Working Paper Proceedings

15th Engineering Project Organization Conference
with
5th International Megaprojects Workshop
Stanford Sierra Camp, California
June 5-7, 2017

Evaluating the Potential of Neuroimaging Methods to Study Engineering Cognition and Project-Level Decision Making

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EVALUATING THE POTENTIAL OF NEUROIMAGING METHODS TO STUDY ENGINEERING COGNITION AND PROJECT-LEVEL DECISION MAKING

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ABSTRACT

The field of engineering and project management is well suited to partner with cognitive neuroscientists, developmental psychologists, and others to consider how neuroimaging methods can complement pressing research needs. Many empirical studies have investigated the cognitive processes of engineering (i.e. processing information, knowledge attainment, decision making, recognition, and perception), however, a key limitation of this previous work is the subjectivity and imperfection that comes with observational studies, participant self-reporting, and critique of the product or process. A benefit of adopting neuroimaging methods is the clear and consistent mappings between events at the neural level and events at the behavioral level. Measuring neurobiological function is already making an impact in economics. For example, the neural correlates of decision making in reciprocal exchange and bargaining games can predict trust among partners. Thus, these neuroimaging methods do not just measure individual behavior but group and social interactions, which should be of interest to those studying engineering and project management. The purpose of this paper is to introduce neuroimaging methods to study engineering cognition and propose a path towards similar advances in engineering and project management as more recently seen in economics. An overview of cognitive neuroscience leads to a discussion of opportunities and challenges of integrating engineering and neuroscience methods. From the discussion of overarching rationale, the paper transitions to a specific focus on engineering through a brief literature review and suggested areas of future research. An ongoing project is also described, not to report findings, but to offer an example of what research designs could look like and the associated data collection and insight gleaned from these methods.

KEYWORDS

Cognitive neuroscience, neuroimaging, functional near infrared spectroscopy, engineering cognition, engineering decision making.

INTRODUCTION

Too frequent, engineering acts as if the decision maker is fully informed and assumes preferences exist priori (Gonzalez et al., 2005). Cognitive psychology approaches

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decision making from another perspective, more descriptive than normative, analyzing how individual preferences are constructed and cognitive limitations influence choice. Fields including finance (Benartzi & Thaler, 2007), law (Johnson, 1993), and medicine (Johnson & Goldstein, 2003) have improved their theoretical foundations by incorporating these factors. Similarly, engineering and project management hold to improve understanding of crucial early-phase decisions during project delivery.

The same brain that decides what car to buy (economics) is the same brain that learns to recognize faces (psychology) (Hardman, 2009). Further still, is the same brain that negotiates between tradeoffs like rigidity, weight, and performance when choosing a material for a combustion engine (engineering). Thus, no matter the context, decision-making processes, at some level, deal with human ability to identify and choose alternatives based on their values and preferences. This process is measurable, not just by the engineering design outcomes, but by the neurological mechanisms in the brain. For example, decision makers more consistent with expected value maximization tend to collect information sequentially calculating the expected value of each choice. Where as decision makers who deviate from value maximization, are more likely to choose the less risky option, and are observed to not collect information in a sequential mental process. In other words, measuring cognition can lead to a better understanding about how information informs decision making. It is not just about what decision makers see but how they see it and cognitively manage the information (Aimone et al., 2016).

Measuring cognition provides another layer of detail otherwise lost to researchers who in the past were only measuring outcomes of behavioral or decision interventions. Indeed, national academies and foundations recognize the need to understand brain-behavior relationships, specifically in how “collective interactions between brain function and our physical and social environment enable complex behavior” (Understanding the Brain - Special Report | NSF - National Science Foundation). This is a prominent part of the NSF-issued report ED 2030: Strategic Plan for Engineering Design, whose authors envision a future where design tools and methods not only support analysis and decision making from a technological point of view, but also account for psychological and sociological factors.

