order to establish the state of the art in design related neuroscience research, an extensive research was conducted and numerous scientific papers were collected based on keywords of interest. These research papers were used to establish the state of the art when it comes to the use of neuroscientific tools in design research. The bubble diagram below shows the spread of the main research papers according to the keywords and the relationship between them. These research papers also included experimental studies from which inspiration was drawn for our experiment.

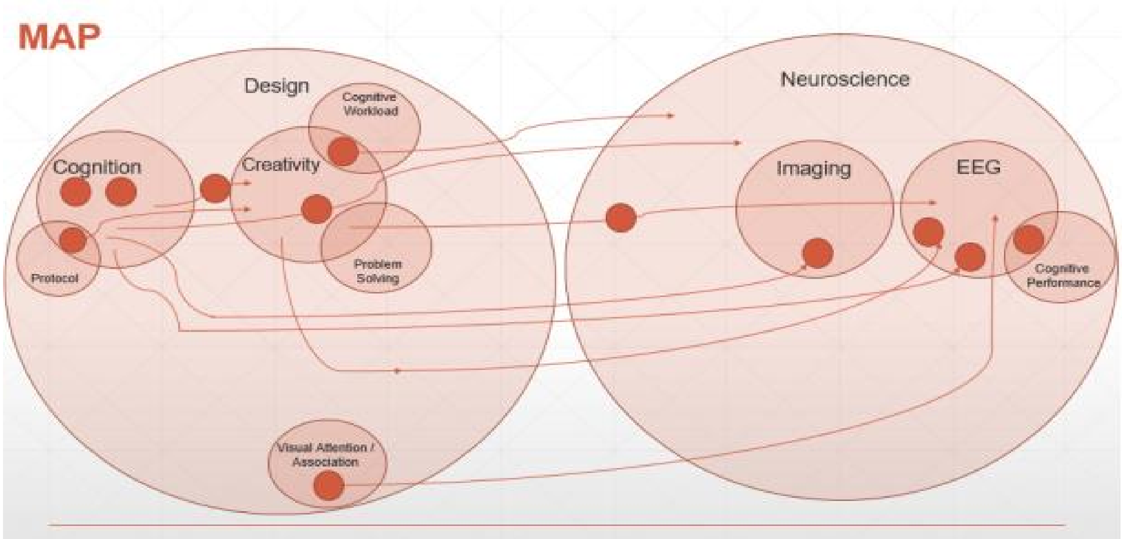



*Figure 5 - State of the Art - Neuroscientific Research in Design*

<u>2.4 Neuroscience, Creativity and Divergent thinking</u>

Creativity is often confused with design and though they are not the same, creativity does play a huge role in the design process. This section explains creativity in the light of neuroscience followed by a review of common results that have been observed in this field of research. Most research studies have focused on divergent thinking and its correlation to creativity, hence the focus of this section is on the correlation of tasks simulating divergent thinking and the corresponding Electroencephalogram (EEG) activity observed.

Creativity is commonly defined as the ability to produce work that is both original and unique, namely novel, and useful within a social context (Fink & Benedek,2012). Playing a significant role in the process of inventing something new, creativity is a vital trait of the human character. Though the study of other psychological sciences has developed in the past 50 years, research that focused on studying creativity have been quite uncommon (Dietrich & Kanso, 2010). Given its significance in various disciplines (not only related to science), the subject of creativity has gained significant popularity in recent years leading to similar raise of interest amongst cognitive and neuro scientists.

Though Electroencephalography (EEG) has been widely used to study creativity, it still doesn't provide a significant conclusion due to the high variability in results (Arden, Chaves, Grazioplene & Jung, 2010). The main reason being the different approaches that have been employed to carry out these experiments and the varying definitions of creativity.

### 2.4.1 Complexity in investigating research comparison

There are several aspects of creativity that make it quite complex to compare existing researches. One of the main aspects is the varying definition of creativity. Not only have researchers been very vague regarding the definition being investigated, but also being characterized differently across different domains contributes to the resulting complexity. For example, some see it as cognitive state or event, others consider it as a personality trait, while a definition that is skewed more towards the design process relates it to divergent thinking. (Fink & Benedek, 2012).

Another aspect contributing to this complexity is the variation in the type of tasks that have been employed to simulate creativity and hence study it. It is debatable as to which tasks actually simulate creativity and which do not. This has also led to the categorization of activities that are commonly used to study creativity. The categories are:

- Remote association tasks
- Insight tasks, and
- Creative Ideation tasks.

Remote association tasks usually require the participants to produce something artistic, like a story, melody, sketch etc. The most commonly used remote association task is the Remote Association Test (RAT). RAT is often used to test human creativity, where participants are given three words that appear to be loosely related and they are required to come up with a forth word that is somehow related to these three words. These tasks rely on the idea that the most original solutions or ideas are not the obvious ones or “remote and far down the associative pathway” (Runco & Yoruk,2014).

Insight tasks, on the other hand, are slightly deceptive and confusing where in order to find the solution the problem requires some kind of cognitive restructuring which eventually leads to limited or only one “ah-ha!” solution (Runco & Yoruk,2014).

Creative ideation tasks can be defined by looking at the most commonly used example; the Alternate Uses Task (AUT), also known as the Guilford’s Alternative Uses Test (Wilson, Guilford, Christensen & Lewis, 1954) were examinees are required to list down as many possible uses for a common household object. This problem simulates the typical conditions of divergent thinking as it requires the participant to not go towards a single solution, but many different solutions employing different pathways. Creativity and divergent thinking are often related, even if the results are not always new and uncommon ideas; several tests point towards the idea that tasks that simulate divergent thinking can be used to estimate creativity (Runco & Yoruk,2014).

When considering the use of EEG for such studies, there are many different techniques that can be employed to study the activity of the brain. For very short timed tasks, event related potential is a widely used method employed on EEG data. Other techniques include studying the overall change in power in the overall brain or just certain regions of the brain. Furthermore, EEG data can be broken divided into specific bands and the above-mentioned techniques can be employed only to study these specific frequency ranges of EEG data.

Given, so many variable factors regarding definitions, experimental procedures and measures being used to carry out such studies, it is still not possible to compare and reach structured and reasonable results (Fink & Benedek,2012).

#### 2.4.2 Divergent thinking

Divergent thinking is described as the process or method of thinking employed to arrive to many possible solutions to a given problem. Guilford defines it as the brain "going off in different directions" during an act of creativity (J. P. Guilford,1959). He used the terms of convergent and divergent thinking in an attempt to differentiate creative and non-creative processes. Many researchers associate the entire creativity process as divergent thinking, but Guilford describes that in order to come up with a unique final solution, the brain also needs to evaluate all the possible solutions and pick the best one (J. P. Guilford, 1950).

Just like creativity, studying divergent thinking with neuroscientific methods has many restrictions. Just considering EEG; the data generated during an EEG recording session have very high frequencies and having a long session would result in huge data sets with highly sensitive and varying data, but on the other hand researchers suggest that creativity tasks shouldn't be times as the added factor of time can act as a distraction for the participant and influence their creativity levels.

### 2.5 Brain Research Technologies and their relation to Design Research

Significant advanced in neuroscientific tools in recent years have widened the bottlenecks present in design research. The main challenge now is to be able to create reliable experimental settings that allow examination of interrelations between design activity and design cognition. The choice of tools used depends on the kind of experiment being conducted and more significantly on the research questions posed. This section provides a brief description of the main technologies available at the moment and their advantages and limitations in relation to design research.

#### 2.5.1 Functional Magnetic Resonance Imaging – fMRI

fMRI measures brain activity by detecting changes associated with blood flow. In simple words, when an area of the brain is active it results in an increased amount of blood flow to that area. This coupled relation is what this technique relies on. The results are in the form of a detailed picture of various brain areas and the oxygen they use over time. Traditional fMRI experiments shed light on the following types of questions: 1) Which brain areas are activated in task A compared to task B? 2) Do individuals in group X and group Y have different brain areas activated by task A and task B?

The obvious limitation of this technology for studying design is that participants will be restricted in cylindrical tubes resulting in limited movement and a high level of distraction from the task being carried out. Another drawback is that fMRI scanners are very expensive and can only be found at hospitals or high-level research labs, making it un-portable and unsuitable for smaller experiments. Hence the high level of physical and time constraints lead to a complex process of designing and planning tasks that are simple to carry out and still provide significant results for further analysis.

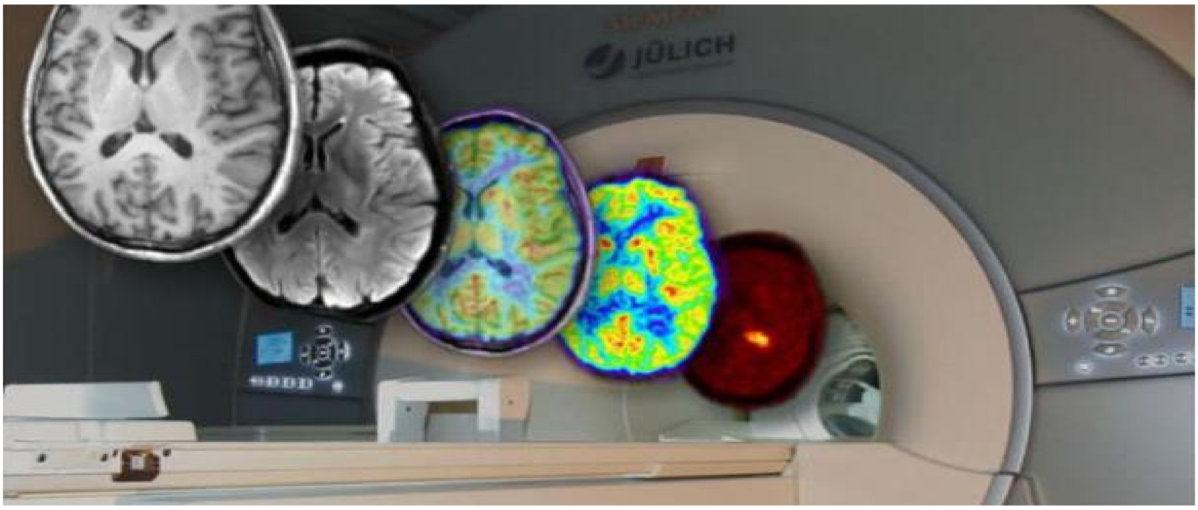



*Figure 6 – Functional Magnetic Resonance Imaging*

2.5.2 Near Infrared Spectroscopy – NIRS

This is an optical imaging technology that utilizes changes in the absorption and scattering properties of light as it travels through brain tissue. When a brain tissue is active, more oxygen travels to that area prompting changes in the properties of light absorption and scattering (Gratton et al.,2001). This kind of technology is portable and does not require a laboratory facility making is suitable for design experiments where natural working environment is of great importance.

2.5.3 Electroencephalography – EEG

Electroencephalography is possibly the oldest brain research technology employed in research experiments. The portability and temporal accuracy on very small-time scales makes it the ideal tool for experiments that do not require a complex laboratory setting. EEG signals are a consequence of electrical neural activity and are picked up from the scalp that is the surface of the head. Event related potentials (ERPs) are averaged fragments of EEG signal indicating brain activity that is temporally related to an event e.g. the appearance of an image or the reproduction of a sound. Visual, somatosensory and auditory components (peaks) of ERPs have been observed, and some features of their relationships to the cognitive functions of perception, memory and attention have been identified. Previous research has revealed activation of the brain's sensor motor areas in response to the stimuli of seeing other people working (Borghi & Cimatti, 2010). An obvious disadvantage in contrast to fMRI is that with EEG it is difficult to identify active brain areas in detail (Seitamaa-Hakkarainen, 2014).


*Figure 7 – Electroencephalography – EEG*

### 2.5.4 Measures in EEG

As mentioned before, EEG activity provides the possibility of employing several approaches that can be used to measure activity of the brain. Past studies have used; spectral power analysis to measure the variation in frequencies in the overall brain or only specific major regions, Event-related potential (ERP) to study the effect of small time range events on the EEG data, Independent Component Analysis (ICA) to decompose data into several components (Physical, Eye, Muscular, Noise or Brain/cognition related) and then carry out spectral or ERP analysis are amongst the most common approaches that have been used.

EEG signal frequency range lies between 1 Hz and 100 Hz and the range can be further classified into smaller frequency bands, namely;

- Delta (1 – 4 Hz)
- Theta (4 – 8 Hz)
- Alpha (8 – 12 Hz)
- Beta (13 – 25 Hz)

### 2.5.5 Review of researches employing EEG to study divergent thinking

Researchers have often employed EEG to study divergent thinking. Most of the studies have focused mainly of the alpha band as it has been frequently associated with divergent thinking or creativity. Most of these studies further divided these frequency bands into smaller sub-bands, for example the alpha band can be further classified into lower (~ 8-10 Hz) and upper alpha (~ 10-12 Hz) bands. The following table reports a review of researches that employed EEG to study divergent thinking:

| STUDY | BANDS | SUB-BANDS | FUN. CON. | DESIGN | COVARIATE |
|---|---|---|---|---|---|
| Bazanova & Aftanas, 2008 | α; β; γ; θ | YES | NA | TR; WTC | NA |
| Danko et al., 2009 | α; β; γ | YES | NA | TR; BTC | NA |
| Fink & Neubauer, 2006 | α | YES | NA | TR | Verbal IQ; Gender |
| Fink & Neubauer, 2008 | α | YES | NA | TR; BTC | Introversion/Extroversion |
| Fink et al., 2006 | α | YES | NA | TR; BTC | DTTT |
| Fink et al., 2009 | α | YES | NA | TR; BTC | NA |
| Grabner et al., 2007 | α | YES | PHASE | TR; WTC | NA |
| Jaušovec, 2000 | α | YES | CO | TR | IQ; TTCT |
| Martindale & Hasenfus, 1978 | α; - | - | - | WTC; BTC | AUT; RAT |
| Martindale & Mines, 1975 | α; - | - | - | WTC; BTC | NA |
| Martindale et al., 1984 | α; - | - | - | WTC; BTC | AUT; RAT |
| Mölle et al., 1999 | α; β; δ; θ | NA | NA | TR; BTC | NA |
| Razumnikova et al., 2009 | α; β; θ | YES | CO | TR; BTC | NA |
| Razumnikova, 2005 | α; β; θ | YES | CO | TR; WTC | Gender |
| Razumnikova, 2007 | α; β; θ | YES | CO | TR; WTC | NA |
| Shemyakina & Danko, 2007 | α; β; δ; θ | YES | CO | TR; WTC | NA |
| Jauk et al., 2012 | α | YES | NA | TR; BTC | NA |
| Fink, Schwab, Papousek, 2011 | α | YES | NA | TR; WTC | NA |
| Benedek et al., 2014 | α; β; θ | NA | NA | TR; WTC | NA |

*Note:* AUT = Alternate Uses Task; BTC = Between Task Comparison; CO = Coherence; DTTT = Divergent Thinking Task Training; FUN. CON. = Functional Connectivity measure; IQ = Intelligence Quotient; NA = Not Avaiable; NS = Non-Significant difference; RAT = Remote Associates Test; TR = Task-Rest Comparison; TTCT= Torrance Test of Crative Thinking; WTC = Within Task Comparison; α = Alpha Band; β = Beta Band; γ = Gamma Band; δ = Delta Band; θ = Theta Band.

*Table 2 - Review on EEG and divergent thinking studies*

- Few of these studies did not find a significant variation in alpha signal (Danko, Shemyakina, Nagornova, & Starchenko, 2009; Martindale & Hasenfus, 1978; Shemyakina & Danko, 2007).
- Among the other frequency bands, beta was the only one with some evidence of correlation with creativity tasks; most reported an increase in activity (Danko et al., 2009; Mölle, Marshall, Wolf, Fehm, & Born, 1999; Razumnikova, 2005; Razumnikova, 2007) while only one study reported decrease (Shemyakina & Danko, 2007).

