Frontal Brainwave Synchrony Between Hemispheres: A Function of Visual Semantic Categorization

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Introduction

As a byproduct of neural activity, the human brain emits electric waves of different frequencies; colloquially, these are referred to as brainwaves. These waves are tiny in magnitude and are emitted from all activated neural tissue (Campbell et al., 2009). However, due to their low power, only the waves emitted from the surface of the cortex are detectable, and then only by very sensitive equipment. Brainwaves are able to tell researchers a great deal about the cellular working of the brain because they correspond directly to activity of the cortex, as confirmed through the use of imaging technology (Freeman, Ahlfors, &Menon, 2009). When this information is combined with concurrently measured behavioral data, researchers are able to draw correlations between the location of the activity, the electrical response detected, and the behaviors displayed.

Using this information, science has begun to decode brainwaves. Different frequencies relate to different cognitive processes: certain frequency bands correspond to excitatory activation while others correspond to inhibition (Klimesch, Sauseng, &Hanslmayr, 2007). The same frequency band could contain both evoked (time locked to an event, meaning the relation of the event to the activity is fixed) or invoked (not time locked to an event) activity during the same trial (David, Kilner, & Friston, 2006; Herrmann, Frund, & Lenz, 2009). Despite some conflicting findings, neuroscientists have begun to formulate theories about the cognitive function of brainwaves within specific frequency bands.

Frequency Bands

Brainwaves span a spectrum of frequencies, ranging from 0.1Hz to possibly well over 100Hz (Chawla, Gupta, &Sengar, 2004; Kisley& Cornwell, 2006; Pockett, Bold, & Freeman, 2009). By long convention, there are five bands of human brain activity: the delta band, the theta band, the alpha band, the beta band, and the gamma band. Three of the bands have been reliably shown to be related to higher level cognitive processes: theta, alpha, and gamma (Ward, 2003; Basar et al., 2001).While the general ranges of the frequency bands are accepted by researchers, the exact ranges have not been agreed upon. This lack of agreement is demonstrated by the fact that many researchers choose their own upper and lower values to define the bands, which sometimes overlap the definitions of other researchers (Yeung et al., 2006; Kirmizi-Alsan et al., 2006; Coan& Allen, 2003). This disagreement is further complicated by the fact that some researchers use whole numbers to define bands while others use decimal values, while still others split their defined bands into sub-bands (Klimesch, Sauseng, &Hanslmayr, 2007; Freunberger et al., 2008). The theta frequency band, which is typically defined as the band of activity between 4Hz and 8Hz, is known to be indicitave of inhibitory processes, such as selective attention (Basar et al., 2001). Kirmizi-Alsan et al. (2006) demonstrated that higher theta amplitudes were elicited by a Go/No-Go paradigm task rather than a continuous attention task. In particular, this increase in amplitude was discovered during the no-go trials, which relied on the participants inhibiting their response. Theta waves were displayed particularly strongly in ipsilateral (same hemisphere) portions of the brain not directly related to the task, and in the contralateral (opposite) hemisphere (Freunberger et al., 2008).

The theta band is also involved in memory and recall, particularly short term, or working, memory (Ward, 2003). Theta band's role in working memory may possibly be connected to its aforementioned role in short term attention. In a study of the Wechsler Adult Intelligence Scale (WAIS) and related EEG activity, theta activity was found to correlate most strongly with working memory tasks (Polunina & Davydov, 2006). During a working memory task for language, the left frontal and temporal lobe was most active; similarly, during a task for spatial reasoning the right frontal and temporal lobe was active. This finding suggests that groups of task-specific neurons hold information for short term storage by oscillating at theta frequency (between 4Hz and 8Hz), and that such activity is an important part of memory storage and recall.

The alpha frequency band, which isdefined by Coan and Allen (2003) as the waves in the range of 8Hz to 15Hz, is also believed to be a sign of inhibitory activity; however, alpha waves tend to represent slightly different inhibitive activity than theta waves. Klimesch, Sauseng, and Hanslmayr (2007) have proposed the inhibition-timing hypothesis to explain the purpose of the activity that produces brainwaves in the alpha band. According to the hypothesis, neurons in all lobes constantly put out a small but steady alpha rhythm, which keeps neurons across the entire brain in a state of perpetual readiness to activate. When a portion of the brain is activated, the alpha rhythms in that focal section de-synchronize their rhythm with the rest of the brain. At the same time, task irrelevant areas and areas immediately surrounding the activating portion increase the amplitude of their alpha rhythms while remaining synchronized. An activation pattern such as this would indicate that not only does the alpha band represent inhibitive activity, but that alpha rhythms might be essential to maintain. The inhibition timing hypothesis has been supported in subsequent research. Freunberger et al. (2008) have shown that a sharp positive increase in alpha band activity known as the P1 was stronger in ipsilateral, task-irrelevant portions of the brain than it was in contralateral, task-relevant portions. This could possibly indicate that cells producing alpha frequencies had a role in suppressing activity in areas near the activated site that were not directly related to the task, rather than suppressing activity in task relevant, un-stimulated portions of the brain.

Gamma waves are the most recently discovered frequency band of brainwaves that have been found to reliably correlate with mental activity (Chawla, Gupta, &Sengar, 2004); as a result, there has been a massive amount of research conducted on gamma activity in recent years. Gamma waves are generally defined as being waves with a frequency greater than 30Hz. Research has established that waves in the gamma band are associated with cross modal sensory processing, which is processing responsible for combining information from two or more senses (Kisley& Cornwell, 2006; Nieuwenhuis, Yeung, &

*This author wrote the paper as a senior thesis under the direction of Dr. Robert Glassman.

