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Exploring the Use of Electroencephalography to Gather Objective Evidence of Cognitive Processing During Problem Solving

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Abstract Currently, there is significant interest being directed towards the development of STEM education to meet economic and societal demands. While economic concerns can be a powerful driving force in advancing the STEM agenda, care must be taken that such economic imperative does not promote research approaches that overemphasize pragmatic application at the expense of augmenting the fundamental knowledge base of the discipline. This can be seen in the predominance of studies investigating problem solving approaches and procedures, while neglecting representational and conceptual processes, within the literature. Complementing concerns about STEM graduates' problem solving capabilities, raised within the pertinent literature, this paper discusses a novel methodological approach aimed at investigating the cognitive elements of problem conceptualization. The intention is to demonstrate a novel method of data collection that overcomes some of the limitations cited in classic problem solving research while balancing a search for fundamental understanding with the possibility of application. The methodology described in this study employs an electroencephalographic (EEG) headset, as part of a mixed methods approach, to gather objective evidence of students' cognitive processing during problem solving epochs. The method described provides rich evidence of students' cognitive representations of problems during episodes of applied reasoning. The reliability and validity of the EEG method is supported by the stability of the findings across the triangulated data sources. The paper presents a novel method in the context of research within STEM education and demonstrates an effective procedure for gathering rich evidence of cognitive processing during the early stages of problem conceptualization.

Keywords STEM education · Problem solving · Methodological approach · Cognition · EEG

Introduction

There is currently a considerable drive to promote Science, Technology, Engineering and Mathematics (STEM) education in an attempt to meet the demands of global economic development. Despite the considerable interest placed in advancing the STEM agenda, a number of potential issues have been cited across the spectrum of STEM education. Chiefly among these issues is the unprepared nature of many new graduates entering the workforce (National Academy of Engineering 2004). Besterfield-Sacre et al. (2014) discuss the need to reconceptualize the way that STEM faculty engage in teaching and learning practices. The National Academy of Engineering (2004) go on to discuss the lack of ability among new graduates in STEM disciplines when it comes to solving advanced problems. Issues with students' abilities to solve problems are pervasive and well demonstrated in many research studies and reports within STEM education disciplines (National Academy of Engineering 2004; McCormick and Davidson 2009).

The importance of these skills for enhancing graduate competencies and therefore bolstering the STEM agenda necessitates a research focus which aims to further understand the underlying complexities of problem solving. This places increased demands upon researchers in the area to devise novel

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methods to capture evidence which can further enhance our understanding of different sub-processes in order to inform teaching and learning practices within STEM education. A research focus, driven by economic pressures, also carries the potential for significant methodological misalignments that limit the advancement of knowledge and understanding within the STEM education research field. For example, the literature is inundated with studies aiming to investigate methods of improving students' problem solving behavior (Novick and Bassok 2005; Kirsh 2009; Ohlsson 2012) and these primarily take the form of effect type studies where interventions are tested for potential improvements. The result of such an approach may be the betterment of student competency, in light of economic and societal concerns, but there is a certain sacrifice in enhancement of the knowledge base within a discipline (Stokes 1997).

This paper presents a mixed-method approach applicable to the investigation of the underlying cognitive mechanisms of problem solving. The paper will firstly discuss the arena of problem solving research and then consider some of the current issues facing research in the field. The paper will then explore a research methodology aimed at addressing these contemporary concerns and finally conclude with a discussion surrounding the implications for STEM education research.

Research on Problem Solving

Within STEM education, many learning tasks encountered are ill defined in nature such as design-orientated problems (Kimbell and Stables 2008). Well-defined tasks are commonly used for the purposes of developing the cognitive competencies and scaffolds needed for more advanced problem solving approaches (Jonassen 1997). There is little doubt that the use of problem-based approaches to learning is a critical aspect of STEM educational provision and there are significant benefits to their implementation. This places research on problem solving as a critical focus within STEM education and it is necessary to briefly consider some of its historical perspectives and associated criticisms.

Problem solving research is, by historical standards, a recently established field and as such suffers from a lack of established theoretical and empirical foundations. Ohlsson (2012) aptly described the major historical advances that lead the field of problem solving research. This begins with the dominance of the behaviorist paradigm of cognitive research which above all emphasizes past experiences as critical informers of current processing. The behaviorist view can be criticized for its limited account of the adaptive capabilities of human reasoning in unfamiliar situations (Ohlsson 2012). This perspective evolved into an emphasis on the processes of solving problems and a fundamental set of principles related to heuristics which was extensively investigated by (Newell and Simon 1972). This work, emphasizing an interaction between the construction and heuristic search of a problem space, has provided the guiding principle for the majority of problem solving research (Ohlsson 2012). However, as discussed by Jakel and Schreiber (2013), the progress of new theoretical understandings in problem solving research has slowed since.

Much research on problem solving, until recently, has overstressed the procedures of solving problems and determining generalizable trends and approaches (Novick and Bassok 2005; Kirsh 2009). Newell and Simon (1972) even focused on the model of the "General Problem Solver" which was a general approach for solving all problems. This hope of achieving a general model that explains all problem solving behavior may be impossible and certainly an inefficacious effort when considering the recent influences of the field of situated cognition. There is strong evidence to suggest that the domain of application (where the problem or task is situated) has a significant effect on the process and that domain knowledge is itself a critical component of problem solving expertise (Chi et al. 1981; Schnotz et al. 2010).

Traditionally, the procedures for solving problems are typically related to the latter stages of problem solving and research focusing on them commonly neglect the earlier stages of the process (Kirsh 2009). Kirsh's (2009) work in this context refers to the wider influences of situated cognition which may not have been adequately captured in the traditional approaches to researching problem solving. It should be noted that much fruitful work has been conducted on the role of representational use in the solving of problems (Chi et al. 1981; Hegarty and Kozhevnikov 1999; Bodner and Domin 2000, Liu and Shen 2011; Boonen et al. 2014) and it is clear the nature of a representation or problem space has a clear effect on the outcome of the solution process (Schnotz et al. 2010). It is not the purpose of this paper to address this well-researched area per se, but conversely to consider an alternative approach that may expand understanding in the earlier stages of problem solving. This is echoed in the works of Kirsh (2009), Jakel and Schreiber (2013) and Ohlsson (2012) who discuss the need for an understanding around the situated, affective, cognitive and metacognitive aspects that underlie the research on problem representation.

This goal raises an important philosophical and methodological consideration. The traditional and ubiquitous focus on the stages of representation and heuristic search overemphasizes the outcome and process trace data. This focus sacrifices a core understanding of some of the underlying elements of the problem solving process such as cognitive processes involved in conceiving problems. This clearly places critical importance on developing suitable methodologies to achieve this type of understanding which traditional approaches alone are incapable of capturing. As an example, this paper will focus on problem conceptualization.

Conceptualization

It is widely acknowledged that the representation constructed for a problem has a significant impact on the effectiveness of the solution (Boonen et al. 2014). A representation can take the form of mental or physical artifacts and are treated as an entity constructed to summarize a problem's essential nature (Schnotz et al. 2010). However, as this area of research also evolved out of the traditional psychological paradigms, it fails to capture some of the more complex underlying elements. This paper advocates a focus on the area of problem conceptualization which is the manner in which an individual frames the task or situation which they are currently engaged with (Adams 2001).

Goméz et al. (2000) describe conceptualization as "modelling by the problem solver." This modeling process results in the formation of a "conceptual model" for that problem (Duit and Treagust 2012). A conceptualization or conceptual frame is therefore differentiated from a traditional representation by incorporation of aspects such as such as past experience, ecological constraints and epistemological orientation among others (Kirsh 2009). It is possible that the outcome of a conceptual process results in a representation for a problem. This hypothesis is supported in the discussion by Bogard et al. (2013) who contend that an external representation is a window into an individual's mental model of the problem. The formation of this situated model (representation of the task) is the result of the conceptualization process.