The following table provides summary of previous researches that analyzed Alpha band power changes in different regions of the brain.

| **ALPHA BAND** | **POWER CHANGES IN LOBES** | | | | |
|---|---|---|---|---|---|
| **STUDY** | **Frontal** | **Temporal** | **Parietal** | **Occipital** | **HEMISPHERE** |
| Bazanova & Aftanas, 2008 | INC | NA | ERS | ERS | NA |
| Danko et al., 2009 | NS | NS | NS | NS | NA |
| Fink & Neubauer, 2006 | ERS | ERS | ERS | ERS | NS |
| Fink & Neubauer, 2008 | INC | INC | INC | INC | RIGHT |
| Fink et al., 2006 | ERS | ERS | ERS | ERS | NS |
| Fink et al., 2009 | ERS | ERS/ERD | ERS/ERD | ERS/ERD | RIGHT |
| Grabner et al., 2007 | ERS | ERS | ERS | ERS | RIGHT |
| Jaušovec, 2000 | ERS | ERS/ERD | ERD | ERS | NS |
| Martindale & Hasenfus, 1978 | NS | - | - | - | NS |
| Martindale & Mines, 1975 | INC | - | - | - | RIGHT |
| Martindale et al., 1984 | INC | - | - | - | RIGHT |
| Mölle et al., 1999 | NS | NS | INC | NS | NS |
| Razumnikova et al., 2009 | ERD | ERD | ERD | ERD | NS |
| Razumnikova, 2005 | NS | NS | NS | NS | NS |
| Razumnikova, 2007 | NS | ERD | ERD | ERD | LEFT |
| Shemyakina & Danko, 2007 | NS | NS | NS | NS | NA |
| Jauk et al., 2012 | ERS | ERD | ERD | ERD | RIGHT |
| Fink, Schwab,Papousek, 2011 | ERS | ERS | NS | NS | RIGHT |
| Benedek et al., 2014 | ERS | ERS | ERS | ERS | NA |

*Note:* ERD = Event Related Desynchronization; ERS = Event Related Synchronization; HEMISPHERE = Hemisphere with stronger power/synchronization; INC = Increase in power; NA = Not Available; NS = Non-Significant difference.

*Table 3 - Evidence in Alpha Band*

Majority of these studies show an increase in Alpha activity or event related synchronization whereas few show a decrease or dyssynchronization. Half of them also identify the hemisphere with higher activity with majority showing higher activity in the right hemisphere. The relationship between higher activity in one hemisphere is often attributed to the dominant side of the person. The results of the review also suggest so as majority of people have the right side as the dominant one.

2.5.6 EEG Alpha Power and Creativity

As can be seen from the results reported in the above tables, most researches have consistently shown a relationship between alpha activity and creativity related tasks, but at the same time in can be seen that they are not consistent. Researches that show significant variation in alpha power usually report the activity being higher in the frontal and posterior regions of the brain, something that is also coherent with medical researches; that suggest alpha activity usually generating in these two lobes.

Some studies, like (Molle, 1999), have also tried to study the difference in activity during divergent thinking and convergent thinking tasks; providing further evidence that alpha activation is higher in divergent thinking tasks as compared to convergent thinking ones. Studies have also shown some relationship between the level of creativity and corresponding power of alpha activity; tasks demanding more creativity and originality usually result in a stronger alpha activity and vice versa (Fink, Benedek, Grabner, Staudt, & Neubauer,2007; Fink & Benedek,2012).

Other studies (Razumnikova et al., 2009; Razumnikova, 2007) reported alpha desynchronization and the reason could be dependent on the relatively long reference period adopted by these studies: 5 minutes of rest with eyes closed, while in other studies reference period do not exceed two minutes. Since the beginning of EEG technique in 1930s by Hans Berger, it was evident the increase in amplitude of alpha wave when individuals have their eyes closed compared to when they have their eyes open. Since resting periods are usually used as a base-mark to evaluate the activity during tasks, having a high alpha activity in the resting phase (due to closed eyes) wouldn’t provide credible results as the comparison would lead to an overall low alpha activity when the participants were carrying out the tasks (hence having their eyes open).

Other studies have also carried out comparisons between subjects based on their individual characteristics or qualities; such as creative vs less creative people (Jausovec,2000), male vs female participants (Fink & Neubauer, 2006), and extrovert vs introvert participants (Fink & Neubauer, 2008). These basically involve clustering the participants based on the chosen criteria of the experiment and requiring the subjects to carry out tests.

Another category of these researches has investigated how training, creativity enhancing or other cognitive stimuli could influence the activity of the brain (Fink, Grabner, Benedek, & Neubauer,2006; Fink, Schwab, & Papousek,2011). For such experiments participants had to carry out two tests, one before the training or stimuli and another after it. These experiments also conclude that cognitive stimuli enhances the alpha activity of majority of participants.

Summing it up; although there is still no solid evidence and significant overlap between the results of these experiments, we can still witness at least some level of relationship between alpha activity and creativity.

## 2.6 The Research Question and the Choice of Tool

The FBS framework discussed earlier and others like it are developed through decades of research consisting of numerous protocol studies and elaborate coding schemes whose validity and reliability, according to some, is debatable at best. Along with comparing our experimental results to those reported in Table 2 and 3, we also want to investigate whether these cognitive processes can be identified using the latest neuroscience technology paving way for further research that can verify or better substantiate such frameworks that attempt to describe the design process. Since design activity is a complex task we have decided to focus on two of the cognitive processes, namely Analysis and Synthesis, and see if it's possible to recognize and distinguish them using neuroscience technology? Professor Pirita Seitamaa-Hakkarainen in her paper "How can neuroscience help understand design and craft activity? The promise of cognitive neuroscience in design studies" outlines the feasibility of different neuroscience technologies for design research.

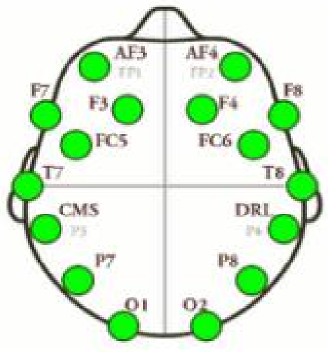
After having evaluated carefully the potential and the feasibility of different neuroscience technologies with respect to design research, we decided to use EEG as our choice of technology for this experiment. The biggest advantage of EEG over other methods is outstanding temporal resolution allowing us to observe the neural activity at the level of milliseconds. Such temporal resolution is the best approximation for neural events. After having decided to use EEG as our preferred technology for this experiment, we evaluated various options for the EEG headsets available off the shelf in the market (See Appendix E). Some of the things that were taken into account were no. of channels, sensor frequency, battery life and software support.

| Neuroscientific method | Parameters measured with this method | Temporal resolution (accuracy in time) | Spatial resolution (accuracy of locating active brain areas) | Pros for design studies | Cons for design studies |
|---|---|---|---|---|---|
| fMRI (functional magnetic resonance imaging) | BOLD-signal (blood-oxygenation-level-dependent signal), changes in blood flow after increased neuronal activity | Block design studies: several seconds to minutes<br>Event-related studies: hundreds of milliseconds | From several millimeters to sub-millimeter accuracy | Some fMRI study protocols are quite well suited for design studies | Equipment cannot be removed from the laboratory; sequence of activities is difficult to study |
| EEG (electroencephalo-graphy) | Electric potentials from scalp, directly resulting from neuronal activity | Less than a milisecond | Problematic due to distortion of electric potentials, less than 1 cm in good conditions | Portable instruments, natural environments, some EEG study protocols are quite well suited for design studies, measurements of several hours are practically possible | Location of brain activity is difficult to determine |
| MEG (magnetoencephalo-graphy) | Magnetic fields outside the head, directly resulting from neuronal activity | Less than a millisecond | Less problematic than EEG, in good conditions clearly less than 1 cm | Some MEG study protocols are quite well suited for design studies, long tradition of well-controlled experiments stemming from EEG, optimal time-space-resolution | Equipment cannot be removed from the laboratory; location of brain activity is quite difficult to determine |
| MRI (magnetic resonance imaging) | Structures of the brain (structural MRI), neural tracts (DTI, diffusion tensor imaging) | No accuracy in time | Less than 1 mm | Good for studies comparing groups of people | Equipment cannot be removed from the laboratory |
| PET (positron emission tomography) | Structural image of concentration of metabolically active tracer, usually oxygen | Contrast of two conditions: no accuracy in time | Less than 1 cm | Good for comparing groups of people or natural tasks | Radioactive tracer is injected into participants; equipment cannot be removed from the laboratory |
| NIRS (near-infra-red spectroscopy) | Diffusion and absorption of near-infra-red light in tissues, depending on hemodynamic and electromagnetic changes in brain tissue | hemodynamic NIRS: hundreds of milliseconds, electromagnetic NIRS: millisecond (according to some researchers) | Theoretically less than 1 cm | Portable instruments, natural environments, some NIRS study protocols are quite well suited for design studies, measurements of several hours are practically possible | Difficulties in determining the location of brain activity, not many groups yet using NIRS for cognitive studies |

*Figure 8 - Pros and Cons of Neuroscientific Methods for Design Studies (Seitamaa-Hakkarainen, 2016)*


*Figure 9 - Shortlisted Headsets for the Experiment*

After an investigation, it was concluded that the Emotiv Epoc+ was the only research grade headset available in the market and preferred by the research community [9]. The Emotiv Epoc+ is a 14 channel wireless EEG headset designed for contextualized research and advanced brain computer interface applications. It comes with the Pure EEG software that allows access to dense array high quality raw EEG data.




| | |
|---|---|
| Number of channels | 14 (plus CMS/DRL references) |
| Channel names (Int. 10-20 locations) | AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1, O2 |
| Sampling method | Sequential sampling, Single ADC |
| Sampling rate | ~128Hz (2048Hz internal) |
| Resolution | 16 bits (14 bits effective) 1 LSB = 1.95μV |
| Bandwidth | 0.2 - 45Hz, digital notch filters at 40Hz and 60Hz |
| Dynamic range (input referred) | 256mVpp |
| Coupling mode | AC coupled |
| Connectivity | Proprietary wireless, 2.4GHz band |
| Battery type | Li-poly |
| Battery life (typical) | 12 hrs |
| Impedence measurement | Contact quality using patented system |

*Figure 10 - Scalp Locations and Specifications - Emotiv EPOC+*

### 2.6.1 Research Question

Do engineers exhibit distinct EEG patterns while engaging in prototypical tasks of Analysis and Synthesis?

# 3. EXPERIMENT

An experiment was designed to answer our research question and validate the usability of EEG for studying the design process. Three different tasks were constructed, one of which was assumed to involve the cognitive function of analysis and the other two of synthesis. A typical problem involving analysis comprises of identifying all relevant factors to a given situation and breaking a subject into parts to better understand the problem. While synthesis involves finding partial solutions among feasible alternatives and possibly integrating them into one single form. EEG brain activity of engineering students was recorded while they carried out tasks simulating the cognitive conditions of the Analysis and Synthesis phases of the design process. The experiment was conducted in the form of EEG recording sessions (corresponding to the number of participants); each divided into two resting phases and three cognitive phases. Collected raw data was then cleaned and classified for further analysis.

## 3.1 Participants

### 3.1.1 Population

The target population consisted of Master Level Engineering students that had pursued their bachelor in any of the engineering disciplines that fall under the major branch of Mechanical Engineering. The accessible population was then filtered and shrunk down to students of Polytechnic University of Turin that met the mentioned requisites, were willing to participate and gave consent to carry out the EEG recording session.

The purpose of considering only Master level students was to ensure that the level of expertise and ages of the participants were similar, making it possible to control the level of homogeneity of the selected sample. To further increase the homogeneity only male students were considered.

### 3.1.2 Sample size

A very common question in neuro-research experiments is regarding the number of subjects required to obtain reliable results. Past researches show a huge variance in the number of participants, going from as little as 5 to up to 400 participants. According to a systematic review of 100 randomly chosen EEG studies; 0 out of 100 reported sample size calculations (Larson & Carbine, 2017). Absence of such information hinders accurate determination of sample sizes for such researches.

Though traditional brainwave collection technologies use between 100-150 subjects to obtain consistent results, Dr Stephen F. Sands argues in his paper that the increased sensitivity of EEG measures requires fewer participants to obtain the same level of reliability (Sands, 2009). To formally answer this question, he carried out a power analysis to statistically test the number of participants that would be required to reach an acceptable threshold, such as 95% likelihood of being correct. The power analysis was carried out using the Neuro-Engagement-Factor (NEF) (a Z-score derived from the electrical activity of the brain) to show that approximately 30-40 subjects are required to have a 1% chance of error. The smallest pool of subjects that showed some level of significance (5% chance of error) was approximately 4.

One possible approach would be to carry out a sequential analysis. In this case, the sample size is not fixed in advance and data is evaluated as it is collected, while further sampling is stopped as soon as significant results are observed. Considering the standardized nature of the experiment, it is possible to perform a sequential analysis in the long-term if the experiment is repeated in the future by other researchers.

Due to time limitations and infeasibility of carrying out the experiment on a large scale, a sample size of 12 was selected, which, according to Dr Sands analysis would provide results with lower than 5% chance of error.

#### 3.1.3 Sample

A sample of 12, male, masters level engineering students, ageing between 23 and 27 years old (Average = 25.6, Standard Deviation = 1.39) were selected from the accessible population to participate in this research. All participants were healthy individuals, with no obvious disorders that could affect the recorded data. Due to huge amounts of distortion and noise, data from 3 of the 12 recording sessions were rejected during the data preparation and cleaning process. After cleaning the data and extracting epochs for each task, we obtained 27 data sets in total (3 for each subject) but 7 of them had to be excluded from the final analysis. The process of rejecting these data sets in further explained in detail in the next chapters.

The experiments were conducted considering the participants routine to ensure they were not tired, stressed or hungry during the recording sessions. The participants were informed about the experiment in detail and asked to read and sign a consent form before beginning the session.

### <u>3.2 EEG Apparatus</u>

#### 3.2.1 EMOTIV EPOC+

The EEG was measured using the EMOTIV EPOC+; a high resolution, multi-channel, portable EEG system designed for practical research applications. The EPOC + features 14 channels, plus 2 reference channels, offering optimal positioning for accurate spatial resolution and ensuring 'whole brain' measurement.

The 14 electrodes are located at positions (according to the international 10-20 locations): AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 and the reference electrodes are located at positions P3/P4 locations in the CMS/DRL configurations. The electrode sites are labelled with a letter and a number. The letters refer to the area of the brain under the electrode e.g. F – Frontal Lobe and T – Temporal Lobe. Even numbers denote the right of the head and odd number the left side.

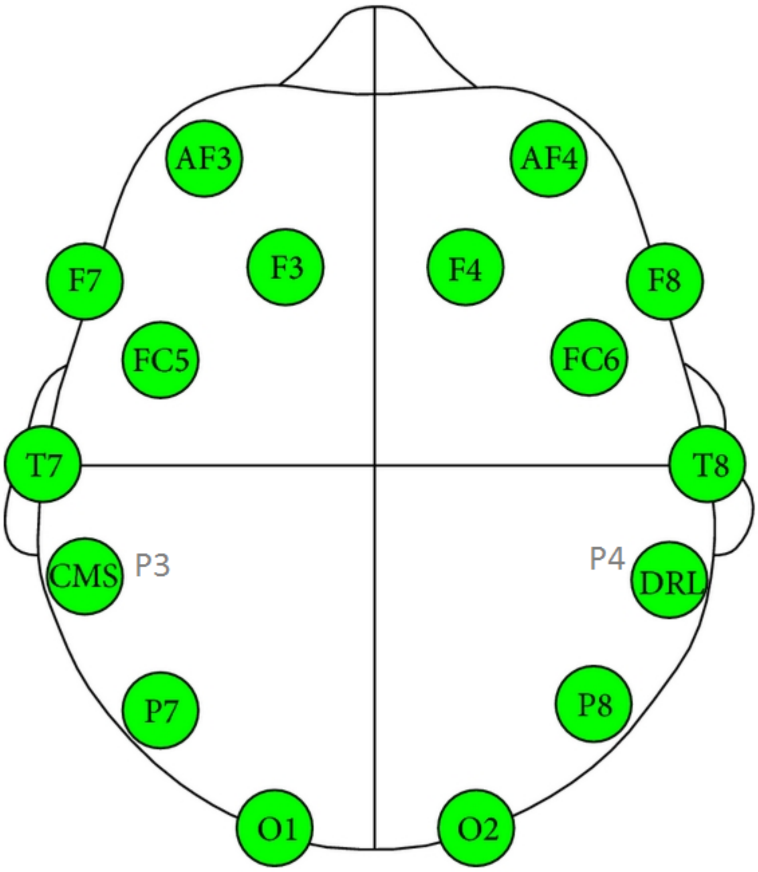



*Figure 11 – EMOTIV EPOC+ channels (International 10-20 locations)*

### 3.2.2 EMOTIC Xavier Pure.EEG

The EPOC+ allows recording raw EEG data using its subscription-based software, the Xavier Pure.EEG. The software collects data packets via a wireless USB device and shows real time display of headset data streams including Raw EEG, motion data, data packet acquisition or loss and sensor contact quality. It also offers recording to be stored on their online cloud storage and playback or export at any time.