Cohen, 2004). A study performed by Kanayama, Sato, and Ohira (2007) measured brainwaves during a task involving the rubber hand illusion, an effect that demonstrates cross modality. The rubber hand illusion leads the participant to believe that they have tactile sensation of what they watch happening to a fake hand placed in front of them. This study discovered a high amount of synchronized gamma activity across multiple sites when a similar stimulus was applied to the same location on the real hand as on the rubber hand, at the same time. The gamma response could be decreased by altering the distance between the touch location on the real hand and on the rubber hand, or by altering the latency of the touches, confirming that there is a relationship between cross-modal processing and gamma band activity. Gamma band activity has also been found to be related to memory matching (Herrmann, Frund, & Lenz, 2009). Herrmann et al. (2004) found that evoked gamma activity was highest when a stimulus picture matched a target in short term memory. A subsequent test revealed that this effect holds for long term memory as well: line drawings of real objects elicit more of an induced gamma response than distorted pictures of the same object. In other words, a larger gamma response was elicited when the stimulus successfully matched a preexisting schema in long term memory. This finding remains even when the stimulus is visually complex or altered (Martinovic et al., 2008). Together, these two categories of findings (gamma band activity in cross modal processing, and in memory matching) indicate the importance of gamma in combining different brain processes to achieve a single cognition. This theory is supported by research on schizophrenic patients, who display a significantly lower level of gamma activity than do normal people, further illustrating the importance of gamma activity in the proper organization of brain processes (Slewa-Younan et al., 2001).

There is also evidence of the importance of the different bands of activity working in tandem. A study on cognitive decline in healthy elderly individuals and patients with mild cognitive impairment, or MCI, showed that an abnormal ratio of theta to gamma band activity correlated with a significant negative effect on performance of a memory task (Moretti et al., 2009). If participants displayed increased theta activity peak amplitudes and decreased gamma peak amplitudes during memory recall task, they typically performed poorly on the task. Only the combined effect of the two bands affected memory performance; there was no significant main effect of either band by itself. Even within participants with MCI, a high theta to gamma ratio was able to correlated with strong participant memory performance. Other research has found that the interaction of alpha and theta action has an effect on intentional memory. Molle et al. (2002) found that an increase in frontal lobe theta synchrony occuring at the same time as a decrease in alpha synchrony in the temporal and parietal lobes correlates with a subject's increased ability to recall word items in a memory task, indicating that an interaction between activity in the alpha band and the theta band may be key for forming new memories or encoding stimli for later successful recall. This type of interaction between different bands of activity may be key to understanding proper neural functioning, and to understanding what is happening when the brain is not functioning correctly.

EEG Measurements

Traditionally, EEG readings have been taken from many points on the head at a single time, and activity detected in one site was measured against many other sites. Many researchers look at the amplitude of the waves and the changes in the amplitude across different sites. It is believed that amplitude changes correspond with activity: the higher the increase in amplitude in a given band relative to the baseline, the more activity(Nunez & Srinivasan, 2006).

A popular method for detecting changes in the EEG record is known as event related potentials, or ERP. ERP is typically done by measuring the baseline of activation, defined as the period of time directly before an event, such as the presentation of stimuli, and comparing it to activity immediately after the event. Typically, these measurements are averaged across dozens or sometimes hundreds of trials from the same electrode, resulting in a clear representation of positive and negative changes in amplitude relative to an event. Using this method, researchers are able identify consistent positive and negative peaks in amplitude that are time-locked to the event being researched.

ERP has been able to tell us much about the processing of the brain, particularly during tasks involving perception and rapid decision making. For example, during an ERP analysis of a selective attention task, researchers found that induced gamma band activity is not affected by the complexity of an unattended background object, but by the familiarity of the stimulus presented (Martinovic et al., 2008). The importance of this finding is that it illustrates the top-down nature of gamma-band activity. Rather than being the result of perceptual processes which happen early after event onset, the finding indicates that gamma activity is more likely to occur during object interpretation, which is the period of time after perceptual processes have occurred. In other words, the activity that produces gamma waves is later relative to the presentation stimulus, which is typically indicative of higher level cognitive processing of sensory information. This finding supports a growing body of evidence which suggests that the role of activity in the gamma band is to combine different cognitive processes in order to form a single higher level behavior (Kisley & Cornwell, 2006). This theory has been supported by research on patients diagnosed with schizophrenia, the pathology of which includes the inability to integrate and comprehend distinct neural processes. Ferrarelli et al. (2008) studied the effect of transcranial magnetic stimulation on people diagnosed with schizophrenia. Using ERP analysis, they found that patients diagnosed with schizophrenia consistently showed a significantly weaker and slower gamma response to stimulation than did control subjects. ERPresearch has been instrumental in classifying activity in different frequency bands and understanding the cognitive processes they correlate with.

The processes involved in object identification and decision making based on the identification have also been examined using ERP methodology. Research has shown a relationship between the time at which a gamma-band response was recorded and the response speed of a subject on a decision making task (Martinovic, Gruber, & Muller, 2007). The researchers found that for the rarer of the two available responses, there was a trade-off between the speed of the reaction and the accuracy of the response; this delay also correlated to the timing of the evoked gamma activity. While the authors focused on the more common of the two decisions, the significant effect for the rarer decision might indicate that both the later onset of the gamma band activity and the longer reaction times for the rarer of the options were collectively the result of the participants' speed of classifying and deciding on the appropriate reaction. In other words, the gamma band response discovered after the initial evoked response might indeed be related to decision making cognitive processes.

