fNIRS Imaging of the Prefrontal Cortex During Narrative Tasks

ABSTRACT

When working with people who have communication impairments, there are not enough cognitive assessment tools to discern between baseline neural function, mild cognitive impairment (MCI), and traumatic brain injury (TBI). While there are some available measures, we would like to expand the repertoire and ensure that they hold up against test/re-test principles, including accurate tracking over time. This study proposes to expand these tools of studying neuronal activity, looking at tasks linguistically and with functional near-infrared spectroscopy (fNIRS) to explore what brain regions are used during human discourse.

Statement of the Problem (Description of the Project):

It can be hard to accurately assess differences between mild cognitive impairment (MCI), traumatic brain injury (TBI), and normal aging, so it is important to have appropriate tests to differentiate between them. It is possible to use linguistic tests to analyze these differences and we plan to connect this to the prefrontal cortex in the brain, which will be described more in the literature review. Ultimately, the goal is to learn more about which brain regions are involved in complex narrative tasks. In the lab, we are giving a control population procedural narrative tasks and observing how blood oxygen levels fluctuate between and within tasks. This will tell us what areas of the prefrontal cortex are more (or less) active during these planning and speaking tasks. Studies have been able to differentiate typical cognition from mild cognitive impairment (MCI) and/or traumatic brain injury (TBI). These studies have utilized tasks such as “plan a trip to New York City” or “describe the steps of withdrawing money from an ATM”, determining what to expect from a “control population”. Our goal is to create more tests that are like this, such as “plan a dinner party” and “explain the steps of pumping gas”. Upon finding parallel or equivalent forms to the current “Trip to New York” task (explained further in literature review), we will use them for testing and retesting. I will take this further and examine the parts of the brain that are activated in these procedural planning tasks, including looking at the equivalence of difficulty and relationship to prefrontal cortex function. It is expected that planning and executive function will certainly be localized to the prefrontal cortex but it will be interesting to see how language fits on the frontal lobe map and compare processing demands related to linguistic performance. We will norm these results and then potentially compare them to those with MCI or TBI, which would take this one step further.

Chapter 2: Literature Review (Review of Previous Work)

Currently, the research shows that not enough natural communication tasks exist to assess neurological injury and that there are still gaps in knowledge about associated prefrontal cortex activation. This review of literature will discuss research about the use of discourse tasks in assessing baseline cognitive function versus those with mild cognitive impairment (MCI) or traumatic brain injury (TBI). It will also cover studies about which brain areas are used during these tasks, how the prefrontal cortex (PFC) is involved in discourse, and what this could mean for people with TBI. Identifying these discourse deficits following brain damage and determining patterns in brain activation can result in better therapy and increased quality of life for individuals with traumatic brain injury.

It can be hard to accurately assess differences between mild cognitive impairment (MCI), traumatic brain injury (TBI), and normal aging, so it is important to have appropriate tests to differentiate between them. By assessing communicative and linguistic abilities through standardized tests, it is possible to clinically diagnose patients with cognitive disorders and memory impairments (Moro et al., 2013). However, clinicians and speech language pathologists lack some of the tools necessary for diagnoses. In clinical settings, there is a limited knowledge of discourse assessment tools and simply not enough TBI-specific standardized assessment instruments to create reliable diagnoses (Steel & Togher, 2018). Even typical cognitive-communicative tasks like the MMSE (Mini-Mental Status Exam) are not sensitive enough to subtle changes (Harris et al., 2008), and often subtle differences are all that can discern between normal aging processes and something like MCI. Due to this, new standardized discourse tasks are needed to assess communication deficits of people with TBI and other non-aphasia (language-related) neurological injury.

MCI is characterized as "cognitive impairment that is greater than would be expected for an individual's age and educational background" (Fleming & Harris, 2008). It affects between 3% and 19% of individuals over 65. Though people with MCI revert to normal cognitive function, 50% of people with MCI progress to Alzheimer's dementia within five years (Fleming & Harris, 2008); thus, it is very important to detect MCI as early as possible to provide the best healthcare and intervention options. The primary distinction between MCI and normal cognitive aging remains somewhat unclear, since there are signs seen in both like "expected declines in sensory acuity, speed of processing, and executive function" (Fleming & Harris, 2008).