The software also allows to customize and view frequency data of recorded sessions with automatic FFT (Fast Fourier Transformation) and power band graphs.

During the experiment, headset settings were kept at default; recording at a sampling rate of 128 Hz and 14-bit resolution. The headset has an internal sampling rate of 2048 which is filtered and down sampled to 128 per second per channel.


*Figure 12 – EMOTIV XAVIER Pure EEG real time display*

## 3.3 Experiment Procedure

### 3.3.1 Environment

The recording sessions were conducted in a silent and comfortable workspace with minimum interference and no audio or visual distractions. Though the sessions were carried out over a period of one month, the room environment was kept constant for each session. A desk and chair was arranged on one corner of the room for the participant and an LCD screen was positioned at a comfortable reading distance, to display the tasks.

### 3.3.2 Pre-Experiment Protocol

The EEG devices were charged and hydrated half an hour before each recording session. An instructional presentation was prepared to provide a brief description and example of each phase, as well as the general do's and don'ts to be followed during the experiment. The participant was provided with a pen and some plain A4 sheets to express their solutions. To ensure a consistent connection, the EEG recording system was prepared and fitted on the participant and left for some time at the beginning of the instructional presentation. Once the experiment details were clear to the participant and all their questions had been answered, they were asked to read and sign a consent form. After ensuring that all EEG sensors had established proper connection, the coordinators then proceeded to start the experiment.

### 3.3.3 Recording Session

A timed power-point presentation was used to guide the participant through the recording session. The resting phases, tasks and transition phases were organized in a consistent and orderly manner. This ensured that the collected raw data for each participant could be easily divided into the relevant sections for further analysis. The following diagram shows a complete timeline of how each session was organized:

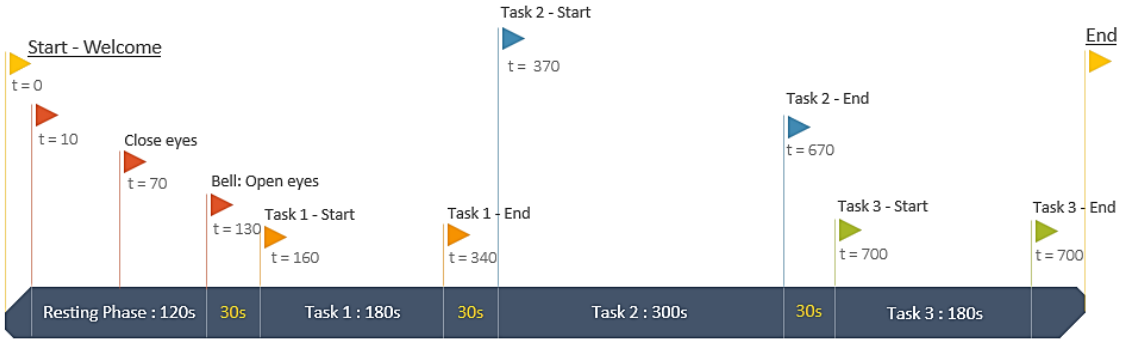



*Figure 13 – Recording Session Timeline*

The session began with a welcome screen followed by two resting phases of 60 seconds each; one with eyes open and one with eyes closed. A bell was used to signal the end of the 'eyes closed' resting phase. The data recorded during the resting phase would serve as a baseline to evaluate the data during the cognitive phases.

At the end of each task, a 30 second waiting screen was displayed. This only served as a transition phase between tasks, allowing participants to stop thinking about the previous activity and therefore avoid any overlap of cognitive phases.

Throughout the recording sessions, the experiment coordinators monitored the participant's behaviour and kept note of possible actions or disturbances that could possibly affect EEG data – all the while, making sure not to cause any disturbance to the participants. Notes taken during these sessions were later used to remove segments of un wanted data.

## 3.4 Tasks

The tasks were chosen after carefully considering that they simulate the cognitive conditions exhibited during the Analysis and Synthesis phases of the design process. Three tasks were chosen; one for Analysis and two for Synthesis, which would not only allow to evaluate the differences in wave patterns between analysis and synthesis but also to evaluate possible similarities between the two synthesis tasks.

All three tasks were kept rather simple since the aim is not to mimic an actual design process but to encourage participants to think in a different way for each problem. The simplistic nature of the tasks also meant that the time limit for each was rather short so that participants do not get bored and lose their attention from the task on-hand.

### 3.4.1 Task 1 – 'What Bothers you?' problem – Analysis Phase

The analysis phase is described as identifying all relevant factors to a given situation and breaking a subject into parts to better understand the problem. This is also sometimes termed as the 'problem definition phase'.

In task 1 participants were asked to write down and define all the problems related to the use of public transport. The participants were specifically asked to identify, clarify and define but not solve the problem. They were given three minutes for this task.

This exercise led the participants to identify a list of problems (that require solutions) caused or related to the use of public transport, simulating the analysis phase of the design process.

### 3.4.2 Task 2 – Mathematical Problem with many possible solutions – Synthesis Phase

The synthesis phase is described as finding partial solutions among feasible alternatives and possibly integrating them into one single form. It is also known as the scheme of generating possible ways that a product will work.

Task 2 is a common mathematical puzzle where one is given five numbers and asked to use all five numbers and any mathematical operators to make up another given number. Participants where given the numbers 2,3,5,10 and 24 and asked to make the number 120. This problem has many solutions, for example: (10-5)*24*(3-2) = 120, [(3*24)+(5*10)]-2 = 120, 24^(3-2)*(10-5) = 120 and so on.

Participants were given 5 minutes for this problem during which they tried to use different combinations of numbers and mathematical operators to achieve the required solution. Though not all the participants succeeded, they realized the need of coming up with partial solutions that can then be combined to make the number 120. This kept them engaged in conditions that closely simulate the synthesis phase for the complete 5 minutes.

### 3.4.3 Task 3 – Guilford's Alternative Uses Test – Synthesis Phase

In the Alternative Uses Test (Wilson, Guilford, Christensen & Lewis, 1954) examinees are asked to list down as many possible uses for a common household object. During the experiment, participants were given 3 minutes to do so for a newspaper.

This task simulates the synthesis phase by encouraging participants to generate the possible ways they can use this object.

## 3.5 Raw Data – Output

Raw data collected was stored by the Pure.EEG software in EDF format, a standard binary format, that is compatible with many EEG analysis programs such as EEGLab. The files can also be exported to CSV formats allowing to view and analyse them using Excel and other software.

The following screenshot gives an example of how the Raw data looks like when viewed on Excel in CSV format.

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 4208.205 | 4083.077 | 4114.359 | 4116.41 | 4206.667 | 4066.154 | 4114.872 | 4127.692 | 4122.051 | 4107.179 | 4203.077 | 4159.487 | 4253.333 | 4208.205 |
| 1 | 0 | 4198.461 | 4062.051 | 4113.333 | 4103.59 | 4258.974 | 4076.41 | 4122.051 | 4133.846 | 4138.461 | 4154.359 | 4204.103 | 4156.41 | 4255.897 | 4204.103 |
| 2 | 0 | 4184.615 | 4058.974 | 4109.744 | 4105.128 | 4276.41 | 4075.897 | 4122.564 | 4130.256 | 4138.974 | 4190.769 | 4193.333 | 4151.795 | 4249.744 | 4193.846 |
| 3 | 0 | 4168.718 | 4051.795 | 4113.846 | 4106.154 | 4237.949 | 4074.359 | 4123.077 | 4134.872 | 4136.923 | 4163.077 | 4196.41 | 4154.359 | 4243.077 | 4187.692 |
| 4 | 0 | 4147.692 | 4022.564 | 4111.282 | 4092.308 | 4230.769 | 4077.436 | 4120.513 | 4141.025 | 4143.59 | 4154.872 | 4191.795 | 4150.256 | 4230.256 | 4169.744 |
| 5 | 0 | 4120.513 | 4006.667 | 4100 | 4085.641 | 4241.539 | 4074.872 | 4111.795 | 4127.692 | 4132.308 | 4153.846 | 4171.795 | 4133.333 | 4206.154 | 4140 |
| 6 | 0 | 4106.667 | 4014.359 | 4096.41 | 4090.769 | 4231.795 | 4076.41 | 4114.359 | 4125.641 | 4125.641 | 4152.82 | 4169.23 | 4126.667 | 4192.308 | 4125.641 |
| 7 | 0 | 4100.513 | 4009.743 | 4097.949 | 4084.615 | 4235.384 | 4076.41 | 4120.513 | 4139.487 | 4143.077 | 4164.615 | 4178.974 | 4128.718 | 4188.718 | 4122.051 |
| 8 | 0 | 4078.461 | 3988.718 | 4097.949 | 4068.718 | 4252.308 | 4067.692 | 4114.359 | 4129.23 | 4137.949 | 4153.846 | 4160 | 4112.308 | 4166.154 | 4096.41 |
| 9 | 0 | 4056.41 | 3984.615 | 4091.282 | 4070.256 | 4222.051 | 4067.179 | 4111.282 | 4109.23 | 4117.949 | 4150.256 | 4132.308 | 4091.795 | 4137.436 | 4069.231 |
| 10 | 0 | 4050.769 | 3990.769 | 4086.667 | 4074.872 | 4212.308 | 4072.82 | 4115.384 | 4107.692 | 4119.487 | 4157.436 | 4131.795 | 4089.743 | 4128.205 | 4066.667 |
| 11 | 0 | 4047.692 | 3988.205 | 4087.179 | 4064.615 | 4253.846 | 4066.154 | 4110.769 | 4111.795 | 4120 | 4122.051 | 4135.384 | 4090.256 | 4115.897 | 4061.538 |
| 12 | 0 | 4041.538 | 3983.59 | 4087.692 | 4057.949 | 4251.795 | 4058.974 | 4106.154 | 4110.256 | 4106.154 | 4113.333 | 4124.103 | 4082.051 | 4101.539 | 4051.795 |
| 13 | 0 | 4038.974 | 3988.718 | 4088.718 | 4066.667 | 4206.667 | 4065.128 | 4109.744 | 4108.205 | 4106.154 | 4134.872 | 4113.333 | 4075.897 | 4100.513 | 4051.795 |
| 14 | 0 | 4042.051 | 3994.359 | 4085.128 | 4069.743 | 4209.744 | 4067.179 | 4107.692 | 4106.154 | 4114.872 | 4106.667 | 4118.974 | 4081.026 | 4097.436 | 4053.333 |
| 15 | 0 | 4040.513 | 3988.205 | 4081.026 | 4060.513 | 4254.359 | 4063.59 | 4103.077 | 4105.128 | 4108.205 | 4101.025 | 4124.615 | 4087.692 | 4090.256 | 4052.308 |
| 16 | 0 | 4036.41 | 3982.564 | 4085.128 | 4060 | 4252.82 | 4064.615 | 4104.103 | 4104.615 | 4099.487 | 4163.077 | 4114.872 | 4082.564 | 4088.718 | 4049.231 |
| 17 | 0 | 4040 | 3992.82 | 4087.692 | 4072.308 | 4234.872 | 4067.179 | 4105.641 | 4105.128 | 4110.769 | 4181.025 | 4109.23 | 4080 | 4086.154 | 4048.205 |
| 18 | 0 | 4047.179 | 4002.564 | 4089.231 | 4079.487 | 4251.282 | 4068.205 | 4106.667 | 4111.795 | 4121.025 | 4136.923 | 4118.974 | 4088.718 | 4085.128 | 4052.82 |
| 19 | 0 | 4050.769 | 3996.923 | 4091.282 | 4076.923 | 4242.051 | 4064.103 | 4113.846 | 4127.179 | 4121.025 | 4137.436 | 4130.769 | 4094.359 | 4102.051 | 4061.026 |
| 20 | 0 | 4051.795 | 3993.333 | 4091.282 | 4074.872 | 4224.103 | 4063.59 | 4120.513 | 4140.513 | 4131.795 | 4160.513 | 4130.256 | 4092.308 | 4110.256 | 4060.513 |
| 21 | 0 | 4047.692 | 3997.949 | 4087.179 | 4079.487 | 4259.487 | 4070.256 | 4120.513 | 4143.59 | 4138.974 | 4140 | 4121.539 | 4086.154 | 4093.333 | 4049.743 |

*Figure 14 - Raw Data CSV Format*

Since the sessions were recorded at a sampling rate of 128 per second, each row corresponds to 1/128 second of data i.e. one data sample. Successive rows correspond to the next data sample, meaning that one second of data is stored on 128 successive rows.

3.5.1 Data Description:

The first column acts as a counter that can be used as a time base. It runs from 0 to 128 for corresponding to the data samples recorded in each second.

The second column is flag to indicate if a data packet was dropped during the recording session. Flag = 0 means that the data was good.

Each column from C to P correspond to locations of individual sensors, in the order: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4. The numerical values under these columns correspond to the recorded electrical activity from each sensor. It is the measure of voltage fluctuations within the neurons of the brain and is recorded in Micro-Volts (uV).

Columns after P contain other information such as sensor contact quality, gyroscopic measures, markers etc.

The file also contains a single line in the beginning referencing to information for the rest of the file. This includes title, recording time and date, sampling rate, and other labels.

3.5.2 DC Offset

Raw EEG data is stored directly in these files as floating-point values; the values are directly converted from the unsigned 14-bit ADC output from the headset. Since the floating DC level of the signal occurs at approximately 4200 uV, this means that all negative values are transmitted as positive values less than the average level, and positive values are transmitted as positive values greater than the average.

It is important to note that before applying any kind of analysis on this data, it is necessary to remove the DC offset. The simplest approach is to simply subtract the average from the entire data, but this is a very inaccurate method. Ideally one should apply a high pass filter that matches the characteristics of the electronics. While another method is to apply filters using Matlab, that can track the background level and subtract them.

## 4. DATA PREPARATION AND INDEPENDENT COMPONENT ANALYSIS (ICA)

This chapter acts as a step by step guide regarding the tools and processes used to clean the data and prepare in for analysis. The objective of this part of the thesis is not only to prepare data that can help test our hypothesis but to also layout the guidelines for anyone interested in furthering related research.

### 4.1 EEGLAB – MATLAB Toolbox

EEGLAB is a MATLAB toolbox for processing data from electroencephalography (EEG), magnetoencephalography (MEG), and other electrophysiological signals. EEGLAB allows implementing various kinds of analysis, such as independent component analysis (ICA), time/frequency analysis, artefact rejection and several possibilities of visualizing data in 2D and 3D. It allows importing data in several different binary formats, executer data cleaning algorithms, extract event related epochs and perform the above stated analysis. Artefactual ICA components may be subtracted from the data, and components representing only brain activity may be further analysed. The toolbox also allows creating studies for several subjects in different conditions or to cluster the independent components that were obtained using ICA.

