Personal Section

The family dinner table was silent, my sisters shoveling forkfuls of food and answering text messages. We might as well have eaten separately. Gauging tone of voice marked my own text message conversation. Did "it was fine" mean my friend thought the movie was good or bad?

Tired of the disconnect, I suggested my family place our phones in the center of the table. Finally, we could tell a story without someone receiving a text message and providing a "give me a second" story delay as they reached for their cell phone. We tried this practice at each meal for about a week. The result was remarkable.

Dinner felt so different – as though a usual guest at the dinner table had not showed. And then something started to bother me – text messaging is such an integral part of our everyday lives, yet I barely knew anything about how this form of social communication affected both myself and my personal relationships. I turned to Internet searches and found the research conducted on text message communication had been mostly psychology based.

Flash forward a year later, when a serendipitous opportunity to work for the summer of 2015 at the Yale Brain Function Laboratory in New Haven, Connecticut under the direction of Dr. Hirsch arose. In the months before my arrival at the laboratory, the Yale Brain Function Laboratory had become the first laboratory in the world to possess a full two-head fNIRS system. Such a neuroimaging system meant that a laboratory could gauge, for the very first time, the full cortical brain activity of two interacting partners as they engaged in natural conversation. The laboratory had not yet examined how the brain activity of two interacting partners as they texted each other compared to the brain activity of the interacting individuals as they communicated in person, and thus I knew immediately that subject was what I wanted to explore.

To begin the exploration, I first read a wealth of fNIRS studies to learn both the technology behind fNIRS and the work that had been done using fNIRS thus far. To control the fNIRS machine, as well as guide the discussion of my subjects as they spoke or texted, I learned the computer program Python with laboratory members' guide. I then delved into subject recruitment and finally data interpretation, which consisted of interpreting graphs and neuroimages.

Before joining the Yale Brain Function Lab, I had always viewed my concurrent interests in science and the humanities as competing. Whether I saw my future self running a PCR or writing a novel would waver. So many people all throughout high school would always say, " I don't get it. Are you a STEM or a humanities person?" I was both, and I believed that at some point I would make Sophie's Choice between the two.

However, after my experience at the Yale Brain Function Laboratory, I now see science, neurobiology specifically, as the nexus between STEM and the humanities. Through analyzing the human brain, one can gain deep human understanding. I watched hours of subject video footage, analyzing interpersonal interaction by the number of laughs or times in which the subjects made eye contact. I analyzed how well the speaker was listening to his partner through the amount of oxygenation in the listener's Broca's area. A finite and beautiful window into high-level interpersonal interaction, which makes us human, opened with my project.

STEM allows us to understand, by measurable and true means, the questions around us. The process of answering these questions is difficult and, in its challenges and its opened windows, exquisitely beautiful.

Research Section

Background

During interpersonal interaction, humans utilize complex language (Hari & Kujala, 2007). Humans utilize such language to cooperate, compete, imitate, help, inform, question, negotiate, bargain, lie, and vote. Until about 20 years ago, much of this communication was conducted in-person or through telephones. However, digital communication within the past 20 years has continued to rise, thus replacing these forms of interaction (Williams, 1977).

Emerging adults, who report texting as their dominant daily mode of communication, comprise the largest proportion of texting and instant messaging users. 63% of these emerging adults report exchanging text messages every day, in stark contrast to the 35% of emerging adults who report engaging in face-to-face interaction outside the classroom and the 14% of emerging adults who report speaking to their friends on a landline (PewResearchCenter, 2012). Thus, communication amongst adolescents and early adults has increasingly become digital and text-based.

Yet, only face-to-face socialization enables communicators to practice nonverbal cues, such as a smile, head nod, a lean toward the conversational partner, and a hand gesture, which have been found to build feelings and commitment within a relationship (Gonzaga *et al.,* 2001). Furthermore, face-to-face socialization provides interacting partners with a window into the other's gender, personality, and intentions through audio cues (Nass & Gong, 2000).

In the absence of these verbal and nonverbal cues, individuals record lessened personal connection between themselves and their communicating partners (Sherman, Michikyan & Greenfield, 2013). Individuals report video chat as the form of digital communication most conducive to establishing a strong interpersonal relationship and instant messaging least conducive. Such self-reports suggest both typing and the ability to view a subject's face alter the interaction. Although a plethora of behavioral analyses exploring digital communication point toward an acquired social disconnect between interacting partners, no study has delved into the neural mechanism behind the digital interaction nor the level of cross-brain coherence between the communicators.