Recently, however, the ERP methodology has come under fire (Yeung et al., 2006). ERP analysis is only concerned with the time surrounding the event, and assumes that oscillations found during other points in the continuous EEG are random and therefore inconsequential. This window of time is sometimes too small to track any changes of brainwaves rhythms in the time surrounding the event epoch. Additionally, the averaging of multiple trials together loses oscillation differences found between trials. In other words, brainwave oscillations are averaged out during analysis because they are assumed to be noise that is not related with the epoch of time in which the ERP researchers are interested.

However, new research has found that the patterns of oscillations found in the continuous EEG are not random at all. The relative degree of synchronized oscillations of neurons, matching their activity rhythmically across different loosely related structures, may be one of the most important and reliable indicators of combinations of neural activity and communication across brain regions. The purpose of studying synchrony is to discover whether the synchronization of neural oscillations within a single band results purely from chance, or whether synchrony has a functional role to play in the working of the brain.

Studies suggest that the action of synchronization may be essential for the basic functioning of the nervous system. A review of Vida et al. and Bartos et al. (as cited in Fries, 2009) attributes synchronization in the gamma band to the activity of a group of interneurons known as basket cells, which are inhibitive cells connected with other basket cells and with excitatory neurons. When one of the basket cells fires in response to increased excitatory activation in the surrounding network, it passes its inhibition activity onto other basket cells within close proximity. The inhibitive effect of the signal on the basket cells diminishes simultaneously, causing those cells to fire all at once and spread the inhibition signal to subsequent neighboring cells. Rapidly, this inhibitory signal spreads throughout the entire local network within only a few repetitions of the cycle; this effectively dampens the activation of the excitatory cells in a rhythmic pattern, causing them to fire in synchrony. Knowing that potentials remain in synapses for only a very short amount of time, and knowing that it takes a significant change in charge to fire a post-synaptic neuron (Breedlove, Rosenzweig, & Watson, 2007), the proposed function of the synchronization of potentiation allows the post-synaptic neurons to receive a temporal summation of potentials. Rather than relying on a group of potentials to arrive at the same time by chance, synchronization allows the post-synaptic neuron to receive a summation of the activity that preceded it. In other words, excitatory activity arrives at its post-synaptic destination in time with other potentials, allowing the potentials to be maximally effective. This finding is supported by research which has shown that activity connected to perceptual systems gradually increases and remains at an increased level until a response has been made, indicating that synchronized activity may be essential for certain cognitive processes (Heekeren, Marrett, & Ungerleider, 2008).

Studies of different neural processes and different bands of activity have shown a positive correlation between synchrony and improved neurological function. For example, in a study of the reaction speed of first time schizophrenic patients, Symond, Gordon, and Williams (2005) discovered that control participants had relatively stable degree of frontal gamma synchrony for about 100ms after the stimulus was presented, which decreased during neural processing and then returned to baseline as the participant responded. By contrast, the schizophrenic participants had a significantly lower level of frontal gamma synchronization during the 100ms following stimulus onset, and recorded slower reaction speeds; even though synchronized gamma activity of the schizophrenic participants actually increased to the same level as controls during the time in which the participant responded, after the response period synchrony returned to a lower baseline than the controls. These findings suggest that poorly synchronized gamma band activity might be responsible for both the poor performance on the task and the cognitive dysfunction associated with schizophrenia.

There is evidence also that increased synchronized activity in the brain is important for maximal cognitive ability, and may play a significant role in intelligence (Grabner, Stern, & Neubauer, 2003). Taxi drivers with higher IQs had a significantly lower alpha de-synchronization ratio during a reasoning test than did the low IQ drivers, and also performed significantly better. The difference was particularly salient in the right frontal lobe. To contrast this finding, during a map test both IQ groups had similar levels of de-synchronization and performance. This finding suggeststhat the degree to which cortical activity in the brain is synchronized and the ability of the brain to maintain that synchrony during periods of activity could be directly correlated with intelligence, rather than expertise at a task.

In a related study, music expertise was shown to have a direct effect on the degree of synchronization across structures, particularly the left frontal lobe in musicians, during a mental rotation task (Bhattacharya et al., 2001). Similar to the taxi drivers' expertise task, there was no reported difference between groups in successful performance on the mental rotation task. However, musicians who had mastered their instruments displayed a significantly higherdegree of oscillation synchrony during the mental rotation as well as during a baseline sample when compared to the control group. If a degree of musical mastery could be interpreted as an increase in cognitive ability, then this finding would indicate a strong positive association between cognitive ability and synchronization across the entire cortex.

Synchrony across different structures is often measured with respect to frequency of brainwaves rather than phase. Phase refers to timing of the oscillations in the signal; oscillation phase typically is affected by a small lag time as an electrical pattern travels from one portion of the brain to the other (Plewnia et al., 2008). In synchrony while there is much focus on the similarities of signal phase across different sites, an underlying assumption of brainwave synchrony research is that there are similarities in the frequency of the oscillations (Ward, 2003; Yeung et al., 2004). Without similarity in the distribution of frequencies, there would be no point in studying similarities in phase.