Investigating problem conceptualization has the potential to uncover significant evidence relating to the process of problem solving. The concept of problem representation is not a new area of consideration in problem solving research. However, the contributory factors in the generation of conceptual problem frames (leading to the representation) are often tacit in nature and difficult to unearth (Jakel and Schreiber 2013). This adds increased complexity to the process of devising a suitable methodological approach to capturing insightful data. It is clear that traditional approaches to problem solving research are not alone sufficient to enhance understanding of these early stage processes.

Common Methods Used in Researching Problem Solving

Given, the complexity of the process of problem solving, designing suitable methodologies to capture evidence of each of the underlying phenomena is a multifarious undertaking. The majority of studies available within the pertinent literature on problem solving within STEM education disciplines tend to adopt interpretive qualitative approaches. The adoption of an interpretive paradigm when conducting research into problem solving behavior provides a number of advantages such as allowing the researcher to understand the process from the perspective of the individual. As Luttrell (2010) discusses, qualitative research is a powerful approach, which acknowledges every individual as an active participant in making meaning both of themselves and the world in which they live. This article does not intend to provide a detailed critique and analysis of the various philosophical paradigms underpinning the design of methods. This paper instead will focus on some commonly used methods that are implemented to gather evidence of the different elements of problem solving phenomena. Given the ubiquitous use of qualitative approaches within the area of problem solving research, it is prudent to consider some of the methods commonly adopted.

The use of visual and verbal protocol analysis within the area of problem solving research is a commonly used and highly effective qualitative method capable of gathering rich data relating to individuals' behavioral, cognitive and metacognitive processes (Middleton 2008; Montague et al. 2011). The gathering of verbal data concurrent with individuals reasoning episodes has been demonstrated as a robust method of observing the underlying intellectual processes (Newell and Simon 1972; Novick and Bassok 2005). Verbal data analysis is further enhanced when gathered in conjunction with visual observations. An example of this synthesis was demonstrated by Middleton (2008) who examined the sketching behavior of students using a robust coding scheme based on the visual and verbal analysis of the data. The data revealed a number of key findings relating to students' cognitive processes used during the sketching process. Relating to problem solving research in particular, the use of visual and verbal protocols is applicable to studies involving both well-defined and ill-defined tasks and its use is exemplified in the work of Newell and Simon (1972).

Interview techniques have specific application to the area of problem solving research and are capable of explicating cognitive and affective states that may underpin the problem solving process (Goldin 1997). Artzt and Armour-Thomas (1992) also demonstrated the advantageous nature of interview techniques in uncovering the metacognitive elements of problem solving as well. Interview techniques, within problem solving research, are often complimented by using stimulated techniques such as asking a participant to comment on a presented solution or task stimulus (Lyle 2003).

Visual-verbal protocols and interview techniques are two of the more commonly used methods to gather evidence in research studies investigating elements of problem solving phenomena. As with all qualitative approaches, there have been a number of criticisms of these methods. Namely, a significant objection to the use of qualitative approaches is the lack of objectivity which can be assigned to the tradition (Madill et al. 2000). Gaining an understanding of the phenomena underlying elements of the problem solving process, using qualitative methods, involves a significant amount of inference on the part of the researcher. Clearly, there are elements of the process which cannot easily be captured using observational or introspective approaches. For example, the tacit nature of the process of framing a problem situation and this may be a difficult phenomenon to capture qualitatively. Ohlsson (2012) also raises a similar issue when investigating problem solving traces where many of the underlying processes cannot be explicated from the qualitative data given their tacit and unconscious nature. This highlights the significance of considering methods capable of capturing valid and reliable data of the underlying elements of problem solving episodes. The next section will consider one such approach.

Quantitative Analysis of Cognition

There have been several approaches developed to analyzing the cognitive processes underlying learning mechanisms in recent years. These include psychophysiological approaches such as eye-tracking (Lai et al. 2013) which has been applied in studies of user interaction with problem representation (Liu and Shen 2011), media instruction (Mayer 2010) and cognitive load (Amadieu et al. 2009) among others. Another field with potential application to educational research is the field of cognitive neuroscience. However, there have been a number of issues with the integration of neuroscientific principles into educational practice and research. Namely, the often erroneous promotion of the brain-based learning agenda which is often pressed by commercial entities (Ansari and Coch 2006). These agendas have led to the proliferation of "neuromyths" such as hemispheric advantages in certain learning domains and this has mainly occurred as a result of poor communication between the fields of neuroscience and education (Sigman et al. 2014). As the number of empirical studies utilizing neuroscientific approaches within educational research contexts is very small, it is hardly surprising that the bridging of the two fields has been arduous and often unsuccessful.

While acknowledging the limitations of the field of cognitive neuroscience, there are benefits to be gained from understanding the neurological mechanisms of cognition within educational contexts. This paper considers the application of this approach within STEM education and in particular to the investigation of problem framing phenomena. It is precisely in a situation such as this that a tool from the field of cognitive neuroscience could yield informative and objective evidence of the underlying processes. Given the tacit nature of the hypothesized cognitive processes interacting during conceptualization, relying entirely on qualitative paradigms can only capture a limited view of the phenomena. Therefore, it is pertinent to explore the use of a quantitative measure of cognition.

Overview of Brain Imaging Methods

The functional category of imaging methods utilizes the changes in blood flow and metabolic rate to determine areas of activation within the brain. The most commonly used strategy to achieve this is functional magnetic resonance imaging (fMRI) which assesses changes in the oxygenation of blood in the brain (Banich and Compton 2011). The use of fMRI has a number of advantages including non-invasiveness and the ability to measure deep brain structures such as activity in the hippocampus (Ward 2010). There are however limitations in the capturing of functional data as what is measured is a hemodynamic response which is much slower (normally occurs approximately two seconds after the event) (Freeman and Quiroga 2013). This presents issues for studies looking at particular stages of performance in applied tasks, as the data is an average over an entire episode (Banich and Compton 2011).

Another method in the family of functional methods is positron emission tomography (PET). PET allows researchers to investigate the presence and activity of a specific substance in the neuro-anatomical system (Banich and Compton 2011). Normally, this is achieved by the introduction of a radioactive substance into the body by means of an injection (Ward 2010). PET is very advantageous in the study of metabolic disorders in the brain or the impact of various substances on neural activity (Banich and Compton 2011). Eysenck and Keane (2010) cite its advantage as having accurate spatial resolution but a significant disadvantage being the poor temporal resolution. PET is capable of capturing accurate readings of activated areas of the brain but this can only be captured across large time spans.

The previously discussed methods rely on analyses of the metabolic rates of activity within the brain. The following methods presented capture electrical activity produced by neurons or neuronal networks and are referred to as electromagnetic recording techniques. The most simplified of these methods is the "single-cell recording," where a sensor is placed on the surface of the brain (Banich and Compton 2011). This is normally conducted in animal research and makes it an unsuitable candidate for educational research due to the highly invasive nature.

One of the most popular electromagnetic recording methods is the electroencephalogram (EEG). This technique utilizes a series of sensors placed on the scalp which record activity from the cerebral cortex in the form of electrical currents (Ward 2010). This technique is less invasive than single-cell recordings and modern EEG equipment comes in a variety of portable forms such as headsets, which makes them a strong candidate for educational research contexts (Esfahani and Sundararajan 2012). One of the strengths of EEG research is the high temporal resolution, which can be achieved during recording. Behavioral events can be tied to underlying neural activity with great accuracy, often within milliseconds of the occurrence (Banich and Compton 2011). This process is often referred to as event-related potentials (Freeman and Quiroga 2013).