With engineering researchers already pushing the boundaries of knowledge with practice of complex engineering skills, the field of engineering and project management is well poised to partner with cognitive neuroscientists, developmental psychologists, and others to consider how neuroimaging can complement or supplement pressing research questions relevant to human behavior and decision making. While neuroscience is the broad study of the structure and function of the brain, cognitive neuroscience focuses on empirical data from both human behavior and the brain in order to explore human cognition (thinking, planning, decision making) (Eysenck & Keane, 2015). Neuroimaging techniques are increasingly used to understand how the brain processes information. The approach is frequently a systems view about how brain regions function together and how context influence brain regions of interest (Rick, 2011). The current cross-disciplinary work by neuroscientists and economists is leading to new advances in decision theory (Platt &

Glimcher, 1999). For example, descriptive decision theories posit that decision-makers behave as though different options have different subjective values and through neuroimaging this can be observed in the brain (Kable & Glimcher, 2007).

The purpose of this paper is to introduce neuroimaging techniques as a method to study engineering cognition (i.e. processing information, knowledge attainment, decision making, recognition, and perception) and to propose opportunities for similar advances to engineering as those seen in economics. In the first section, an overview of cognitive neuroscience is provided that will enable a discussion of opportunities and challenges of integrating engineering decision making and neuroscience research. The second section transitions from the discussion of overarching rationale to a specific focus on engineering contexts through a literature review and suggested areas of future research. The final section of the paper, lists experimental design methods and an ongoing project is described, not to report findings, but to offer an example of what research designs could look like and the associated data collection and insight gleaned from these methods.

COGNITIVE NEUROSCIENCE

Broadly, cognitive neuroscience is making sense of brain-behavior relations in a search to understand the functional architectures of cognitive systems (Coltheart, 2001; Eysenck & Keane, 2015). For example, how does some function of interest (e.g., risky decision making) occur and in what region? To explore such a question requires a model about how the brain works and is organized. Significant bodies of research are built upon the simplifying assumption of modularity. In terms of scientific inquiry, this means that merely a function must be induced (e.g., present the image of jobsite safety hazard), identify the specific areas of the brain involved, and we will have reliably characterized the architecture of that function (e.g., environmental risk). Further, if we see those areas of the brain involved in any future task then assumptions can be made that the participant is performing the function of interest. Though, as imaging techniques and computational power have improved, the modularity assumption has loosened to instead investigate correlations between modules and identify the networks involved with specific functions (Eysenck & Keane, 2015).

Today, researchers can construct a more detailed understanding of the time of neural processing and network coordination between brain regions. Understanding the demand patterns and functional coordination of activation in the brain is important because researchers can begin to assess where deficiencies occur and, for example, how training and mnemonics may enhance either the temporal response (how fast we detect) or reduce the cognitive load (the energy required) to comprehend, forecast, and make a decision. While the focus here is on decision making related to engineering and project management, these novel techniques and methods, bridging neuroscience to engineering, can also advance fields such as transportation, from individual driver behavior to air traffic controllers' ability to detect flight collision. This could lead to future work exploring differences in cognition between real world risks and those experienced in virtual reality. There are also opportunities to advance cognitive neuroscience by addressing the data collection challenges that arise when extending methods from lab experiments to more cognitively complex real-world field experiments that engineering and project management can provide.

COLLECTION TECHNIQUES

Two common methods used to explore neural processes of decision-making under laboratory conditions are electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). EEG involves a head cap which places electrodes on the scalp and measures electrical changes in the brain. Temporal resolution is very good (detects millisecond level changes) though spatial resolution (where the change occurs) is poor because signals often interfere with one another and make it difficult to pinpoint specific brain regions involved in the processing. EEG methods are mainly of value when stimuli are simple and the task involves basic processes (e.g., target detection) triggered by task stimuli (Eysenck & Keane, 2015).