Current Research

The purpose of the current research was to discover whether there is a relationship between higher cognitive processes and changes in synchrony of gamma, alpha and theta waves, between the hemispheres of the frontal lobe. Subjects participated in a timed Go/No-Go decision task based on semantic categorization of visual stimuli. Semantic categorization is a higher level processing task that involves visual processes as well as memory matching and recall (Gruber et al., 2008); typically, there is little gender difference in performance on this task (Cameron, Wambaugh, & Mauszycki, 2008). Research has shown that activity in the frontal lobe correlates with decision making processes (Breedlove, Rosenzweig, & Watson, 2007). Various studies have shown differences in activation and synchronization across the hemispheres of the frontal lobe during decision tasks across all bands of interest, particularly with tasks involving visual stimuli. The current study used a Go/No-Go task, which has been shown to reliably increase de-synchronization in the theta band (Kirmizi-Alsan et al., 2006), as well as evoke amplitude changes in the gamma band (Katsumata et al., 2009).

This research focused on the gamma, alpha, and theta bands of activity. It was hypothesized that there would besignificant differences in the degree of synchrony within each of these bands between response conditions (Bhattacharya et al., 2001; Grabner, Stern, & Neubauer, 2003; Symond, Gordon, & Williams, 2005). During the No-Go trials, theta and alpha synchrony was expected to decrease relative to baseline, as parts of the brain are unilaterally activated to inhibit a response; little to no change in the degree of synchrony was expected in the gamma band. During the Go trials, gamma synchronization was expected to decrease relative to baseline during the time the participant translateda decision into motor action. Therefore, a Go response should correspond to a lower degree of gamma synchrony and a higher degree of synchrony in the alpha and theta bands. Conversely, a No-Go response should correspond with a higher degree of synchrony in the gamma band, but lower in the alpha and theta bands.

Methods

Participants

Participants were recruited from Professor Robert Glassman's psychology classes during the spring semester of 2010 at Lake Forest College, IL. All participants were undergraduate students, and ranged in age from 19 to 35. An equal number of males and females were sought. With the exception of one of the classes, all participants were given a brief in-class presentation on the basics of EEG study and brainwave analysis before being asked to sign up to participate at their convenience. Subjects were rewarded with extra credit in the course as well as candy after their participation. To avoid familiarity, only individuals who had never participated in previous research with the Neuroscience lab were eligible.

Setting

All testing was performed in the Lake Forest College Beta BetaBeta study lounge. During a previous investigation, it was found that the room presented no electrical interferenceeven with the lights on,including 60Hz buzz,when all EEG equipment was battery powered,. The room was well lit with fluorescent lighting. An experimenter was present at all times during the study. Subjects were seated comfortably in a chair at a table in front of the laptop computer, an arms-length away.

Materials

All testing was performed on Lenovo laptop computer with a USB mouse attached. Data was collected using a custom made program which was written in National Instruments LabVIEW (version 8.6). The program was designed to keep a minimum of items on the screen during runs (see Figure 1.). The only items on the screen during the testing were: instructions, a large grey box in the center, two labeled buttons underneath the box (one to indicate readiness, the other labeled "Click!"), a box containing participants most recent reaction speed, and a small feedback box, which would indicate to the participants whether the response was correctly or incorrectly.

The stimulus pictures were selected at random from a group of ten photographs of real objects, sized 400x400 pixels; five of the pictures were of animate objects and five were of inanimate objects. The selected picture was displayed prominently in the center of the screen in a large grey box. The five animate objects were: a buck, a puppy, lichen growing on a tree, bacteria, and a purple flower. The five inanimate objects were: an open book, a crashing ocean wave, a hot air balloon, a sailboat, and a desktop computer. The subject of the picture was obvious, clearly visible and identifiable.

EEG Recording

Data was recorded from two points on the scalp, over the frontal lobe, using a differential recording technique. TheEEG recording happened concurrently with the behavioral recording. Electrodes were Ag/AgCl electrodes, 3cm in diameter, covered in conductive adhesive. These were single use, and were discarded after each subject. The active recording sites were points F3 and F4 according to the International 10-20 System of electrode placement. The passive sites were electrodes attached to the earlobes. The central reference for differential recording was attached to the tip of the nose. The signals were amplified x1000 on the respective sides using a pair of Grass Technology EEG amplifiers powered by two 9v batteries. The EEG was recorded in two channels along with the behavioral data using a program designed in National Instruments LabVIEW (version 8.6). The program had a sampling rate of 1000/second.

Procedure

Volunteers were given a consent form to sign whichoutlined the purpose of the experiment and gave the subject instructions on how to perform it and what to expect. After consenting, subjects were brought into the testing room. Subjects were seated in a chair with a backrest; subjects were asked to let down hair and remove earrings or nose rings. Using a tape measure, experimenters measured the surface distance of subject's head from the inion to the nasion over the top of the head and around the side, over the ears. Using these coordinates, the locations of the active recording sites were calculated. The sites were scrubbed with a small cotton pad soaked in rubbing alcohol, and dried with a rough tissue to gently exfoliate the skin, which would increase contact quality. Electrodes were then placed over the sites and the leads attached. The leads were held in place with the use of elastic surgical tubing or with a clean rag tied around the site, which would decrease the chances of errant recordings resulting from a "loose" electrode (one that did not have sufficient contact with the skin). The cleaning and exfoliating process was repeated with the indifferent and the ground sites; these leads were held in place through the use of masking tape.

As the electrodes were being attached, subjects were given a two page, ten item questionnaire. The questionnaire contained only two items of interest: a question regarding the handedness of the subject, and a question about head trauma within the period of a month prior to testing. Both of these were exclusion criteria, as both left-handedness and head trauma such as concussions have been shown to be correlated with irregular EEG rhythms (Pointinger et al., 2002).No data were omitted due to the exclusion criteria. All other questions were distraction items, with the exception of the descriptive variables of age and gender.

