THESIS

PHASE-LOCKING OF GAMMA AND BETA IN AN AUDITORY EEG PARADIGM AND THEIR RELATIONSHIP TO SELF-REPORTED SENSORY SENSITIVITIES

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ABSTRACT

PHASE-LOCKING OF GAMMA AND BETA IN AN AUDITORY EEG PARADIGM AND THEIR RELATIONSHIP TO SELF-REPORTED SENSORY SENSITIVITIES

Phase-locking factor (PLF), one way to analyze electroencephalography (EEG) data, is the consistency of the brain's response in particular frequency bands to stimuli across multiple trials. Studies in the past have correlated PLF of different brainwave frequencies to behaviors; however, none have looked at the correlation to sensory sensitivities. The objective of the present study was to examine the relationship between PLF and behavioral measures in neurotypical adults. The participants were 38 neurotypical adults aged 18-25. This study involved an auditory paradigm in which three series of eight tones each were presented to the participant while he or she watched a movie. The first series presented eight tones that were identical, the second series presented a deviant tone in the 4th position with the other seven tones identical to the tones presented in the first series, and the third series had a deviant tone presented in the 5th position with the other 7 tones identical to the tones in the first series. These series of tones were presented in pseudorandom fashion while the participants' brainwaves were recorded with an EEG system. To examine the relationship between the consistency of the brain's response to these tones and sensory sensitivities, the participants filled out the Adult/Adolescent Sensory Profile (AASP). It was hypothesized that the PLF value at the onset of the first tone in the series of tones with no deviants would be greater than the subsequent tones in the same series. In the series of tones with no deviants, PLF for gamma (30-50 Hz) for tone 1 was higher than all but one of the PLF responses to subsequent tones. PLF in the beta region (18-30 Hz) in response to tone 1 was higher than the PLF response to all subsequent tones in the series with no deviants.

Some, but not all, of these findings reached significance. It was also hypothesized that PLF at the onset of a deviant tone would be greater than PLF at the onset of non-deviant tones 2-8 in the same series. For the series of tones with a deviant in the 4^{th} position, gamma increased from tone 3 to tone 4 for central electrode sites and decreased for frontal electrode sites, although none reached significance. For the series of tones with the deviant in the 5^{th} position, PLF for gamma at tone 5 was greater than at tone 4 for 4/6 electrodes. For the series of tones with a deviant in the 4^{th} position, PLF in the beta region increased from tone 4 to tone 5. For the series of tones with a deviant in the 5^{th} position, PLF in the beta region increased from tone 4 to tone 5 for half of the electrode sites. It was hypothesized that PLF in response to the first tone of a series would not be significantly different from PLF in response to a deviant tone of the same series. PLF in the gamma region did not ever significantly differ from the first tone to the deviant tone. PLF in the beta region did not significantly differ from tone 1 to tone 4 in the series of tones with the deviant in the 4^{th} position, but PLF for tone 1 was significantly higher than PLF for tone 5 for 2/6 electrode sites during the series of tones with the deviant in the 5^{th} position. Lastly, it was hypothesized that individuals who have higher PLF will demonstrate low neurological thresholds as measured by the AASP. Spearman Rho correlations revealed that nearly all significant findings found between PLF and scores on the AASP were positive correlations. Results indicated that better phase-locking in the brain correlates positively with increased sensory sensitivities, as demonstrated by the AASP. Additionally, this study supports prior research indicating that a decrease in PLF does occur from tone 1 to tone 2 when the tones are identical, but questions whether PLF reflects habituation that may occur in response to three or more of the same stimuli.

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TABLE OF CONTENTS

CHAPTER 1

Sensory Processing Disorders

Life in America today can be full of a wide variety of sensory experiences – a screaming child, music, and banging of pots and pans create a cacophony of sounds all within a single restaurant. Our vestibular systems are often rattled when a moving vehicle makes fast turns or suddenly stops. Our visual systems often take in more information than we are aware of, for example, bars with 10 different television screens playing five different shows simultaneously, and chefs everywhere attempt to please our taste buds with the latest and most creative concoctions of flavors. The sensory systems in the majority of people are able to effectively cope in these environments, but there are many who struggle. People whose everyday lives have been negatively impacted due to an inability to organize and appropriately respond to sensory input from the environment are said to have a Sensory Processing Disorder (SPD, Kranowitz, 2006).

Sensory Processing Disorder (sometimes called Sensory Integration Dysfunction and also Sensory Modulation Disorder) was first described by Jean Ayres in the 1960's (Ayres, 1969) with children. Since then, SPD has been linked to numerous other developmental disorders including autism spectrum disorders (ASD), attention deficit disorder (ADD), attention deficit hyperactivity disorder (ADHD), obsessive-compulsive disorder (OCD), and a variety of anxiety disorders (Dunn & Bennett, 2002; Hofmann & Bitran, 2007; Kern et al., 2006; Marco, Hinkley, Hill, & Nagarajan, 2011; Savage et al., 1994). SPD is often studied in children, but adults have also been described as having SPD. Kinnealey, Koenig, and Smith (2011) found significant differences between adults with Sensory Overresponsive (SOR) and those without SOR on bodily pain, general health, vitality, and social functioning. The study concluded that as SOR increases, mental health and social functioning decrease. Because SPD affects one's quality of life, it is important to better understand it in order to provide optimal treatment and care for the people affected by it.

One way to better understand many development disorders, including SPD, is to look at how brain processing is differentially affected by the diverse disorders. This is often done through the use of magnetic resonance imaging (MRI), computed tomography (CT), positron emission topography (PET), and electroencephalography (EEG). The ultimate goal of understanding the neural mechanisms behind these disorders is twofold. First, understanding deficits in brain processing can help guide what type of treatment individuals should receive. Second, EEG and other ways of measuring brain processing can help determine if the treatment is effective by examining changes at a neural level. An excellent example comes from the field of occupational therapy in research involving children with SPD. Recently, there has been a wealth of studies using EEG to show that the brains of children with SPD do not process auditory stimuli in the same manner as age-matched, typically developing children (Davies, Chang, & Gavin, 2009; Davies & Gavin, 2007; Gavin, et al., 2011). It is important to differentiate SPD when it occurs by itself or when it occurs in concurrence with other disorders because other disorders might complicate cortical responses. At this point in research, it would be better to differentiate these disorders in order to, through therapy, change cortical processing in individuals with SPD with the aim of normalizing behaviors.

An Introduction to EEG

In order to advance our knowledge about how therapy works and its effectiveness, one must be able to link behaviors to cortical activity of the brain in both typical and atypical people, and research has begun to do this. Electroencephalography (EEG), the study of brain electrical activity, is an excellent way to do this. EEG is non-invasive, relatively inexpensive, and extremely temporally accurate. When studying brain processing, temporal accuracy is important because this lets the researcher directly link any extra or abnormal activity to a specific external stimuli. EEG is, however, limited in spatial resolution, where MRI and PET scans excel. The initial set up for EEG includes placing electrodes on a person's scalp (a non-invasive process) and making a connection to the brain electrical activity through a gel conductor applied to occupy the space between the electrode and the scalp. After the data are collected, computer processing programs amplify the original signal received, then reject unwanted artifacts, such as muscle activity and external noise.

Event-Related Potentials

There are two main ways to analyze EEG recordings. A common method, one that has been used for decades, is to average and analyze specific sections of the running EEG- event-related potentials (ERPs)- which are found after an event or stimulus onset. ERPs, the brain's response to a specific stimulus, often auditory or visual, consist of several components (the building blocks of ERPs), and have been thoroughly studied and described in different populations. The letter in front of a named component denotes a positive 'P' or negative 'N' voltage sway. The number at the end of the name denotes the time after stimulus onset, measured at the peak of the named component. For example, the P300 component, well known to reflect higher thought processes, especially to novel stimuli, is a positive voltage shift roughly 300 milliseconds after the presentation of a stimulus (Stern, Ray, & Quigley, 2001). ERPs are believed to be the direct result of a fixed, specific stimulus, but recent research suggests that ERPs might be a blend of responses to stimulus and ongoing electrical brain activity (Makeig, Debener, Onton, & Delorme, 2004). This means that conclusions drawn solely from ERP analysis might not be entirely valid since ERPs are not the result of just one external variable as we make them out to be. The primary benefit of using ERPs to analyze EEG activity is the temporal accuracy of the response to the stimulus. A limitation of studying ERPs alone is that each component of an ERP is often dominated by a single frequency response of the brain. In reality, the brain responds to external stimuli with numerous frequencies, not just one, so studying specific components of ERPs oversimplifies the brain's responses (Kolev & Yordanova, 1997; Makeig et al., 2004). Another major limitation is that heightened ERP amplitude can be the result of an increase in power (a stronger response to stimulus) or an increase in consistency of frequency responses. By using ERPs alone, one does not know the source of large amplitudes, thus a second way to analyze running EEG has been developing concurrently.

Time-Frequency Analysis

Time-frequency analysis measures the brain's response to specific stimuli both across time and throughout different frequency bands (Kolev & Yordanova, 1997). A specific method of time-frequency analysis is called phase-locking factor (PLF), and looks specifically at the consistency of the brain's response to stimuli across multiple trials. One benefit of using time-frequency analysis to analyze a running EEG is that this method differentiates between the brain responding more to a stimulus (an increase in power), and the brain responding more consistently in a particular frequency to a specific stimulus (an increase in phase-locking). Roach & Mathalon (2008) describe these two events as "changes in magnitude of the rhythmic field potentials or changes in their degree of synchronization," respectively (p. 909). Another benefit of using time-frequency analysis is that we are also able to compare the synchronization either within or between spatial locations of the brain (Roach & Mathalon, 2008). Lastly, oscillations at numerous frequencies reflect many neuronal processes co-occurring in response to a single event and time-frequency analysis allows one to see this dynamic information processing simultaneously (Roach & Mathalon, 2008). Thus, in order to understand the underlying mechanism of how ERPs are formed, it is beneficial to conduct both ERP and phase-locking factor analyses (Makeig et al., 2004).

The frequency bands, from lowest to highest frequency, are delta, theta, alpha, beta, and gamma. Delta is often seen in deep sleep, theta is related to working memory functions, alpha is often evoked with any sensory stimulation, and beta and gamma are thought to be involved with higher cognitive processes (Herrmann, Crigutsch, & Busch, 2004). Gamma activity has been linked to cognitive efforts involved in learning, emotional evaluation, and attentional selection of sensory information (Engel, Fries, & Singer, 2001). Gamma-band activity 300-500 ms post auditory stimulus has also been associated with long-term memory (Lenz, Schadow, Thaerig, Busch, & Herrmann, 2007). Beta (ranging anywhere from 18-30 Hz) is thought to be involved in sensory processing, specifically related to P50 suppression (Hong, Buchanan, Thaker, Shepard, & Summerfelt, 2008) and is also involved with motor activity, increasing immediately following both real and imagined motor activity (Herrmann et al., 2004). It is not surprising that both gamma and beta are thought to play similar roles in higher cognitive processing because they are often linked temporally, with a large gamma response often preceding beta oscillations (Haenschel, Baldeweg, Croft, Whittington, & Gruzelier, 2000).

Many studies have tried to understand the role of particular frequency bands in ERP components. Very generally, slower band components such as delta and theta are thought to contribute to later-induced ERPs such as P300 (Başar-Eroglu, Başar, Demiralp, & Schürmann, 1992). More commonly studied is the association of gamma activity, often cited as 30-50 Hz, and the P50 component, with results supporting the hypothesis that the P50 is a subcomponent of the gamma band response (Clementz, Blumenfeld, & Cobb, 1997; Johannesen, Bodkins, O'Donnell, Shekhar, & Hetrick, 2008). Gamma has also been shown to have a strong response in the N100 during a visual classification task (Herrmann, Mecklinger, and Pfeifer, 1999). In addition to the preceding information regarding beta and gamma, these two frequency bands will be studied because of their associations with sensory gating auditory paradigms (Hong et al., 2004; Hong et al., 2008). Currently, no previous studies could be found that studied gamma and beta as key frequencies during orientation or habituation auditory EEG paradigms. These paradigms are discussed in depth below.

EEG Paradigms

Many EEG studies involve specifically designed paradigms for participants to engage in while their brainwaves are recorded. These paradigms allow patterns to be detected in the brainwaves of both typically and atypically developing people. There are many kinds of sensory stimuli used in these paradigms, and the current study will use auditory stimuli in the form of simple tones. Many studies have successfully developed and implemented simple auditory paradigms using this same concept. Boutros, Belger, Campbell, D'Souza, and Krystal (1999) used a “short-trains” paradigm where they presented five identical tones followed by a sixth deviant tone, each separated by 500 ms (called the interstimulus interval, or ISI). Each short train of tones was separated by eight seconds. This study concluded that people with schizophrenia have difficulty inhibiting irrelevant stimuli, as measured by the P50. Using the same auditory paradigm to study brainwaves of people with epilepsy, (Rosburg et al., 2004) found that the P50 amplitude decreased from the first to the second click, but remained stable until the last deviant click, where it rose again. Other studies have used a similar paradigm, but altered the ISI or amount of tones in a sequence (Rosburg, Zimmerer, & Huonker, 2010). The major benefit of using paradigms with multiple auditory clicks or tones is that researchers can collect data on a variety of constructs with only one paradigm.