In contrast to EEG, fMRI technology measures activity indirectly through changes in blood flow in the brain. As a brain region is activated, the body sends more blood to that region and fMRI detects these changes by imaging the blood oxygen level-dependent contrast (BOLD) signal in a special magnetic scanner (Eysenck & Keane, 2015). Blood flow changes occur over time, so the temporal resolution of fMRI is not as fast as EEG (i.e. order of seconds compared to milliseconds), but the spatial resolution is very high and thus amenable to pinpointing changes within specific regions. Data collection can be uncomfortable and constraining as participants must remain still while partially enclosed inside the MRI scanner.

A third option, called functional near infrared spectroscopy (fNIRS), overcomes the limitations of EEG (spatial recognition) and fMRI (unrealistic environment) to study complex processes in more realistic environments. fNIRS is unique compared to EEG because of the spatial resolution, better able to detect regions of activation. fNIRS is unique compared to fMRI because participants can operate a computer or perform a task in an upright sitting position. fNIRS is also safe, portable and noninvasive. It is worn as a cap, similar to EEG, and emits light at specific wavelengths (700-900 nm) into the scalp. The light scatters, and some is absorbed, before reflecting back to the sensor. Oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) absorb more light than water and tissue in the brain. An increase in neural activity produces an increase in the ratio of HbO relative to HbR. The change in HbO and HbR is measured by the amount of near infrared light being reflected or absorbed.

The drawback from fNIRS is its lack of depth in high spatial resolution compared to fMRI. It is effective to investigate areas such as the prefrontal cortex associated with executive function (e.g., planning, problem solving, decision making, and design) but not sub-cortical regions like emotions.

BRAIN REGIONS OF INTEREST

The cerebral cortex is the outer surface of the brain and is divided into two hemispheres and four lobes: the frontal lobes, where much of our conscious thinking seems to occur including language, attention, reasoning, decision making, planning self-regulation, learning strategies, problem solving, consciously controlled movements, and interpretation of other's behaviors; the parietal lobes, which receive and interpret information about temperature, pressure, texture and pain also actively involved in paying attention, processing word sounds, and thinking about the spatial characteristics of objects and events; the occipital lobes, which are responsible for interpreting and remembering visual information; and the temporal lobes, which interpret and remember complex auditory information and appear to be important in memory for information over the long run.

One of the primary uses of neuroimaging is to pre-identify regions of interest in the brain indicated by the literature. This is necessary because baseline brain activity even at rest is still very active and thus it is best to demonstrate both that a stimulus causes additional activation in a region of interest and that it does not cause additional activation in a nonrelated region. Brodmann's areas are numbered regions which researchers commonly use to describe specific regions within the lobes of the cerebral cortex (Brodmann, 2007). These regions are discrete and well defined. In particular, the prefrontal cortex (PFC) associated with executive function (planning, decision making, trade-offs, rationalizing future consequences) includes Brodmann areas 8, 9, 10, 11, 12, 45, 46, and 47. These areas are directly related to engineering cognition and shown in Figure 1, an example of fNIRS placement along the dorsolateral pre-frontal cortex and result sensitivity analysis showing increased activation during an engineering task.