One of the disadvantages associated with this method is its poor spatial resolution in comparison to techniques such as fMRI (Eysenck and Keane 2010). This makes it difficult to locate exact neuronal areas which are used during an event. This inaccuracy in the spatial domain can be improved with appropriate processing techniques and much of the modern studies utilizing EEG have shown, with accuracy, activation of various neural regions (Fink et al. 2009; Anderson et al. 2011). Another established electromagnetic approach is that of "magneto-encephalography" which uses concentrated magnetic fields to assess brain activity. This approach has high temporal and spatial resolution but is extremely expensive and requires large amounts of equipment plus cooling agents to operate (Eysenck and Keane 2010).

Clearly, from a pragmatic and ethical point of view, there are some examples of neuroscientific measurements presented previously which are less applicable to applied educational research contexts due to costs and invasiveness. An example would be the use of fMRI to investigate a phenomenon within a classroom context given the nature of equipment and expense required. Having considered the assortment of research techniques for measuring physiological function, EEG presents itself as the most promising approach owing to its non-invasive nature and relatively low costs. While the functional imaging methods provide accurate spatial resolution of activated brain regions during an event, the poor temporal resolution can make them unsuitable for a process such as problem solving. This is especially true when the research endeavors to analyze specific instances of problem solving behavior such as the conceptualization phase. Although EEG has relatively poor spatial resolution in comparison to other strategies, these issues can be overcome using appropriate analysis strategies (Delorme and Makeig 2004).

Presented thus far are a brief review of the traditional approaches to problem solving research and two of the more common methods for investigating problem solving phenomena that have evolved from these perspectives. Also discussed are the various limitations with these traditional focuses, namely the overemphasis on the end stages of problem solving and the product. The need to focus on the earlier stages of the process, and those elements that are difficult to explicate from qualitative evidence, is also considered. In addressing these concerns, objective quantitative measures of cognitive activity were considered and the next section will detail the methodological approach to investigate these underlying phenomena that support the process of solving problems.

Methodological Design

As discussed in the previous sections, there are inherent limitations present in using primarily qualitative methods in investigating this complex element of problem solving. For these reasons, the methodological approach presented in this section will consider an alternative approach to that commonly found in the STEM education literature. The overall mixed-method approach is demonstrated in Fig. 1. Given the complexity involved in the problem solving process, it is imperative that there exist synergies between the methods employed.

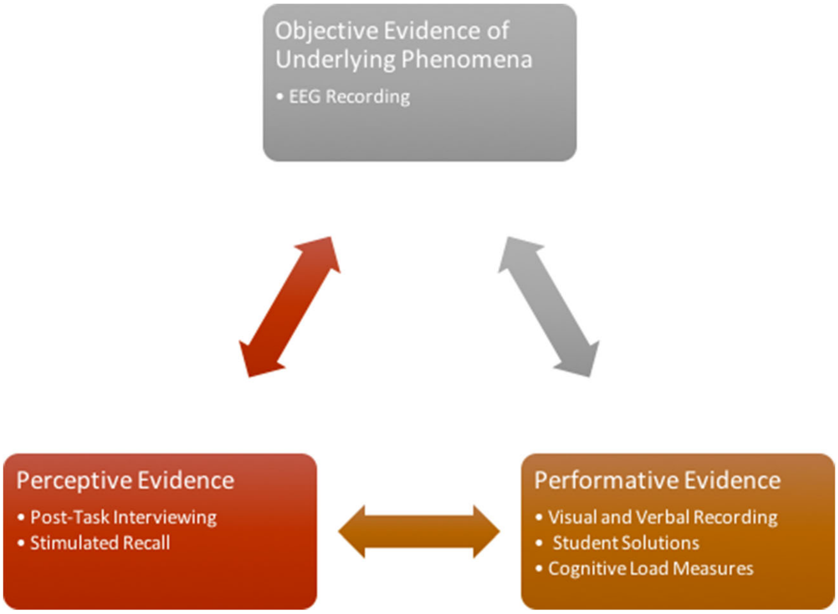


Fig. 1 Mixed-method approach

In Fig. 1, each method is presented under a general heading of the phenomenon, within the problem solving activity, under investigation. As discussed previously, objective evidence is typically achieved through assessment of the product of the problem solving process and this is still a core element of this methodology. However, in this case, it is more concerned with determining aspects of performance as opposed to understanding the underlying cognitive mechanisms of the problem solving episode. For obtaining objective evidence of the process of problem solving, the use of EEG is adopted. This provides a more robust approach to studying underlying phenomena as reliance on inference from perceptive mechanisms is not necessary. These perceptive elements are still included in order to synthesize the perceived approach of participants with the actual approach as captured by the objective measures.

Outlined in Fig. 1 is the overall methodological approach applicable to investigating problem solving phenomena. While the perceptive and performance measures are well-established approaches in the field, the use of EEG within an educational context is a novel endeavor and will be the predominant focus for the remainder of the paper.

Delahunty et al. (2015) employed this mixed-method approach in order to explicate the underlying relationships between conceptual framing and performance. Along with providing multiple sources of data, the mixed methods strategy facilitated triangulation of methods, which increased the validity and reliability of the data collected during the study (Johnson and Onwuegbuzie 2004; Cohen et al. 2007; Bryman 2008). Including the neuroscientific tool strengthens the research approach by providing objective evidence of the cognitive phenomena underlying the process of problem solving. This is presented in the following section. As an example of the application of this methodological approach, a focus on problem conceptualization (Delahunty et al. 2015) will be adopted for exemplary purposes.

Objective Cognitive Measurement (EEG)

The early stages of the problem solving process involve the conceptualization and representation of the problem situation. This early stage of the process was of core interest to the study for which this methodological approach was designed. Analysis of an individual's problem representation can be achieved through examination of the external representation (sketch, diagram, gestures) created for a particular problem (Hahn and Chater 1998). This could also be achieved through interview protocols or/and think-aloud data (Chi et al. 1981; Gick 1986). However, the fact remains that these approaches still require a certain level of inference on the part of the researcher to extract the cognitive meaning from the data. In addition, relying on introspective accounts may fail to capture some of the more tacit cognitive elements involved in the conceptualization process. This presented challenges to validity and reliability and required the consideration of more objective means. A neuroscientific approach was chosen to address this concern.

The specific tool selected for the current study was an EEG headset developed by Emotiv technologies. The headset contains 14 sensors which make contact with the scalp and record electrical activity emitted from the cerebral cortex. It is important to note that the number of sensors on this mobile headset is far less than those that are commonly used within medical applications which typically contain hundreds of sensors. This, of course, means that the spatial capabilities of this device are less than those available in laboratories, but the advantage it offers is in the wider arenas of application. There are several studies that have used this headset previously and data has shown reliability and validity (Anderson et al. 2011; Esfahani and Sundararajan 2012; Badcock et al. 2013; Call et al. 2016) and some that are explicitly associated with educational contexts (Delahunty et al. 2013, 2015). Badcock et al. (2013) provided a review of the headset and have concluded that it provides a valid alternative to laboratory grade devices. Utilizing this approach allowed an objective measure of cognitive activity to be obtained which provided indicators of the cognitive nature of the conceptual frame individuals built in response to a prescribed problem. However, it was also necessary to gain evidence of the approach adopted and this required consideration of qualitative strategies to compliment the use of the EEG.

Post-Task Interviews

Aligning with the concerns cited by Byrnes and Vu (2015) where misappropriate weight is placed on the novelty of the neuroscientific approach, the methodology attempted to synthesize the use of the objective neuroscientific tool with educational and psychological approaches (Fig. 1). This provided a more comprehensive data set relating to the underlying phenomena of problem conception for an individual. In order to clarify the conceptualization processes and subsequent approaches of the participants during the problem solving episodes post-task interviews were implemented. For the purposes of this study, two stages of interview were implemented for each participant in the study, an immediate post-task interview and a follow-up stimulated reflection. The use of a post-task interview was necessary to uncover specific aspects of a participant's conception of the applied tasks.

The core focus of this interview method was on introspective accounts of behavior therefore, a number of potential concerns existed. An example is the incorporation of potential biases within participants' responses. With the subjectivity of a participant's conceptualization of a task as an innate independent variable, this potential issue required consideration.