During setup the experimental procedure was explained to the participants, and they were encouraged to ask any questions related to the study. Subjects were asked to refrain from movement as much as possible because it would cause artifacts in their data, and rest after the completion of one trial to allow their brainwaves to return to baselinebefore pressing the ready button to begin the next trial. When the subject indicated that they understood all instructions, the laptop was unplugged from the wall, the amplifiers were connected to the computer, and the program was started. Subjects were given an opportunity to see a live display of their brainwaves before the task began.

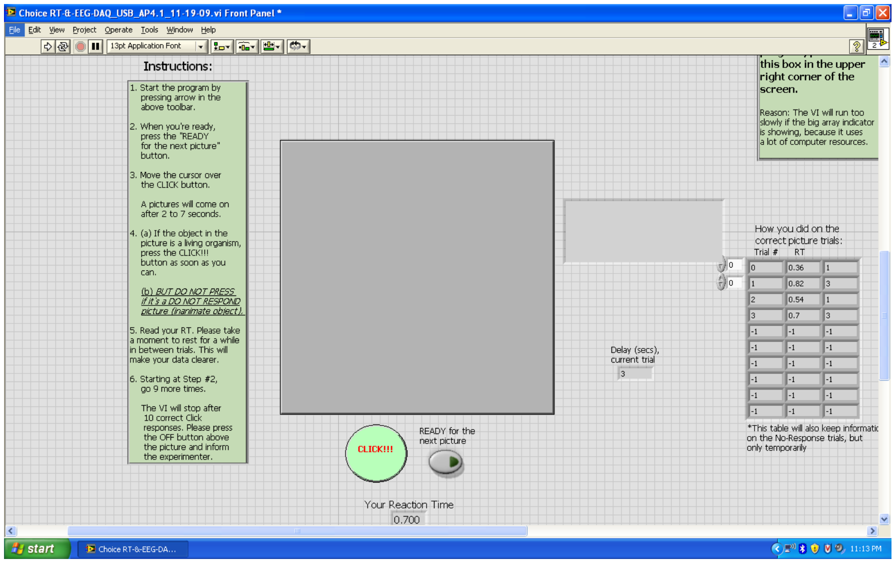

Figure 1: Data Acquisition Program Layout

The design of the task was a Go/No-Go timed reaction task based on categorizingvisual stimuli into living or non-living categories. Participants were informed that the experiment involved simple decision making, and that their reaction time would be recorded along with their response. Subjects were instructed to look at the picture and decide as quickly as possible whether the picture featured a living object or an inanimate object. If the object was living, they would have to click the mouse as fast as possible, and if the object was inanimate, they would do nothing.

Using the mouse, the subject would click a button (the ready button) on the screen to indicate readiness, and then would move the pointer to a second, larger button, labeled "Click!" (the target button) and await stimulus presentation. Betweenthe ready-button press and the stimulus onset, subjects would wait for a random intervalof between 2 and 7 seconds. The purpose of the interval was to encourage the subject to pay attention, as a variable stimulus onset would require more sustained focus than an expected one. After the interval period, a random stimulus picture would appear over the grey box in the middle of the screen. If they identified the object as animate, they had to click on the target button before the picture disappeared; if they identified the object as inanimate, they were to do nothing. The stimulus would disappear after one second, or when the subject clicked the target button, whichever happened first.

After the stimulus picture was hidden, participants were instructed to take a small amount of time (the suggested interval was three to five seconds) before clicking on the ready button again and beginning the next trial. Subjects were instructed to remain as still as possible from the time they clicked the ready button until a few seconds after the stimulus presentation. Participants who moved consistently during trials were reminded to remain as still as possible.

A single run lasted until the participant had correctly responded to a total of ten Go trials. There was no limit on the number of No-Go trials that a subject could be exposed to; however, these varied randomly around an average of about 10. Incorrect negative responses (failure to click during a Go trial) were not counted towards the total. After a test, the experimenter would reset the program and a second run began. Subjects were asked to perform a total of five complete runs.

After the experiment was completed, the subjects had the electrodes carefully removed using a cotton pad soaked in rubbing alcohol to release the adhesive from the skin and hair. They were given a debriefing sheet, and were asked if they would like to see their brain waves. Subjects who did not wish to see them were offered a reward in the form of sweets and/or extra credit in Professor Glassman's course, and were thanked for their participation and patience. Those who wished see their brainwaves were led into the adjacent room, where they were shown the analysis program running the analysis of one of their EEG and behavioral files. Subjects were given a brief demonstration of how the researchers would be using the program to investigate their brainwaves, and were encouraged to ask any questions that they might have.

EEG Analysis

Data on event related synchronywas analyzed in a novel way that applied some of the methodology of ERP analysis to the synchrony analysis on the level of a single trial. One second long segments, also called snippets, of activity in each channel during different times and conditions were compared against each other. The segments corresponded to: event related activity (ERA), which was defined as the one second period of time after the presentation of the stimulus; and baseline activity, which was defined as the one second period of time occurring 1.5 seconds after the participant indicated readiness. The purpose of using second long segments of the record was to capture the de-synchronizing activity evoked by the event, while trying to avoid the recording activity after the oscillation synchrony had reset (Yeung, Bogacz, Holroyd, & Cohen, 2004). This method focused on any changes immediately following the event by comparing the degree of synchrony in the ERA to the degree of synchrony at baseline at the individual trial level. Using segments only one second long would prevent the measurement of the synchrony changes from baseline to ERA to being contaminated by any oscillations recorded after the ERA that have reset to baseline synchrony. Research has shown that differences exist between activity immediately following a decision-making event and activity 400ms after task relevant changes in amplitude, with the latter activity resembling baseline measurements (Ratcliff, Philiastides, &Sajda, 2009). The current method should allow experimenters to find changes in oscillation synchrony on a trial-by-trial basis that may be undetected by researchers using epochs of data longer than a second. Additionally, by using a unique baseline for each trial rather than a single common baseline, data would be largely immune to contamination due to state differences that may occur during the experiment. This would eliminate many confounding variables that could otherwise influence data: examples include changes in environment, changes in subject's mood and temperament, task mastery, boredom, or fatigue.