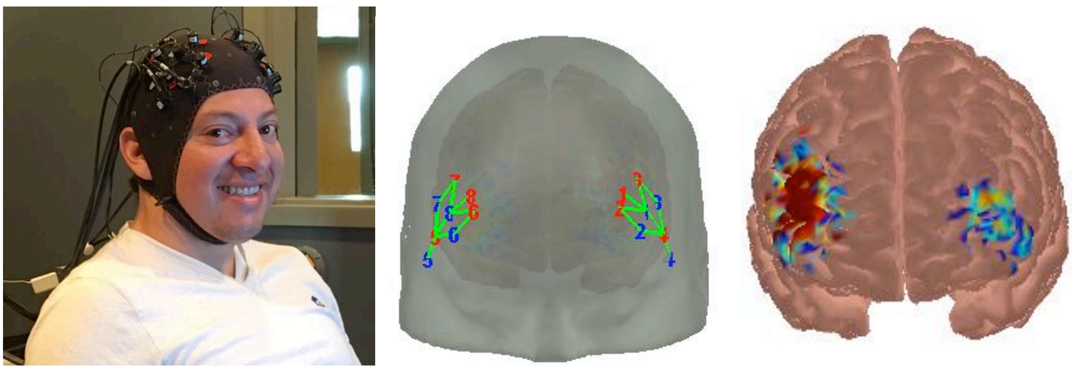

Figure 1: Example fNIRS placement along the frontal cortex (left and middle) and result sensitivity analysis showing increased activation during engineering task (right)

INTEGRATING ENGINEERING DECISION MAKING AND NEUROSCIENCE RESEARCH

The field of engineering project management is suited to partner with cognitive neuroscientists, to consider how neuroimaging can complement or supplement pressing research questions. For example, building and transportation systems account for the vast majority of human energy use and associated climate changing emissions, yet design continues to yield oversized, uncomfortable homes and sprawling, crowded highways that do not meet our needs and damage the natural environment. It is therefore vital to understand the cognitive processes that yield various design outcomes. However, this is an area where brain imaging research is scarce, in part because study requires the integrated understanding of both design and neuroscience that this paper is suggesting be developed.

Design cognition is increasingly recognized across engineering, architecture, and psychology, with the construct of “design thinking” being applied to physical, social, and societal (e.g., business and medicine) problems. Learning, exploration and development are also key concepts in cognitive/social development and education. There is little research related to engineering using cognitive approaches to investigate cognition related to design or decision-making processes in engineering. Most studies still investigate basic cognitive processes and use simple cognitive tasks and focus mainly on technological progresses and data analyzing procedures (Ferrari & Quaresima, 2012).

LITERATURE REVIEW

To better understand the degree to which neuroimaging research is being discussed and reported in engineering, all ASCE journals and the Engineering Project Organization Journal was searched for any mention of EEG, fMRI, and fNIRS. The review was stretched further to capture possible human-computer interaction research including the Automation in Construction Journal. To capture possible engineering education studies, the Journal of Engineering Education (JEE) and proceedings from American Society of Engineering Education were also included. None revealed current research using fNIRS. Two papers were related to EEG in construction from Automation in Construction. However, both papers relate to safety, missing the opportunity to explore project level decision making. Althoguht, the results about safety were intriguing. One paper provides experimental results showing that neural signals are valid for mental load assessment of construction workers. The research also describes the development of a prototype for a wearable electroencephalography (EEG) safety helmet that enables the collection of the neural information required as input for the measurement approach (Chen et al., 2016). The second paper provides similar findings that EEG can effectively reflect and quantify construction workers' perceived risk level. The results were from a small pilot study of construction workers suggests future implementation of wearable EEG devices on jobsites needs to be more thoroughly tested (Wang et al., 2017).

Six papers mentioned fMRI in ASCE journals but after further review none of the papers actually used fMRI. Rather, the papers mention the possibility of using fMRI or relate their findings to a study that used fMRI. EEG was mentioned 64 times and fMRI 18 times in ASEE proceedings. Although, none report the results of empirical studies that specifically used either method. Almost all papers related to EEG or fMRI were discussing engineering instrumentation labs or signal processing. Only one paper discussed fMRI as being a useful methodology to study how engineering students solve problems that are expected to promote critical thinking, reflection, or transfer (Hicks et al., 2014) but, again, falls short in testing the method.