The decision to utilize a second post-task interview strategy was informed by this. It was decided to adopt a second post-task interview strategy in an effort to reduce potential biases and inaccuracies in participants' accounts. This follow-up strategy involved a retrospective reporting of the problem solving episode. The use of a stimulated recall framework was adopted as it was most appropriate to the research questions. Stimulated recall safe guards against possible biases in students' reflection on actual events (Lyle 2003). It does this by presenting participants with a more objective account of their actual behavior during the event in question. In addition, it also allows students a suitable time-frame to reflect on the event and research has shown that allowing a night's sleep after the event and before the stimulated recall allows for the consolidation of memories (Maquet 2001).

Note on Performance Measures and Task Selection

As the goal of the research study was to examine the nature of problem conceptualization and its relation to approach and performance, a method of observation was necessary. As discussed previously, visual and verbal protocol (think-aloud) analysis has the potential to capture behavioral and underlying evidence of cognition within the problem solving epoch. This strategy also provided a visual account of the participants' performance in real time. The selection of tasks for a study investigating problem solving phenomena is of paramount importance. The tasks for this study were selected from a battery of tasks designed on principles taken from the PISA framework (OECD 2004) which ensured validity (O'Donoghue and Kooij 2007).

EEG Recording

The participants placed the headset on themselves and the researcher aided them with adjustments so that a good contact was found between the electrodes and the scalp. Once this was completed, the materials and process were explained. In order to obtain an accurate EEG measurement, the use of baseline interval recordings was selected. This process was adapted from a previous study by Esfahani and Sundararajan (2012) who used Emotiv EEG activity to classify reasoning and comprehension of different geometric forms for use in a brain-computer interface program. This process is a common approach used in EEG research (Pfurtscheller and Silva 1999), where a baseline fixation segment is used for comparison with the period of activity of interest. The baseline fixation recording in this study asked participants to sit still and view a neutral stimulus on a PowerPoint presentation for a period of time. The stimulus was a simple black cross approximately 100 mm × 100 mm similar in nature to the stimulus employed by Fink et al. (2009). This temporal data collection process is represented graphically in Fig. 2.

The separation of the signal into distinct bins of activity is useful for analysis purposes following the data collection process. This analysis process involves subtracting values in the fixation period from the activity period, which leaves an accurate measure of activity related to the task. This is the basis of the "task related power" (TRP) method described by Pfurtscheller (1992). Aligning with previous research from Fink et al. (2009), the first fixation period at the beginning of the session was 60 s in length and all subsequent fixation periods between tasks were 20 s in length. The rationale for allowing a longer period at the beginning is to allow the participant to become familiar with the process and to dampen the effect the visual nature of the environment may have on collection of data. The EEG data was collected using Emotiv software, which ran on the researcher's laptop using a wireless connection to the headset. Shown in Fig. 3 is the recording setup of the problem solving session with a single participant.

The webcam was positioned at a height of 270 mm to ensure optimum visibility of the workbook and video capture software was running in the background behind the tasks, which were presented in the PowerPoint presentation. The materials, which were provided for students, consisted of a calculator, pencils and a setsquare. They were explicitly told

Fig. 2 Temporal process of data collection

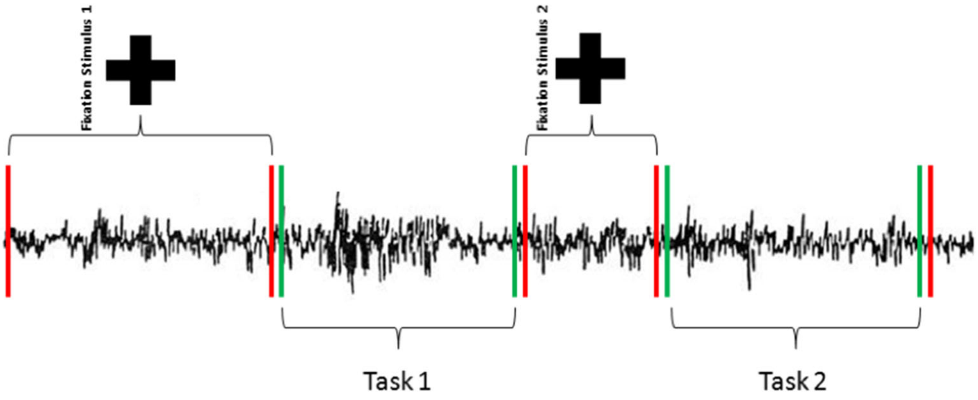
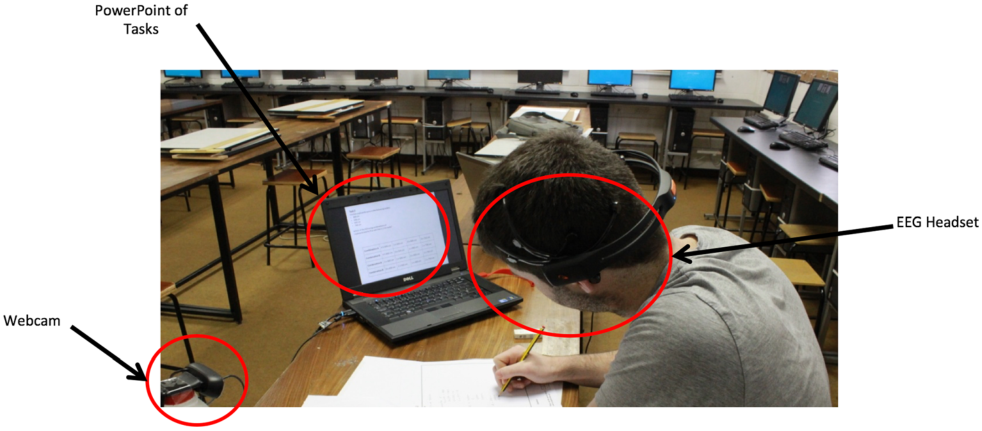


Fig. 3 Recording setup



that there was no necessity to use any of them except for the pencils and they could approach the tasks anyway they desired.

Post-Task Interviews

Two post-task interview sessions were utilized. One was conducted immediately following the problem solving session. This took the format of a semi-structured interview and was conducted to ascertain information of the participants' approaches and conceptions of the tasks. The second follow-up interview was conducted the following day. This was the shortest conceivable time following the period of activity in which the stimulated recall interview could take place. The visual data from the problem solving session needed to be reviewed and performance needed to be assessed prior to the conducting of this follow-up session. Performance scores were assigned to students' solutions and three tasks were selected for the focus of the stimulated recall procedure. A task encompassing high, low and average levels of performance were selected. During the session, participants observed the video of their performance in these tasks and provided commentary on their approaches. This session was treated as more open where issues could be discussed as they were raised by the participant.

Analysis of the EEG Data

This section will outline the analysis of the data collected with the EEG method employed during the study. While this data was triangulated with a number of qualitative methods, it is beyond the scope of this paper to present the full data set gathered by all approaches utilized. The primary focus of this paper is to demonstrate the use of the EEG tool within the paradigm of educational research in STEM. The most complex aspect of applying this tool is the data analysis which follows and therefore warrants careful consideration and explanation.

Data Processing

Once the data has been gathered, it is stored in an Emotiv file format with a large DC offset. The large DC offset ensures the accurate wireless transmission of data from the headset to the software (Anderson et al. 2011). Pre-processing is therefore necessary to remove this DC offset and enable the viewing of the raw activity readings in microvolts. This is achieved using the EEGlab program (Delorme and Makeig 2004) which is a widely used analysis package in EEG research.

Data from the recorded session is imported into Matlab and then opened in the EEGlab toolbox. A high and low pass filter are applied at a frequency of 0.16 and 50 Hz respectively to remove the DC offset and high frequency artifacts such as motor movement which are unrelated to underlying cognitive activity recorded during the process (Esfahani and Sundararajan 2012). The result of this can then be viewed as a raw signal (see Fig. 4).