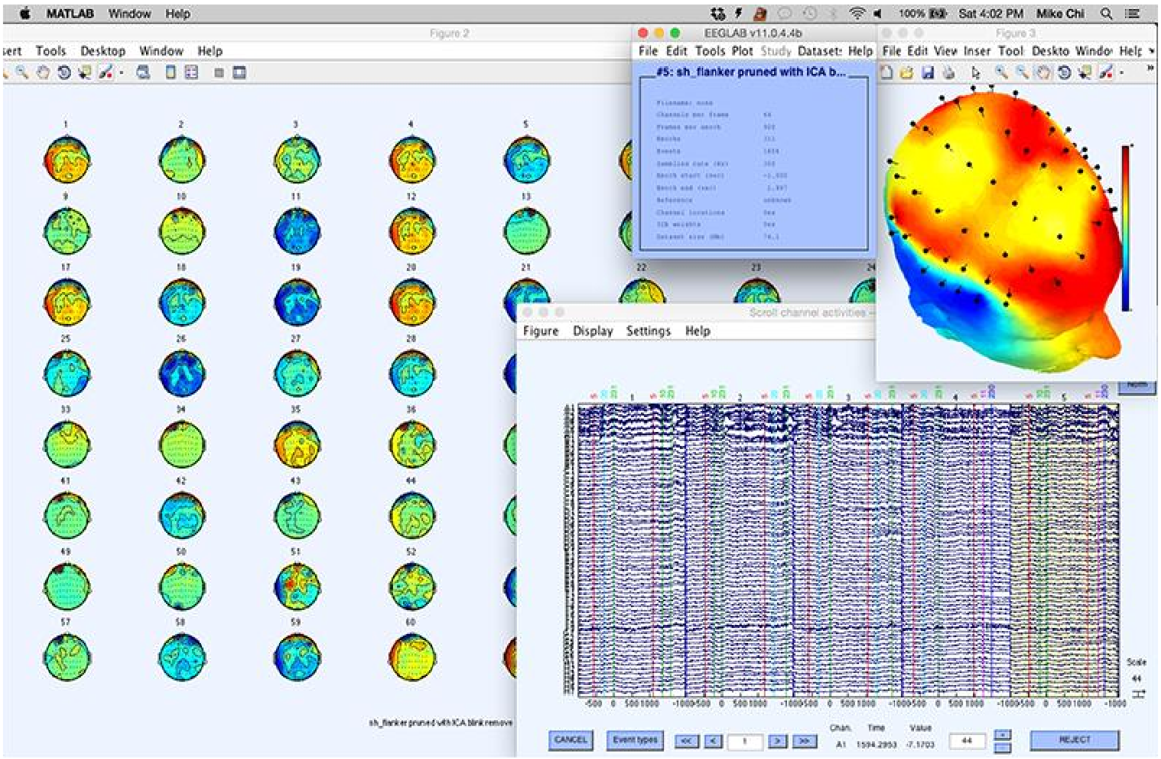



*Figure 55 - EEG Toolbox*

## 4.2 Data Preparation

In this section of the chapter, the steps are presented to prepare the raw data from Emotiv EPOC+ to be further processed in the EEGLAB toolbox. For the sake of this section, raw data from one subject of our experiment is used to explain the steps performed to prepare it for further analysis.

### 4.2.1 Importing Emotiv EPOC+ Data into EEGLAB

The computer software that comes with the band (EMOTIV Xavier Pure EEG) exports the recorded data in (.edf) and (.csv) file formats. This comma separated values file format can be seen in figure 16. This file contains the data from all 14 sensors (channels) of the headset along with several other columns corresponding to data point serials, gyroscope data, data transfer quality, markers and timestamps. We are mainly interested in the data from the 14 channels which are 128 values recorded per channel per second. We open this .csv file in Matlab and import only the columns corresponding to the EEG channels. This will be imported as a table typically under the name of “Untitled”. Next we convert this table into an array and then transpose it. Simply because EEGLAB takes an array as an input where rows correspond to the channels and the columns correspond to EEG values. Following is the short script for this procedure:

```
array = table2array(Untitled);
eegarray = array.'
```

Now we have an array (matrix) of nXm dimension where n is the number of channels, 14 in our case, and m is the number of recordings. For us this is around 118912 because we recorded at 128 Hz and the experiment lasted around 15 minutes. This array can now be imported into the EEGLAB as a dataset.

File > Import Data > Using EEGLAB functions and Plugins > From ASCIII/Float File or Matlab Array

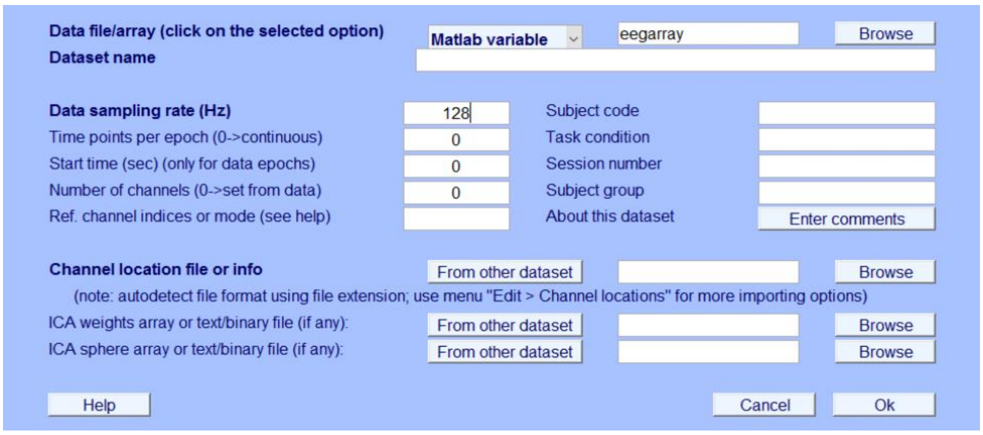



*Figure 16 – Importing EEG Data*

Specifying the Matlab variable name and the sampling rate, the data can be imported into EEGLAB.

4.2.2 Setting up Channel Information

The next step is to enter the channel information so EEGLAB knows which column of EEG data values corresponds to which point on the scalp. Fortunately, the Emotiv EPOC+ adheres to an internationally recognized method to describe and apply the location of scalp electrodes in the context of an EEG test or experiment called the International 10-20 system as shown in Figure 17. We know from the raw data files the sequence in which the electrodes correspond to the 14 columns of the .csv file. The sequence is as follows: AF3 F7 F3 FC5 T7 P7 O1 O2 P8 T8 FC6 F4 F8 AF4. Now that we have these codes we can look up the coordinates that describes the position of each of those electrodes on the scalp and input them into EEGLAB. EEGLAB takes in this information in a very specifically formatted .txt file detailing the coordinates of these channels on the scalp.

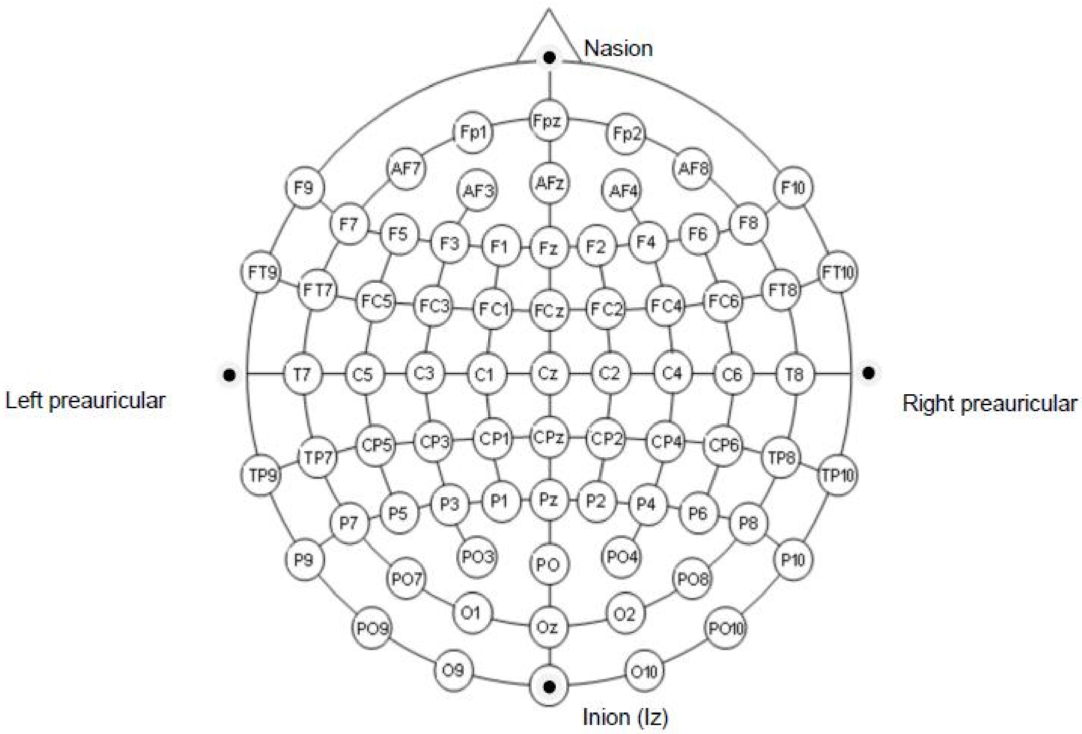



*Figure 17 – International 10-20 system*

These coordinates are easily available on the web and need to be put into a structure as shown in the picture below.

| Number | labels | theta | radius | X | Y | Z | sph_theta | sph_phi | type | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | AF3 | -23 | 0.411 | 0.885 | 0.376 | 0.276 | 23 | 16 | 1 | 1 |
| 2 | F7 | -54 | 0.511 | 0.587 | 0.809 | -0.0349 | 54 | -2 | 1 | 2 |
| 3 | F3 | -39 | 0.333 | 0.673 | 0.545 | 0.5 | 39 | 30 | 1 | 3 |
| 4 | FC5 | -69 | 0.394 | 0.339 | 0.883 | 0.326 | 69 | 19 | 1 | 4 |
| 5 | T7 | -90 | 0.511 | 6.12e-017 | 0.999 | -0.0349 | 90 | -2 | 1 | 5 |
| 6 | P7 | -126 | 0.511 | -0.587 | 0.809 | -0.0349 | 126 | -2 | 1 | 6 |
| 7 | O1 | -162 | 0.511 | -0.95 | 0.309 | -0.0349 | 162 | -2 | 1 | 7 |
| 8 | O2 | 162 | 0.511 | -0.95 | -0.309 | -0.0349 | -162 | -2 | 1 | 8 |
| 9 | P8 | 126 | 0.511 | -0.587 | -0.809 | -0.0349 | -126 | -2 | 1 | 9 |
| 10 | T8 | 90 | 0.511 | 6.12e-017 | 0.999 | -0.0349 | -90 | -2 | 1 | 10 |
| 11 | FC6 | 69 | 0.394 | 0.339 | -0.883 | 0.326 | -69 | 19 | 1 | 11 |
| 12 | F4 | 39 | 0.333 | 0.673 | -0.545 | 0.5 | -39 | 30 | 1 | 12 |
| 13 | F8 | 54 | 0.511 | 0.587 | -0.809 | -0.0349 | -54 | -2 | 1 | 13 |
| 14 | AF4 | 23 | 0.411 | 0.885 | -0.376 | 0.276 | -23 | 16 | 1 | 14 |

*Figure 18 – EEG Channel Coordinates*

This file can then be imported onto the dataset that was imported earlier. This file of course must be made only once and can be used for multiple datasets.

Edit > Channel Locations > Read Locations

### 4.2.3 Adding Events to Dataset

Once the dataset and the channel locations are loaded into the EEGLAB, one can start adding more information onto the dataset that is specific to ones' experiment. In our case, these events are the markers that signal the beginning to different phases of the experiment. The markers / events in our recording are detailed on a timeline in Figure 13. We will now add these events onto our data. As with channel information, events also need to be codified and put in a specific structure in order to be imported onto the dataset. When adding events onto the dataset, there are two obligatory pieces of information that one must input which are "Latency" and "Type". More variables can be added as well of course. We codified our events as follows:

| Latency | Type | Description |
|---|---|---|
| 20 | ES | Experiment Start |
| 30 | RP1S | Resting Phase 1 Start |
| 60 | RP2S | Resting Phase 2 Start |
| 90 | W1S | Wait 1 Start |
| 120 | T1S | Task 1 Start |
| 300 | W2S | Wait 2 Start |
| 330 | T2S | Task 2 Start |
| 630 | W3S | Wait 3 Start |
| 660 | T3S | Task 3 Start |
| 840 | EE | Experiment End |

*Table 4 Event Latency Parameters*

The experiment was always started 20 seconds after the start of the recording session for it to stabilize. These were prototypical markers that correspond to our experiment.

These were obviously finetuned for subjects with some variation in recording time. These variations were noted during the recording sessions (See Appendix F). This information was again put in a .txt file in the structure as shown in the figure to be mapped onto the dataset.

| Latency | Type |
|---|---|
| 20 | ES |
| 30 | RP1S |
| 60 | RP2S |
| 90 | W1S |
| 120 | T1S |
| 300 | W2S |
| 330 | T2S |
| 630 | W3S |
| 660 | T3S |
| 840 | EE |

*Figure 6 - Event Codes*

File > Import Event Info > From Matlab Array or ASCI II File

It is important to describe the heading names in lowercase and indicate the number of rows dedicated for the headings as shown in the figure below.

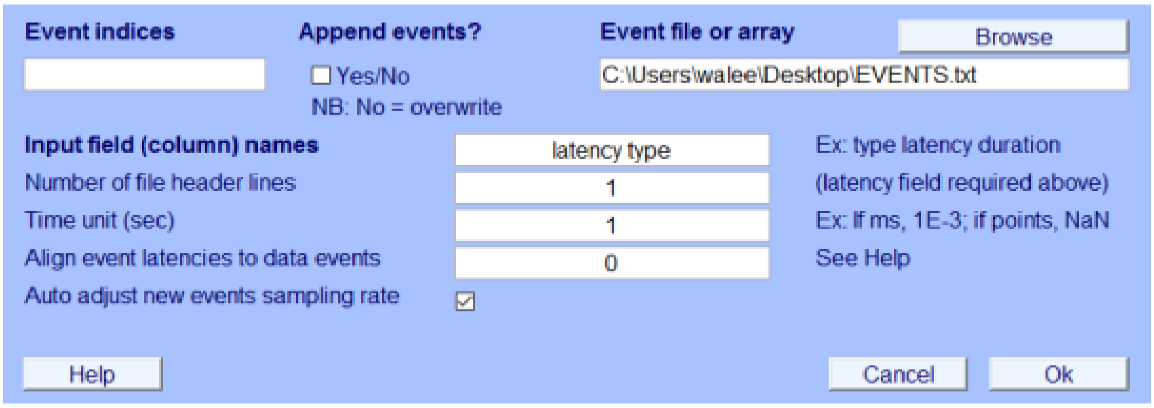



*Figure 19 - Adding Events EEGLab*

## 4.3 Data Cleaning

Raw EEG data usually contains lots of noise which can affect the analysis procedure resulting in unreliable results. The noise is usually due to outside electromagnetic interference (that is difficult to shield off), bad channels or moving sensors during the recording process. It is a critical step particularly for average referencing, because the averaging process considers the signal of all channels. Since any interference can cause huge distortions in the data, average referencing before cleaning that data will result in the complete data set being skewed towards bad data.

There are many methods of cleaning raw data, including manual approaches by scrolling through each channel and removing distorted data. Manual approaches are not very desirable as it is difficult to spot all bad data by the human eye and it leaves a previously continuous data with interruptions. Researchers these days use sophisticated algorithms that can detect bad signal and channels while maintaining the original length and continuity of the dataset. The algorithm used for our research comes in the form of the cleanraw_data( ) EEGLab plugin.

4.3.1 Cleanraw_data( ) – EEGLab Plugin

Christian A. Kothe from the Technische Universität Berlin wrote this algorithm as a plugin for the EEGLab Toolbox which removes non-stationary high variance signals from EEG and reconstructs missing data using a spatial mixing matrix. It uses very robust calibration statistics to minimize any effect of artefacts. The basic idea of this algorithm is that since EEG is highly co-related it can estimate content of one channel based on the content of its neighbouring channel. The same works for not only one channel but a linear combination of multiple channels.