Further still, looking outside of engineering for research related to decision making but not necessary about engineering, many articles exist. Notably, in *Science*, *Neurobiology*, *Nature Neuroscience*, and the *Journal of Neuroscience, Psychology, and Economics*. Now, this is not a full systematic review. Rather, the purpose is to highlight areas of potential overlap related to similar challenges and problems faced in cognitive science and engineering project management. Research that probes the neural basis of decision making in the context of social interactions combines behavioral paradigms from game theory with a variety of methods from neuroscience. The neural correlates of decision making in reciprocal exchange and bargaining games can help explain a set of brain regions and neurotransmitter systems involved in decision making in social interactions (Rilling et al., 2008). This is leading to neuro-mechanistic accounts of how information from others is integrated with individual preferences that may explain preference-congruent susceptibility to social signals of safety and risk (Chung et al., 2015). For example, in an economic trust game, data showed how one player strongly predicts future trust expressed by their partner (King-Casas et al., 2005). Thus, neuroscience does not just measure individual behavior but group and social interactions, which should be of interest to those studying engineering project organizations.

Related to other areas of engineering, fNIRS is used more frequently in human factors engineering (McKendrick et al., 2017), transportation engineering (Tsunashima & Yanagisawa, 2009) and virtual reality and simulations (Karim et al., 2012). For example, related to aviation operations, increasing the number of aircrafts managed by a controller led to an increase in cognitive work load up until about 18 aircrafts and then saturation was reached in cognitive activation. Through training, the number of aircrafts being managed increased before reaching the same saturation level (Bunce et al., 2011). The aircraft example illustrates the ability to measure cognitive ability expanding through training. While fNIRS are providing insight into other areas of engineering, empirical research lacks in combining engineering project level decision making (or engineering education for that matter) with neuroimaging. The next section explores possible rationale for why such integration would be beneficial.

SUGGESTED AREAS OF FUTURE RESEARCH

A benefit of cognitive neuroscience is the clear and consistent mappings between events at the neural level and events at the behavioral level and neurobiological function can provide valuable new measurements to advance theories in engineering and project management. Though, brainstorming a complete list of needed research or opportunities to combine neuroimaging with engineering is not realistic, rather the list below is meant to illustrate examples within the context of engineering risky decision making, engineering design cognition, systems thinking, and hazard detection because these domains are within the domains of research conducted by the author.

DESIGN COGNITION

To date, many empirical studies have investigated the cognitive processes of individuals during the design processes (Coley et al., 2007; Cross, 2001; Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Mosyjowski, & Seifert, 2014). However, a key limitation of this previous work is the subjectivity and imperfection that comes with observational studies. For example, cognition is usually not directly measured, instead only the products of an individual's thinking are observed and recorded. Neuroimaging can provide researchers an additional tool to better triangulate behavioral findings. fNIRS in particular is well suited because of its spatial abilities to identify activation. This type of data holds promise to revolutionize the study of design cognition because this type of information can help construct a more detailed understanding of the processes and the network coordination between brain regions during thinking. fNIRS can be used in naturalistic settings in the real world, compared to fMRI, during actual events and design tasks.

SYSTEMS THINKING

The ability to think in systems is critical to advance, for instance, sustainability because inherently sustainability is a systems problem that requires a shift in thinking from individual parts to the relationships between them (Olson, 2006). For example, an ecosystem is not just a collection of species, but a series of living things interacting with each other and their environment. However, traditional education may over emphasize linear, or analytical thinking, which may reduce an engineers' ability to think about sustainability as a system (Mulder, 2004). Neuroimaging techniques can help measure systems versus linear thinking related to challenges like sustainability. The expectation is linear thinking, will not lead to the same conceptual understanding and will require less cognitive activation compared to systems thinking. Through practice, the expectation is the temporal response and magnitude of response becomes less for systems thinking. Thus, neuroimaging provides a gauge of how quickly subjects can process information as a system. Quickness does not just mean the temporal response in activation but also the functional connectivity between brain regions of interest (i.e. how fast regions coordinate). Training, context, and experience influence the way in which participants approach problems. Neuroimaging can help account for these variations in "styles of reasoning" among engineering professionals by measuring the discernable differences in patterns and response time. Overtime, patterns of activation across subjects may help predict behavioral or decision outcomes. Thus, leading to new types of interventions in training elicit cognitive activation that facilities the appropriate response.