Data is then visually inspected for continuous, high amplitude activity, which can be indicative of further artifacts or signal noise contaminating the cognitive signal (DaSilva 2010). An example of high amplitude signal noise is shown in Fig. 5.

One of the core problems associated with the EEG is source localization of neural activity. Cortical sources of EEG activity are difficult to separate from the entirety of the recorded data. This concept is known as "volume conduction" where activity from multiple sources are recorded at single electrode sites (Onton and Makeig 2006). The recorded activity is therefore a mix of underlying neural activity, indicative of possible cognitive activity, and contaminative sources such as eye blinks (Esfahani and Sundararajan 2012). Delorme and Makeig (2004) devised an analysis function within the EEGlab

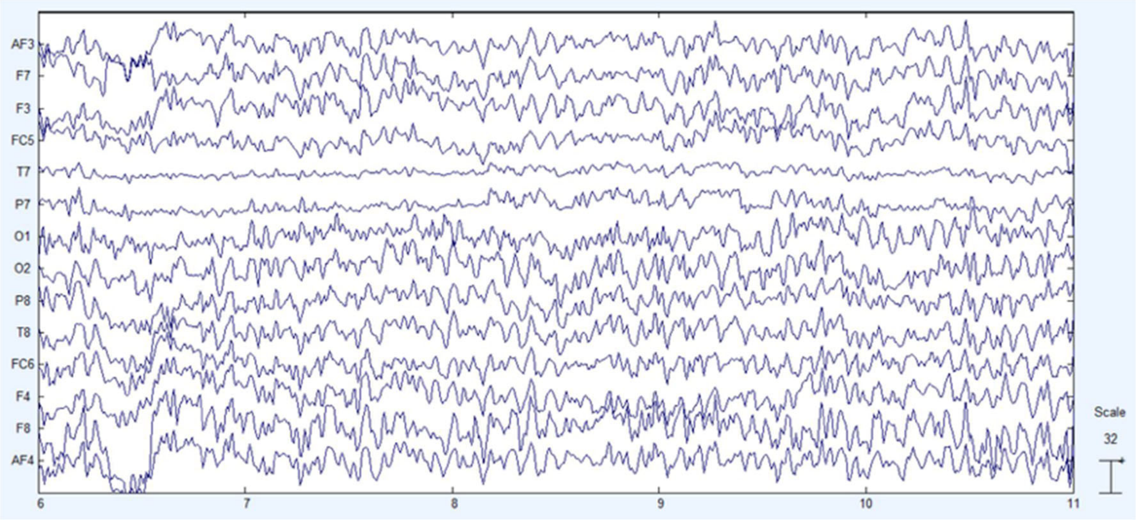


Fig. 4 Raw signal plotted as waveform

interface based on independent component analysis (ICA) which has been shown to accurately separate the sources (Esfahani and Sundararajan 2012). As the Emotiv headset has 14 sensors, it is assumed that there exist 14 independent source components (Esfahani and Sundararajan 2012). The resulting plots obtained after running ICA display the neural and contaminated sources. A typical eye blink component scalp plot is shown in Fig. 6. Once these artifacts are identified in the data, it is a matter of removing them from further analysis thereby enhancing the accuracy of the data.

Frequency Power Analysis

When the data has been cleared of artifact sources, the signal is transformed from the raw microvolt recordings to frequency bands which have been shown to be related to different cognitive processes such as convergent/divergent thinking (Razoumnikova 2000), creative cognition (Molle et al. 1999) and memory (Osaka 1984). This is achieved using a "Fast Fourier Transform" (FFT) which decomposes the complex signal, gathered in the raw EEG, into its spectral elements (Freeman and Quiroga 2013). The frequency bands most utilized within EEG research are the theta (4–8 Hz), alpha (8–13 Hz) and beta (13–30 Hz) frequencies (Klimesch 1997, Razoumnikova 2000). Matlab has an inbuilt FFT function, which allows the output of graphical topographic scalp maps. These highlight the active locations for specified frequency bands. An example of these can be viewed in Fig. 7. In addition to the graphical outputs, values for these can be exported to external programs such as SPSS for further analysis and investigation.