This method is more commonly known as Artefact Subspace Reconstruction (ASR) method, which basically involves extracting clean sections of the existing data using calibration statistics over 1-second windows of data and calculating the probability that a signal is due to an artefact. It then separates the high amplitude signals (potential artefact components) and classifies each component as high variance or nominal variance and reconstructs the high variance content using content from nominal variance components.

After installing the cleanraw_data( ) plugin onto the EEGLab toolbox, datasets can be individually opened and cleaned using the algorithm.

Tools>Clean continuous data using ASR

The recommended settings for the algorithm are the default ones, as shown in the figure below.

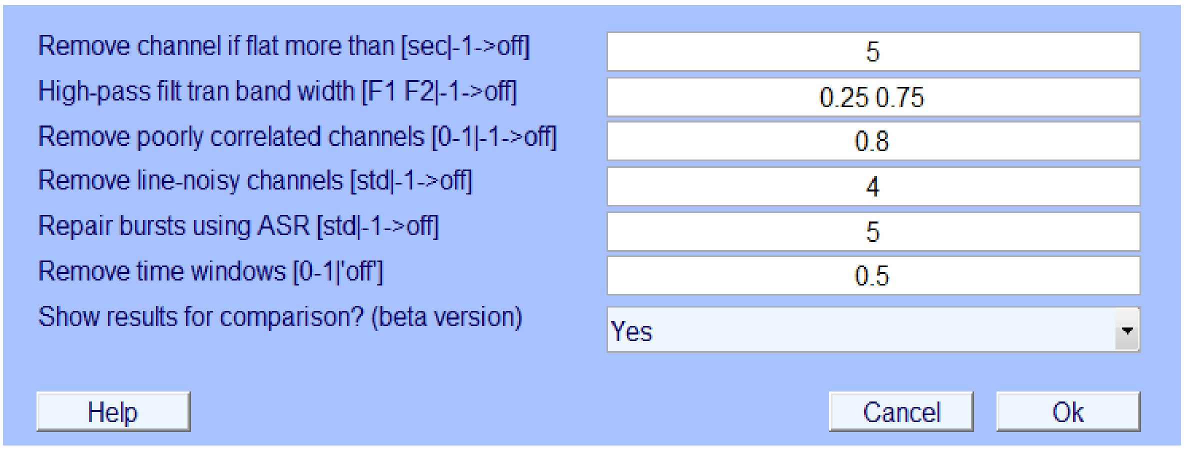



*Figure 20 - Data Cleaning parameters EEGLab*

The end of the cleaning process is followed by a summary of the data that was rejected. The figure below shows a small section of one of the data sets that was cleaned using the plugin. The red trace shows the data channel scrolls before the process while the blue trace shows the data channel scroll after the cleaning process.

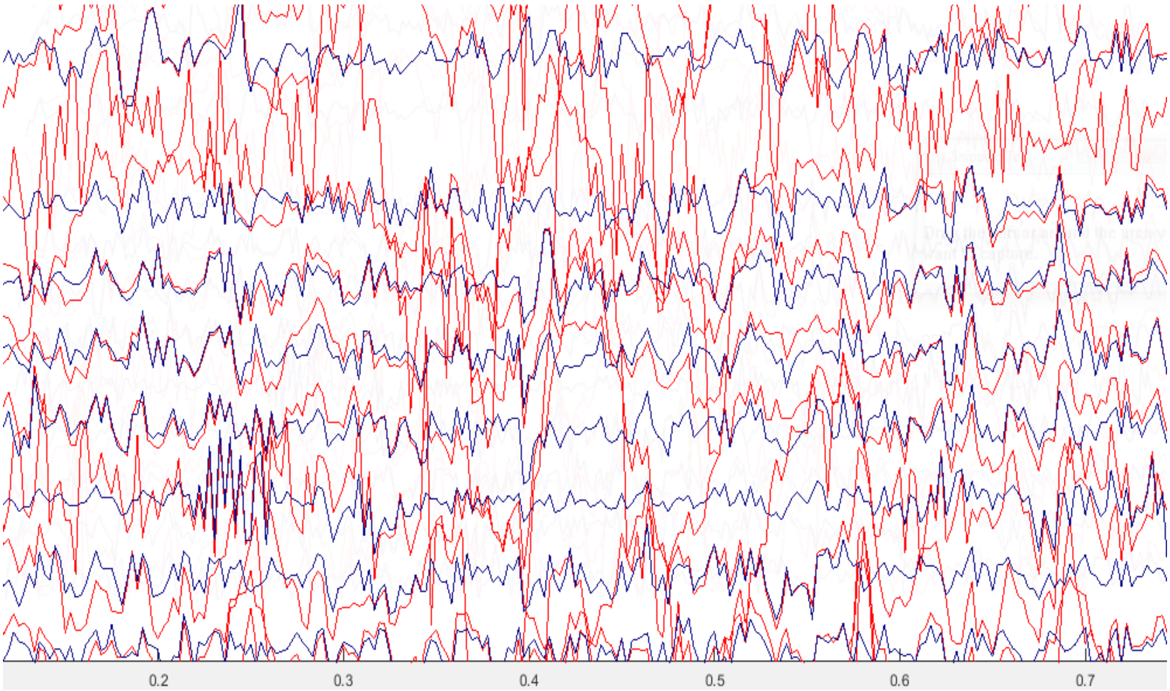



*Figure 21 - cleanraw_data() before and after*

As explained, the process also removes bad channels. This is a critical step before the data averaging process as even the presence of 5-10% of bad channels will lead to noise in all channels as it considers average of all channels, good and bad.

Removal of bad channels may lead to potential bias in the averaging process. For example, if 0 channels were rejected from the right hemisphere and 0 from the right, the average bias will be towards the right. Hence the last step before re-referencing the data is to interpolate the electrodes.

As mentioned in chapter 3, after running the data cleaning algorithm 3 of the 12 data sets were rejected. The data cleaning algorithm rejected more than 7 of the 14 channels for participants no. 1, 9 and 11, while for other participants no more than 2 of the 14 channels were rejected which could be easily reconstructed using electrode interpolation.

4.3.2 Re-referencing the Data

EEG voltages recorded by each electrode or channel are relative to what is termed a reference channel or a common channel. Often these reference channels are placed on the mastoids since they are relatively closer to the other channels and experience lesser electrical signal from the brain (for example, TP10 in the 10-20 System, the electrode coloured red in the picture below). Generally, these are placed on both sides of the scalp symmetrically in order not to generate a bias in the data. As a rule of thumb, reference electrodes are chosen to be as far away as possible from the electrodes of interest. There is no best position for a reference electrode. Some researchers claim that a non-scalp reference electrode (nose, knee etc.) is a better choice but such claims still lack scientific evidence. EEGLAB allows you to re-reference the data. Our headset uses two fixed reference electrodes (P4 and P3) but we have decided to re-reference the data to what is called "average reference", a practice widely advocated by researcher in the field. The idea rests on the fact that the outwards positive and negative currents summed across a sphere (assumed to be electrically isolated) will sum to zero (Ohm's law).

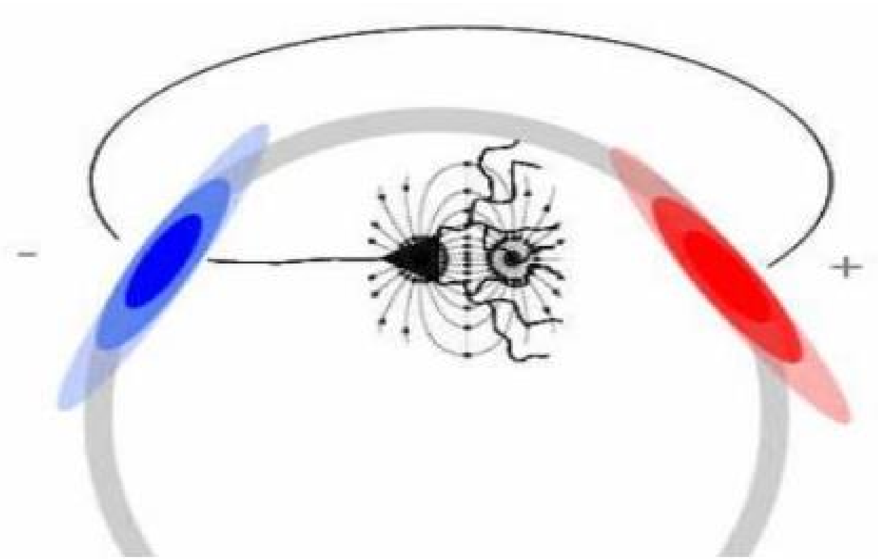



*Figure 22 - Average Referencing*

For example, in the figure above a tangentially-oriented electrical source is associated with a positive inward current to the left (here, blue) and an opposing outward negative current to the right (red). If the current passing through the skull or the body is assumed to be negligible, one 42 may assume that the sum of the electric field values recorded at all (sufficiently dense and evenly distributed) scalp electrodes is always 0 (the average reference assumption). Obviously, such an assumption requires the electrodes to be even distributed over the scalp which is not the case as some areas of the scalp sport more electrodes than others. To re-reference the data in EEGLAB, select

Tools>Re-reference

This will call the matlab function pop_reref.m and we select 'compute average reference' since we already didn't include the data from mastoid channels in the beginning when we imported the raw data.

4.3.3 Extracting Epochs

To study the event-related EEG dynamics of continuously recorded data, we must extract data epochs time locked to events of interest (for example, data epochs time locked to onsets of one class of experimental stimuli) by selecting

Tools > Extract Epochs

In our case these data epochs correspond to the three tasks which we expect to have distinct cognitive processes and wish to see whether that is evident via EEG. The epochs can be extracted and saved as separate datasets. Already having the events set is useful in extracting epochs. For the sake of this explanatory section, we extract the epoch corresponding to Task 1 from these 43 datasets to be used in the next section. Task 1 lasted for 180 seconds. We shall extract the epoch from 30s to 150s as a convention to neglect the boundary effects.

#### 4.3.4 Filtering the Data

Filtering transforms the signal and so in an ideal world, we shouldn't be doing that. However, it is often necessary before moving on with data analysis due to several factors. The main reason is the removal of the 50Hz line noise (60Hz in the United States). The second reason is to remove high and low frequency noise from the data. Moreover, filtering the data removes any linear trends from the raw data. EEGLAB allows Finite Impulse Response filtering. Tools > Filer the Data > Basic FIR Generally, if the aim is to carry out ERP analysis, the lower and upper filter edges are defined as 0.1Hz and 30Hz, respectively. These exact values can vary. This bandpass filtering serves the purpose of suppressing the 0Hz offset and the 50Hz DC line noise. It is recommended to apply the filters one by one as it is fairly resource intensive computationally. To perform this procedure, it is recommended to install the Matlab Signal Processing toolbox.

### 4.4 Independent Component Analysis (ICA)

This section gives a brief description of the Independent Component Analysis, how it can be performed using EEGLab and how to we deal with the resulting components. It also explains why ICA could be helpful for studying our experiment and what approach was used to reject unwanted artefacts from our datasets. The dataset of a single task from one of our subjects is used to explain the steps carried out for the decomposition and component rejection process.

#### 4.4.1 What is ICA

EEG is composed of signals arriving from several sources. These sources could be neural activity, blinks, eye movement, muscle movement or pulse. Existing research shows that each source projects a unique topographical scalp map and these maps are mixed together according to the principle of linear superposition. ICA helps to reverse this superposition into independent components or scalp maps that can then be used for research purposes.

Independent component analysis (ICA) is a very powerful method of separating linearly mixed signals from several sensors. In the case of electroencephalogram (EEG), these components are artefacts embedded in the data. The decomposition involves changing the basis of the data from a data collected from single channels to a spatial basis. In simple terms, original EEG data is in the form of rows of data along the time course, each representing the voltage of a single sensor with respect to one or more reference channel. After ICA decomposition the data is the time course activity of each component or artefact.

The mixing process of data from several channels during ICA is passive and linear, hence adding no information to the data. Changing the channel order or changing the order in which points are plotted has virtually no effect on the algorithms outcome since it has no priori about electrode location.

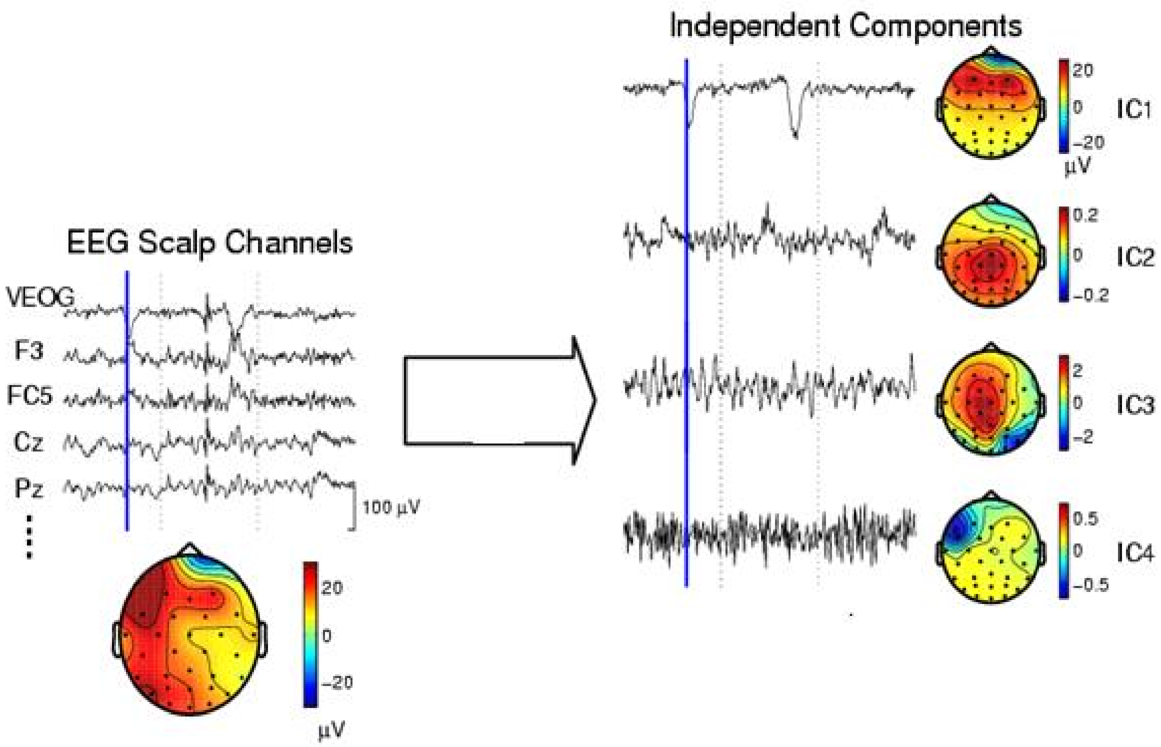



*Figure 23 - ICA Decomposition*

The figure above shows how the decomposition outcome looks like visually. The data on the left is the orginal EEG data in the form of signals from each channel. Data from each channel is divided into components and then mixed with the same components from the other available channels.

4.4.2 Running ICA and component rejection

EEGLab has built in tools to perform ICA decompositions. To run the algorithm, we simply select:

Tools > Run ICA

This is followed by a window to select the kind of algorithm we would like to run. For simple low density channels the default runica( ) algorithm is recommended. Once the process is complete the following window opens up, showing the 2-D spectras of all the components extracted.