In order to capture “multiple neural processing occurring and interacting” (Roach & Mathalon, 2008, p.908) in the brain simultaneously and the dynamic nature of time-frequency analysis, a paradigm that reflects multiple levels and types of processing is necessary. The current study will use a paradigm called the Orientation/Habituation paradigm, which reflects three types of processing in one paradigm – orientation, sensory gating, and habituation. The response to the first tone in any series is called an orienting response (Sokolov, 1963) and is based on the premise that a tone is a new stimulus in an otherwise quiet environment, thereby requiring the participant to orient to the stimulus. The response to the second tone in a series of two or more tones is considered to be a gating response (Orekhova et al., 2008). This is based on the premise that once the brain has responded to new stimulus, it no longer needs to respond to similar stimulus, thus it represses a full response (Rosburg et al., 2004). When more than two stimuli of the same accord are presented, if the brain’s response continues to decrease throughout the presentation, this is considered habituation (Fruhstorfer, Soveri, & Jarvilehto, 1970). This is beneficial in real-life applications because it allows one to concentrate on what is important (such as writing a thesis proposal) rather than focusing on incoming background information and noise (such as traffic rushing by). In this example, when one first sits down to write the paper, one may “orient” to the traffic because it is a new sound but hopefully, after some time, “habituation” occurs and the person no longer pay attention to the noisy traffic. A gating response can be shown when one is startled by the sound of a fire alarm; the first blare might be so unexpected it scares a person, but by the second blare, the brain is not as alerted by the noise. All paradigms with multiple tones in one segment, often called short-train paradigms, incorporate all of these concepts in one, similar to the Orientation-Habituation paradigm which will be used in this study.

Relating Behavior to Brainwaves

When studying the brain through EEG, the desire is to understand the basic mechanisms of how the brain responds to events, which in turn should be related to behavior. This is often referred to as the brain-behavior association. When trying to understand this association, researchers often use diagnoses because a diagnosis is often associated with specific differential behaviors that distinguish it from other diagnoses. Rourke (1975) reviewed many studies and confidently decided that cerebral dysfunction is a crucial factor that limits children with learning disabilities that display particular behavioral symptoms. Evans and Maliken (2011) used EEG to study repetitive, compulsive-like behaviors in typically developing children and linked those behaviors to faster processing of asymmetrical target stimulus in an oddball task, one that requires the participant to react in a certain way when presented with a deviant stimuli. Research has shown that children that exhibit socially deviant behavior, behavior that does not adhere to accepted social or culture norms, have no differences in EEG patterns when compared with age-matched peers (Matsuura et al., 1993). That same study found that contrary to children with socially deviant behavior, children with ADHD who display hyperactive behaviors have significantly different EEG patterns than their age-matched peers, suggesting a biological and cortical dysfunction rather than psychosocial issue.

Measures from ERPs have not been the only EEG measure to be correlated to behavior. Some studies have correlated the resulting values from time-frequency analysis with behavior as well. Hanslmayr and colleagues (2005) found that, in healthy subjects, increased pre-stimulus alpha phase-locking is associated with good perceptual performance during a visual discrimination task. Additionally, they also found that better memory performance was associated with higher power of alpha, meaning the brain had a greater response in the alpha frequencies, not better phase-locking of alpha, which would indicate a more consistent response between brain responses in the alpha frequency.

Self-Reported Assessments of Responses to Sensory Stimuli

For the context of this study, a response to sensory stimuli is the behavior of interest, thus it will be referred to as a behavioral assessment. Many different types of behavioral assessments have been developed in order to assess how people respond to or interpret incoming environmental stimuli. The current study will use the Adult/Adolescent Sensory Profile (AASP) because the EEG data were collected on a group of adults without disabilities.

The Adult/Adolescent Sensory Profile (AASP), developed to measure adults' responses to common sensory experiences, has been shown to be both reliable and valid for use in practice settings (Brown, Tollefson, Dunn, Cromwell, & Filion, 2001). The Brown et al. (2001) study found the following four reliability measures (as measured by coefficient alpha) for the subscales of the AASP (defined below): Sensation Seeking (alpha = .79), Sensory Sensitivity (alpha = .81), Sensation Avoiding (alpha = .66), and Low Registration (alpha = .82). The AASP is based on two basic premises, the first being a reflection of the individual's nervous system and the second reflecting a behavioral response. Because one of the aims of this study is to examine the brain-behavior association, the AASP is an appropriate assessment to use. The AASP's approach to including constructs of the nervous system is to describe a neurological threshold continuum. The authors describe that if a person has a low neurological threshold (NT), the nervous system will detect and react to a small amount of a stimulus, thus resulting in a heightened sensitivity (see Table 1). An example of sensitivity would be a person insisting that the TV is too loud when other members in the room can hardly hear it. In contrast, if one is able to easily habituate to sensory information, one is said to have a high neurological threshold. On the behavioral axis, one can respond in accordance to or by counteracting the designated NT. Using these premises, four quadrants have been developed: low registration (a combination of accordance with threshold and high NT), sensation seeking (counteracting threshold and high NT), sensory sensitivity (accordance with threshold and low NT), and sensation avoiding (counteracting threshold and low NT). This model is used to study both

Table 1

Relationships between behavioral responses and neurological thresholds on the AASP (adapted from Figure 1 in Dunn, 1997, p. 24)

	Behavioral Response Continuum	
Neurological Threshold Continuum	***responds in ACCORDANCE with threshold***	***responds to COUNTERACT the threshold***
HIGH (habituation)	Low Registration	Sensation Seeking
LOW (sensitization)	Sensory Sensitivity	Sensation Avoiding

typical and atypical adults and teens, attempting to categorize their behaviors in response to various stimuli. Rieke and Anderson (2009) discovered that adults with obsessive-compulsive disorders (OCD) scored higher than typical adults (from archival data) on sensory sensitivity, sensation avoiding, and low registration, but scored lower on sensation seeking.

The purpose of the current study is to examine the consistency of the typically developed adult brain's response to stimuli across multiple trials. Each individual's PLF value will then be correlated to his or her responses on the AASP in order to examine the relationship between PLF and sensory sensitivities. This study will collect baseline data from neurotypical adults in order to eventually be able to compare cortical responses of atypical adults and children. These comparisons will lead to the development of better therapy programs for populations with sensory processing disorders.

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CHAPTER 2

Our daily lives are filled with sensory experiences – riding in a car, enjoying a tasty meal in a crowded restaurant, and watching movies on big-screen TVs with loud auditory accompaniment. The human brain is typically able to take this sensory input, filter out unnecessary information, and process the important and desired stimulus. Auditory stimuli are commonly presented during brain studies because auditory stimuli are large parts of the everyday human experience and are easily replicated and controlled in a lab setting. Sokolov, Wadenfeld, Worters, & Clarke (1963) first used auditory stimulation to study alpha rhythm activity in the brain.

Specific paradigms are designed and used in EEG in order to capture and study particular aspects of brain function. The current study will use a paradigm called the Orientation/Habituation paradigm, which reflects three types of processing – orientation, sensory gating, and habituation – all in one paradigm, allowing the researchers to collect a wide variety of data. The response to the first tone in any series is called an orienting response (Sokolov, 1963) and is based on the premise that a tone is a new stimulus in an otherwise quiet environment, thereby requiring the participant to orient to the stimulus. The response to the second tone in a series of two or more tones is considered to be a gating response (Orekhova et al., 2008). This is based on the premise that once the brain has responded to new stimulus, it no longer needs to respond to similar stimulus, thus it represses a full response (Rosburg et al., 2004). When more than two stimuli of the same accord are presented, if the brain's response continues to decrease throughout the presentation, this is considered habituation (Fruhstorfer, Soveri, & Jarvilehto, 1970). There is, however, controversy in EEG literature on the definitions of gating and habituation, not only whether or not the latter exists, but if it does exist, what causes it (Boutros, Belger, Campbell, D'Souza, & Krystal, 1999; Rosburg, Zimmerer, & Huonker, 2010; Coch, Skendzel, & Neville, 2005).

EEG measures voltage changes on the scalp that are related to the underlying neural activity. It is non-invasive, relatively inexpensive, and extremely temporally accurate. Temporal accuracy is important when studying brain processing because it allows the researcher to directly link any extra brain activity to specific external stimuli. One way to understand the meaning behind any voltage changes is to examine the data via time-frequency analysis (TF). TF measures the brain's response to specific stimuli both across time and throughout different frequency bands (Kolev & Yordanova, 1997). One specific method of TF is called phase-locking factor (PLF), which looks at the consistency of the brain's response in particular frequency bands across trials.

There are many frequency bands that have been described in the literature, but this study focuses on beta (18-30 Hz) and gamma (30-80 Hz) because they are often associated with the phenomena of interest. Beta is thought to be involved in sensory processing, specifically associated with sensory gating for auditory stimulus (Hong, Buchanan, Thaker, Shepard, & Summerfelt, 2008), and gamma has been linked to cognitive efforts involved in learning, emotional evaluation, and attentional selection of sensory information (Engel, Fries, & Singer, 2001), as well as memory (Hermann & Demiralp, 2005). Additionally, beta rhythms have been thought to associate between brain regions; gamma bursts, on the contrary, tend to stay more localized to one specific location (Kopell, Ermentrout, Whittington, & Traub, 2000). Continuous brain activity involves oscillations co-occurring at numerous frequencies, reflecting multiple neuronal processes in response to a single event, and TF analysis allows one to see this dynamic information processing simultaneously. A benefit to using time-frequency analysis specifically is that this method differentiates between the brain responding more to a stimulus (an increase in power), and the brain responding more consistently at a particular frequency to a stimulus (an increase in phase-locking) (Roach & Mathalon, 2008). The reason for measuring the latter, PLF, is that poor consistency in neural responses has been associated with cognitive deficits (Roach & Mathalon, 2008). Additionally, good phase-locking is characteristic of normal development (Werkle-Bergner, Shing, Muller, Li, & Lindenberger, 2009).

It is important to note here that the definitions of orientation, sensory gating, and habituation described above are only used when measuring voltage amplitude of specific components in event-related potentials (ERPs). These phenomena have not been associated in the literature with time-frequency analysis, thus, this paper will use phrases such as "paralleling the habituation effect" due to the lack of terminology in current literature for phenomena related to phase-locking and time-frequency.

When studying the brain through EEG, the desire is to understand the basic mechanisms of how the brain responds to events, which in turn should be related to behavior. It has been well established that brain dysfunction at the cortical level is linked to a variety of developmental or behavioral problems (Rourke, 1975; Evans & Maliken, 2011; Matsuura et al., 1993). One way to better understand this brain-behavior association is to relate the findings from brain studies back to some sort of behavioral measure. The current study will use the Adult/Adolescent Sensory Profile (AASP), which was developed to measure adults' responses to common sensory experiences, and has been shown to be both reliable and valid for use in practice settings (Brown, Tollefson, Dunn, Cromwell, & Filion, 2001). The AASP is based on two basic premises, the first being a reflection of the sensitivity of the individual's nervous system and the second reflecting the behavioral response, and whether it is in accordance with or counteracting to the sensitivity of the nervous system. Questions on the AASP are sorted into six different subtests: Taste/Smell Processing, Movement Processing, Visual Processing, Touch Processing, Activity Level, and Auditory Processing. Scores from these subtests are then combined and contribute to the individual's total score on the four different quadrants (Table 1 in Chapter 1, page 10).

Having a high neurological threshold results in a person not noticing subtle changes in environmental stimuli. Contrary to this, having a low neurological threshold means that a person is extra sensitive to surrounding stimulus. On the behavioral axis, if one responds in accordance with the threshold, it means he or she does not go to any measures to prevent being in an environment that is too harsh or too bland for their taste. Contrary to this, if a person counteracts the threshold, he or she will try to control the surrounding environment in order to cater to his or her neurological needs.

Purpose

This study examines how typical adult brains respond to auditory stimuli using PLF. Additionally, this study will attempt to correlate brain processing with behavior in order to better understand the relationship between brain processing and behavior. Understanding these relationships will provide a foundation to support the development of better methods for evaluating sensory processing and guide the expansion of novel treatment approaches for people with dysfunctional sensory processing. Questions to be addressed are:

1) Does phase-locking in the gamma region (30-50 Hz) change throughout the presentation of tones in the Orientation/Habituation paradigm?

Hypothesis 1.1: During the train of tones with no deviants, phase-locking in the gamma region will be significantly higher for the first tone response when compared to subsequent tone responses.

Hypothesis 1.2: During the train of tones with deviants in the 4th and 5th position, phase-locking in the gamma region will be significantly higher during the response to the deviant tones when compared to the responses of non-deviant tones 2-8.

Hypothesis 1.3: During the train of tones with deviants in the 4th and 5th positions, phase-locking in the gamma region will not be significantly different between tones 1 and 4 and 1 and 5, respectively.

2) Does phase-locking in the beta region (18-30 Hz?) change throughout the presentation of tones in the Orientation/Habituation paradigm?

Hypothesis 2.1: During the train of tones with no deviants, phase-locking in the beta region will be significantly higher for the first tone response when compared to subsequent tone responses.

Hypothesis 2.2: During the train of tones with deviants in the 4th and 5th position, phase-locking in the beta region will be significantly higher during the response to the deviant tones when compared to the responses of non-deviant tones 2-8.

Hypothesis 2.3: During the train of tones with deviants in the 4th and 5th positions, phase-locking in the beta region will not be significantly different between tones 1 and 4 and 1 and 5, respectively.

3) In typically developing adults, is there a relationship between phase-locking of gamma, beta, or gamma and beta together, and scores on self-reported sensory inventories?

Hypothesis 3.1: There will be a positive relationship between the strength of phase-locking in the gamma region during response to deviant tones and scores on the neurological threshold continuum as measured by the Adult/Adolescent Sensory Profile (AASP).

Hypothesis 3.2: Individuals who have better phase-locking will demonstrate a low neurological threshold as measured by the AASP. Conversely, individuals with poor phase-locking in the gamma region will demonstrate higher thresholds as measured by the AASP. A low neurological threshold will be defined by the two quadrants on the AASP, Sensory Sensitivity and Sensation Avoiding, and a high neurological threshold will be defined as the remaining two quadrants, Sensation Seeking and Low Registration.

Methods

Participants

Approval for the study was granted by Colorado State University's Institutional Review Board. Data were previously collected from 38 healthy adults that were recruited from an undergraduate university via online advertisement. Average age of the participants was 19.6 years (SD 1.46 years), 39.6% were male, and 89.5% were white. All participants signed consent forms. All participants were given artifact training prior to participating in the study. This includes teaching them that "quiet brainwaves" are the ones we want to record and the best way to achieve these is by sitting still, not smiling, and not over-blinking - actions that require muscle activity. The participants sat in a quiet room and a step procedure was used to screen for hearing levels of the participants.