Data analysis was performed using a custom-made program developed in National Instruments LabVIEW (version 8.6). Trials in which the baseline snippet overlapped the beginning of the ERA were discarded. Trials containing movement artifacts (eye blinks, facial movement, etc.) were identified on the display of the continuous EEG and discarded. Trials were marked as containing artifacts if the positive peak to negative peak amplitude of the trial exceeded 100μV, a method similar to one used by Garcia-Garciaet al.(2010). Trials in the first run were not analyzed, as participants typically reported needing a few repetitions to become used to the procedure. The snippets of EEG were further classified as being either correct positive (pictures in which the participant correctly chose to click on a stimulus within the time frame) or correct negatives (pictures in which the participant correctly chose to do nothing). Only trials in which the participant responded correctly were included.

Synchrony Measurement
Synchrony between the two hemispheres of the frontal lobe was calculated based on the similarity between the signals recorded from each side of the head. Signal similarity was calculated using a measurement called signal coherence, also called coherence, which has been used in previous research to determine the degree of synchronization between two different EEG recording sites (Delorme & Makeig, 2004; Weiss & Rappelsberger, 2000; Bressler & Coppolat, 1993). The higher the coherence value for the two signals, the stronger the frequencies of the signals are correlated. The coherence measurement that was used in data analysis reflected the coherence of the signal between the two sites. Prior to calculation of the coherence, the snippets were filtered with a digital bandpass filter, set to different values for each band of interest (gamma: 30-100Hz; alpha: 8-15Hz; theta: 4-8Hz). The filter was applied to each unfiltered snippet to separate one band of interest at a time from the rest of the signal.

The coherence between the two channels in the filtered EEG snippets was calculated using a signal coherence function built into the analysis program. The formula was built using LabVIEW Spectral Analysis VIs, and was similar to the EEG coherence functions described by Plewnia, et al., (2008) and Serrien(2008):

$$Coherence(f)XY = \frac{\{Cross\ Power\ Spectrum(f)XY\}^2}{\{Auto\ Spectrum(f)X\} * \{Auto\ Spectrum\ (f)Y\}}$$

Cross Power Spectrum of signals X and Y was calculated with the following formula:

$$Cross\ Power\ Spectrum(f)XY = \frac{FFT(X) * FFT(Y)}{N^2}$$

where N represents the length of the input signals, or number of samples in the signal (National Instruments, 2009). The auto-spectrum of the signals was calculated with the following formula:

$$Auto\ Spectrum(f)X = \frac{\{FFT(X)^*\} * \{FFT(X)\}}{n^2}$$

where n represents the number of points in the signal and FFT(X)* represents the complex conjugate of the Fast Fourier Transform of the signal(National Instruments, 2009). The coherence formula used measures only the similarities in the frequency spectrum; differences in signal phase did not affect the coherence values. These values, representing the "synchrony" of the signals in the right and the left sites, were entered into SPSS for data analysis. They were classified according to the frequency band analyzed, the trial condition (Go or No-Go) and time relative to the event (baseline or ERA).

Results

Behavioral
A total of seven white and Hispanic individuals (two male) participated in the study. One participant (female) was removed from the data pool due to an error during the experiment setup on the part of the experimenter, leaving the final data pool at six. A second female was dismissed before the experiment setup due to difficulty attaching electrodes due to hair implants. The mean age of the sample was 23.1 (SD=5.53).

All trials that did not meet the elimination criteria were included in analysis. Out of a possible 80 trials for each subject, each subject had an average of 43 trials included (SD= 12.9). Across all subjects, a total of 259 trials were analyzed; 143 trials (55.2%) were Go trials. The mean reaction time for all participants' Go trials was .435 seconds (SD=0.07). An ANOVA of all Go trial pictures and reaction time showed no effect for stimulus on reaction time. An ANOVA of the pictures and the coherence values showed no significant main effects of picture on coherence, and no interaction effect between bands of activity for either condition or stimulus picture.

EEG
The coherence value for each test was averaged together for each band during baseline and during ERA for each participant separately. A paired sample t-test on mean coherence showed that response condition had a significant effect on the degree of signal coherence in the ERA snippets (see Figure 2).

Coherence decreased significantly during the No-Go trials in the theta (t_5= 2.603, p=.048) and alpha (t_5= 2.727, p=.041) bands. Coherence did not significantly change in the gamma band between the trial conditions(see Table 1).There was no significant difference between baseline coherence for any of the bands.

A second paired samples t-test showed a significant change in the mean coherence between baseline and ERA snippets during the No-Go trials (see Figure 3.). Coherence significantly increased from baseline to ERA in the gamma band (t_5= 3.585, p=.016), the theta band (t_5= 3.58, p=.016) and the alpha band (t_5= 2.567, p=0.05). No significant differences were found between the means of the baseline coherence and ERA coherence in the Go trials (see Table 2).