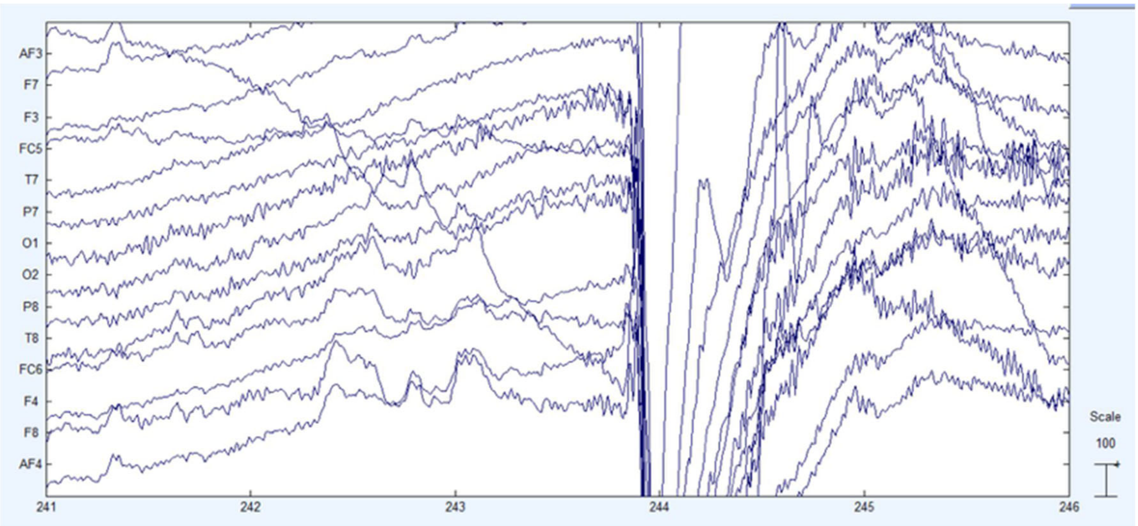


Fig. 5 Example of high amplitude signal noise

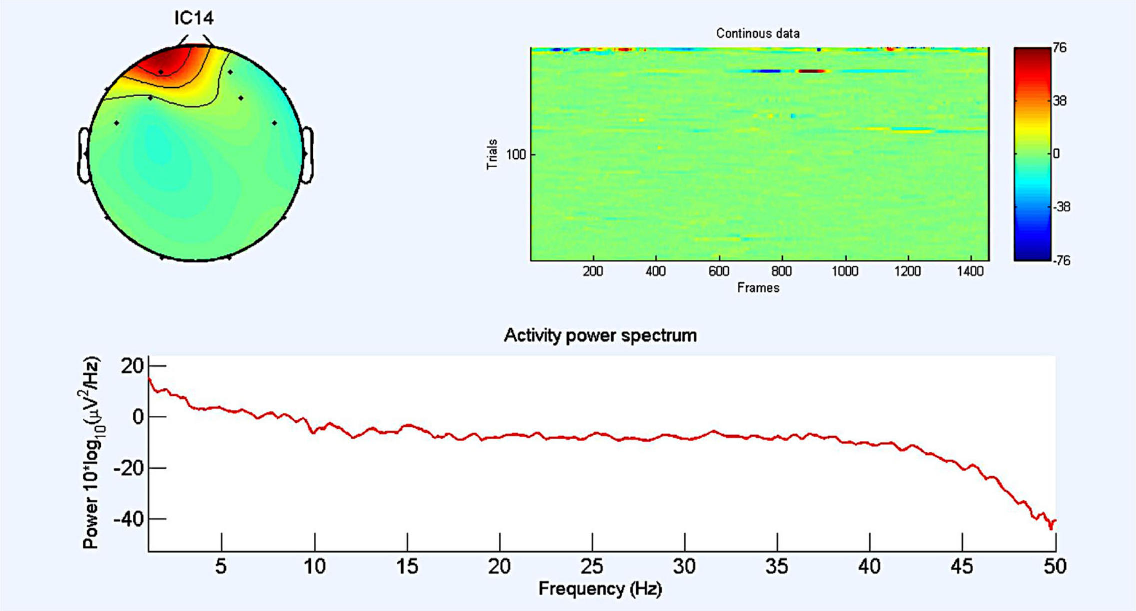


Fig. 6 Eye blink artifact detected using ICA

Interpretation of the Cognitive Data

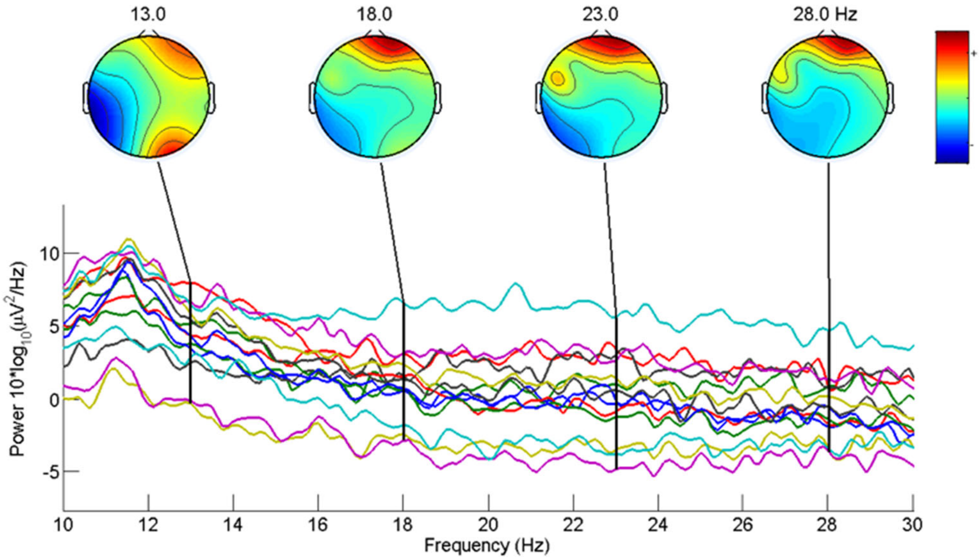
This section will present the process of interpreting the data that was introduced in the previous section. In particular, it will explain the process of interpreting synchronization/de-synchronization data and topographic scalp maps.

Synchronization/De-Synchronization of Cognitive Activity

The synchronization/de-synchronization data was gathered in line with the TRP method (Pfurtscheller and Silva 1999). This involves subtracting the activity recorded during a neutral time period from activity recorded during a specific task or event. It is important to note that the neutral activity for each participant is different in terms of cognitive patterns and amplitude. Utilizing this neutral activity period for analysis purposes allows accurate calibration of the EEG device on an individual participant basis.

After the neutral period of data is subtracted from the activity of interest, the resultant is the task-related synchronization (increase) or de-synchronization (decrease). This can be completed per sensor which total 14 or as was the case in this study for groups of sensors. The rationale for creating groups

Fig. 7 Frequency scalp plot



of sensors is to reduce the effects of "volume conduction" on the data (Rowan and Tolunsky 2003). Volume conduction is a phenomenon where multiple sensors may register the cognitive data, which is being emitted from a single source within the cortex. Within this study, 6 groupings were used which encompassed the frontal, centrotemporal and parietooccipital regions across both hemispheres (left and right). This is displayed in Fig. 8.

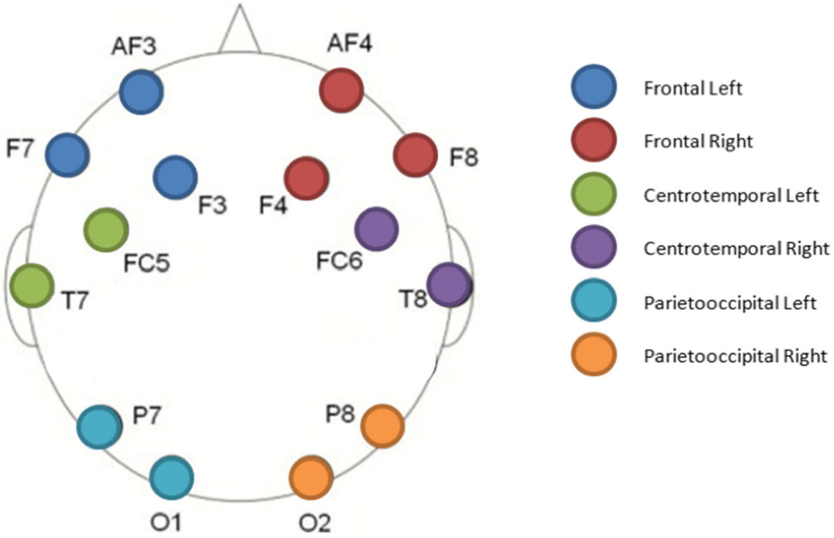
It is useful for interpretation purposes to consider briefly the various cognitive functions associated with each area.

- *Frontal Left*: Typically associated with working memory functions particularly those addressing analytical or phonological processes (McGilchrist 2009)
- *Frontal Right*: Also indicative of working memory processes and particularly active during visuospatial processes (Stillings et al. 1995)
- *Centrotemporal Left*: Associated with long-term memory processes, particularly episodic processes when theta is synchronous in this area and semantic processes when alpha is de-synchronized in this area (Klimesch 1999)
- *Centrotemporal Right*: Generally associated with long-term memory for specific visual objects (Gill and O'Boyle 2003)
- *Parietooccipital Left*: Associated with long-term recall when theta is synchronous in nature in this region and visuospatial cognition (mental rotations) when alpha is de-synchronized in this area (Cabeza and Nyberg 2000)
- *Parietooccipital Right*: Indicative of visuospatial cognition particularly the generation and manipulation of visual mental imagery (Rescher and Rapplesberger 1999)

Worth noting here is the involvement of each of these areas in wider cognitive networks such as the "default mode network" (Uddin et al. 2008) but for the purposes of this current article a brief description highlighting each area's cognitive function is sufficient. During the FFT calculations, values are obtained for the power of the theta and alpha frequencies at each sensor. To obtain the grouped values, an average was calculated for all the sensors contained within each of the 6 groupings. For display purposes, these values were then converted to percentage synchronization/de-synchronization and presented in bar chart format as is shown on the top left of Fig. 9. It is important to note that these graphs only refer to data gathered during the first 32 s of the task given the focus problem conceptualization in this study. The colors of the bars refer to a particular zone in the cortex as illustrated on the right of Fig. 9. This indicates activity occurring in that area. The next stage in interpreting these graphs is to analyze the nature of the activity and ascertain whether the data is synchronous or de-synchronous in nature.