Due to these unclear distinctions, more communication assessment tools should be created and normalized for patients. Discourse, or natural communication, tasks are important in assessment. One such task that has been shown to detect subtle differences is an experimental discourse task called "Trip to New York". This task involves asking people to plan a trip to New

York City. This involves planning, problem solving, and communicative skills. Harris's study showed that those with cognitive deficits provided less thematic information and had more irrelevant comments and words than others without cognitive impairment. The sparseness in description by the MCI group reflected the inability of the MCI patients to retrieve words and provide detailed discourse (Fleming & Harris, 2008). However, "Trip to New York" is just one assessment tool and more equivalent tasks should be normalized to increase options for testing patients.

In addition to linguistics, it is important to know the neuroscience behind communication tasks to better diagnose cognitive impairment. Linguistic data from discourse tasks like "Trip to New York" do not necessarily shed light upon neuronal functioning, whereas brain activation data during these tasks can. In the past, it was thought that speech production and comprehension was localized to the brain's left hemisphere, but now it is known to recruit an "extensive bilateral network… [with] extensive coupling in extralinguistic areas such as the mPFC (medial prefrontal cortex)" (Silbert et al., 2014). Not only is the PFC involved in speech comprehension and production, it controls expression and executive function as well. Executive function is higher-order thinking that involves planning, memory encoding, and short-term "working" memory. This working memory is used in understanding and producing speech (Moro et al., 2013). The dorsomedial PFC is also implicated in responding to task instructions and is linked to "non-automatic, intentional cognition" (Seibörger et al., 2007). Thus, it is important to study the PFC as it applies to language, cognition, and general executive function. Having more tangible brain activation data via brain imaging could help clinicians to see what was going on in patients' prefrontal cortexes with MCI or TBI, and compare it to a baseline. Then, healthcare providers could use this information and apply it to a more comprehensive treatment or management plan.

One previous study used functional magnetic resonance imaging (fMRI) to deduce cortical activation patterns during varied discourse tasks. When readers in this study were asked to read text with less structure, it was associated with increased cortical activity because the prefrontal cortex was more active in processing the story's organizational elements (Cannizzaro et al., 2012). However, this is regarding reading comprehension and cortical activation, not natural communication, which is more relevant to real life. It would also be important to know how people use their prefrontal cortices in oral discourse, including procedural narrative tasks such as the "Trip to New York", in order to have better baseline knowledge of the neuronal basis of procedural discourse. This has implications in TBI discourse comparisons and treatment options as well. Another thing to note is that this study was done using fMRI, which does not have good temporal resolution. It would be important to use a device with good temporal resolution to detect small changes in brain activation and track exactly when these changes happen.

Electroencephalographic (EEG) recordings have good temporal resolution and have been recently used to investigate the brain processing cost associated to "misalignments with respect to the way information is expected to be organized within utterances" (Rocca et al., 2016). It is found that people's brains react electrically when sentences are spoken in an unexpected way – for example, if one were to say, "She got a job" and there was no way to know who "she" is. This could be helpful in looking at mild cognitive impairment and seeing if the same or a lessened reaction is elicited in this population. However, the issue with EEG is that it does not have good spatial resolution and it is hard to pinpoint exactly where in the brain the electrical changes are happening. There needs to be a device that bridges this gap – functional near-infrared spectroscopy (fNIRS) has a better spatial resolution than EEG and better temporal resolution than fMRI, making it very useful for discourse studies.

fNIRS "capitalizes on the changing optical properties of… tissues by using light in the near-infrared range to measure physiological changes" (Farzin et al., 2006). Essentially, this headband-like device uses infrared light to measure changes in oxygen levels in the bloodstream, suggesting neuronal activation. This works because neuronal activity is fueled by glucose and oxygen consumption, so blood filled with glucose and oxygen (via oxygenated hemoglobin) rushes to the site of the brain that is activated. fNIRS can track these oxygenation changes quickly because "both oxygenated and deoxygenated hemoglobin have characteristic optical properties in the… near-infrared light range, [so] the change in concentration of these molecules… can be measured using optical methods" (Farzin et al., 2006). Since fNIRS uses the optical properties of the tissues to deduce brain activation, it is flexible and fast, making it a popular neuroimaging technique. It also has very good temporal resolution, meaning that it picks up on cortical activation almost instantly due to using infrared light and the optical properties of tissues.