Equipment

The BioSemi ActiveTwo EEG/ERP acquisition system was used to collect all data. The EEG set-up followed the 10/20 system with 32 electrodes measuring brainwaves and two reference electrodes placed on the ear lobes. Four electrodes were placed on the face and two on the mastoids in order to capture muscle activity. Participants wore ear foam inserts to listen to the sequences of tones, which were produced using EPrime software.

EEG Paradigm

The Orientation/Habituation paradigm was completed by all participants. This paradigm consists of three sequences of eight tones each. The first sequence, all standard tones, was presented at 1 kHz and 70 dB. The second series has the 4th tone as a deviant tone, which is 3 kHz and is at the same decibel level as the other tones. The last series has a similar deviant tone, but in the 5th position instead of the 4th. In the series with deviant tones, all tones except for the deviants are the same as the series without deviants. Each sequence was played in pseudorandom fashion 80 times, for a total of 240 sequences of tones played. Each sequence had an inter-trial interval (ITI) of random length, lasting between 8 to 10 seconds. Within the sequences, each tone was separated by 500 ms (called the interstimulus interval, or ISI). In all series, every tone lasted 50 ms. During the EEG collection, a silent film, "Shaun the Sheep," was played for the participants.

Sensory Measures

Each participant completed the Adult/Adolescent Sensory Profile (AASP) (Brown et al., 2001) after participating in the EEG section of the study.

Electrophysiological Data Analysis

All data analysis was performed by the author of this study. The EEG data were analyzed off-line using Analyzer and MatLab software. First, the raw EEG was referenced to the average of sensors on both ear lobes. Then it was filtered at 10-75 Hz. A baseline correction of -200 to 0 ms before the first tone in a series was applied in order to account for any pre-stimulus brain activity in order to best understand the effects of the tones. Artifact rejection was performed in order to get rid of ambient frequencies and man-made artifacts such as muscle movement and eye-blinks. After segmenting, baseline correction, and artifact rejection, the segments were averaged for each individual, based on the tonal series presented, and then a grand average of all individuals was produced.

In order to determine which EEG electrode (aka channels or sites) displayed the most significant differences in amplitude from baseline during stimulus presentation, t-maps were created for each series of tones (as an example, see Figure 1). Channels used for further analysis

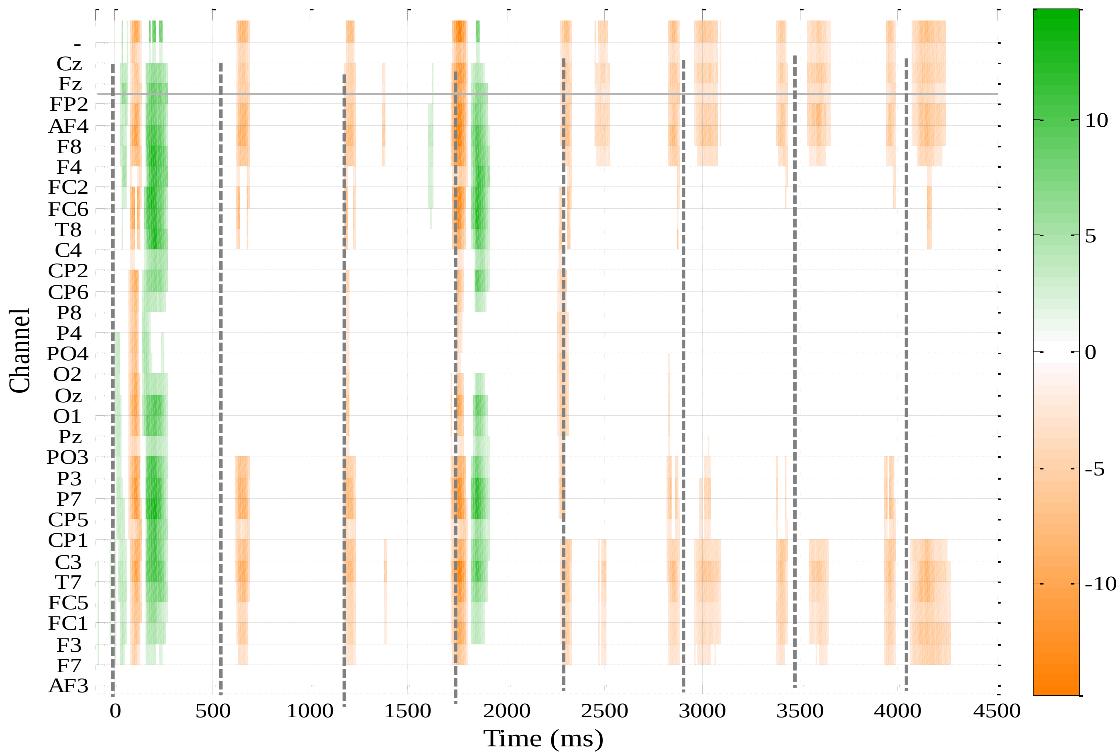

Figure 1: An example of a t-map taken from the series of tones with a deviant in the 4th position. Grey dotted lines depict the place in time where tones were presented. Green depicts positive t-values and orange depicts negative t-values.

were chosen not only based on these maps, but on past literature as well. The t-maps not only depicted which electrodes had the most significant differences in amplitude from baseline, but also what time frame in milliseconds after each tone was the most significant. Each series was segmented from -1400 ms to 5000 ms in order to capture slightly before and after the entire tonal series (not shown in Figure 1). Overall significance was defined as either 3 or 5 consecutive significant *t* values between data points in order to protect against Type 1 error. Three and five were chosen based on prior studies conducted by the Brainwaves Research Lab, and were found to be the best choices based on number of significant points.

Based on these t-maps, time-frequency maps were created. As an example, please see Figure 2, which depicts the CZ site for the series of tones with a deviant in the 4^{th} position. Frequency (in Hz) is on the y-axis and time (in ms) is on the x-axis. Phase-Locking Factor (PLF) data were calculated for two separate frequency regions –gamma, defined as 30-50 Hz, and beta, defined as 18-30 Hz, across the six sites that were chosen from the t-maps. Regions of interest were created in these time-frequency maps, as shown in Figure 2 by the yellow boxes for gamma, and the pink boxes for beta. The regions of interest were analyzed for all 8 tones in the same manner – a time window of 40 ms beginning 30 ms after the click for gamma and a time window of 80 ms starting 60 ms after a click for beta. In the example graph, the pink box outlines frequencies 18-30 Hz (beta) and time window 60-140 ms (since click 1 occurred at time 0). The yellow box outlines 30-50 Hz (gamma) and the time window 30-70 ms. All data points within these boxes were averaged together to get a single PLF value, and these boxes were created for all 8 tones for all three series (not shown on example graph due to clutter). These single values were then used for all of the following statistical data analyses.

Behavioral Data

The behavioral data as measured by the AASP were entered into a template designed specifically for the questionnaire in Microsoft Access. AASP data were managed and scored in ACCESS. From there, the data were statistically analyzed using SPSS 21.0 Windows (IBM SPSS Statistics, Inc., Chicago, IL).

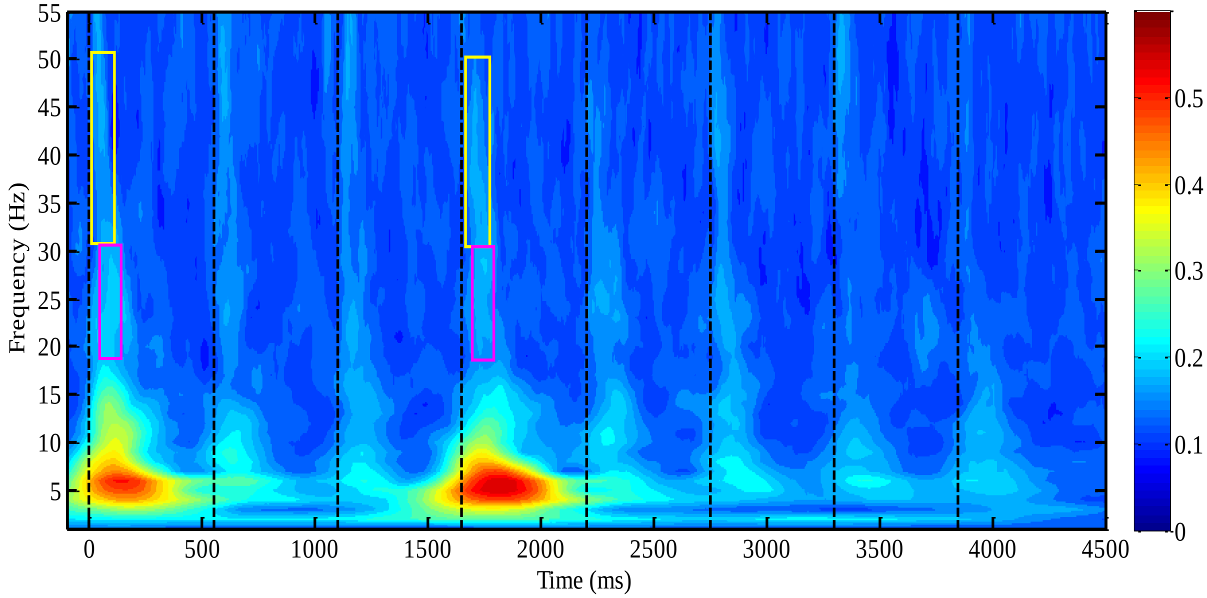

Figure 2: Time-Frequency map for the series of tones with deviants in the 4^{th} position at channel CZ. The dotted lines depict the place in time where tones were presented. The color table on the far right represents phase-locking values, with dark red being higher, or better phase-locking and dark blue being poorer phase-locking.

Statistical Data Analysis

In order to test the hypotheses for Questions 1 & 2, ANOVA and a priori comparison t-tests were used. The ANOVAs were run to obtain the mean square values in order to calculate the a priori t-test. In these, if Mauchly's Test of Sphericity was significant, the Greenhouse – Geisser correction for the mean square value was used. For the a priori *t* – tests, significance was defined as $t > 1.686$ with $p < 0.05$, based on the one-tailed *t*-test and degrees of freedom equal to 38. To test the hypothesis for Question 3, Spearman Rho Correlation Coefficient analyses were used because the electrophysiological data did not meet the normal distribution assumption needed for parametric statistics. Regression analysis was used to test which specific behaviors accounted for the most variance in PLF. Based on the results from the Spearman Rho analyses, the Sensory Sensitivity quadrant of the AASP was always the dependent variable and various phase-locking measures were introduced as independent variables.

Results

From the t-maps (for example, see Figure 1), the electrodes displaying the most significant difference in amplitude from baseline were CZ, C3, C4, FZ, F3, and F4. The means and standard deviations of phase-locking values are reported in Table 2 for the gamma frequency and Table 3 for the beta frequency for these six electrode sites. Time-frequency graphs for channel CZ are shown in order to visually represent the differences found in PLF, as well as the points within boxes that were averaged together to create a single data value (see Figures 3 and 4, also see Figure 2).

The PLF values for each tone based on the averages taken from the time-frequency analyses are illustrated in Figures 5 -16 for the six electrode sites showing significant differences as described above. Six of the figures are for beta oscillations (18-30 Hz), one for each of the six electrode sites, and six of the figures are for gamma oscillations (30-50 Hz), one for each of the six electrode sites. Figures 5 - 16 display PLF values (on the y axis) for each tone (on the x axis), and each series of tones is represented by a unique color. A solid, bold line between two tones means that phase-locking factor values were significantly different between those tones. For example, in Figure 5, the bold green line means that in the series of tones with no deviants, PLF in response to tone 1 was significantly higher than the PLF value recorded at tone 2. A bold, dashed line between three or more tones means PLF values were significantly different between the first and last tones of the dashed lines. Unless otherwise noted at the bottom of the figure, PLF values of the intermediary tones in the bold, dashed lines were not significantly different from the responses at other tones. For example, in Figure 6, the red, bold, dashed line means that

Table 2

Descriptive Statistics for PLF for Gamma (30-50 Hz). The mean PLF value is listed as the top number, the standard deviation is the bottom number. N=38

Site	Series	*Tone 1*	*Tone 2*	*Tone 3*	*Tone 4*	*Tone 5*	*Tone 6*	*Tone 7*	*Tone 8*
	deviant 4th	.1697 .08258	.1616 .07124	.1578 .07677	.1663 .07888	.1509 .05959	.1619 .07949	.1496 .06963	.1387 .05821
CZ	*deviant 5th*	.1727 .07282	.1573 .09224	.1582 .08179	.1455 .06720	.1654 .07508	.1531 .08972	.1610 .10555	.1464 .05367
	no deviant	.1826 .07865	.1464 .06445	.1517 .05260	.1493 .05849	.1549 .07245	.1467 .06104	.1552 .07975	.1517 .07077
	deviant 4th	.1536 .06410	.1539 .04208	.1497 .07779	.1584 .06914	.1408 .05247	.1541 .07158	.1507 .07630	.1301 .05369
C3	*deviant 5th*	.1596 .05601	.1432 .08620	.1503 .07012	.1396 .05986	.1448 .06748	.1478 .06847	.1469 .08708	.1410 .04870
	no deviant	.1573 .06325	.1503 .05580	.1377 .05684	.1381 .05396	.1395 .05336	.1442 .07145	.1451 .05730	.1546 .07208
	deviant 4th	.1555 .06412	.1405 .05749	.1468 .06986	.1619 .07221	.1554 .05496	.1533 .08580	.1487 .07117	.1366 .04608
C4	*deviant 5th*	.1463 .06293	.1383 .05623	.1452 .07788	.1566 .07090	.1462 .05955	.1345 .07198	.1465 .07082	.1325 .06437
	no deviant	.1541 .06516	.1428 .06182	.1402 .05030	.1318 .05312	.1439 .06743	.1343 .05501	.1350 .06336	.1603 .08403
	deviant 4th	.1811 .09232	.1636 .06329	.1798 .07525	.1646 .06880	.1730 .06844	.1794 .07444	.1717 .07082	.1508 .05453
FZ	*deviant 5th*	.1905 .07412	.1768 .07377	.1777 .08120	.1540 .07704	.1591 .06872	.1613 .07952	.1718 .08729	.1606 .04419
	no deviant	.1882 .06102	.1719 .07042	.1719 .05710	.1717 .06652	.1651 .06375	.1495 .05544	.1652 .05963	.1604 .08287
	deviant 4th	.1564 .07450	.1466 .05498	.1631 .06247	.1510 .05995	.1511 .05714	.1494 .05679	.1444 .06018	.1346 .04965
F3	*deviant 5th*	.1638 .07238	.1575 .07179	.1542 .05528	.1486 .06747	.1506 .07086	.1427 .05684	.1488 .05197	.1447 .05489
	no deviant	.1668 .05106	.1529 .08255	.1646 .07442	.1540 .05069	.1455 .05527	.1632 .06735	.1606 .07068	.1466 .06892
	deviant 4th	.1564 .07712	.1484 .04681	.1654 .07492	.1466 .06548	.1672 .06664	.1593 .07005	.1512 .05727	.1459 .06151
F4	*deviant 5th*	.1723 .07849	.1527 .06986	.1516 .06660	.1570 .07705	.1519 .06177	.1333 .05835	.1489 .06528	.1564 .06398
	no deviant	.1611 .06278	.1435 .05290	.1510 .04941	.1597 .05836	.1552 .06136	.1504 .06191	.1472 .05777	.1451 .07107