Synchronization (increase) in the theta frequency is a known indicator of cognitive activation (Klimesch 1999). This is the opposite within the alpha frequency where de-synchronization (decrease) is known to be associated with cognitive activation (ibid). Both frequency bands typically indicate different types of cognitive process depending on the location of the activity on the scalp. For example, theta generally indicates activation of memory-related process such as episodic recall in the left centrotemporal area and working memory activation when it is located in the frontal areas (Klimesch 1999). Alpha generally refers to semantic recall in the left centrotemporal areas and visuospatial cognition in the parietooccipital areas (Cabeza and Nyberg 2000). Another pattern to note is the relationship of synchronization and de-synchronization between the theta and alpha frequencies. Generally, as cognitive load in an area increases, theta synchronizes whereas alpha de-synchronizes. Illustrated in Fig. 9 is a lack of this form of activity (alpha de-synchronization and

Fig. 8 Sensor groupings



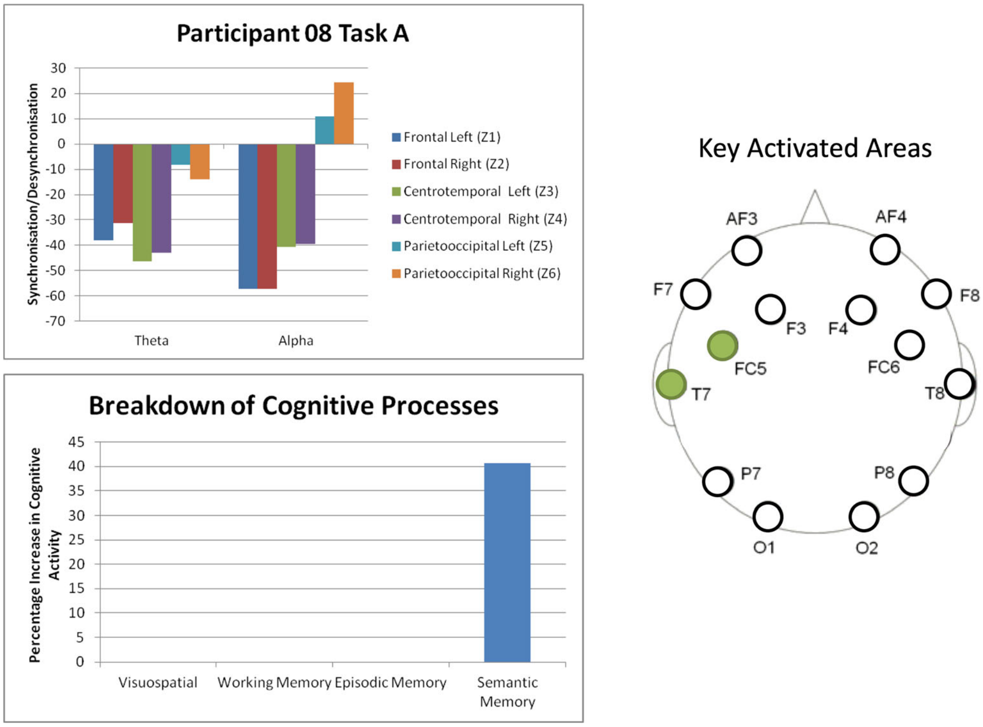


Fig. 9 Sample of conceptualisation data

theta synchronization) which indicates a lower level of cognitive load. Given the large level of theta and its location (left centrotemporal), it can be inferred that the participant utilized a conceptual approach that involved a large amount of semantic processing (Cabeza and Nyberg 2000; Razoumnikova 2000).

In addition to presenting the synchronization/de-synchronization data, an additional graph was provided to clarify the types of cognitive activity indicated during a task. These graphs, which can be seen on the bottom left of Fig. 9, encompassed indicators of visuospatial cognition, working memory, episodic and semantic long-term memory processes. These graphs were created for representative purposes and were calculated using the synchronization/de-synchronization data values relevant to specific cognitive processes as defined in the literature. These are as follows:

- *Visuospatial Cognition*: Related to de-synchronization within the alpha frequency located in the parietooccipital regions (Rescher and Rapplesberger 1999). Therefore, the values in alpha for these regions were added and the negative value was removed for presentation.
- *Working Memory*: Indicated by theta synchronization in the frontal areas (Klimesch 1999) so the values in theta were added for these regions.
- *Episodic Memory*: Indicated by theta synchronization located in left centrotemporal sites (Cabeza and Nyberg 2000; Klimesch 1999). The theta value for this area was taken to represent this function.
- *Semantic Memory*: Related to alpha de-synchronization within left centrotemporal locations (Klimesch 1999) therefore, the alpha value in this site was taken to represent this function. Once again, the negative value associated with de-synchronization was removed for presentation purposes.

Here, positive values indicate implementation of that cognitive process whereas a value of zero illustrate that this processes was not evident in the data. In addition to this rich data on the first 32 s of the task, analysis of the EEG data over the entirety of the problem solving episode was achieved using topographic scalp maps produced by the EEGLab software (Delorme and Makeig 2004). This will be discussed in the next section.

Interpretation of Topographic Scalp Maps

This section will deal specifically with the interpretation of the topographic scalp maps. These are produced during the data analysis stage within the EEGlab software environment. The synchronization/de-synchronization graphs were calculated in reference to a neutral activity period. This was not the case for the topographic scalp maps as these were utilized to observe changes in cognitive patterns with regard to location of activity during the task period. Therefore, the data that is referred to in the topographic maps may highlight areas, which are not task relevant if they are interpreted without the synchronization/de-synchronization data (Fig. 9). A sample topographic plot for the alpha frequency for the same participant (Number 8) throughout a task is illustrated in Fig. 10.

The alpha frequency encompasses values from 8 to 13 Hz and a range of these values is plotted above. The rationale for this is to capture a wider range of frequencies within alpha that can demonstrate whether changes are occurring, at any frequency level, in patterns during the task. Figure 10 presents distinct stages of the task beginning with the first 32 s (of interest in the particular study by Delahunty et al. (2015)). This is the same period of data analyzed in the synchronization/de-synchronization graphs presented earlier.

Semantic memory was indicated for this participant in Fig. 9 and this is located in the left centrotemporal area within the alpha frequency. Looking at the topographic activity throughout the task it can be seen that the overall cognitive strategy for this participant did not deviate significantly throughout the task. It is important that the synchronization/de-synchronization data is interpreted first to determine the conceptual activity and then the topographic maps are interpreted to observe any changes in cognitive pattern during the problem solving episode.

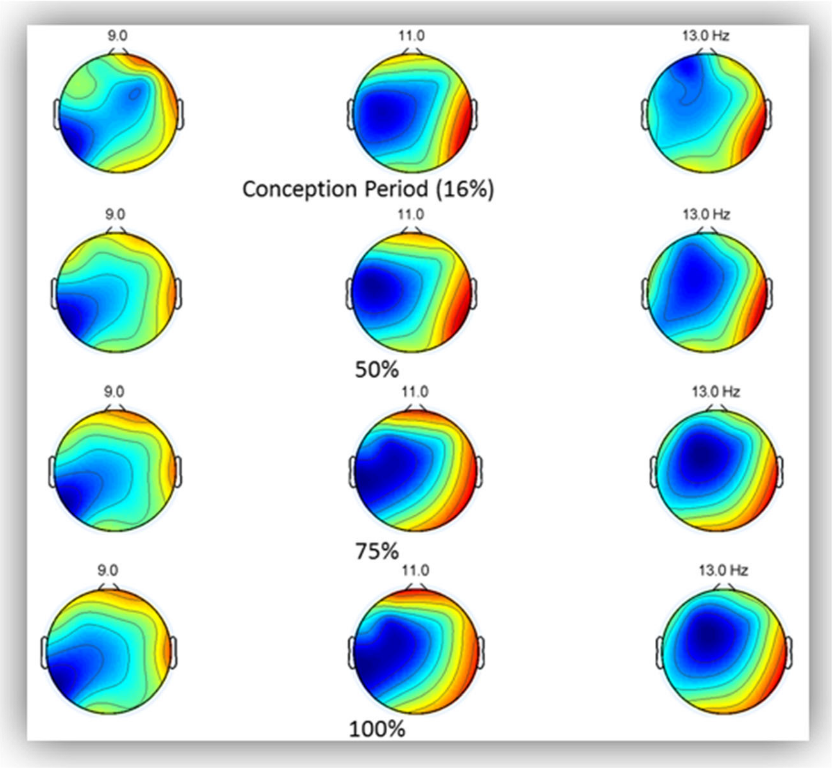
Applicability of the EEG Tool to Studies of Problem Solving