CONTEXTUAL COMPLEXITIES OF ENGINEERING PROBLEMS

If/how engineers attend to embedded social, cultural, political, and/or ethical complexities and context in generating solutions to design problems is exceptionally relevant to those studying engineering project organizations. Context is necessary for every action, interaction and intra-action. While think-alouds, observational studies, and analysis of solution artifacts may lend some insights, neuroimaging can help see specifically if and when such complexities and context are cognitively attended to because of the very different areas of the brain that may be involved in these processes. Better accounting for embedded complexities and contextual specificities from real life is possible with relatively new techniques like fNIRS that are more mobile allowing research participants to walk, talk and interact with others in the real world.

HAZARD DETECTION

By measuring cognitive demand and localization of brain activation during hazard detection, researchers can construct a more detailed understanding of time, neural processing and network coordination between brain regions. Understanding the demand patterns and regions of activation in the brain is important because researchers can begin to assess where deficiencies occur and how training can enhance either the temporal response or reduce the cognitive load to comprehend, forecast, and make a decision towards hazard reduction. The expectation is a high correlation in temporal response and the magnitude of risk associated with hazards and significant difference in the cognitive load (i.e. BOLD response) to comprehend (interpret and evaluate) hazards of different energy types (i.e. gravity, chemical, mechanical). Once a baseline is established, empirical interventions could then be tested and new measurements of the temporal responses and pattern of activation could then be measured to gauge response. While the focus of the previous examples is professionals, here the scope could include construction workers. Varying levels of experience and training associated with a trade may likely influence response time and hazard detection by type.

RISKY DECISION MAKING

Knowing the mechanistic activation in the brain can help devise new mathematical representation of risky decision making and can be useful in better describing and predicting behavior. For example, the notion of hyperbolic time discounting that predicts people behave impulsively when faced with the right combination of incentives does not actually seem to hold true given new data from neuroimaging studies (Benhabib et al., 2004, 2010). Greater relative activity in affective cognitive systems was associated with choosing earlier rewards more often. Understanding that hyperbolic time discounting stems, in part, from competition between the affective and cognitive systems, leads to the prediction that factors that strengthen or weaken one or the other of these influences will cause people to behave more or less impulsively. Thus, the notion of quasi-hyperbolic time discounting provides a more accurate mathematical representation of precisely such a two processes system in the brain (Benhabib et al., 2010).

This bridge between decision making and neuroscience is already making an impact in economics. In fact, neuroscience is suggesting new insights and useful perspectives on old problems. For example, the economic model assumes that the utility for money is indirect, only valued for the goods and services it can procure. Thus, standard economics would view the pleasure from food and the pleasure from obtaining money as two different experiences. However, neural evidence suggests, the same reward pattern in the brain is activated for a wide variety of reinforcements: cultural objects like cars (Erk et al., 2002), drugs (Schultz, 2002), and money (Peterson, 2005) provide a similar arousal of dopamine.

EXPERIMENTAL DESIGN METHODS

Necessary to note, there are two general experimental setups: block and event related design. A block design is the separation of experimental conditions into distinct chunks so that each condition is presented for an extended period of time. The difference between blocks is the independent variable. The independent variable is kept at a constant level throughout the block and transition between blocks represent changes in the level of the independent variable. Another approach is the alternating block design, which two or more different conditions are alternated in order to determine the differences between the two conditions, or a control may be included in the presentation occurring between the two conditions. Trials typically last between 10 seconds to 1 minute. As mentioned earlier, the BOLD response lags behind neuronal activation. On average 5 seconds to the peak HbO response. So, if blocks are too short the response per trial may appear as a peak response for the entire block. Further, too long and fatigue is a consideration. Block length should be chosen so that the same mental processes are evoked throughout and best determined by rehearsal with subjects and validated for face and content validity.