Table 3

Descriptive Statistics for PLF for Beta (18-30 Hz). The mean PLF value is listed as the top number, the standard deviation is the bottom number. N=38

Site	Series	*Tone 1*	*Tone 2*	*Tone 3*	*Tone 4*	*Tone 5*	*Tone 6*	*Tone 7*	*Tone 8*
CZ	*deviant 4th*	.1989 .07142	.1571 .05360	.1600 .05909	.1791 .06975	.1672 .06034	.1620 .09201	.1409 .06450	.1395 .05416
	deviant 5th	.1827 .07009	.1629 .07066	.1669 .07077	.1479 .06306	.1621 .06520	.1653 .07653	.1537 .06787	.1471 .05295
	no deviant	.1944 .09302	.1669 .07901	.1438 .05009	.1486 .05120	.1574 .05723	.1627 .06551	.1433 .06803	.1751 .05775
C3	*deviant 4th*	.1870 .08462	.1544 .05440	.1436 .06054	.1768 .06415	.1512 .05464	.1562 .08746	.1511 .05929	.1442 .05969
	deviant 5th	.1927 .07170	.1520 .06656	.1540 .06997	.1435 .07188	.1585 .05992	.1524 .06451	.1447 .04877	.1372 .04882
	no deviant	.1967 .07981	.1564 .06668	.1493 .04823	.1507 .05795	.1490 .06476	.1588 .06761	.1470 .06425	.1609 .05204
C4	*deviant 4th*	.1892 .07265	.1557 .05047	.1579 .06837	.1709 .05754	.1580 .06237	.1576 .08232	.1335 .05561	.1408 .05510
	deviant 5th	.18033 .05450	.1525 .06985	.1503 .05851	.1619 .08800	.1552 .06066	.1548 .08013	.1427 .05967	.1474 .05502
	no deviant	.1852 .08973	.1558 .06916	.1383 .04497	.1459 .05212	.1535 .05724	.1544 .06342	.1394 .05975	.1627 .05399
FZ	*deviant 4th*	.2213 .09137	.1528 .05486	.1616 .07313	.1876 .07656	.1720 .07042	.1618 .09624	.1449 .04442	.1476 .06346
	deviant 5th	.1966 .07575	.1630 .06775	.1677 .07456	.1632 .06386	.1603 .06729	.1660 .07066	.1457 .05820	.1482 .06277
	no deviant	.2284 .08827	.1622 .06737	.1431 .05020	.1514 .05443	.1587 .05074	.1599 .07082	.1523 .05947	.1701 .06065
F3	*deviant 4th*	.1990 .08456	.1506 .06311	.1523 .07659	.1704 .06381	.1482 .06495	.1535 .07987	.1425 .04761	.1447 .04465
	deviant 5th	.1918 .06975	.1500 .06206	.1565 .06937	.1491 .05955	.1516 .06108	.1515 .04490	.1417 .06447	.1449 .06257
	no deviant	.2047 .07543	.1436 .06453	.1370 .05079	.1463 .04841	.1532 .05124	.1508 .06087	.1489 .06249	.1733 .06059
F4	*deviant 4th*	.2024 .07878	.1467 .06028	.1554 .08248	.1752 .07395	.1595 .05255	.1471 .06195	.1403 .04396	.1432 .05652
	deviant 5th	.1998 .06412	.1523 .05887	.1498 .06079	.1594 .06121	.1482 .06824	.1548 .05982	.1396 .06107	.1434 .05549
	no deviant	.1992 .09659	.1499 .05731	.1390 .04477	.1444 .04997	.1570 .05626	.1466 .04930	.1531 .06083	.1596 .06573

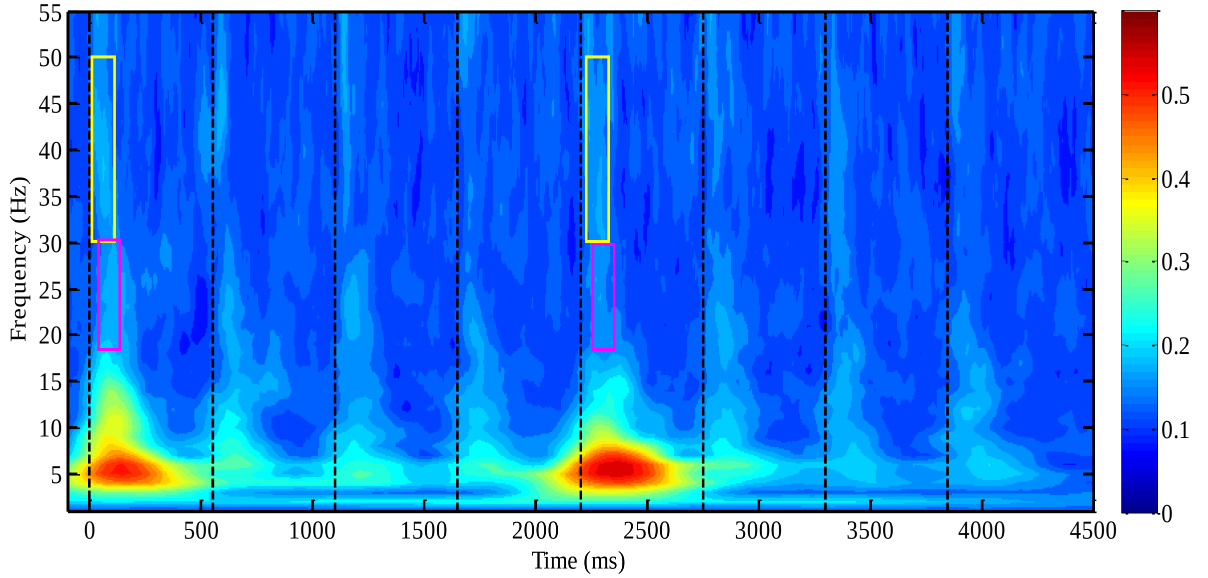

Figure 3: Time-Frequency map for the series of tones with deviants in the 5th position at channel CZ. The dotted lines depict the place in time where tones were presented. The color table on the far right represents phase-locking values, with dark red being higher, or better phase-locking and dark blue being poorer phase-locking.

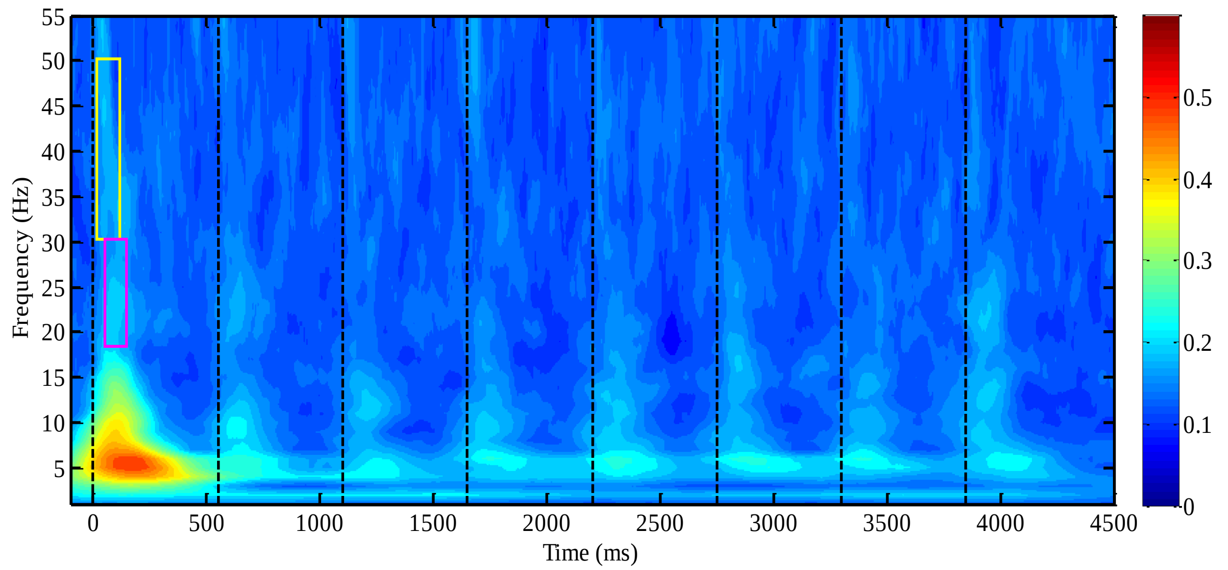

Figure 4: Time-Frequency map for the series of tones with no deviants at channel CZ. The dotted lines depict the place in time where tones were presented. The color table on the far right represents phase-locking values, with dark red being higher, or better phase-locking and dark blue being poorer phase-locking.

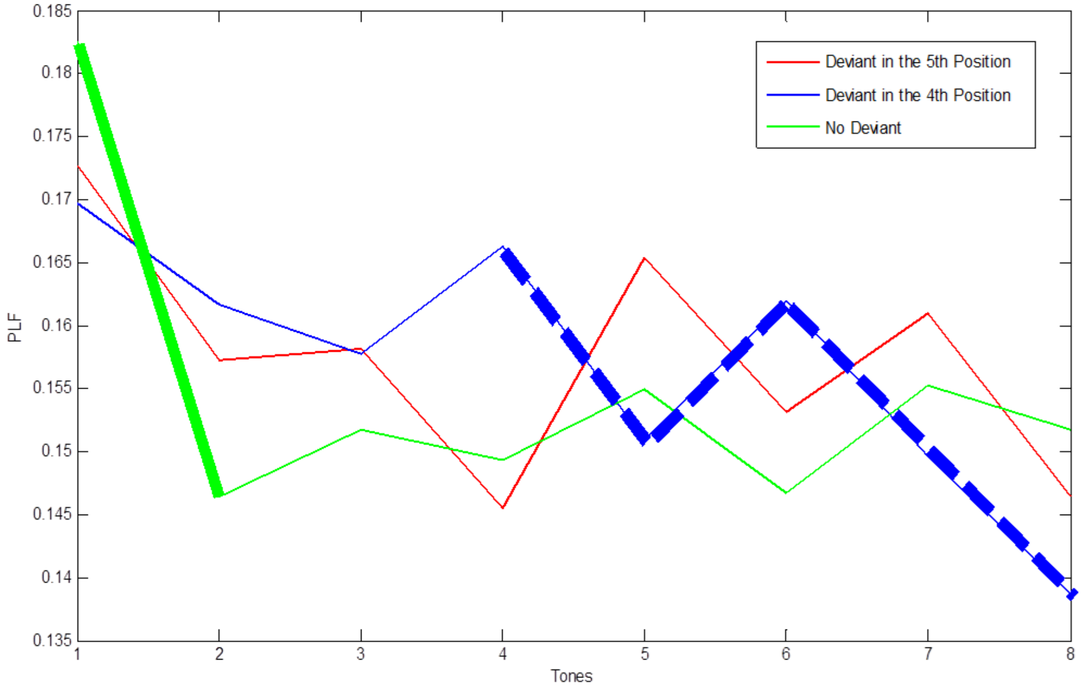

Figure 5: Electrode site CZ for Gamma (30-50 Hz), all three series of tones (see legend). Note: In the series of tones with no deviant (green), tone 1 is also significantly different than tones 4 and 6.

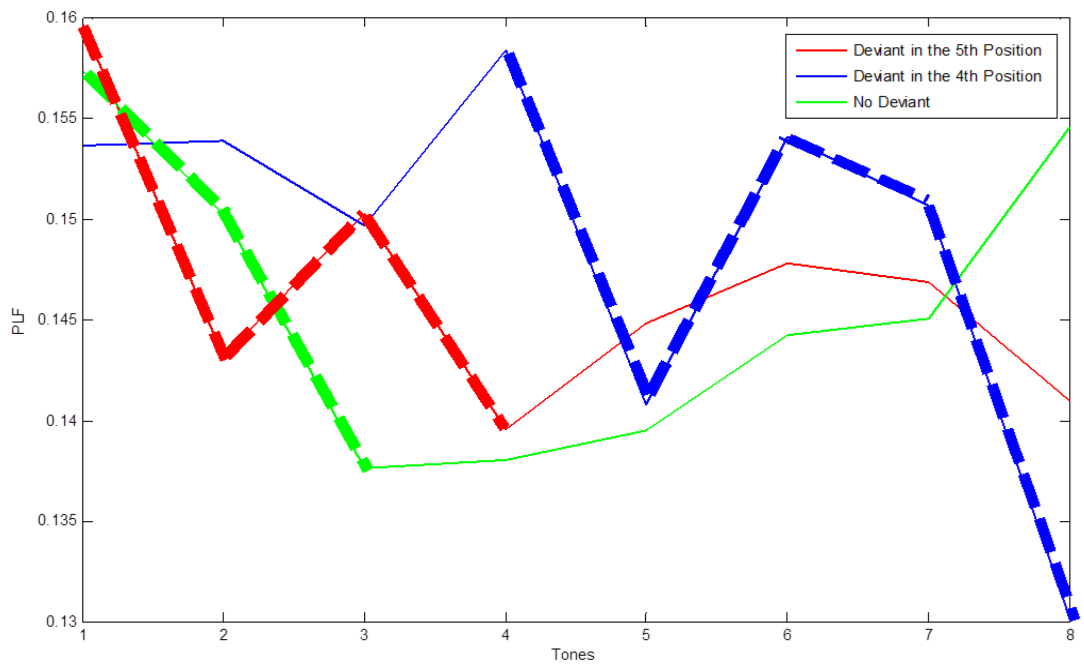

Figure 6: Electrode site C3 for Gamma (30-50 Hz), all three series of tones (see legend). Note: In the series with no deviant (green), tone 1 is also significantly different from both tones 4 and 5.