Cross-brain coherence, marked by correlation between two neural signals of brain activity (Cui, Bryant & Reiss, 2012), has been utilized to examine the dynamic interactions between individuals. It has been found that a significant increase in cross-brain coherence in the left inferior frontal cortex exists during a two-person face-to-face dialogue task, while no such coherence increase exists during back-to-back dialogue, face-to-face monologue, and back-to-back monologue in any brain regions (Jiang, Dai, Peng, Zhu, Liu & Lu, 2012) (Hirsch *et al.,* 2014). The amount of cross-brain coherence and the level of listener understanding reveal a positive correlation (Stephens, Silbert & Hasson, 2010).

This experiment examined the differences in cross-brain coherence and neural activity during texting and in-person interaction utilizing a brain imaging technique known as fNIRS (functional near-infrared spectroscopy).

Design Considerations

fNIRS is a relatively upcoming noninvasive neuroimaging technique that was originally utilized in the 1950's as an add-on optical device (Sitaram, Caria & Birbaumer, 2009) and rediscovered in the 1990's for its ability to analyze functional activation of the human cerebral cortex (Ferrari & Quaresima, 2012). More traditional forms of noninvasive functional neuroimaging include EEG (electroencephalogram) and fMRI (functional magnetic resonance imaging).

fMRI utilizes the intrinsic BOLD (blood oxygen level-dependent) response. The BOLD response relies upon the assumption that a brain region of high neural activity undergoes a response in which blood releases oxygen to the active neurons and thus increases the amount of detectable oxyhemoglobin and decreases detectable deoxyhemoglobin in the respective region (Ogawa & Lee, 1990). Such relative amounts of oxyhemoglobin and deoxyhemoglobin are magnetically detectable. In contrast, EEG looks for brain voltage differences with electrodes capable of measuring voltage differences and, likewise, detecting the brain's postsynaptic potentials.

fMRI has dominated neuroimaging investigations (Pflieger & Barbour, 2012) due to its superior ability to detect neural signals across brain regions. However, fMRI does not permit brain activity recordings in realistic, ecologically valid settings. An fMRI subject must instead remain immobile and isolated within essentially a large magnet. To interact with external stimuli, a subject must listen to recordings or view computer tasks on a projector screen alone (Stephens *et al*., 2010) (Montague *et al*., 2002).

Consequently, fMRI is incapable of most realistically studying natural interpersonal interaction. The most useful technique for studying human brain activity in ecologically valid settings, particularly during interpersonal interaction, is fNIRS (Noah *et al.,* 2015). fNIRS subjects essentially must wear fNIRS caps resembling swimming caps on their head to measure brain activity, thus enabling subjects to perform natural tasks such as standing up, talking, dancing, and singing.

fNIRS determines neural activity through emitting and detecting light. fNIRS contains lasers that emit light into the scalp along the 700-900 nm absorption spectrum of oxyhemoglobin and deoxyhemoglobin. Oxyhemoglobin and deoxyhemoglobin within nervous tissue then interact with the emitted light, and finally photodetectors capturing the light waves emerging from the interaction indicate relative levels of oxygenated hemoglobin and deoxygenated hemoglobin. Based upon these levels of oxyhemoglobin and deoxyhemoglobin, regions of high and low brain activity 30 mm from the surface of the head can be detected (Leon- Carrion & Leon-Dominguez, 2012) (Shimadzu Corporation, 2015).

Methods

20 healthy adults, 12 females and 8 males ranging between 18 and 29 years old, were recruited for this experiment. Subjects were primarily undergraduate or medical students.

Fliers and a Facebook post in the Yale University group, as well as mass emails to previous laboratory subjects, were utilized to recruit subjects. Two subjects were scheduled for a given time slot to form a subject pair. Each subject received 20 dollars for his/her participation in the research at the end of the study.

Subjects communicated with each other in four different conditions – speaking face-to-face, speaking occluded, text-based chatting face-to-face, and text-based chatting occluded (Figure 1). Each condition was 370 seconds long, and the order in which subjects were exposed to each condition was randomized utilizing a MatLab random number generator. During any occluded condition, a foam board separator prevented the subjects from seeing each other.

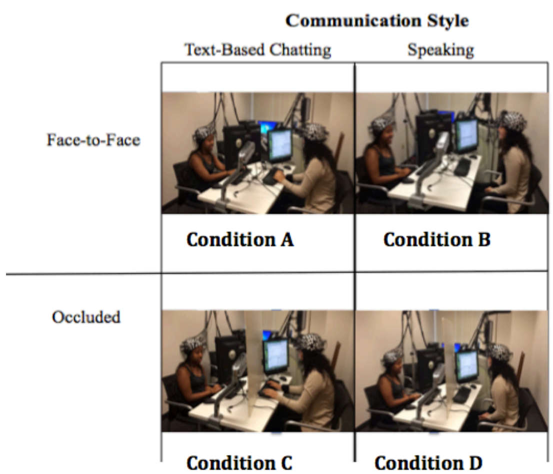

Figure 1. Experimental paradigm conditions include text-based chatting, text-based chatting occluded, speaking face-to-face, and speaking occluded. Each subject pair was exposed to each condition for six minutes. The order in which subjects were exposed to each condition was randomized. A foam board served as the occlusion during occluded conditions. During text-based conditions, subjects wore earplugs to avoid hearing the other subject's keyboard interfering with the experiment. Individuals used in graphic are laboratory assistants, not subjects. Graphic by author.