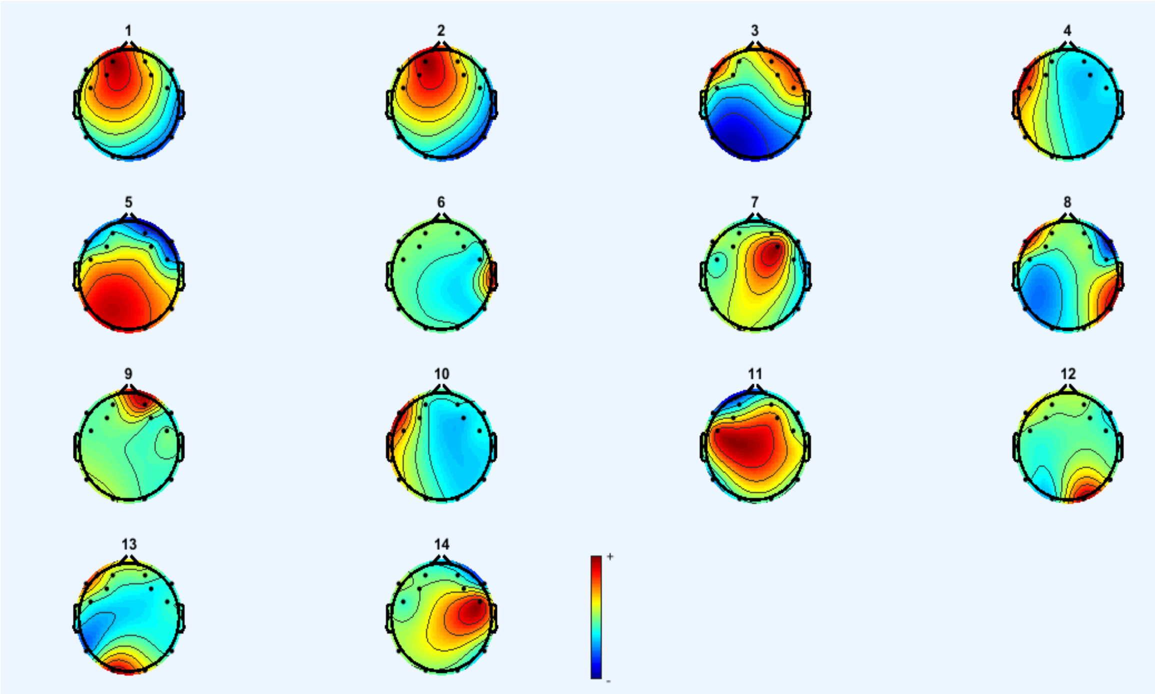



*Figure 24 - ICA components 2D spectras*

Note that the scale in the above plot uses arbitrary units. However, the component scalp map values multiplied by the component activity time course would give us the same units as the data.

Although the ICA decomposition separates the data into many different linear components, before further analysis, it is important to identify and eliminate components that are not concurrent with the research objective. In our case, we would like to reject all components that are not related to brain or cognitive functions.

The process of identifying the different types of components maybe a complicated one, but existing research and tutorials provided by EEGLab experts make it much simpler. This section explains what criteria was used to reject unwanted independent components and determine what component is strictly related to brain or cognitive functions.

The main steps used for identifying components that maybe related to eye movement, blinks, muscle movement, noise, channel pops or the brain components are first to analyse the scalp maps of each component, followed by the component activity power spectrum. We use the figure above (taken from one of our trials) to explain the process.

Eye artefacts are amongst the easiest to identify. For example, looking at component 3 and 9 from the above decomposition:

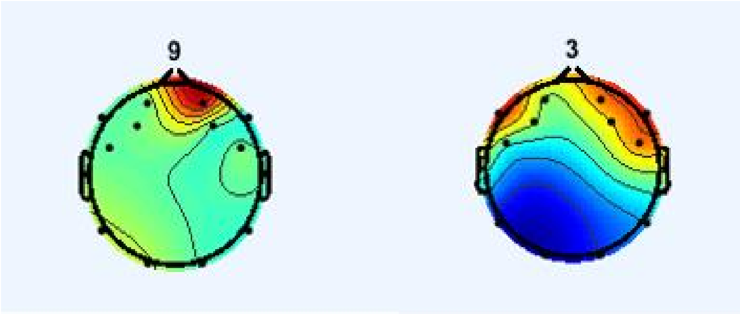



*Figure 25 - Eye artefacts*

Component 9's scalp map shows activity concentrated on the far frontal area of the scalp, which is very typical of eye movement. While component 3's scalp map shows a smoothly decreasing eeg spectrum which is typically related to blinks.

Other artefacts that are easy to identify for rejection are components related to muscle activity. An example is component 6 from the above decomposition:

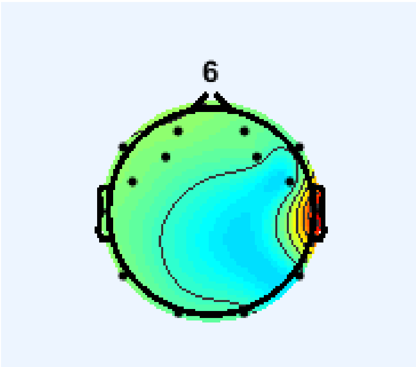



*Figure 26 - Muscle Artefact*

Muscle artefacts show spatially localized scalp maps, with high activity at those points of localization. The above could be due to strong movements of the right jaw or muscles near the right ear.

Another kind of artefact that is easy to identify are due to channel pops. This is when during the recording session, a single channel goes off or experiences high amount of channel noise. An example from the above decomposition would be component no. 4 and 10:

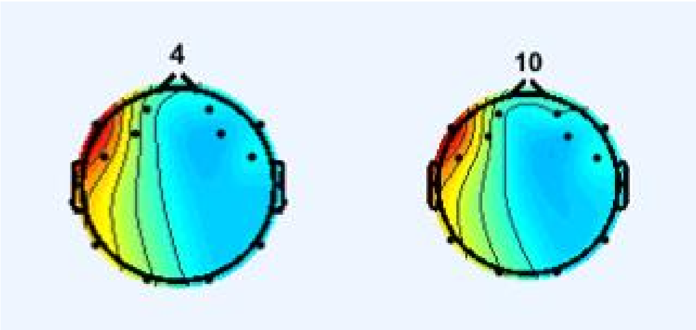



*Figure 27 - Channel pop artefacts*

Although there would be many components that appear to be brain like, that show scalp maps localized in the centre of the scalp. There main criteria for recognizing components that are strictly related to brain activity are that they exhibit scalp maps that have single or multiple dipoles, and their activity power spectrum shows peaks at typical brain related frequencies (for example in the alpha band 7.5 – 12.5 Hz). To show a clear example, we used component no. 4 of subject 12, during task no. 3, that shows a very clear dipole-like scalp map and exhibits a strong alpha band peak at around 10 Hz.

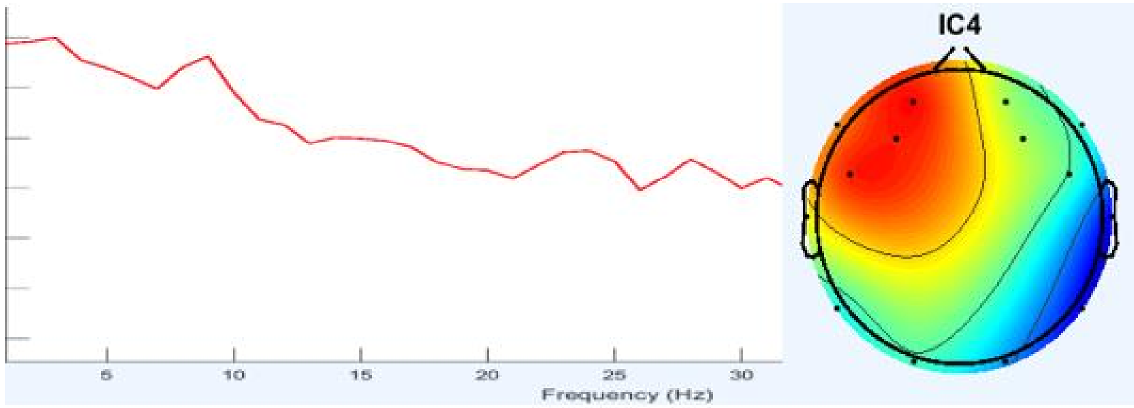



*Figure 28 - Brain related component*

The above explained criteria was applied on all the data sets to obtain brain/cognitive related components for all the data sets that we obtained after the cleaning and decomposition process. The process is fairly simple on EEGLab once the ICA has been completed. By selecting:

Tools>Reject Using ICA>Reject components by map

We obtain scalp maps of all the components with a button next to it to either accept or reject the component. By clicking on each the scalp maps we can also view the activity power spectrum graph, which plots the Frequency (Hz) against the Activity Power:

$$10 * \log_{10}(\mu V^2/Hz)$$

Just like the data cleaning process, the ICA decomposition also leads to rejection of some data sets. Some of the data-sets never completed the decomposition process while some gave a warning of bad data at the end of the process. To avoid bad data interfering with our final evaluation, we decided to not include these data sets in the final analysis. The following table represents the final data-sets that were used:

| Participant | Task 1 | Task 2 | Task 3 |
|---|---|---|---|
| **01** | Rejected | Rejected | Rejected |
| **02** | Accepted | Accepted | Rejected |
| **03** | Accepted | Accepted | Rejected |
| **04** | Accepted | Accepted | Accepted |
| **05** | Accepted | Accepted | Accepted |
| **06** | Rejected | Accepted | Accepted |
| **07** | Accepted | Rejected | Accepted |
| **08** | Rejected | Accepted | Accepted |
| **09** | Rejected | Rejected | Rejected |
| **10** | Rejected | Accepted | Accepted |
| **11** | Rejected | Rejected | Rejected |
| **12** | Accepted | Rejected | Accepted |

*Table 5 - Datasets Accepted for final evaluation*

## 5. RESULTS

This chapter discusses the results and possible conclusions that can we can arrive to after carrying out the data processing and analysis described in the previous chapter. We then try to compare our findings with the literature review in chapter 2.

### 5.1 Results and Evaluation

The original aim of this thesis was to design and conduct an experiment that could help distinguish EEG patterns for the cognitive functions of analysis and synthesis. After designing and conducting the experiment as described in chapter 3 on twelve male individuals we obtained initial results in the form of Raw EEG datasets. These datasets then went through a long pre-processing pipeline followed by the Independent Component Analysis as described in chapter 4.

The final results were in the form of strictly brain related components for each dataset that survived the whole process. The scalp maps and the corresponding activity power spectrum were then arranged together for each task to look for possible patterns.

The following figures show these scalp-maps along with their activity power spectrum, which plots the Frequency (Hz) on the x-axis against the Activity Power (y-axis):

$$10 * \log_{10}(\mu V^2/Hz)$$

#### 5.1.1 Task 1 Results – Public Transport Problem – Analysis Phase

Task 1 shows no pattern or possible relationship between the spectrums of different participants. Participants 2 and 7 show very flat activity power spectrums, which are typical of resting phases. Some participants show peaks at the low frequency band (between 0 -7 Hz) that are typical of Delta and Theta bands, while only one of them shows some activity around 10 Hz (alpha band). In terms of hemisphere activation; only two participants show activation of the left region while the remaining four exhibit high activity on the right hemisphere of the brain.

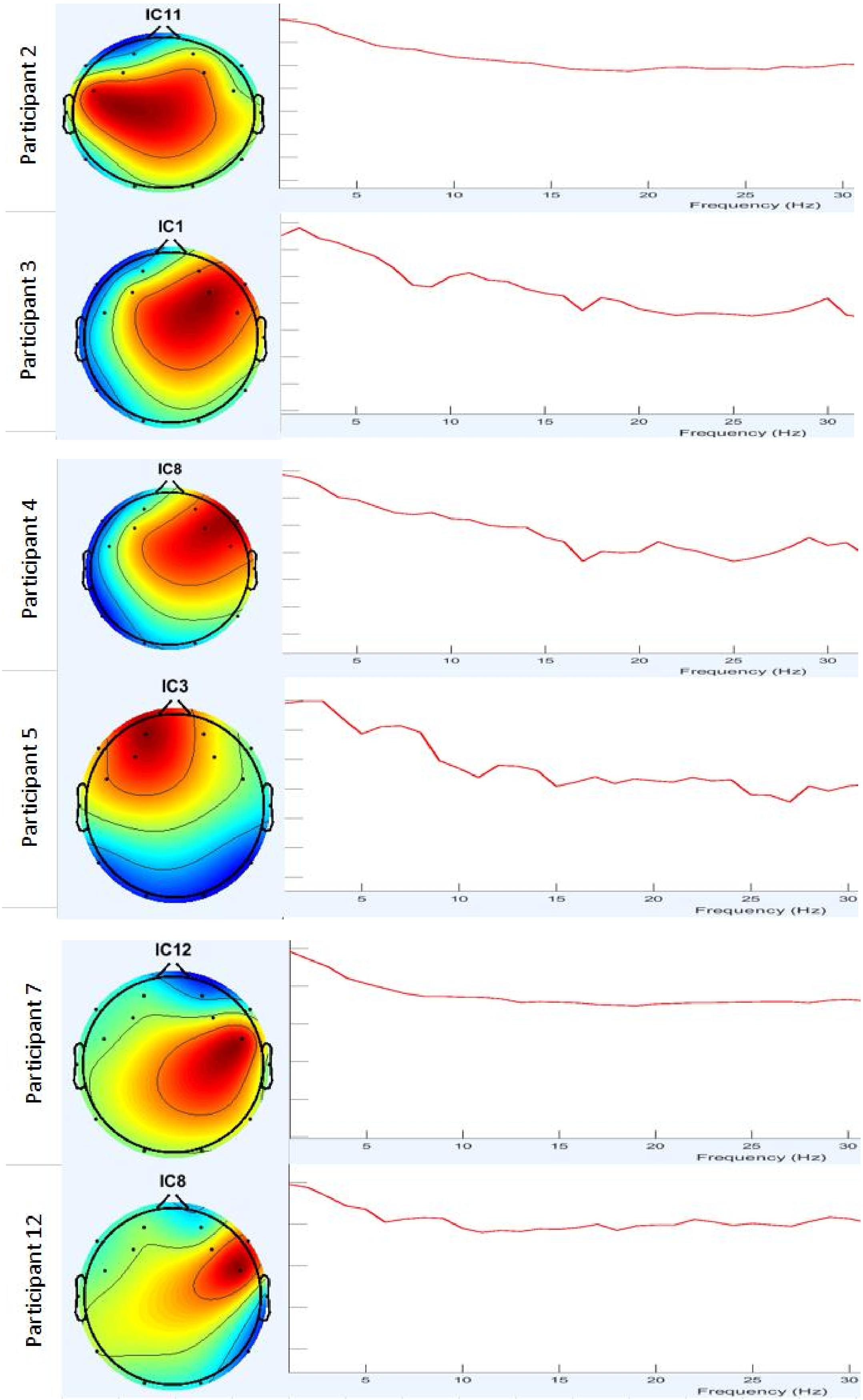
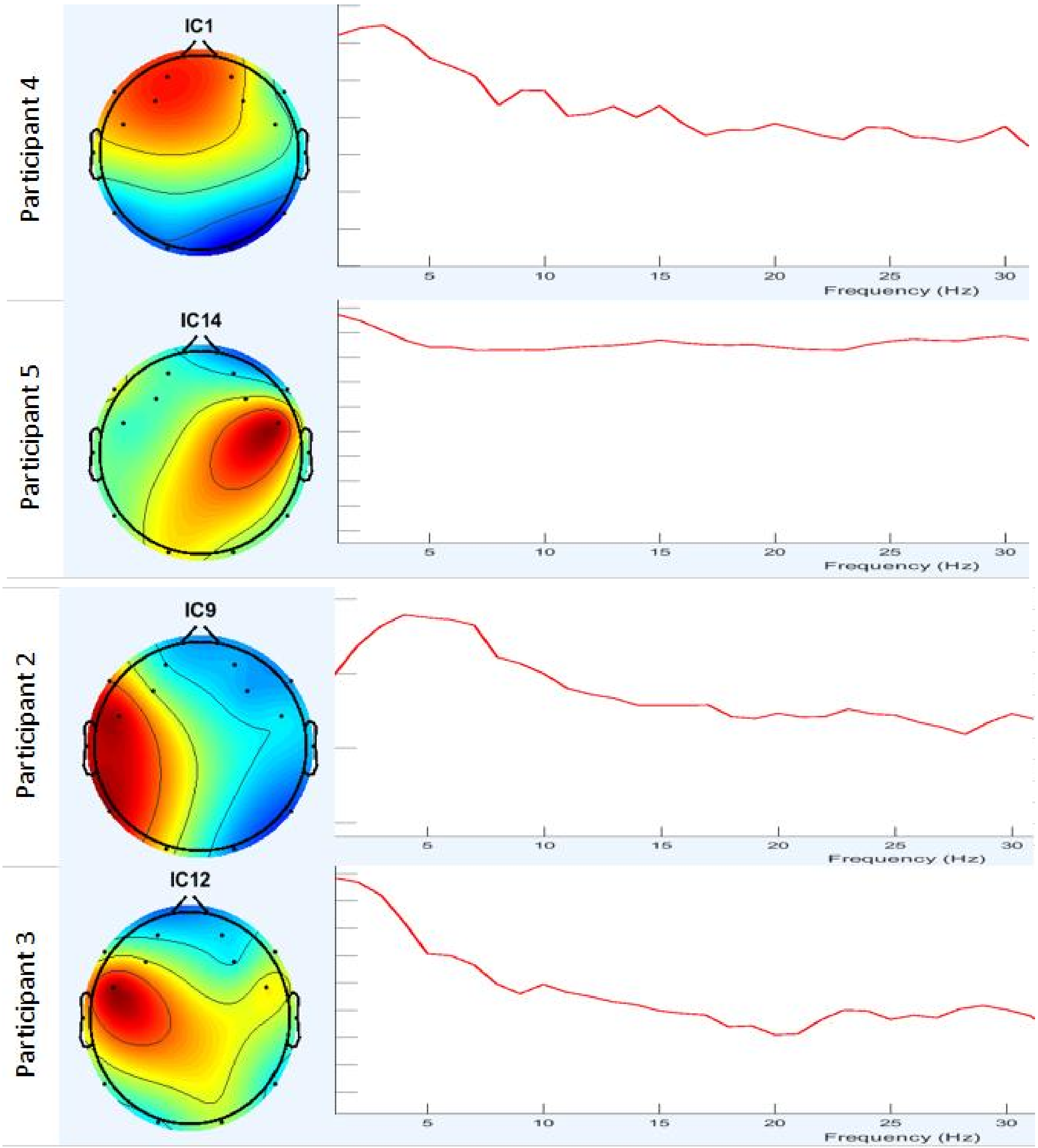