In the past, fNIRS has been shown to be helpful for understanding primary and secondary responses to brain injury in adults and children (Farzin et al., 2006). It also shows promise in studying the brain at rest, otherwise known as resting-state functional connectivity, between the left inferior frontal cortex and superior temporal cortex, both associated with dominant language regions (Quaresima et al., 2011). Though there are some downsides - it has limited spatial resolution, there is risk of attenuation of the light signal by outer layers of the skin, skin pigmentation can hinder signal detection, and there can be difficulties obtaining baselines of types of hemoglobin (Farzin et al., 2006) – it is ultimately a relevant and reliable tool to study PFC activation during discourse tasks.

Past fNIRS studies have shown that specific parts of the brain are activated during the use of working memory of speech. One such study used the Logical Memory Test of the Wechsler Memory Scale to investigate the encoding and retrieval processes of memory and measured brain activation response with fNIRS imaging. They found a moderate activation in the bilateral ventrolateral prefrontal cortex (VLPFC) and a broad activation in the bilateral dorsolateral prefrontal cortex (DLPFC). The VLPFC is known to be involved in selection, comparison, and decision about the information held in a memory. The DLPFC monitors and manipulates information. Therefore, these two parts of the prefrontal cortex clearly work together to manipulate information in a way that makes sense.

Natural communication and fNIRS should be more frequently combined to find more equivalent discourse tasks such as "A Trip To New York" and to establish the role of the prefrontal cortex in discourse. These future communication tasks will be useful in looking at adults with and without brain injuries and finding a baseline of brain activation in non-brain injured individuals to act as a baseline. It is especially important to find equivalent tasks so clinicians can effectively track patient progress. It is shown that cortical activation related to discourse processing is possible to measure using the fNIRS, so once PFC activation patterns are found, this research will assure equivalence of tasks. Using fNIRS, this study will also be able to determine processing demands of various natural communication tasks, having implications in further research and healthcare. Hopefully clinicians will be able to use these tools for better diagnostic testing in the office and people will live more productive lives having more information about the way they process and produce discourse.

Significance

This project is significant because current tests still render it difficult to discern between mild cognitive impairment (MCI) and general traumatic brain injury (TBI). Detecting MCI as soon as possible is incredibly important in intervention and treatment options. Thus, finding more discourse tasks that can accurately assess communication differences between the two is essential in providing better healthcare in the future. Furthermore, it is important to know the neural underlying of these communication pathways. Linguistic discourse tasks do not explore executive functioning, whereas using fNIRS to observe oxygenation changes in the prefrontal cortex can. This is because the prefrontal cortex is involved in executive function, decision-making, and communication tasks. By linking linguistic discourse tasks and functional brain imaging, clinicians could then use this information to apply it to a more comprehensive treatment and management plan.

Proposed Methodology

This research involved creating new discourse tasks such as “plan a dinner party” or “describe the steps of pumping gas” like the “Trip to New York” task. Also, a functional near infrared spectroscopy (fNIRS) device was used to measure blood oxygenation level fluctuations in the prefrontal cortex during discourse tasks as well as during previously-normalized tasks such as “Trip to New York”. Upon analyzation, these oxygen levels will show where in the brain (and where during the task) high levels of brain activation occur. fNIRS-compatible computer software will analyze these results and detect patterns within and throughout the data.

Facilities and IRB Approval:
The laboratory in Rowell is equipped with all the necessary supplies (just the fNIRS device) to perform the methods described. Human subjects were used in this project. Project falls under IRB#M12-230, P.I. [xxx].

Timeline
We plan to run 10-15 more subjects (hopefully on Thursday or Friday afternoons in the Rowell lab) using the same proposed methodology as described above. This will be done within the semester. Starting in October, I will analyze the data and complete the thesis by the end of March.

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