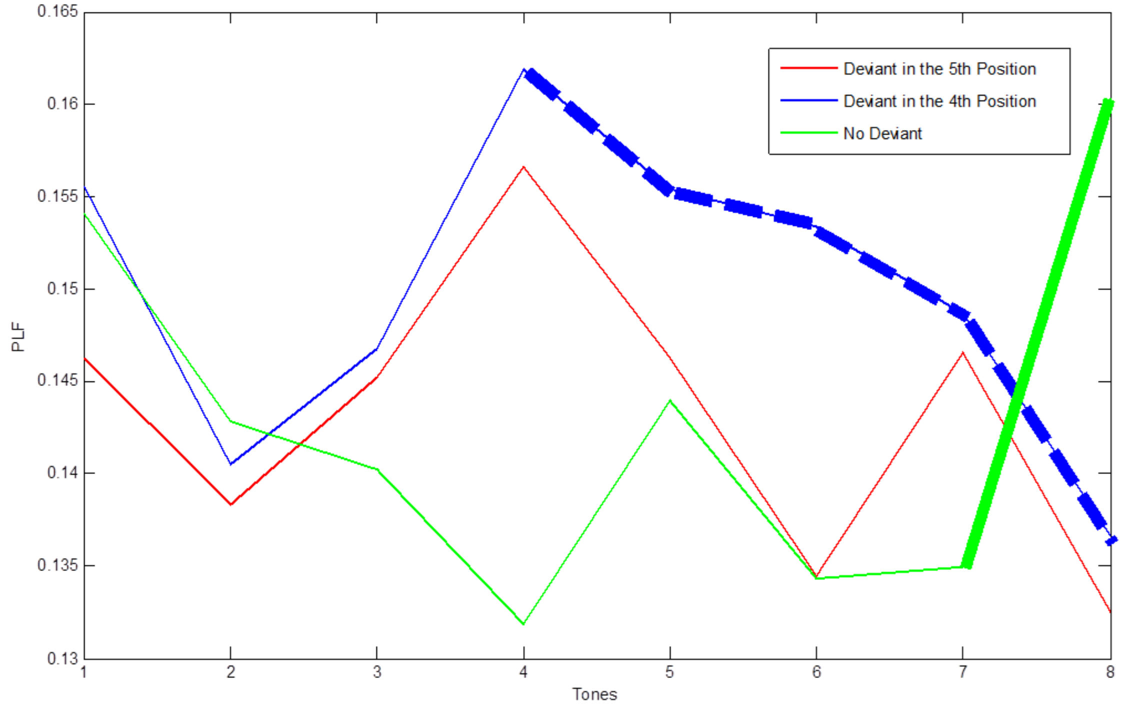

Figure 7: Electrode site C4 for Gamma (30-50 Hz), all three series of tones (see legend).

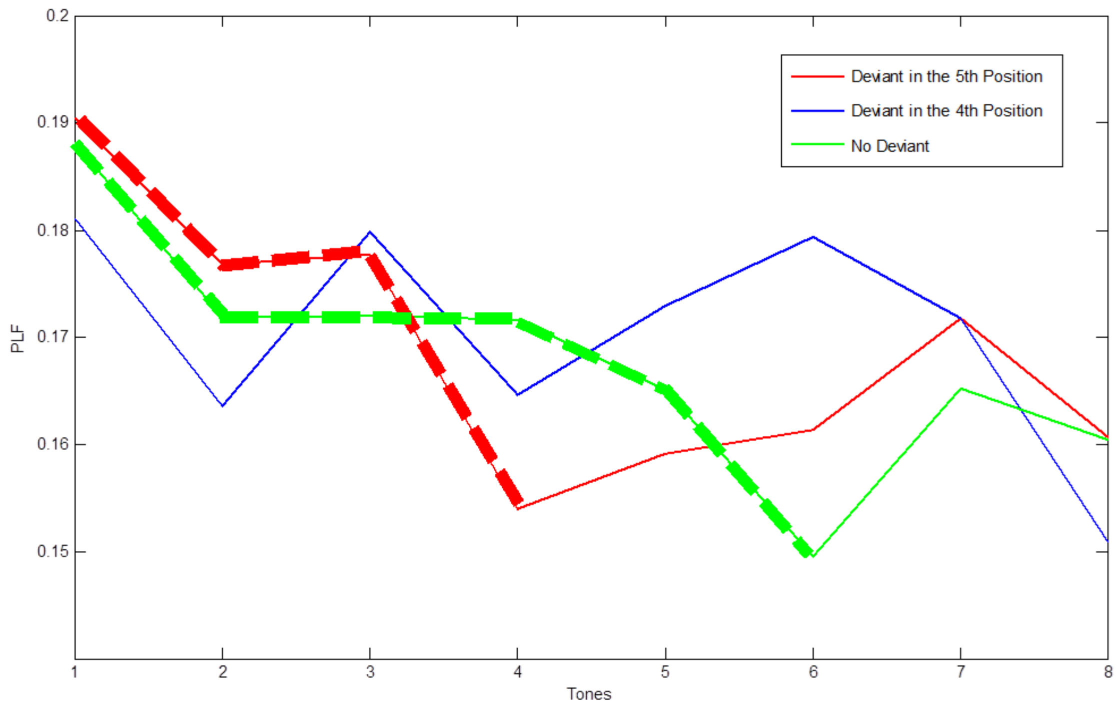

Figure 8: Electrode site FZ for Gamma (30-50 Hz), all three series of tones (see legend).

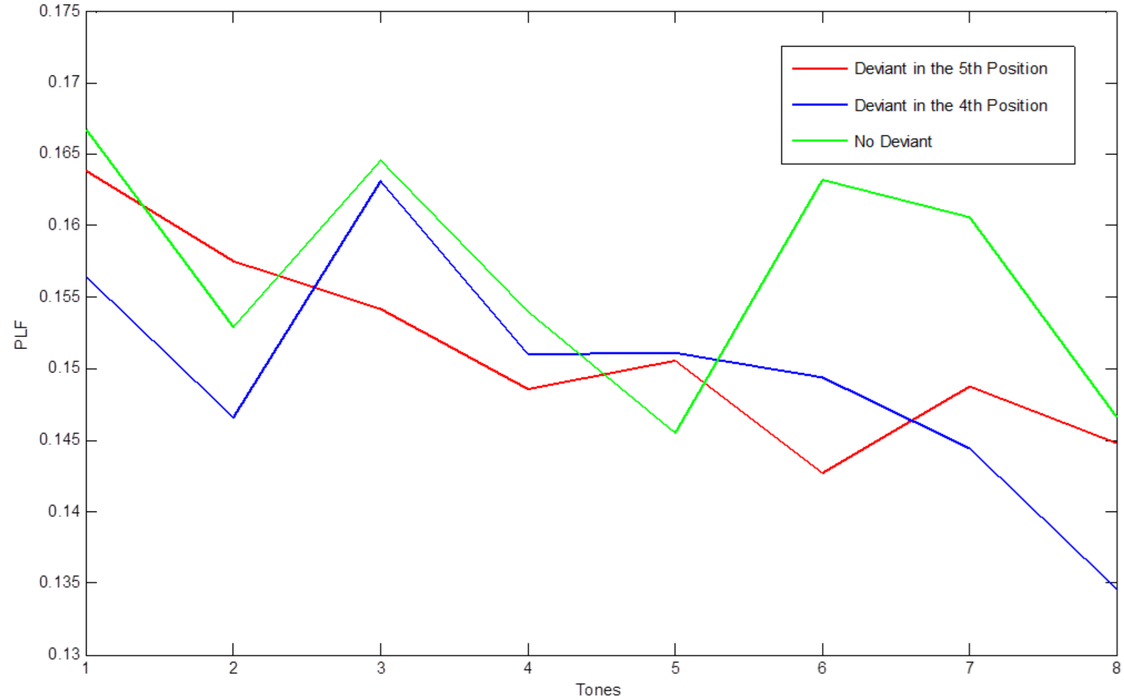

Figure 9: Electrode site F3 for Gamma (30-50 Hz), all three series of tones (see legend).

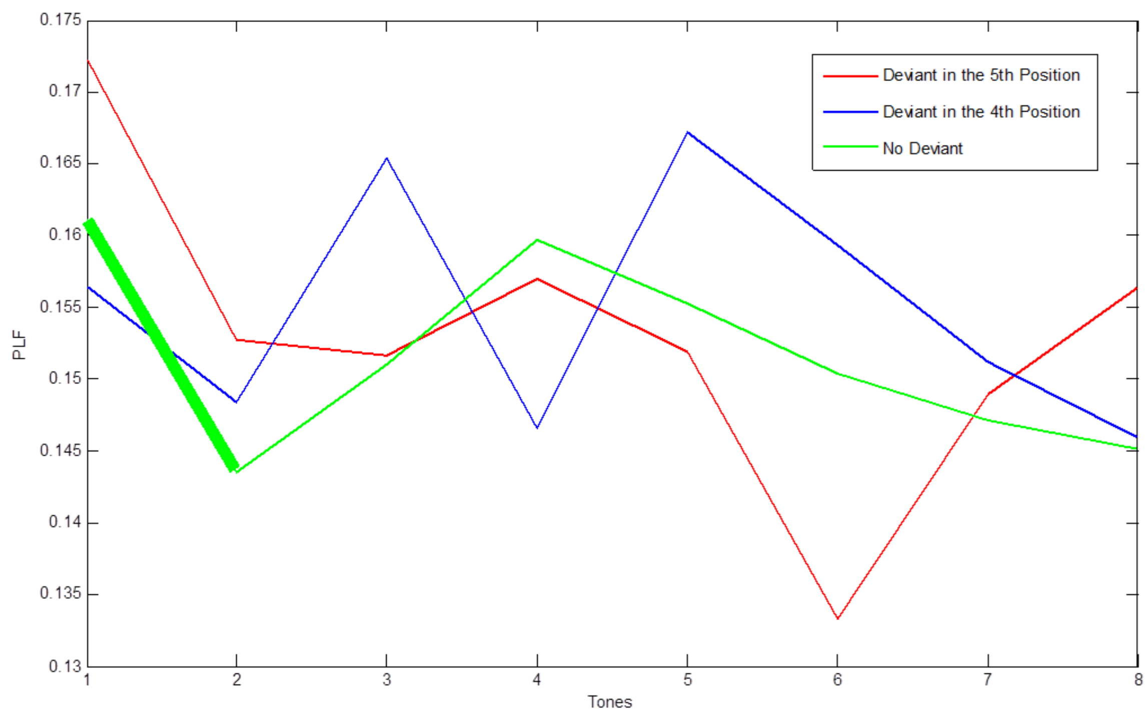

Figure 10: Electrode site F4 for Gamma (30-50 Hz), all three series of tones (see legend).

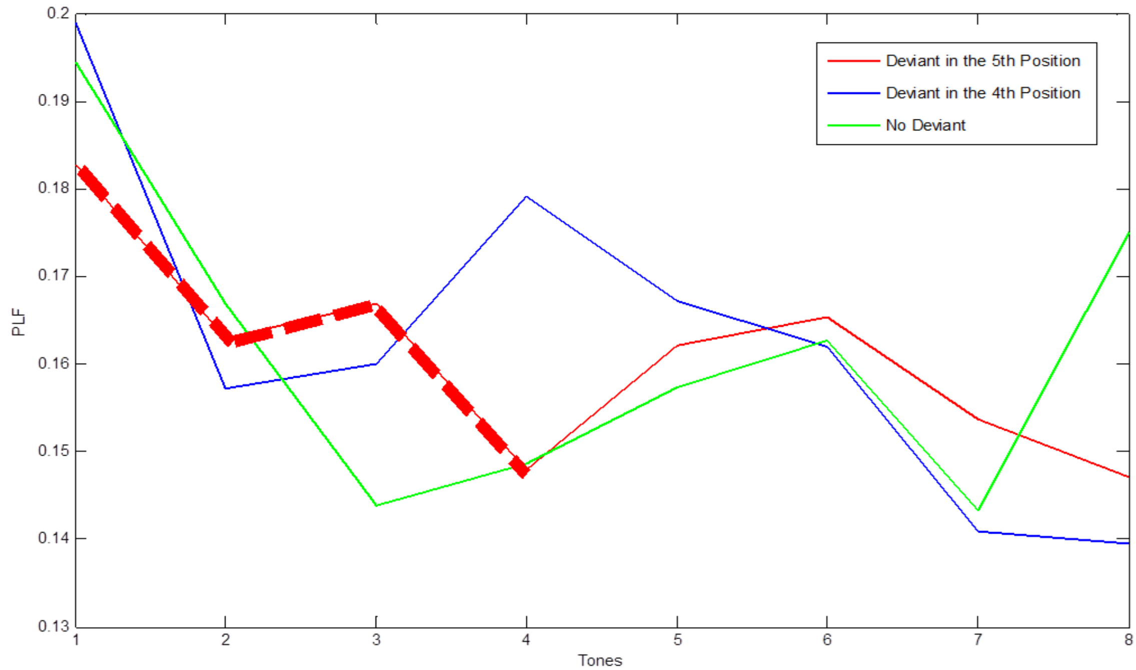

Figure 11: Electrode site CZ for Beta (18-30 Hz), all three series of tones (see legend).