Within each of the four conditions, the dyad was randomly exposed to six different personal prompts to generate conversation. These 24 personal prompts generated by the principal investigator ranged from "talk about your siblings" to "talk about what you would have for your last meal."

One subject was instructed to discuss the personal prompt to his/her partner via typing or speaking, depending on the condition, for 30 seconds. After 30 seconds, the prompt changed black to red, or vice versa, and a beep sounded to indicate that the other subjct should first provide a response to his/her partner and then start addressing the prompt himself/herself for 30 seconds. After these 30 seconds, another prompt appeared on the screen and the original speaker again began addressing the new prompt for 30 seconds (Figure 2). The order in which subjects spoke for each of the four conditions was completely randomized via a MatLab random number generator. PsychoPi was utilized to create this program. To collect brain data during each condition, fNIRS caps were positioned on each subject's head before the experiment began.

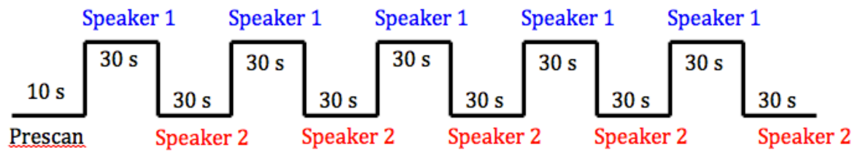

Figure 2. Design for each of the four typing or speaking conditions. The person selected as speaker 1 was randomized for each trial. Ten seconds into the condition, speaker 1 began addressing a personal prompt that appeared on the screen for 30 seconds. After 30 seconds, the listener (Speaker 2) then provided a response to his/her partner and began speaking about himself/herself in relation to the prompt for 30 seconds. The speaker change was indicated by the prompt changing color and a beep sounding. This process was repeated six additional times for 370-second total condition time. Graphic by author.

Neural signal processing was then performed by an associate research scientist, Dr. Xian Zhang, working in the laboratory responsible for performing the laboratory's data management. Finally, the resulting neural activity diagrams and cross-brain coherence graphs were created and interpreted.

Results and Discussion

A specialized neural circuitry for type-based interaction, as well as a specialized neural circuitry for in-person interaction, was identified. This suggests different neural structures are responsible for mediating different modes of communication. Furthermore, a larger distributed network of cross-brain coherence during in-person interaction was found. Interestingly, despite smaller distribution, text-based interaction involved higher cross-brain coherence in regions associated with high-level social processing.

Significant differences in the neural circuitry during face-to-face speaking, meant to model a natural conversation, versus occluded typing, meant to model a natural digital conversation, were found. Face-to-face speaking revealed higher activity in the left middle temporal gyrus, right superior temporal gyrus, right superior frontal gyrus, left superior temporal gyrus, right precuneus, and left precentral gyrus. In contrast, occluded typing revealed higher activity in the left posterior cingulate, left postcentral gyrus, right supramarginal gyrus, left precentral gyrus, and right precentral gyrus (Figure 3).