Some experiments cannot use blocked design due to the transience of the neural activity. The “n-back” paradigm is an example. In the n-back test, the subject is presented with a sequence of stimuli, and the task consists of indicating when the current stimulus matches the one from *n* steps earlier in the sequence. The load factor *n* can be adjusted to make the task more or less difficult. Typically, from one step prior to three. This is an event-related design because there is no categorization, meaning the independent variable is randomized and the time in between stimuli can vary. Event-related design has the potential to address a number of cognitive questions with a degree of inferential and statistical power. Each trial can be composed of one experimentally controlled (such as the presentation of a word or picture) or a participant mediated "event" (such as a motor response).

A mixed design incorporates an event as a trial within a block. Conceptually the difference is the grouping of events. The purpose is to maintain a cognitive state where as the individual stimuli in an event related design is assumed to evoke a particular cognitive process. An important difference between mixed design and the other types of designs is that mixed designs allow analysis of independent variables that change on different time scales. Mixed design allow identification of separate brain systems that underlie state and event related aspects of their task.

As mentioned earlier, fNIRS and EEG are able to be used in more naturalistic environments compared to fMRI, where neither a block or controlled standardized (discrete) event may occur. Far fewer studies use this approach because of the lack of control in independent variable or known occurrence of stimulus. This type of approach is more likely seen in real world settings of engineering tasks thus are critical in the future.

Inter-disciplinary research set in the real world, without a block or event related design, is a small but growing field called neuro-architecture. It is a collaboration among neuroscientists and architects to explore, through scientific methods, the range of human experiences to validate architectural design (Mallgrave, 2011). The purpose is to explore, with neuroscience methods, what is actually happening in people's brains when they enter spaces, how dispositions are modified, and how this activity in the brain then changes people's frame of mind (Eberhard, 2008). The field is still rapidly evolving but hold promise to bridge design and science closer together. In fact, there is some evidence that certain types of building spaces actually promote the growth of new neurons (Edelstein & Macagno, 2012; Linebaugh, 2013). Though, not only is the field about how buildings influence humans but also includes neuroscience of the design process, which looks at the architect's brain activity in the development of a project. Neuro-architecture, measuring the designers brain during a project, is closely associated with the proposition of measuring engineering cognition and project level decision making using neuroscience methods postulated in this paper.

DATA ANALYSIS

Field experiments like those of neuro-architecture are very much at the cutting edge of neuroimaging ability. This requires complex preparation and timing. Syncing the recorded brain activation data, possible video data, or eye tracking data is not straightforward. It requires coordinated effort creating markers in each of the data sets at the same time. Further, the BOLD response, when using fNIRS, is related to an increase in oxygenated blood, which not only occurs during cognitive tasks but during physical activity. So, in addition to monitoring cortical activation, scalp interference must also be recorded using a short channel separation measuring blood at the scalp. The BOLD response can also be influenced by physiological changes in heart rate, instrument noise and experimental error. Pre-process filtering using high and low band pass filters can help correct these errors. Once the data is filtered, there are numerous methods to analyze the data. The most typical methods for analysis include some form of measuring:

1. Delta amplitude
2. Peak amplitude
3. Time to reach peak
4. Slope measurement
5. Area under the curve

Further analysis includes general linear models, especially for block design experiments where the expected response would be an increase in the canonical BOLD function during the trial and a return to homeostatic levels following a rest. As mentioned earlier, others use a multi-variant approach. More still, a recent approach is using Support Vector Machines (Chen, Zhao, Fang, & Wang, 2007). For more on data processing methods see (Tak & Ye, 2014).

EXAMPLE PROJECT

In an example project, to illustrate the potential of neuroscience methods to inform engineering research, freshmen and senior engineering students (n=23) were given 5 engineering challenges based on Richard Smalley's list of the most pressing issues facing humanity in the next 50 years (Smalley, 2003). The order in which they received the challenges was random. Each challenge was displayed on the screen for 60 seconds followed by a rest period of 30 seconds. Students were asked to verbally provide solutions to the challenges and a researcher tallied the number of responses. Experiments about brainstorming are typically based on the number or novelty of solutions generated. In this study, the number of responses was the main measurement because of its objectivity.