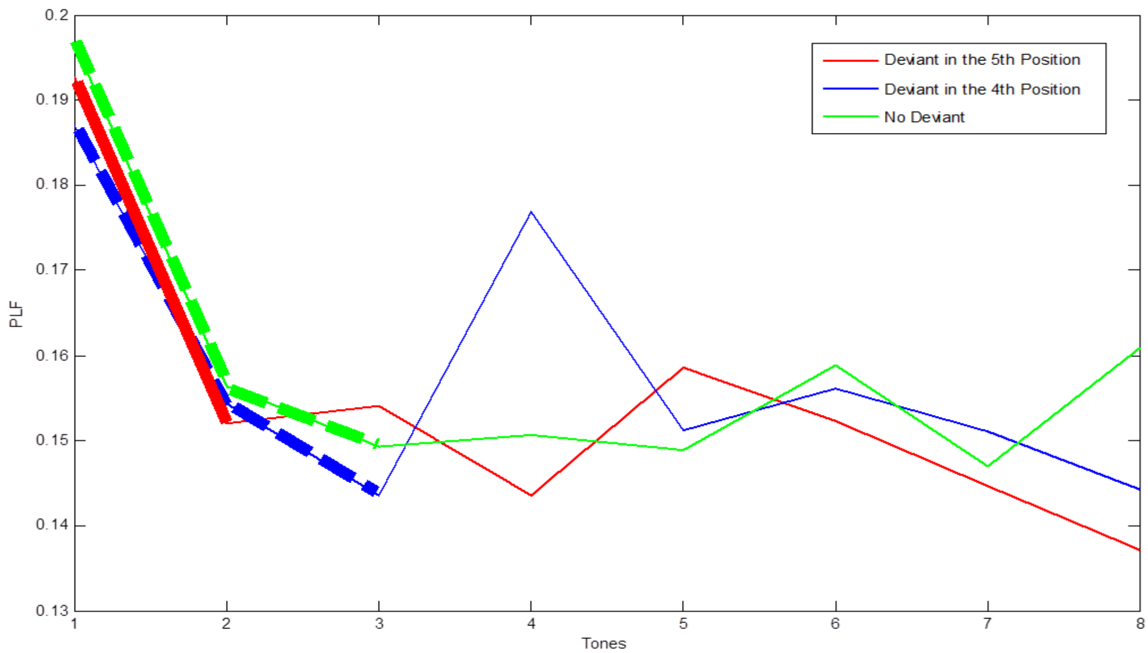

Figure 12: Electrode site C3 for Beta (18-30 Hz), all three series of tones (see legend). Note: In the series with no deviant (green), tone 1 is also significantly different from tones 4, 5, and 7. In the series with the deviant in the 5th position (red), tone 1 is significantly different from tone 4.

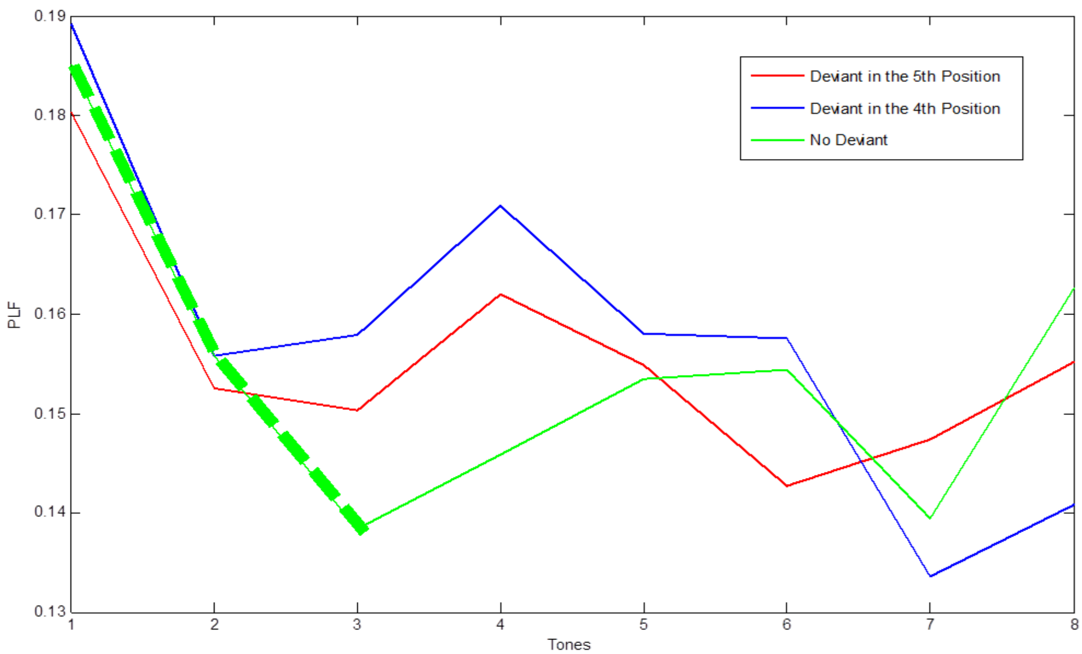

Figure 13: Electrode site C4 for Beta (18-30 Hz), all three series of tones (see legend). Note: In the series of tones with no deviant (green), tone 1 is also significantly different from tones 4 and 7.

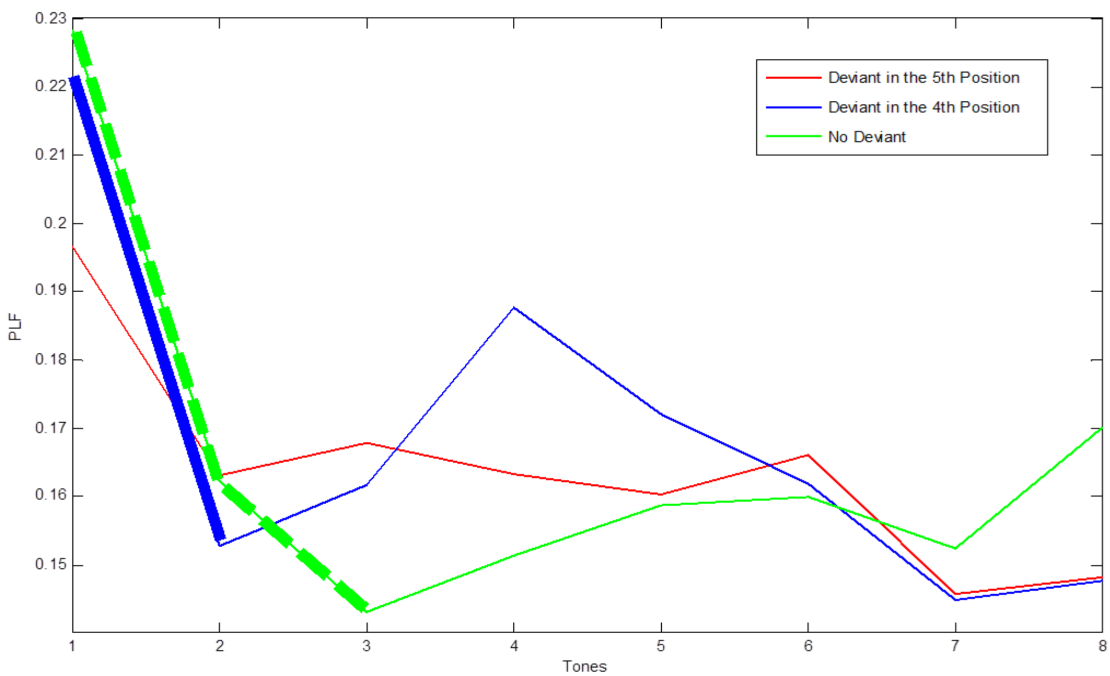

Figure 14: Electrode site FZ for Beta (18-30 Hz), all three series of tones (see legend). Note: In the series of tones with no deviant (green), tone 1 is also significantly different from tones 4 and 7.

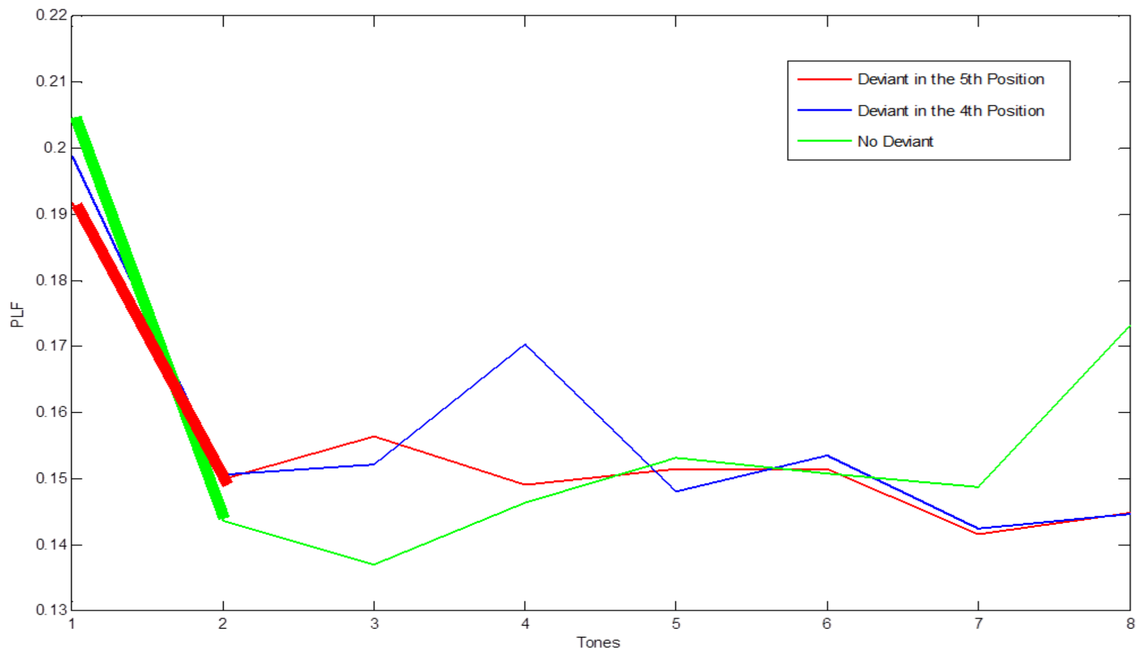

Figure 15: Electrode site F3 for Beta (18-30 Hz), all three series of tones (see legend). Note: In the series of tones with the deviant in the 5th position (red), tone 1 is also significantly different than tones 4 and 5. In the series of tones with no deviant, tone 1 is also significantly different from tones 3 and 4.

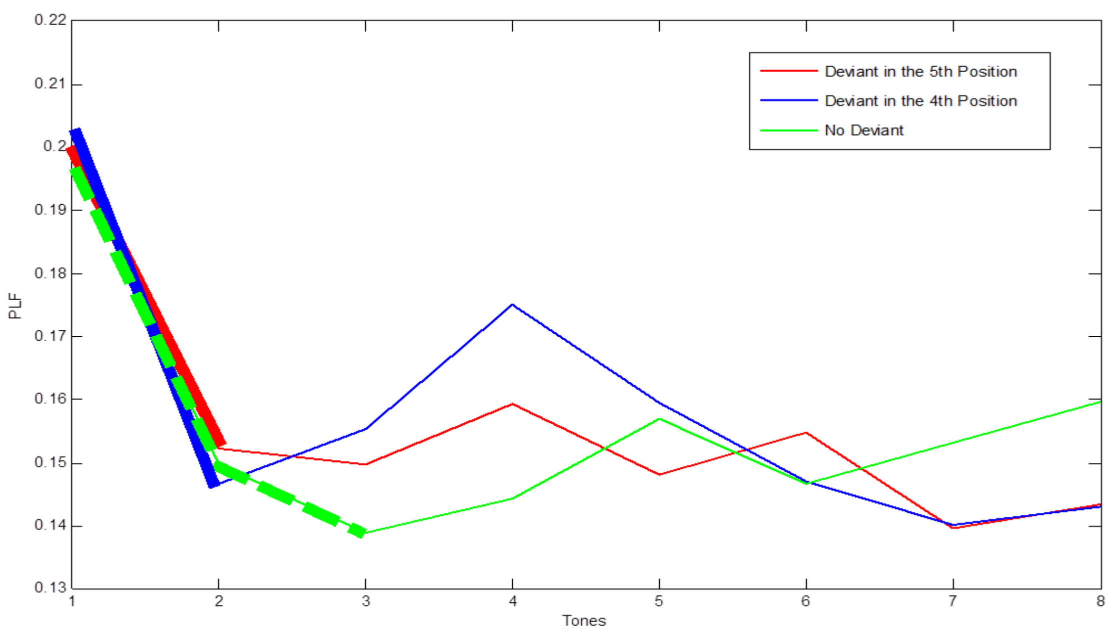

Figure 16: Electrode site F4 for Beta (18-30 Hz), all three series of tones (see legend). Note: In the series of tones with no deviants (green), tone 1 is also significantly different from tone 4. In the series of tones with the deviant in the 5th position (red), tone 1 is significantly different than tone 5.

in the series with a deviant in the 5th position, PLF value at tone 1 was significantly higher than PLF at tone 4, but not significantly different from the values recorded during tones 2 and 3. Some, but not all, of the other significant values between points are mentioned in the captions of the individual figures.