Table 1: Paired Samples t-Test Between Positive and Negative Event Related Mean Coherence.

	Mean	N	Std. Deviation	Difference	Std. Error Difference	t	Sig. (2-tailed)
Gamma ERA,Go trials	.7142	6	.0388	.0123	.0105	1.174	293
Gamma ERA, No-Go trials	.7019	6	.0312				
Theta ERA, Go trials	.8453	6	.0436	.0274	.0103	*2.603	048
Theta ERA, No-Go trials	.8179	6	.0284				
Alpha ERA, Go trials	.8434	6	.0438	.0278	.0102	*2.727	.041
Alpha ERA, No-Go trials	.8156	6	.0289				

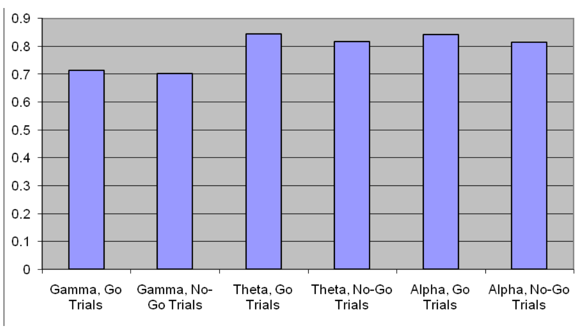

Figure 2: Mean Event Related Coherence by Band and Condition.

Discussion

In the present study, the degree of synchrony between the hemispheres of the frontal lobe during a simple decision making task was measured. There were two primary findings. The first finding was a significant increase of synchrony in the Go trials relative the No-Go trials in the alpha and theta bands, but not in the gamma band. The second finding was an increase in the degree of synchrony from the baseline to the event related activity (ERA) in only the No-Go condition for all three bands tested.

First Finding

The first finding was partially consistent with the hypothesis that alpha and theta synchrony would decrease during the No-Go trials relative to the Go trials, and that gamma synchrony would decrease during the Go trials relative to the No-Go trials. The observed changes supported the hypothesis for alpha and theta bands: synchrony decreased during the No-Go trials. This might be indicative of inhibitive activity in one hemisphere increasing unilaterally in response to the task, desynchronizing the hemispheres temporarily (Coan & Allen, 2003). However, the hypothesis was not supported regarding activity in the gamma band; there was no significant change in gamma synchrony observed between trial conditions.

This finding is consistent with previous research on event related de-synchronization and the inhibitive function of activity in the alpha and the theta band. The trials that required more inhibitive activity in order to correctly prevent a response were associated with decreases in alpha and theta synchrony from baseline to event. This study was able to show a connection between successfully inhibiting a neural process and decreased synchrony between the two related regions in the alpha and theta band. These results support previous research on the inhibitive role of desynchronized activity in the alpha band (Klimesch, Sauseng, & Hanslmayr, 2006; Molnar et al., 2008) and theta band (Kirmizi-Alsana et al., 2006; Basar et al., 2001).

The lack of a significant finding of change in the synchrony of the gamma activity may be due in part to the simplicity of the task. Multiple studies have confirmed a link between high-load tasks and increased gamma band activity (Mulert et al., 2010; Posada et al., 2003). Because the task was not designed to be complex, the expected increases in gamma activity and the resulting significant decrease in synchrony during the Go trials may have been blunted by the relative ease of decision making. Had the study contained an element of problem solving or contained additional rules for responding for subjects to keep in mind, significant differences in gamma synchrony may have been observed.

Second Finding

The second finding failed to support the hypothesis that there would be an increase in synchrony during the ERA relative to the baseline in the theta and alpha bands during the No-Go trials only, and a similar decrease in the gamma band during the Go trials only. A significant increase in degree of synchrony from baseline to ERA in all bands was observed during the No-Go trials only; there was no significant effect in any band during the Go trials. The other finding, of increased synchrony in all bands from baseline to ERA during the No-Go trials, may be the result of a number of other neural processes working simultaneously. There is evidence suggesting that the theta band plays a role in memory retrieval and decision making (Jacobs et al., 2006). During a study on memory retrieval of word lists, theta amplitude increased in the left hemisphere of the brain during successful recall of words, particularly in the parietal lobe. There was a direct relation to the amount of theta power detected and the speed of recall, indicating that there is a correlation between successful memory processes and changes in theta activity. Because that retrieval task referred to words, the portion of the brain that was activated during the task was the left parietal lobe; the left hemisphere and the parietal lobe are both associated with language processing and memory (Kalat, 2009). This finding, in conjunction with previous research which has shown that activity in the theta band also corresponds to contralateral inhibition (Freunberger et al., 2008) may explain the findings of increased theta band synchrony between hemispheres during No-Go trials from baseline to ERA. Since only the later runs were analyzed in the experiment, prior to which the subject had been exposed to most of the stimulus pictures, the theta synchrony increase observed may be the result of stimulus recall as well as simultaneous decision making processes and response inhibition.