*Figure 29 - Task 1 Scalp Maps and Power spectrum*

5.1.2 Task 2 Results – Mathematical Problem – Synthesis Phase

Task 2, once again shows no significant pattern. Participant 5, 6, And 8 show a flat spectrum curve that is typical of the resting phases. Although participants 3, 4 and 10 show some activity around the 10 Hz frequency of the alpha band – The dissimilarity with other participants leads to no significant conclusions or pattern identification. In terms of scalp maps, almost all participants show different regions of the brain exhibiting high activity.



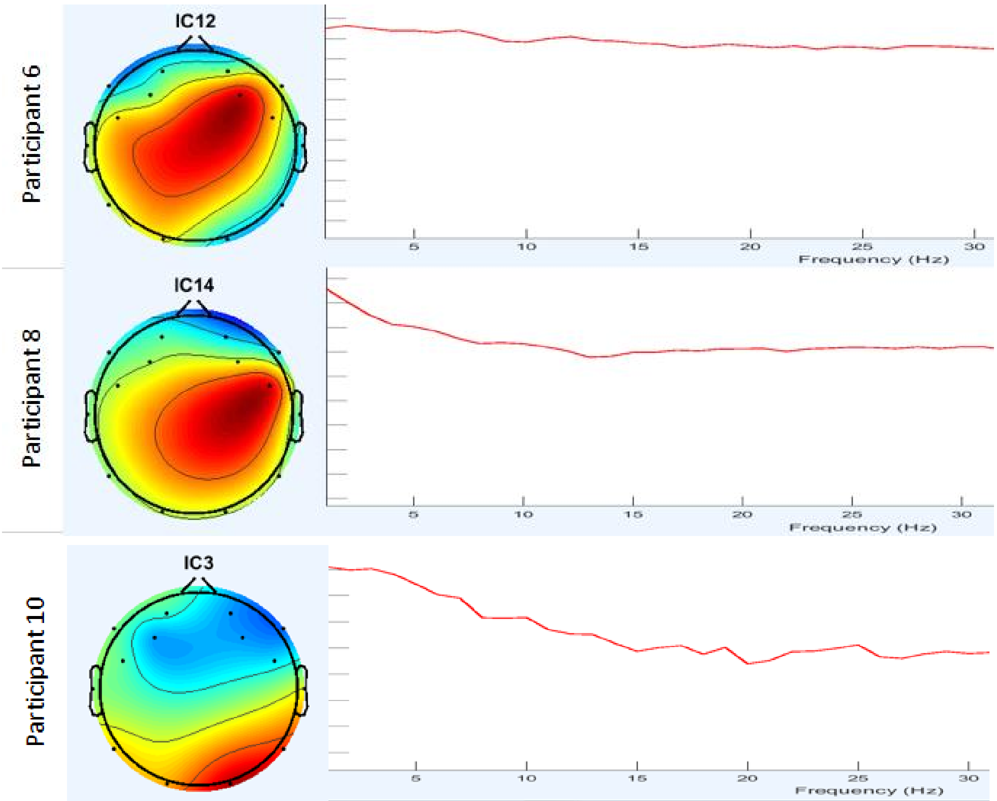



*Figure 30 - Task 2 Scalp Maps and Power Spectrum*

5.1.3 Task 3 Results – Alternative Uses Test (ATU) – Synthesis Phase

The data from Task 3 provided with the most interesting results. Drawing two lines to highlight the alpha frequency band (7.5 – 12.5 Hz); a very clear pattern can be seen. Each participant shows at least some level of increase in activity within this small band in the form of peaks. As pointed out in literature review in Chapter 2; an increase in alpha band has often been associated with creativity and divergent thinking. Table 2 and 3 of Chapter 2 also provides a summary of existing researches that studied the possible relationship of divergent thinking and creativity with alpha band activation and majority of them concluded that there was at least some form of increase or event related synchronization of the alpha frequency. Though, the magnitude of the peaks is higher in some and lower in others, there is at least some form of activation exhibited by each participant. The amount of increase in alpha band activity has been linked to the level of creativity or intelligence in some researches but the purpose of our research was not to test the intelligence of our participants, but to identify possible EEG patterns for each tasks. Another point to be noted is that the scalp maps show activation either in the frontal or the posterior region of the scalp, which are typically related to the alpha band EEG waves.

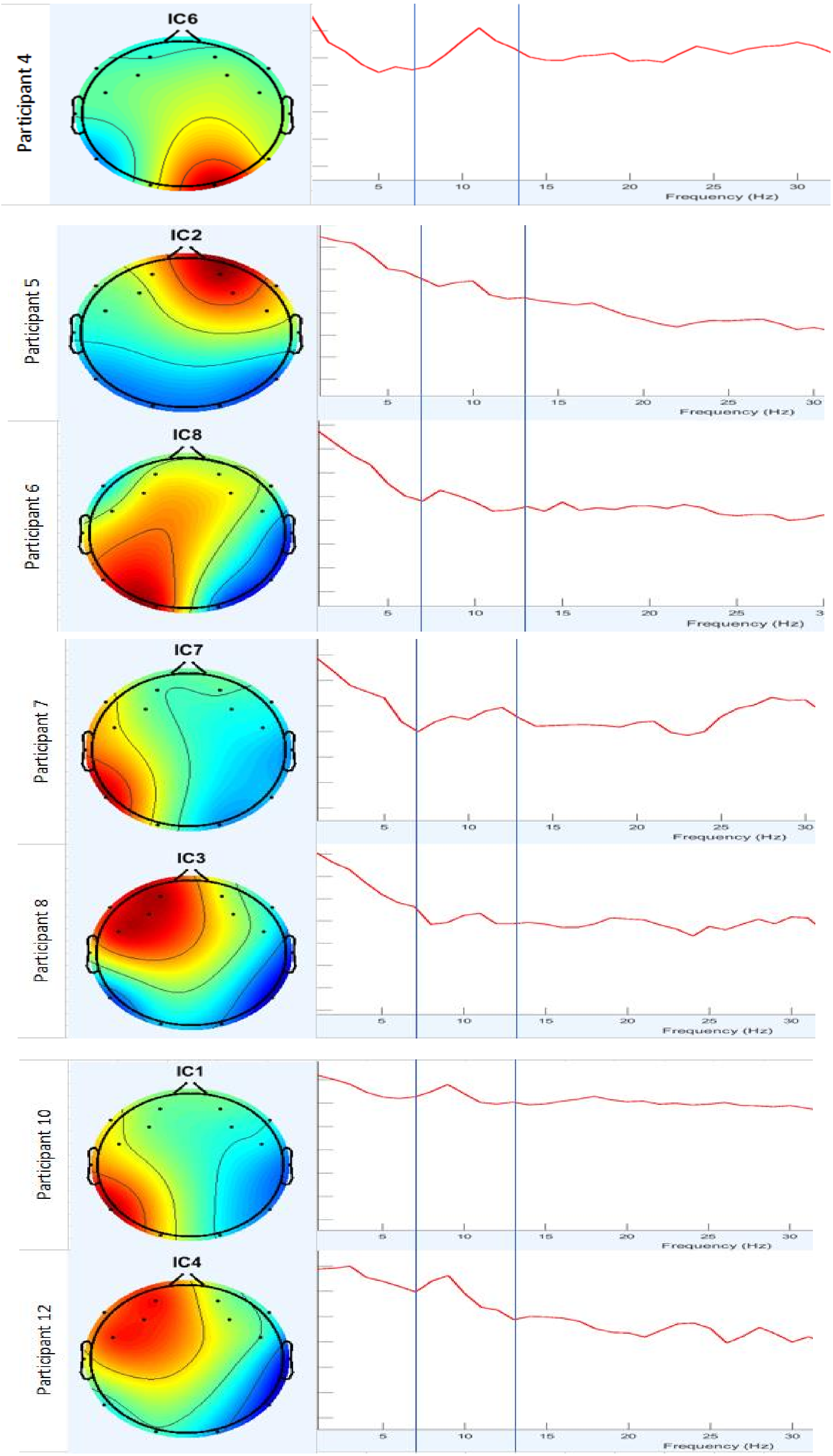



*Figure 31 - Task 3 Scalp Maps and Power Spectrum*

### 5.1.4 Conclusion

There are some apparent conclusions that can be made when one observes these results and keeps in mind the nature of each task. It is likely that Task 1 and Task 2 did not induce a similar thought process in all our candidates as they were not as straight-forward or precise when compared to the nature of Task 3. Task 1 and 2 could be interpreted in different ways, hence prompting different approaches and thought processes to solve them. Task 2 consists of both divergent and convergent phases and hence the final results could be a mix of data exhibited during both these phases. Task 3, on the other hand, being a popularly used task for design research, was the only one that showed identifiable pattern. Since the task is very straightforward and famously known for inducing a divergent thought process, all participants showed some level of activity in the alpha band which is typical of divergent thinking and creativity.

This highlights the importance of the type of tasks that are selected when designing experiments that employ EEG technology. Tasks should be very precise and straightforward so that very specific cognitive conditions are simulated in the case of each subject. In our case, Task 1 and Task 2 failed to do so as the problems were not straightforward prompting participants employ different approaches and consequently exhibiting varying cognitive conditions.

Our initial hypothesis predicted to see distinct patterns for Analysis (Task 1) and Synthesis (Task 2 and 3) phases of the design process. An experiment was designed and conducted on Male Engineering students to test the hypothesis. Recorded EEG data was processed, cleaned and analyzed but as can be clearly seen from the above results, it did not support the hypothesis. Although the results did not prove our hypothesis, the presence of some pattern in Task 3 and the results being concurrent with most of existing research at least shows that there is potential in using Neuroscientific tools for design research. Hence, one can also not completely rule out the possibility of studying the Function, Analysis and Evaluation phases of the design process by employing different approaches to the experiment and using these results as guide towards the design of the experiment.

## 5.2 Future research possibilities

The experiment can vastly be improved by designing tasks that occur over shorter periods of time. EEG data sets get exponentially difficult to analyze with time. Having tasks of shorter periods also allows evaluating the experiment via other EEG analysis tools as well i.e. Event related Potential (ERP), which couldn't be employed in our case due to the length of the data sets. Another recommendation would be to study the design process at an even lower level for pattern identification. Instead of studying the different phases of the design process, one can start by studying the EEG data exhibited due to different types of thinking i.e. divergent and convergent. We recommend designing the experiment in which the cognitive process of interest can be captured over the smallest possible period of time. One way this can be done is by taking advantage of existing research [12] on EEG patterns and incorporating such patterns in constructing design tasks.

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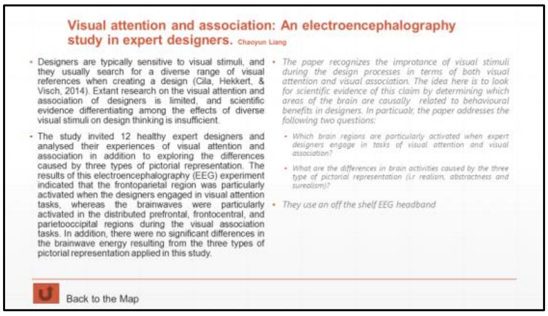
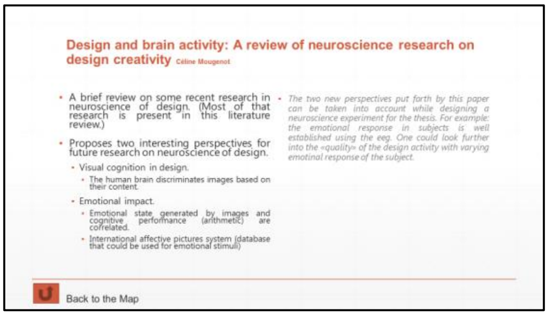
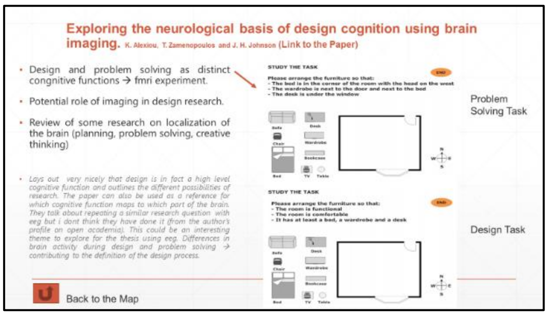
# 7. APPENDICES

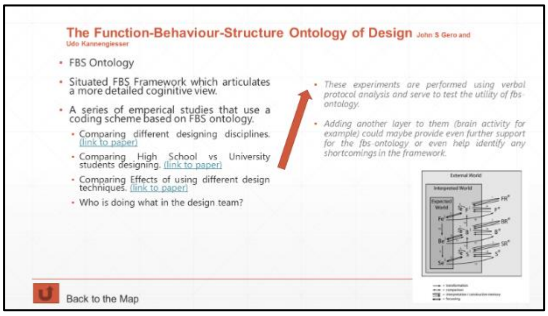
## 7.1 Appendix A

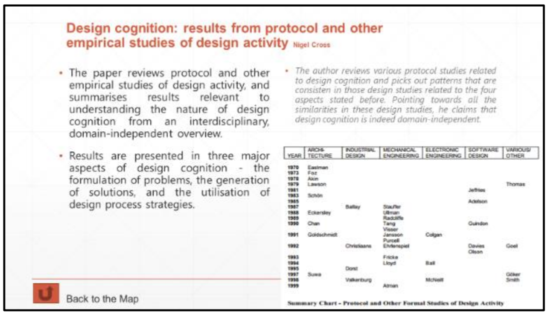


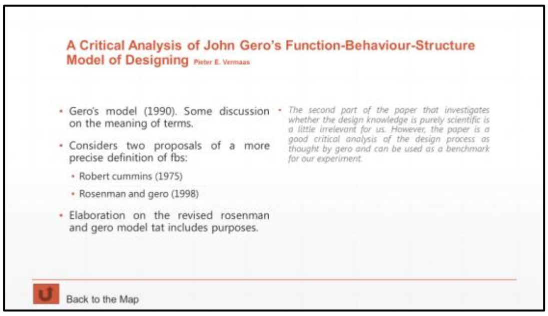



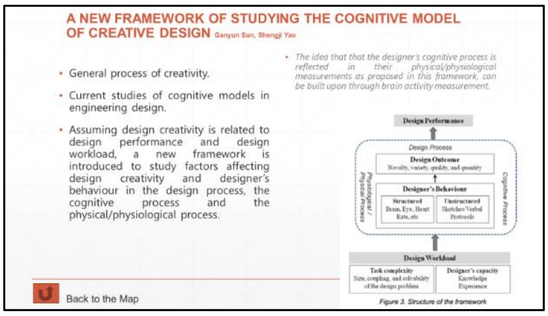




## The Creative Brain: Investigation of Brain Activity During Creative Problem Solving by Means of EEG and fMRI

Andreas Fink Roland H. Grabner

- Brain activity measured during creative thinking via two studies (eeg and fmri).
- The eeg study revealed that the generation of original ideas was associated with alpha synchronisation in frontal brain regions and with a diffuse and widespread pattern of alpha synchronisation over parietal cortical regions.
- Fmri study → task performance was associated with strong activation in frontal regions of the left hemisphere.
- The findings suggest that eeg alpha-band synchronisation during creative thinking can be interpreted as a sign of active cognitive processes rather then cortical idling.