Hypothesis 1.1 states that for the tonal series with no deviants, PLF in the gamma region will be significantly higher for the first tone compared to subsequent tone responses. PLF for gamma (30-50 Hz) for the first tone was higher than all other tone responses with the exception of the 8th tone at electrode site C4 (Figure 7). At sites CZ and F4 for gamma (Figures 5 and 10, respectively), the PLF in the first tone was significantly higher than tone 2 ($t = 1.89$ and $t = 1.72$, respectively). Also at CZ site for gamma, PLF was significantly larger for tone 1 compared to tone 4 ($t = 1.74$). PLF for tone 1 was significantly higher than tones 3, 4, and 5 at C3 site (Figure 6) for gamma ($t = 1.91$, $t = 1.87$, and $t = 1.73$, respectively). PLF for tone 1 was significantly higher than tone 6 for electrode FZ ($t = 2.39$, Figure 8). The hypothesis was partially supported by these data. For all other significant points, see Figures 5 - 10 above.

Hypothesis 1.2 states that in the tonal series with deviants, PLF for gamma will be significantly higher during responses to deviant tones when compared to responses to non-deviant tones 2-8. For the series of tones with a deviant in the 4th position, PLF in the gamma region increased from tone 3 to tone 4 (the deviant tone) at electrode sites CZ, C3, and C4 (Figures 5, 6, and 7 respectively), but decreased from tone 3 to tone 4 (the deviant tone) for FZ, F3, and F4 (Figures 8, 9, and 10, respectively), although none of these findings were significant. PLF for gamma was higher for the 4th tone, although not significantly so, than for the 8th tone for all six sites, and was significantly greater than tone 8 for CZ ($t = 1.70$), C3 ($t = 2.25$), and C4 ($t = 2.01$), figures 5, 6, and 7, respectively. PLF for tone 4 was not significantly different from any other tone for all six electrodes, which does not support this hypothesis. Additionally, for the series of tones with a deviant in the 5th position, tone 5 did not significantly differ from any of the non-deviant tones 2-8 at any electrode. PLF in the gamma region increased from tone 4 to tone 5 in CZ, C3, FZ, and F3 (none were significant, Figures 5, 6, 8, and 9, respectively), but decreased in C4 and F4 (Figures 7 and 10).

Hypothesis 1.3 states that during the series of tones with deviants, PLF for gamma will not be significantly different between the first tone of the series and the deviant tone. For the series of tones with a deviant in the 4th position, PLF in the gamma region for tone 1 was not significantly different than tone 4 at any electrode sites, which supports this hypothesis. For the series of tones with a deviant in the 5th position, PLF in the gamma region for tone 1 was not significantly different than tone 5 at any electrodes, also supporting this hypothesis.

Hypothesis 2.1 states that for the tonal series with no deviants, PLF in the beta region (18-30 Hz) will be significantly higher for the first tone compared to subsequent tone responses. In the series of tones with no deviant, PLF for beta in the first tone was higher than all other tones. PLF in the first tone was significantly higher than tone 2 (paralleling a gating response) for beta at site F3 ($t = 1.99$, Figure 15). It was significantly higher than tone 3 for beta at sites C3 ($t = 1.81$), C4 ($t = 2.18$), FZ ($t = 1.96$), F3 ($t = 2.20$), and F4 ($t = 1.86$) with CZ reaching just short of significance ($t = 1.644$) (see figures 12, 13, 14, 15, 16, and 11, respectively). Tone 1 was not significantly different than tone 8 in the beta frequency band for any electrode, as PLF for tone 8 increased in the beta frequency for all six electrodes. For all other tonal comparisons, please see Figures 11-16 above.

Hypothesis 2.2 states that in the tonal series with deviants, PLF for beta will be significantly higher during responses to deviant tones when compared to responses to non-deviant tones 2-8. For the series of tones with a deviant in the 4th position, PLF in the beta region increased from tone 3 to tone 4 across all six sites (see Figures 11-16), although none reached significance. Additionally, tone 4 had the second highest PLF across all sites (second only to the first tone); however, tone 4 was not significantly different from any of the non-deviant tones 2-8, for all six electrodes. For the series of tones with a deviant in the 5th position, tone 5 did not significantly differ from any of the non-deviant tones 2-8 at any electrode. For the series of tones with a deviant in the 5th position, PLF in the beta region increased from tone 4 to tone 5 in electrodes CZ, C3,and F3 (Figures 11, 12 and 15, respectively), but decreased in C4, FZ, and F4 (Figures 13, 14, and 16, respectively), although none of these findings were significant.

Hypothesis 2.3 states that during the series of tones with deviants, PLF for beta will not be significantly different between the first tone of the series and the deviant tone. For the series of tones with a deviant in the 4th position, PLF in the beta region during tone 1 was not significantly different from PLF in tone 4 across all six sites, supporting this hypothesis. For the series of tones with a deviant in the 5th position, PLF in the beta region during tone 1 was significantly higher than PLF in tone 5 for F3 ($t = 1.85$, Figure 15) and F4 ($t = 1.97$, Figure 16), but not for electrodes CZ, C3, C4, or FZ.

Hypothesis 3.1 states that there will be a positive relationship between PLF and scores on the neurological threshold continuum during response to deviant tones. There were some negative correlations found between phase-locking factor and behavioral measures for deviant tones, although none reached significance. All significant correlations found were positive (see Tables 4 and 5 below).

Hypothesis 3.2 expands on hypothesis 3.1 and states that individuals with better phase-locking will demonstrate a low neurological threshold, and vice versa. Sensory sensitivity had

Table 4

Spearman Rho Correlation Coefficient for Tone 4

	Frequency Band	*Gamma*				*Beta*			
Site	**Behavior Measure/Series**	Visual Processing	Touch Processing	Sensation Seeking	Sensory Sensitivity	Visual Processing	Auditory Processing	Activity Level	Sensory Sensitivity
	deviant 4th				.343				
CZ					.041				
	deviant 5th								
	non- deviant								
	deviant 4th						.399		.338
C3							.013		.038
	deviant 5th								
	non- deviant								
	deviant 4th				.378				
C4					.023				
	deviant 5th								
	non- deviant								
	deviant 4th	.352							
FZ		.035							
	deviant 5th								
	non- deviant								
	deviant 4th	.381			.391				
F3		.018			.015				
	deviant 5th								
	non- deviant								
	deviant 4th				.437				
F4					.006				
	deviant 5th								
	non- deviant								

Note. The top numbers are the correlation coefficients of phase-locking factor and behavioral measures and the bottom numbers are the *p* values associated with them. There were no significant values found in the empty boxes. The specific items from the Adult/Adolescent Sensory Profile included in this table are based on patterns of significant results and hypotheses of the study and are different from those of other tables.

Table 5

Spearman Rho Correlation Coefficient for Tone 5

Site	**Frequency Band** / **Behavior Measure/Series**	*Gamma* Visual Processing	Touch Processing	Sensation Seeking	Sensory Sensitivity	*Beta* Visual Processing	Auditory Processing	Activity Level	Sensory Sensitivity
	deviant 4th								
CZ	deviant 5th								
	non-deviant								
	deviant 4th								
C3	deviant 5th								
	non- deviant								
	deviant 4th								
C4	deviant 5th			.396					
				.017					
	non- deviant								
	deviant 4th								
FZ	deviant 5th								
	non- deviant								
	deviant 4th								
F3	deviant 5th								
	non- deviant								
	deviant 4th								
F4	deviant 5th			.358					
				.027					
	non- deviant								

Note. The top numbers are the correlation coefficients of phase-locking factor and behavioral measures and the bottom numbers are the *p* values associated with them. There were no significant values found in the empty boxes. The specific items from the Adult/Adolescent Sensory Profile included in this table are based on patterns of significant results and hypotheses of the study and are different from those of other tables.

Table 6

Spearman Rho Correlation Coefficient for Tone 1

Frequency Band		*Gamma*				*Beta*			
Site	**Behavior Measure/Series**	Visual Processing	Touch Processing	Sensation Avoiding	Sensory Sensitivity	Visual Processing	Auditory Processing	Activity Level	Sensory Sensitivity
	deviant 4^{th}								
CZ	deviant 5th								
	non- deviant							-.321	
								.049	
	deviant 4^{th}								
C3	deviant 5th								
	non- deviant								
	deviant 4^{th}								
C4	deviant 5th			-.337					
				.044					
	non- deviant								
	deviant 4^{th}		.376		.343				
FZ			.024		.041				
	deviant 5th	.351							
		.036							
	non- deviant								
	deviant 4^{th}	.331	.329		.544				
F3		.042	.043		.000				
	deviant 5th								
	non- deviant								
	deviant 4^{th}	.474	.409		.551				
F4		.003	.011		.000				
	deviant 5th	.330							
		.043							
	non- deviant								

Note. The top numbers are the correlation coefficients of phase-locking factor and behavioral measures and the bottom numbers are the *p* values associated with them. There were no significant values found in the empty boxes. The specific items from the Adult/Adolescent Sensory Profile included in this table are based on patterns of significant results and hypotheses of the study and are different from those of other tables.

eight positive correlations with PLF, sensation avoiding had one negative correlation with PLF, and sensation seeking had two positive correlations with PLF (see Tables 4, 5, and 6 above). Sensory sensitivity in combination with sensation avoiding (the two low neurological threshold quadrants) had 9/11 significant correlations with PLF. There were no correlations found between PLF and the Low Registration quadrant.

Other findings: See Table 7 for means and standard deviations for the Behavioral Data.

Table 7

Descriptive Statistics for Behavioral Data. N = 36

	Low Registration	Sensation Seeking	Sensory Sensitivity	Sensation Avoiding
Mean	30.87	50.53	32.76	33.82
Standard Deviation	6.723	6.741	6.879	6.311

There were two significant negative correlations between phase-locking and behavioral measures. They were: tone 1, electrode C4 with the deviant tone in the 5th position, gamma frequency band, and correlated with the Sensation Avoiding quadrant from the AASP (r = -.337, p = 0.044) and tone 1, electrode CZ with no deviant tones presented, beta frequency band, and correlated with Activity Level from the AASP (r = -.321, p = 0.049). There were numerous other nonsignificant negative correlations. All other significant findings were positive correlations and are listed in Tables 4, 5, and 6.

In the series of tones with no deviants, 8/12 of the figures showed an increase in PLF between tones 7 and 8, and was significant for C4 gamma (t = -1.74, Figure 7).

The Sensory Sensitivities quadrant was selected to be the dependent variable for regression analysis based on its prevalence in the results of the Spearman's Rho correlation. The following variables were entered into the regression model in one step: PLF of gamma for tone 1 of the series with no deviants, PLF of gamma for tones 1 and 4 of the series with a deviant in the 4^{th} position, and PLF of gamma for tones 1 and 5 of the series with a deviant in the 5^{th} position. The only one that reached significance was Tone 1 of the series of tones that had a deviant in the 4^{th} position for electrodes F3 and F4 (adjusted R square = 0.229, $p = 0.015$). Beta was not included in the regression analysis due to a lack of significant findings in Spearman's Rho.

Discussion

In regards to hypotheses 1.1 and 2.1, a decrease in the synchrony of the brain's frequency response from tone 1 to tone 2 during the series of tones with no deviants was always shown (see Figures 5-16), but was only significant in a handful of responses. Sometimes, a significant difference was only found from tone 1 to tone 3. A decrease in PLF can partially explain the parallel to a gating response, which is suppression in response from tone 1 to tone 2 shown by a decrease in magnitude in PLF. Beta (18-30 Hz) captured the decline in PLF from tone 1 to tone 2 (which parallels a gating response) better than gamma (30-50 Hz), consistent with the findings of Hong et al. (2008). Similarly, Lenz, Schadow, Thaerig, Busch, and Hermann (2007) found that beta relates to sensory processing, specifically the suppression of redundant cortical responses.

As expected in hypothesis 1.3, the first tone of a series did not significantly differ from the deviant tone in either series that had a deviant tone in the gamma frequency band. In the series of tones with a deviant in the 4^{th} position, PLF in the beta region during tone 1 was not significantly different than the 4^{th} deviant tone at any electrode. However, for the series of tones with a deviant in the 5^{th} position, PLF in the beta region during tone 1 was significantly higher than PLF in tone 5 for 2/6 electrodes (F3 and F4). Based on the premise that a deviant tone is a new stimulus, the brain should orient to this sound; therefore, the finding at F3 and F4 was unexpected, but was not further analyzed because the finding was infrequent. For the most part, PLF for the first tone was not significantly different than the deviant tone; however, it is worth further research to investigate this phenomenon, especially because it was unique to electrodes over the frontal lobe and the series that had a deviant occur in a later tone. Understanding what regions of the brain contribute to these findings could provide more specific information regarding the brain-behavior association. However, it is difficult to perform source localization with these data due to limited number of electrodes, thus other studies are needed.

The series with a deviant tone in the 4th position in the beta frequency range demonstrated the expected results best, based on value of PLF per given tone, even though the results often failed to be significant. The series with the deviant tone in the 5th position did not follow the expected pattern as well in either frequency band, nor did the series with a deviant in the 4th position with gamma, although it depended on electrode location. Central sites for gamma (i.e. CZ, C3, and C4) responded in the predicted fashion for the series with the deviant in the 4th position, whereas all frontal sites (i.e. FZ, F3, and F4) had sharp increases of PLF for tone 3, followed by a drop in PLF for tone 4. Even though EEG is not known to be spatially accurate, meaning that we cannot assume that data collected from a particular electrode on the scalp came from brain matter directly beneath it, we can make broad assumptions based on general location of electrode (Cincotti et al., 2004). The frontal lobe is known to be involved in many executive functions, including planning, which requires the ability to look ahead in time and generate hypothesis for future events (Chayer & Freedman, 2001). Thus, it is possible that based on the previous couple of tonal series played, participant brains' were predicting a deviant tone in the

4th position, hence a sharp increase in PLF during the 3rd tone followed by a drop in PLF during the deviant 4th tone. This explanation does not work for the series with the deviant in the 5th position, as no evident pattern emerged.