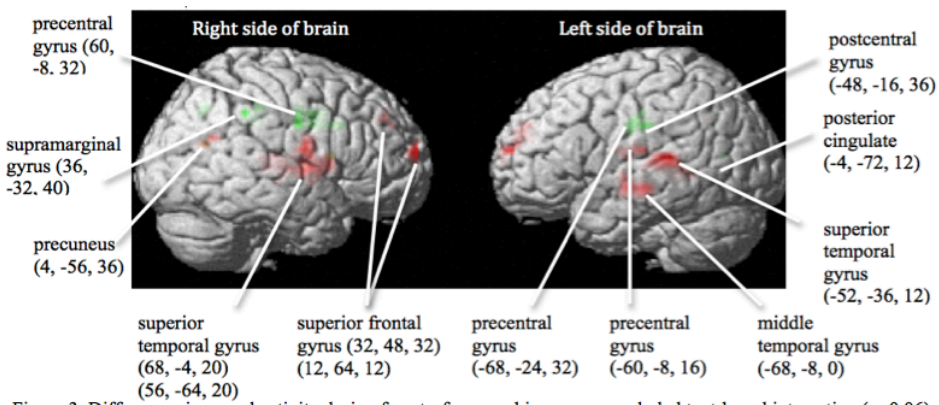

Figure 3. Differences in neural activity during face-to-face speaking versus occluded text-based interaction (p=0.06). Results reveal that during face-to-face speaking, regions of the brain (shown in red) including the left middle temporal gyrus, right superior temporal gyrus, right superior frontal gyrus, left superior temporal gyrus, right precuneus, and left precentral gyrus are more highly activated. Occluded text-based interaction activates brain regions (shown in green) including left posterior cingulate, left postcentral gyrus, right supramarginal gyrus, left precentral gyrus, and right precentral gyrus are more highly activated. The peak MNI coordinates of each brain region are provided.

Such findings suggest that both forms of communication involve voluntary movement. Face-to-face interaction increases activity in brain regions responsible for speech formation and comprehension, facial recognition, self-consciousness, and self-awareness; while texting interaction increases activity in brain regions responsible for attention, empathizing, sensory touch, and theory of mind (the ability to infer the mental states of others and one's own mental state based upon contextual associations). Hence, contrary to behavioral research that indicates that digital communication is a weak form of communication (Sherman *et al.,* 2013), high-level social interaction is processed during texting conversations.

As for cross-brain coherence, the extent to which neural signals of one individual are correlated with neural signals of the interacting partner, a striking 13 brain regions cohered more highly with one another during the speaking condition than during the texting condition. In contrast, 6 brain regions cohered more highly with one another during the texting condition than during the speaking condition (Table 1).

Table 1. Comparison of cross-brain coherence during the typing occluded and speaking face-to-face interaction ($p<0.05$). Results reveal a network of engaged brain regions between two individuals texting that is distinct from the engaged network of two individuals speaking face-to-face. For example, during text-based interaction, neural activity within the angular gyrus of one partner correlates with the neural activity within Broca's area of the other partner.

Higher Coherence During Typing Occluded Interaction	**Higher Coherence During Speaking Face-to-Face Interaction**
1. Angular gyrus, Broca 2. Angular gyrus, angular gyrus 3. Dorsolateral prefrontal cortex Brodmann's region 46, dorsolateral prefrontal cortex Brodmann's region 46 4. Dorsolateral prefrontal cortex Brodmann's region 9, fusiform gyrus 5. Dorsolateral prefrontal cortex Brodmann's region 46, fusiform gyrus 6. Broca, middle temporal gyrus	1. Angular gyrus, dorsolateral prefrontal cortex Brodmann's region 9 2. Angular gyrus, frontal pole 3. Angular gyrus, primary motor cortex 4. Dorsolateral prefrontal cortex Brodmann's region 9, dorsolateral prefrontal cortex Brodmann's region 9 5. Dorsolateral prefrontal cortex Brodmann's region 9, dorsolateral prefrontal cortex Brodmann's region 46 6. Dorsolateral prefrontal cortex Brodmann's region 9, Broca 7. Dorsolateral prefrontal cortex Brodmann's region 9, Wernicke 8. Dorsolateral prefrontal cortex Brodmann's region 9, frontal pole 9. Dorsolateral prefrontal cortex Brodmann's region 46, Wernicke 10. Dorsolateral prefrontal cortex Brodmann's region 46, superior temporal gyrus 11. Dorsolateral prefrontal cortex Brodmann's region 46, somatosensory 12. Broca, superior temporal gyrus 13. Broca, visual

These coherence results indicate that talking activated a wider array of brain regions due to the larger amount of audiovisual information communicated. However, since text-based interaction resulted in coherence within high-level social centers of the brain, texting is a high-level form of social communication utilizing inference and empathy. Similar to reading a book, an equivalent of texting, versus watching a movie about the book, an equivalent of talking, the brain must work harder to interpret from sparser sensory input.

Overall, the results suggest that texting involves high-level social processing, in which due to sparser audiovisual input the texters must form conclusions based upon inference. These texters, quite interestingly, are also able to empathize with one another more than individuals conversing in person. Although the neural network driving text-based interaction is distinct from and narrower than that of in-person interaction, texting is not necessarily less “social.” The brain’s social interpretation system actually is highly effective. Hence, the growth of digital communication within a social and professional setting, contrary to popular public outcry that digital communication is “destroying the generation,” may actually yield positive outcomes.

When looking to communicate direct information necessitating specific audiovisual cues, in-person interaction should be utilized. However, when looking to drive a strong internal reaction from the communicating partner, text-based interaction should be considered.

This research is the first to show how neural activity and brain-to-brain interaction differ during spoken interaction and digital interaction, thus providing a glimpse into the neural and social impacts of an increasingly digital world.

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