After filtering the data, channels were averaged across the whole prefrontal cortex, split between left and right hemisphere and individually analyzed. The hypothesis was that students’ ability to generate solutions varied based on years of education. By measuring hemodynamic responses during brainstorming tasks with freshmen (x=14) and senior (x=9) engineering students the results indicate significant difference ($p<0.001$) in the cognitive activation. Freshmen engineering students showed 5 times greater activation in the dorsolateral prefrontal cortex (known to involve working memory, cognitive flexibility, planning, inhibition, and abstract reasoning) compared to seniors. While seniors show an average of 10 times increase in activation in the premotor cortex (known to be involved in the management of uncertainty, control of behavior, and self-reflection in decision making). The number of solutions generated was also significant ($p=0.032$). Freshmen generated more solutions on average during the brainstorming activity compared to seniors. In many ways, this initial work serves as a proof of concept in using neuroimaging to study the processes involved in engineering design.

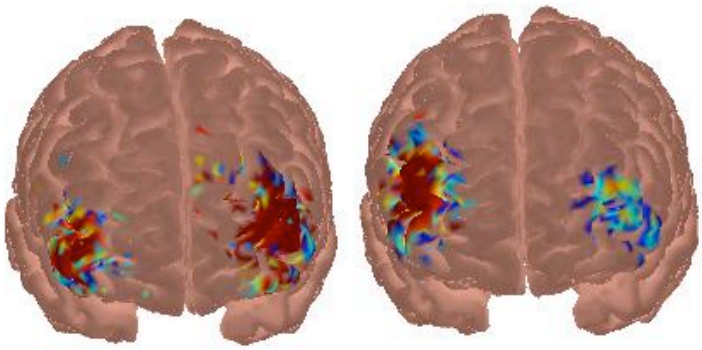

Figure 2: Average cognitive activation among freshmen engineering students (left) compared to average cognitive activation among seniors (right) during brainstorming task. Higher cognitive activation is indicated by red and lower activation by blue.

CONCLUSION

Economists already use neuroimaging methods to understand how risk, uncertainty, social norms, and role models affect cognitive states (Holper et al., 2014). At the same time a growing field in neuro-architecture is illustrating how design impacts bio-physiological states (Adli et al., 2017; Eberhard, 2008). Similar advances are possible in engineering. Neuroimaging methods can measure the change in patterns across cortical regions (e.g. from visual to working memory), enable predictions about behavior or task performance based on the underlying bio-physical response (e.g. activation in prefrontal cortex), and triangulate data like subject self-reporting (e.g. does their physical response match their reported response?). The intent of this paper was to communicate details about these benefits, what is involved in adopting these methods, and the procedures required when considering integrating neuroimaging into an existing study. The benefits are numerous: offering a new data source and opportunity to advance theoretical understanding, which seem to outweigh the learning curve associated with the measurement tool and nuances of the experimental design to successfully integrate neuroimaging into engineering research.

Better understanding the role of certain brain regions during engineering experiments like design cognition or risky decision making across a range of subject groups appears to hold promise to advance theory related to engineering cognition and project level decision making. At the same time, can offer opportunities to advance cognitive neuroscience more generally by addressing the data collection challenges that arise when extending methods from task-oriented problems to more cognitively complex challenges that often lack a standardized event and take place in more real-world settings. While literature provides a rich understanding of which brain regions support which cognitive function (e.g. visual or spatial thinking) there is a lack of understanding about how these processes are developed (i.e. from novice to expert), evolve over time, vary by context, differ among groups of people, how they are influenced by others, or effected by the structure of choices during cognitive processing. These are exactly the types of questions and problems engineers, along side neuroscientists, can help address. A more detailed understanding of the mental processes required for these types of problems can be constructed but only by working to blur the lines between fields.

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