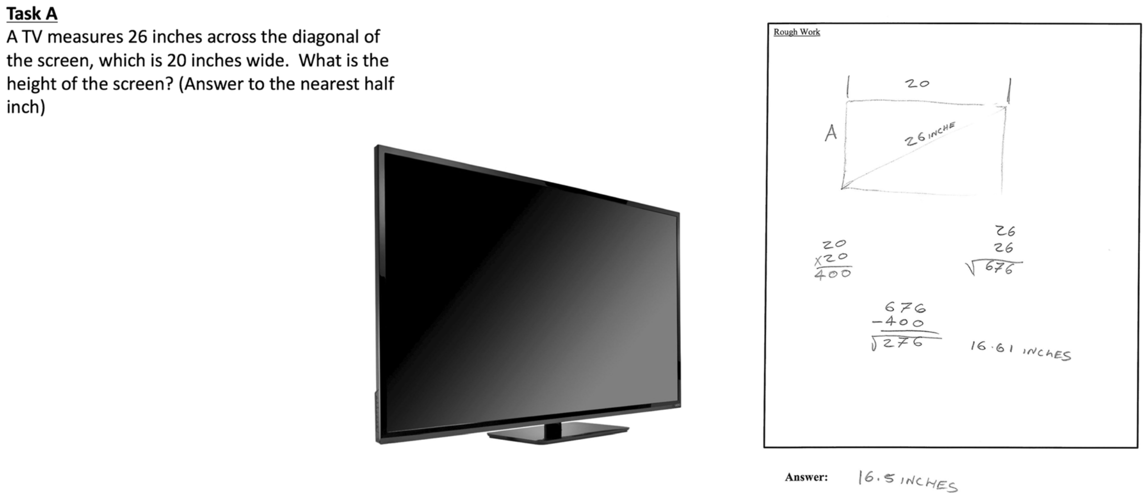
Given the focus of this paper on the application of the EEG tool to an educational research context, it is essential to consider the scope of its use. The intent here is to explore the appropriateness of the application to an educational research study looking at the process of problem solving. Reducing bias involved in adopting a single method was a critical concern in this research given the known seductiveness of neuroscience data. In a study by Weisberg et al. (2008), it was statistically demonstrated that non-experts (presumably in neuroscience) judged poor psychological explanations of phenomena more favorably when presented with data collected with a neuroscientific approach. This presented a clear necessity to include the EEG tool as a single method within a mixed methods paradigm in order to critically explore its application and avoid bias created by the "seductive details effect" (Harp and Mayer 1998).

In order to demonstrate the applicability of the methodological approach, a single data set will be presented and discussed from Delahunty (2014) where the research focus was on the early stages of problem solving involving conceptualization. Data for a single participant are shown in Figs. 9 and 10 and indicate a set of cognitive processes that are memory dominated and low in cognitive load. The task is shown in Fig. 11 along with the participant's solution where it is clear that the individual was competent in applying a known theorem (Pythagoras) to the task. This aligns with the EEG data that demonstrated a pattern of semantic recall.

In addition to the EEG and physical data, post-task interviews were conducted where participants were asked to comment on the approaches they adopted

Fig. 10 Topographic scalp maps





Task A

A TV measures 26 inches across the diagonal of the screen, which is 20 inches wide. What is the height of the screen? (Answer to the nearest half inch)

Fig. 11 Example task and solution

during the problems. Looking at this participant's commentary during the interview sessions, a reliance on memory was evident. When asked during the post-task interview about the general approach adopted to solving the tasks, the participant states:

> "...I probably knew that answer at the start but then probably do a bit of maths... " (Participant 08)

There was also a suggestion of an element of conditioning in the individual's conceptualization potentially as a result of school experience.

> "...you'd be doing a lot of maths problems even in secondary school..." (Participant 08)

In the follow-up interview using a stimulated recall approach, the participant described the overall approach adopted as generally visual:

> "...my first port of call probably for all the problems was visualization..." (Participant 08)

As is evident in this commentary, it would seem that the particular conception this participant had of the tasks was focused on recalling past information of a semantic nature. It is possible that the representation the participant constructed in Fig. 11 facilitated access to the semantic content in their memory system. While a more detailed analysis and presentation of the data from the study is beyond the scope of this paper, the brief data illustrated demonstrates significant promise for this approach. Demonstrated, is the capacity of this commercial EEG headset to capture accurate cognitive data of a participant's underlying cognitive approaches to solving prescribed tasks.

Limitations of the EEG Tool

While the use of the commercial EEG headset offers a number of unique benefits within STEM education research, there are some limitations that must be acknowledged. One of the chief among these is the susceptibility of the equipment to erroneous movements on the part of the individual. Simple head shakes or rapid limb movements can interfere with the cognitive data that is being recorded. While the effects of these artifacts can be reduced using appropriate data screening techniques (Delorme and Makeig 2004), they cannot be completely eliminated from the data. This is a concern in the context of educational research where an investigation may desire to observe students in classroom environments.

A second limitation of the device concerns the poor spatial resolution that is achievable with only 14 active sensors. Most medical grade EEG devices can contain upwards of 256 sensors which obviously provides a much higher level of spatial differentiation in terms of cortical areas of activation. Again, data processing techniques can enhance this resolution but the device utilized within the current study is still limited in this regard. However, the use of medical grade devices, with increased sensor capacity, is limited primarily to strict laboratory conditions. This limitation is due to the immobility of the devices and therefore makes them impractical for application in educational research milieus. While these are two potential limitations of using the device, the insight it can provide in terms of students' cognitive processing warrants its consideration as an insightful research method in STEM contexts.

Implications for STEM Education Research Methodologies

The implementation of the EEG tool for the purposes of collecting quantitative objective evidence of cognitive processing yields robust and rich evidence. One of the key limitations of the majority of educational research to date is the lack of scientific or explanatory power assigned to educational interventions (OECD 2002). Traditional ontological views of scientific enquiry espouse the views of quantification, measurement and objectivity (Madill et al. 2000). Much of the time adopting this as the primary philosophical position for a research study within a STEM education context may not align with the research objective. As an alternative, in much of social science research, the adoption of a qualitative stance may be beneficial as it facilitates a more interpretive philosophy (Johnson and Onwuegbuzie 2004). Adopting such a stance comes at the price of a lack of objectivity and a reliance on the researcher's inference. This can become problematic in a study looking at cognitive phenomena in areas such as problem solving where inference becomes the primary method of elucidating underlying cognition in a learning intervention. The method described in this paper addresses this dearth as it provides an objective and functional approach of capturing this objective cognitive data.

The EEG tool provides a quantitative measure of cognition within the paradigm of a mixed-method approach. The strength of the current study lies in the illustration of the tool as an instrument capable of collecting objective cognitive data involved in the underlying processes of problem solving. This type of data has not been achievable in STEM education research prior to this given the traditionally immobile nature of the equipment. While 14 sensors provide limited spatial detail in comparison to medical grade devices, the strength of the device lies in its mobility and potential for application within classroom settings. This could hypothetically provide a very rich insight into the nature of cognitive processing underlying learning interventions in real time settings. This in turn could provide causal explanatory power to the use of educational interventions and therefore give a more scientific understanding of learning practices (OECD 2002). Specifically, the methodological approach demonstrated within this paper addresses the limitations cited by authors such as Kirsh (2009) who discuss a need for enhanced understanding of the tacit and underlying processes inherent in the earlier stages of the problem solving process. It does so by illustrating its capacity to capture a wider repertoire of phenomena involved and by including an objective measure of cognitive activity. Although this methodology was designed to investigate the conceptual framing of problems, it is applicable to various stages of the problem solving process and adaptable to different research questions. This approach has significant potential for advancing the knowledge base around problem solving, which is a significant element of STEM education interventions. It is envisaged that increasing understanding around the underlying cognitive mechanisms that support problem solving could lead to new and enhanced pedagogical interventions in problem-based learning.

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