- *It seems like this paper could be helpful in designing an experiment when it comes to the the tasks that need to be performed by the participants as well as eeg data analysis.*

Back to the Map

## The Brain as a Distributed Intelligent Processing System: An EEG Study

Armando Freitas da Rocha, Fabio Theoto Rocha, Eduardo Massad

- The neural efficiency hypothesis: individuals with higher intelligence display a more focused cortical activation and hence a lower total brain activation compared with individuals with lower intelligence. (link to paper)
- The hypothesis is assumed to be a property of DIPS (Distributed Intelligence Processing System Theory)
- Correlation between IQ (evaluated with WAIS, WISC) and the brain activity associated with visual and verbal processing was investigated using EEG in order to test the validity of distributed neural basis for intelligence.
- The results support the neural efficiency hypothesis.

- *The paper is fairly complex in procedure but simple in outcomes. One thing that comes to mind after reading their result is whether this would also be true for ill-defined design problems?*

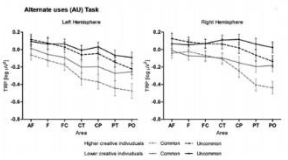

Back to the Map

## Tackling creativity at its roots: Evidence for different patterns of EEG alpha activity related to convergent and divergent modes of task processing

Emanuel Jauk □, Mathias Benedek, Aljoscha C. Neubauer

- The distinction between convergent and divergent cognitive processes given by Guilford (1956) had a strong influence on the empirical research on creative thinking. Neuroscientific studies typically find higher event related synchronization in the EEG alpha rhythm for individuals engaged in creative ideation tasks compared to intelligence-related tasks.
- A sample of 55 participants performed the alternate uses task as well as a more basic word association task while EEG was recorded. On a trial-by-trial basis, participants were either instructed to find a most common solution (convergent condition) or a most uncommon solution (divergent condition).
- The answers given in the divergent condition were in both tasks significantly more original than those in the convergent condition. Moreover, divergent processing was found to involve higher task-related EEG alpha power than convergent processing in both the alternate uses task and the word association task. **EEG alpha synchronization can hence explicitly be associated with divergent cognitive processing rather than with general task characteristics of creative ideation tasks.**

- *If divergent thinking can be taken as a requisite for solving design problems and if there is a way to assess the design quality of a participant. Then an experiment can be designed investigating the role of divergent thinking in solving design related problems.*




Back to the Map

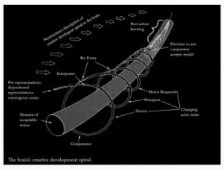
## Design-Neuroscience: Interactions between the Creative and Cognitive Processes of the Brain and Design.

Rachel Zuanon and J. H. Johnson

- Focuses on how the creative and cognitive process of the brain interacts with the creative and cognitive process of design.
  - Imaging, presenting, testing → interprator, actors, comparator (respectively). The table below makes a quick summary.

| CREATIVE PROCESS | BRAIN PROCESS |
| --- | --- |
| IMAGING – CONSTRUCTING MENTAL IMAGES OF A FRAGMENT OF THE WORLD. | INTERPRATOR – CONCENTRATED IN THE LEFT HEMISPHERE OF THE BRAIN DEDICATED TO MANUFACTURE, FANTASIZE AND CREATE IDEAS. |
| PRESENTING – THE WAY DESIGNERS EXTERNALIZE AND COMMUNICATE THEIR MENTAL IMAGES. | ACTOR – OCCIPITAL, PARIETAL AND FRONTAL LOBES WHERE EXTERNAL REPRESENTATIONS ASSUMES THEIR MEANING. |
| TESTING – MEANS USED AND APPLIED BY DESIGNERS TO VERIFY CONSISTENCY BETWEEN PROPOSALS. | COMPARATOR – CONCENTRATED IN THE FRONTAL LOBE DEDICATED TO COMPARE THE HYPOTHESIS RAISED BY THE INTERPRATOR WITHT HE PERCEPTIONS OF THE ACTOR. |

- THE DESIGN DEVELOPMENT SPIRAL BY JONH ZEISEL



The brain's creative development spiral.

- *THE DESIGN PROCESS CONSIDERED HERE IS MORE ITERATIVE AND LESS to-and-fro LIKE GERO'S MODEL. Nonetheless, the parallels drawn here between the brain activity and the design process are considerable and may be tested in an experimental setting (maybe).*

Back to the Map

7.2 Appendix B

# Towards a Neuroscientific Theory of Design Processes Experiment - Consent Form

## Experiment Purpose & Procedure

The purpose of this experiment is to monitor and explore the similarities and difference in EEG wave patterns exhibited during different design tasks.

The experiment session will last approximately 30 minutes, during which you will be asked to solve three tasks. All instructions and required material will be provided before starting the session.

Please note that none of the tasks is a test of your personal intelligence or ability. The objective is to test the usability of our research systems.

## Confidentiality

Electroencephalography(EEG) will be used to record the electrical activity of the brain.

All data will be coded so that your anonymity will be protected in any research papers and presentations that result from this work.

(It is possible that some of the recorded data could identify the participant, for example photographs, audio or video, and be used for research/presentation purposes.

## Finding out about result

If interested, you can find out the result of the study by contacting the researcher Waleed Wasti and/or Ajmaeen Yawar. They can be contacted via the following email addresses respectively: swaleedwasti@gmail.com, ajmaeenyawar@hotmail.com

---

(the following section can be torn off, and retained by the researcher, with participant keeping above information)

## Record of Consent

Your signature below indicates that you have understood the information about the experiment and consent to your participation. The participation is voluntary and you may refuse to answer certain questions on the questionnaire and withdraw from the study at any time with no penalty. This does not waive your legal rights. You should have received a copy of the consent form for your own record. If you have further questions related to this research, please contact the researcher.

| | |
|---|---|
| ________________ | ________________ |
| Participant | Date |
| ________________ | ________________ |
| Researcher | Date |

## 7.3 Appendix C

### Welcome

Towards a Neuroscientific Theory of the Design Process

Introduction to the Experiment

The purpose of this experiment is to monitor and explore the similarities and difference in EEG wave patterns exhibited during different design tasks.

The experiment session will last approximately 30 minutes, during which you will be asked to solve three tasks. All instructions and required material will be provided before starting the session.

Please note that none of the tasks is a test of your personal intelligence or ability. The objective is to test the usability of our research systems.

### Task 1 – What Bothers You?

Task Description

This is an exercise that requires students think about problems and define them but NOT solve them. You are only required to define the problem but NOT solve it. You will be required to simply write down answers to the question "what bothers you?" i.e., find problems that require solutions. This activity leads to a long list of problems that later can be redefined and solved.

### Task 1 – What Bothers You?

Task Example

One example is the "speed bumps problem": Every working day I experience at least 14 speed bumps on my way to and from work, and feel that there is a "problem". In a typical session, participants find more that 20 problems that are related or caused by speed bumps. The following is a "sample" of students' responses:

| Driving/Traffic | Driver | Cost | Environment | Emergency |
|---|---|---|---|---|
| • Cause traffic jams / back ups<br>• Slow down traffic<br>• Cause tailgating + other accidents | • May surprise drivers<br>• Annoying and frustrating<br>• Bad for the body<br>• Cause drink spills | • Expensive to build and maintain<br>• May damage car shocks | • More noise and pollution due to acceleration / deceleration<br>• Animals find them annoying | • They slow down ambulances and firetrucks<br>• May disturb patients in ambulances |

### Task 2 – Mathematical Problem with Many Possible Solutions

Task Description

You will be given several numbers and asked to use **all** of them and any mathematical operators (+, -, /, *, ^) to arrive at a given number in as many ways as possible.

Example

Use the following four numbers (3, 8, 2, 13) and any mathematical operators to make up the number 24. One possible solution is:

$$2 * (3 + 13) - 8 = 24$$

### Task 3 – Guilford's Alternative Uses Test

Task Description

The Alternative Uses Test asks you to think of as many uses as possible for a simple object, like a brick or a shoe. The test will be time-constrained.

Example

Write down as many possible uses of a brick as you can:

- Paper weight
- Door stopper
- A mock coffin at a barbie funeral
- To use as a weapon
- To break a window
- To hit my sister on the head

“

## Questions So Far?

P.S – You will not be allowed to ask any questions during the recording session.

### Do’s and Dont’s

- Please read and sign the privacy and consent form
- Follow the instructions carefully, the possibility of recording trials is limited
- There are no right answers and this is not a test.
- Switch off your cell phone
- Most importantly, relax and have fun!
- Please avoid unnecessary movement and blinking
- Please dont talk / laugh
- Please dont leave your place until the sessions is over
- Try not to remove / adjust the device while the recording session is underway

## Let’s Start!

## 7.4 Appendix D

**Welcome**

Towards a Neuroscientific Theory of the Design Process

"

Resting Phase

Just sit back and relax. This will last around 60 seconds.

"

Resting Phase

Now close your eyes. Open them when you hear a beep.

"

Now you are ready for the first task....

"

Task 2 – Math Problem

Use the following five numbers (2, 3, 5, 10, 24) and any mathematical operators (+, -, /, *, (), ^) to make up the number 120 in as many ways as possible. You have five minutes for this task.

"

You have 30 seconds before the next task... Relax

"

Task 3 – Guilford's Alternative Uses Test

Write down as many possible uses of a newspaper as you can. You have three minutes for this task. Be creative!

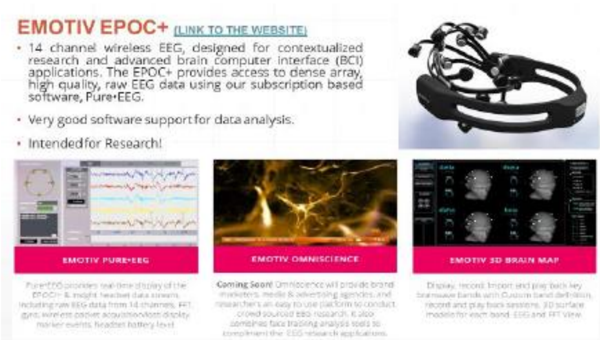
"

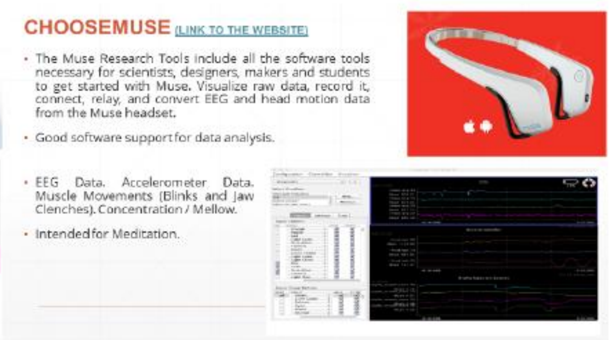
Now just relax for 30 seconds before the session ends

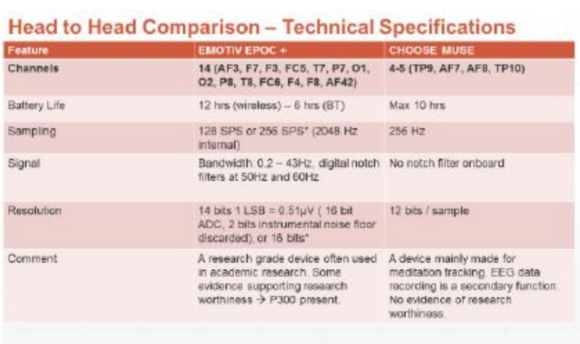
**Thank you for your participation!**

## 7.5 Appendix E







Head to Head Comparison – Technical Specifications

| Feature | EMOTIV EPOC + | CHOOSE MUSE |
|---|---|---|
| **Channels** | **14 (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF42)** | **4-5 (TP9, AF7, AF8, TP10)** |
| Battery Life | 12 hrs (wireless) – 6 hrs (BT) | Max 10 hrs |
| Sampling | 128 SPS or 256 SPS* (2048 Hz internal) | 256 Hz |
| Signal | Bandwidth: 0.2 – 43Hz, digital notch filters at 50Hz and 60Hz | No notch filter onboard |
| Resolution | 14 bits 1 LSB = 0.51μV ( 16 bit ADC, 2 bits instrumental noise floor discarded), or 16 bits* | 12 bits / sample |
| Comment | A research grade device often used in academic research. Some evidence supporting research worthiness → P300 present. | A device mainly made for meditation tracking. EEG data recording is a secondary function. No evidence of research worthiness. |

## 7.6 Appendix F

| | | P-start | Resting 1 | Resting 2 | Transition 1 | Task 1 | Transition 2 | Task 2 | Transition 3 | Task 3 | End/Rest |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Duration | Seconds | 13 | 61 | 61 | 31 | 181 | 31 | 301 | 31 | 181 | 31 |
| | No. of rows | 1664 | 7808 | 7808 | 3968 | 23168 | 3968 | 38528 | 3968 | 23168 | 3968 |
| Rec. 01 | t - seconds | 22 | 35 | 96 | 157 | 188 | 369 | 400 | 701 | 732 | 913 |
| | Row no. | 2816 | 4480 | 12288 | 20096 | 24064 | 47232 | 51200 | 89728 | 93696 | 116864 |
| Rec. 02 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 03 | t - seconds | 22 | 35 | 96 | 157 | 188 | 369 | 400 | x | x | x |
| | Row no. | 2816 | 4480 | 12288 | 20096 | 24064 | 47232 | 51200 | x | x | x |
| Rec. 03-1 | t - seconds | x | x | x | x | x | x | x | 25 | 56 | 237 |
| | Row no. | x | x | x | x | x | x | x | 3200 | 7168 | 30336 |
| Rec. 04 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 05 | t - seconds | 19 | 32 | 93 | 154 | 185 | 366 | 397 | 698 | 729 | 910 |
| | Row no. | 2432 | 4096 | 11904 | 19712 | 23680 | 46848 | 50816 | 89344 | 93312 | 116480 |
| Rec. 06 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 07 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 08 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 09 | t - seconds | 50 | 63 | 124 | 185 | 216 | 397 | 428 | 729 | 760 | 941 |
| | Row no. | 6400 | 8064 | 15872 | 23680 | 27648 | 50816 | 54784 | 93312 | 97280 | 120448 |
| Rec. 10 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 11 | t - seconds | 20 | 33 | 94 | 155 | 186 | 367 | 398 | 699 | 730 | 911 |
| | Row no. | 2560 | 4224 | 12032 | 19840 | 23808 | 46976 | 50944 | 89472 | 93440 | 116608 |
| Rec. 12 | t - seconds | 25 | | | | | 390 | | 800 | 827 | 1010 |
| | Row no. | 3200 | 0 | 0 | 0 | 0 | 49920 | 0 | 102400 | 105856 | 129280 |

## 7.7 Appendix G