Additional evidence for the role memory may have played in the results comes from other studies on the role of theta and gamma in memory recall and stimulus classification, which may help to explain the unexpected finding of increased gamma synchrony. Gruber et al. (2008) found that when participants were exposed to the same stimuli repeatedly, degree of gamma synchrony was higher than it was for novel stimulus, a finding which may explain the increase in gamma synchrony from baseline to ERA. Theta activity was affected by the context in which the stimulus was presented and whether it had been classified correctly during previous exposure to it, suggesting that theta activity has an effect on both the conscious processing and categorization of stimuli. Other studies of memory with respect to gamma band has indicated that there is a significant correlation between synchronized gamma activity and memory processes (Ward, 2003; Herrmann et al., 2009), which may explain the increase in gamma synchrony from baseline to ERA. Taken by itself, this research does not explain the finding of increased gamma synchrony, since the response category also required memory recall. However, during the Go trials, an additional component (the translation of decision into action) was present, which may have accounted for a relative decrease in synchrony. Previous research has pointed to activity in the gamma band as being essential to motor planning (Katsumata et al., 2009), which may have generated enough “noise” to prevent oscillations in the gamma band from being significantly different.

The observed increase in alpha synchrony may have been a reflection of changes in attentional demands during the task. Each trial contained a randomly generated wait time to encourage the participants to remain focused on the screen; once the response was decided, there was no longer a need for sustained attention. Research on the role of alpha band activity in attentional processes has suggested that during a task requiring attention, alpha activity is a key component in suppressing distractions, including other neural processes, particularly during a period of anticipation (Capotosto et al., 2009). Alpha activity has been shown to decrease globally 300 to 700ms after the appearance of stimulus (Ward, 2003). Because the measurement of coherence used in the current study measured only how well the signal frequencies matched, the observed increase in alpha synchrony may have been the result of the simultaneous release of attentional alpha activity, “letting go” of neural inhibition at the same time in both hemispheres.

Methodological Concerns

Despite the promising results of the current experiment, there were a few methodological concerns that the current experiment was not able to address. The most pressing concern was the small sample size. A larger sample with an equal number of males and females would have lent statistical power to the experiment. It would also have allowed for the exploration of other differences in EEG patterns, such as gender differences, which have been suggested by previous research and remain a controversial topic (Jaušovec & Jaušovec, 2009; Gill & O'Boyle, 1997).

A second concern was the possibility of differences in cognitive strategy used for decision making. It was expected that participants’ first reaction to the presentation of stimulus was to respond, which would then be inhibited if they identified the picture as a living object. However, it is possible that some participants chose to adopt a slightly slower, more conservative cognitive strategy of observing the stimulus before categorizing and deciding to respond, in an attempt to increase the chance of a correct hit and end the experiment sooner. The instructions were given to participants in a way that would encourage a more reckless response style: participants were informed that there was no penalty for incorrect responses, they would have only a single second to respond, and the speed of their responses were being measured. This might have been prevented had the experimenter not mentioned that a run of trials would end after 10 correct go responses. A related concern about cognitive strategy concerns different strategies for scanning pictures. Because the stimulus pictures were photographs of real objects, each picture had a unique background containing different colors. There is evidence that males and females differ in their strategies of visually scanning pictures before making decisions in the same task (Adam et al., 1999). It is possible that for some participants, the task may have devolved into a task measuring the association between background color and previous response, rather than recognition of an object. A third possible variation in cognitive strategy may have been the choice to use a language based classification strategy rather than the expected visual strategy. Strategies for a cognitive task and success with that strategy can differ according to gender and major of study, as well as differences in mental state (Li & O'Boyle, 2008).

Areas of Further Research

Despite some methodological drawbacks, the findings of the current study are important to interpret and expand upon. One possible continuation of the current research would be to include phase information in the current method of investigation, in order to allow comparisons of differences in signal phase across conditions, trials and EEG segments. The equation used in the current experiment only measured the similarity between the frequency distributions of the two signals within the three defined bands. It is possible that the addition of phase information could have added a new dimension to the results. For example, allowing for differences in phase would inform experimenters whether the increase in synchronization may have been the result of an effect known as phase resetting (Yeung et al., 2004), in which the timing of the oscillations are reset following an event evoked change. An example of this is found in research on cross-modal processing and decision making (Garcia-Garcia et al., 2010) during which it was found that in a emotionally laden and stressful task, involuntary distractions had the effect of increasing phase synchrony within multiple individual gamma frequencies. Similar research in non-threatening situations has shown a similar effect of other cognitive processes, including decision making, on oscillation resetting (Ratcliff, Philiastides, & Sajda, 2009; Palva, Palva, & Kaila, 2005).

Additionally, the analysis process of the EEG data deserves to be mentioned and possibly expanded. This method represents a slight departure from the normal synchrony analysis in that it isolates specific segments of the continuous EEG that relate to the task and to a baseline taken while the subject was awaiting stimulus, similar to ERP analysis, rather than exploring epochs of activity that last for multiple seconds. However, unlike ERP analysis, this method examines the synchrony of the two signals during the baseline and the ERA for every single trial, rather than averaging them together. In this way, the unique changes in oscillation at each trial are maintained and can be analyzed across response condition and time relative to the event. Additionally, the shortened period of time being analyzed allows the experimenter to explore changes and differences in synchrony without worrying about the effect being averaged out by baseline oscillations in the seconds after the event, something which may be expected to occur with longer epochs. Both of these advantages are supported by the work of Ratcliff, Philiastides, and Sajda, (2009), who have pointed to the importance of trial by trial analysis of synchrony to understanding the working of whole networks. Finally, the finding of significant results with a relatively small number of participants suggests that this method of analysis is a statistically powerful test which can detect signal similarities within segments of the EEG.

The results of the current research lend strength to research on the importance of synchrony in the brain, particularly in response to specific events. Results of this experiment and the analysis indicate that synchrony plays a significant role in response inhibition. Future research should be performed to investigate the nature of the relationship between synchrony and successful inhibition of behaviors.

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