The increase in PLF between tones 7 and 8 in the series of tones with no deviant was an unexpected trend. This contradicts current literature that demonstrates a habituation effect during long series of tones (Fruhstorfer et al., 1970). Interestingly, this trend was not evident for either tonal series that had a deviant in it, despite the three series of tones being played in pseudorandom fashion. Therefore, we postulate this increase in PLF in the series with no deviant occurred as a result of participants' brains waiting for a deviant tone to occur, and when it did not, more attention was given to the tonal series. This increase in PLF was, essentially, the result of knowledge of the end of the series without a deviant tone.

There were many notable findings addressing hypotheses 3.1 and 3.2, which examined the relationship between PLF and behavioral measures, as measured by the Adult/Adolescent Sensory Profile (Brown et al., 2001). Sensory Sensitivity is one of the low neurological threshold quadrants (see Table 1 on page 10) and there were eight positive correlations found between it and PLF, supporting hypothesis 3.1. This means that better PLF is associated with higher scores for the Sensory Sensitive quadrant. High scores in this quadrant represent people who report being more sensitive to sensory stimuli in the environment compared to others. This is in accordance with hypothesis 3.2 as well, demonstrating that those with better PLF (shown by higher values of PLF) will demonstrate low neurological thresholds. The Sensory Sensitivity quadrant of the AASP has one question in the Taste/Smell Processing category (about disliking strong mints or candies), three questions in Movement Processing (about becoming dizzy easily or feeling uneasy while in a car), three questions in Visual Processing (such as becoming bothered by fast moving images), four questions in Touch Processing (i.e. uncomfortable wearing certain fabrics), one question in Activity Level (about difficulty concentrating while sitting in a long class), and three questions in Auditory Processing (i.e. startling easily at noises or being easily distracted from noise).

One of the negative correlations found between behavioral measures and PLF was for Sensation Avoiding on the AASP, the other low neurological threshold quadrant. This means that the higher the PLF, the lower the score on the Sensation Avoiding quadrant. A low score in any quadrant on the AASP correlates with "almost never" for a given item on the profile, and an overall score of "much less than most people." For example, #18 on the AASP is associated with Sensation Avoiding and says "I keep the shades down during the day when I am at home," and if one put "almost never," that person would get a low score for Sensation Avoiding. Relating this back to PLF, this means that an individual with good PLF might demonstrate very few sensory avoidance behaviors, which intuitively negates Hypothesis 3.2, which stated that high PLF would correlate with low neurological threshold measures.

Sensory Sensitivity is a combination of low neurological threshold and behavioral accordance with this threshold while Sensory Avoidance is a combination of low neurological threshold and counteracting this threshold. Without making too many assumptions because neither one of the quadrants had a lot of significant findings compared to the number of significant correlations possible, this could mean that the findings between PLF and those two quadrants relate more to the behavior associated with the quadrant (in accordance to or counteracting) than they do to the neurological threshold level. Specifically, when encountered with low neurological threshold, higher PLF indicates an accordance rather than a counteracting behavior. This would confirm Hypothesis 3.2 – higher PLF is associated with low neurological thresholds; but it might also mean that accordance (the behavior type) is also associated with higher PLF. This means that an individual with high, or good, PLF will have a low neurological threshold, which means he or she will be more sensitive to stimuli around them. Additionally, this person will be more likely to tolerate his or her sensitivity to the surrounding environment instead of avoiding that environment in the first place.

All of these findings for the Sensory Sensitivity quadrant were for tones 1 and 4 in the series with a deviant tone in the 4^{th} position. Interestingly, this pattern did not occur for the first tone in the series with no deviants, nor for the 5^{th} tone in the series where tone 5 is the deviant. Instead, the deviant tone in the series with the deviant tone in the 5^{th} position demonstrated two positive correlations between PLF and the Sensation Seeking quadrant. This finding demonstrated that the better the phase-locking factor, the more likely an individual to engage in sensation seeking behavior (such as doing things spur of the moment, or seeking out loud noises or lots of movement). The Sensation Seeking quadrant consists of high neurological threshold with counteracting behavior, thus, this finding contradicted hypothesis 3.2, which predicted that better PLF will be associated with lower neurological thresholds. However, since there were only two significant correlations found, these results were not strong enough to reject hypothesis 3.2.

The correlations for gamma were able to capture the majority of the PLF/Behavior correlations, with the correlations for beta only capturing three across all six electrodes and all three series. Short gamma bursts often occur immediately post-stimulus, followed by a larger beta burst (Hong, Summerfelt, McMahon, Thaker, & Buchanan, 2004). This might make sense in light of the current study because people who have better PLF in the gamma frequency region might be sensitive to stimuli because they get the sensation from the stimulus instantaneous. The slower moving beta rhythms that follow this might not correlate to sensory behaviors as well, especially sensory sensitivities, because the feedback associated with the stimulus is not as immediate. It has been hypothesized that early gamma oscillation might be critical for early stages of sensory perception (Traub, Whittington, Buhl, Jefferys, & Faulkner, 1999), thus, better PLF in gamma might lead to better (or more sensitive) sensory perception.

There was only one correlation between PLF and Auditory Processing (the deviant tone in the series with the deviant in the 4th position for site C3 in the beta frequency band). This was unexpected because the entire paradigm used during the EEG recordings was based on auditory tones. Instead, PLF correlated better with Visual Processing (six correlations), Touch Processing (three correlations), Taste/Smell Processing (not shown – seven correlations), and Movement Processing (not shown – three correlations). At first glance, it is easy to assume that the correlations with Visual Processing were because the participants were also watching a movie while listening to the auditory tones. However, PLF by definition is consistency in the brain's response in particular frequencies to a stimulus. This is known to be stronger when the stimulus is presented at regular intervals, such as the auditory tones, rather than randomly presented, as is the case of the movie. So it does not make sense that the movie would be the explanation for strong correlations found. The other correlations found also do not seem to make sense – touch was limited to a computer chair and table, participants were not allowed to eat or chew anything during the recording (nor were the other people that were present in the room), and the participants were asked to sit as calmly as they could without fidgeting during the sessions.

One possible explanation is that sensory processing might be cross-modal; that is, areas of the brain that traditionally respond to one specific sensory stimulus (i.e. visual) might actually respond to multiple stimuli (i.e. visual and auditory). This means that the numerous correlations found between PLF and visual, taste, movement, and touch processing might also account for the auditory component of the sensory stimuli. Laurienti and colleagues (2002) used functional magnetic resonance imaging to show that cross-modal inhibitory processes operate within the traditionally-thought-of modality specific visual and auditory cortexes. Many studies concur with the previously mentioned study, and believe that sensory processing of incoming stimulus might be cross-modal, with many cortices amplifying multi-sensory inputs (Calvert et al., 1999; Laurienti et al., 2003; Kayser & Logothetis, 2007). However, Kayser & Logothetis (2007) warn that in this literature review, there was “no clear connection between functional observations and specific anatomical connections” (p. 121).

From the regression analysis, tone 1 from the series of tones with a deviant in the 4th position better predicted higher scores in the Sensory Sensitivity quadrant than tone 4 of the same series. Even then, this was only evident from electrodes F3 and F4. This was an interesting finding and meant that the first tone in a deviant series, but not the first tone in a non-deviant series, was a better predictor of behavior than deviant tones. A cautious suggestion for this is the expectancy effect, which suggests that the participants in a study are able to predict which series is coming- in this case, the series that has a deviant tone. This would help describe why this particular tone best predicted scores in the Sensory Sensitivities quadrant, but does not explain why the same effect was not found for tone 1 of the series of tones with the deviant in the 5th position.

Limitations

Limitations of this study include a small sample size (38 participants) and a young average age of the participants (roughly 19). This limits the generalizability of the results to both typical adults and children because the brains of these individuals are more developed than children but less developed than adults older than around 25. Another limitation for this study is that compared to how many correlations between PLF and behavior could have occurred (60 for each subtest of the AASP), very few actually did. These findings therefore need to be replicated in order to be considered substantial.

Lastly, a major limitation of the study is the lack of control data. There is no data that looks at the cortical responses to just a series of tones with no deviant. With this control data, it would be easier to discern possible explanations for the unique findings of the series of tones with no deviant. These data are, however, currently being collected by the Brainwaves Research Lab at Colorado State University. Likewise, we do not know how the brain responds when a series of tones with one deviant in the same position is presented continuously without interruption.

Conclusion

This study examined the effects of the Orientation/Habituation auditory paradigm on gamma (30-50 Hz) and beta (18-30 Hz) frequency bands in the brain in addition to correlating these findings with behavioral measures from the Adult/Adolescent Sensory Profile on 38 typically-developing adult participants. The series of tones with no deviant best demonstrated a decrease in PLF from tone 1 to tone 2, evident in both gamma and beta oscillations, as well as across almost all six electrode sites. However, this same series also demonstrated an increase in PLF in response to tone 8, with 8/12 series/electrode site combinations demonstrating this pattern. This finding was unexpected and contradicts current literature. The series of tones with the deviant in the 4^{th} position demonstrated the most expected PLF patterns across the series, occurring in 9/12 series/electrode site combinations. These expected patterns seen in the series of tones with a deviant in the 4th position were: a gating effect from tone 1 to tone 2, an increase in

PLF at the deviant tone, tone 4, and a general decline in PLF for the remaining four tones in the series (similar to a habituation effect).

Gamma correlated far more often than beta in the PLF/behavioral measure correlations. Additionally, the series of tones with deviants in the 4^{th} position correlated better than the other two series, and the first tone in this series best predicted scores on the Sensory Sensitivity quadrant of the AASP. More research is needed to confirm these findings due to a limited number of significant correlations.

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CHAPTER 3

The world we inhabit is full of sensory experiences, and the human brain is usually capable of successfully integrating the abundance of sensory information, followed by the production of a reasonable behavioral output in order to accomplish our occupational goals. An occupation can be defined simply as engagement in a meaningful activity (Hasselkus, 2011), and participation in an occupation that requires the use of multiple body systems, including a working sensory system. One's mind is constantly receiving sensory input via our visual, auditory, vestibular, and proprioceptive systems, to name a few. However, some people experience deficits in sensory integration, and in the 1960's, Dr. Jean Ayres recognized this and coined the term Sensory Integrative Dysfunction (SID, Ayres, 1969). This term, and more recently Sensory Processing Disorder (SPD), is given to those who are unable to organize and appropriately respond to sensory input from the environment. Any dysfunction in sensory processing often manifests through behaviors (Miller & Lane, 2000). SPD is often prevalent in other diagnoses such as autism spectrum disorders (ASD), attention deficit disorder (ADD), attention deficit hyperactivity disorder (ADHD), obsessive-compulsive disorder (OCD), and a variety of anxiety disorders (Dunn & Bennett, 2002; Hofmann & Bitran, 2007; Kern et al., 2006; Marco, Hinkley, Hill, & Nagarajan, 2011; Savage et al., 1994).

Despite consistent controversy regarding the existence and, therefore, treatment of SPD (Hoehn & Baumeister, 1994; Humphries, Snider, & McDougall, 1993), occupational therapists often address SPD during clinical practice with the aforementioned diagnostic groups. A common approach to sensory integration therapy is one developed by Dr. Jean Ayres - an approach which emphasizes incorporating the just-right-challenge of sensory activity in order to attain occupational goals (Ayres, 1972; Miller, Coll, Schoen, 2007; Case-Smith & Bryan, 1999). For children, occupational goals might include being able to play in the sandbox with others, roll down a grassy hill, or be able to focus on what a teacher is saying during class. For adults, these goals might be related to being able to take public transportation, dress in a variety of materials, or being able to converse with friends in a crowded restaurant. Many studies have attempted to demonstrate the effectiveness of sensory-based interventions via measures of behavior, such as with the Sensory Profile (Dunn, 1999) and the Adult/Adolescent Sensory Profile (AASP; Brown, Tollefson, Dunn, Cromwell, & Filion, 2001), but results are often inconclusive (May-Benson & Koomar, 2010; Case-Smith & Arbesman, 2008). Due to inconsistent findings of sensory integration and lack of strong methodology used during research studies, many from occupational therapy and other professions call for more research on the subject (Schaaf & Miller, 2005).

In order to improve SID research, it is important to recognize that Ayres (1969) hypothesized that sensory integration therapy would lead to positive neurological changes in the brain, and a good way to evaluate this hypothesis is by using technology such as electroencephalography (EEG). To test this assumption of SI theory, research has begun to measure neurologic mechanisms in the brain related to SPD. The first step is to understand the intricate details of brain processing of sensory stimuli. In order to do this, a baseline of how typical adults respond to stimuli must be developed, which was done in the current study, then we can compare these responses to those of people thought to have SPD. Thus, the second step is to determine the difference in brain processing between people who have sensory processing difficulties compared to those without these difficulties. Davies & Gavin (2007) performed this comparison with children and concluded that children with SPD demonstrated less sensory gating than their typically developing peers. Like the Davies & Gavin (2007) study, most research on SPD focuses on children, but adults are known to have SPD as well, hence the benefit of the current study. Once we understand these differences, we will be able to develop treatment methods that lead to the positive neurological differences Ayres predicted. Researchers have only begun this process, thus more studies on adults and children alike are needed not only to understand those who have sensory challenges, but also to better understand the developmental trajectory of sensory processing. In the end, this will give us a more unifying representation of brain processing of sensory stimuli and what might be different between children and adults with sensory challenges.

Our study captured the neurologic changes that occurred in response to simple auditory stimuli in typical adults. We showed that when redundant auditory stimuli are presented, typical adults are able to engage in sensory gating, or a decrease in neurological response to repeated stimuli. These results were shown by the decrease in phase-locking factor (PLF) from the first tone to the second or third tone in a series, where the brain response to repeated stimuli became more inconsistent compared the to the brain response to the initial stimulus. This automatic decrease in a neural response, which parallels the gating concept, is important in real life applications because it is what allows one to effectively ignore redundant and unimportant sensory input, such as the sound of boots walking in the hallway during a lecture, or the announcement of an incoming train when socializing with friends.

One important finding from our study was the increase in synchrony of frequency bands to multiple auditory tones, notably, a rise in PLF for tone 8 during the series with no deviants. This finding contradicts other EEG studies and common sense. This was attributed to the combination of multiple series of tones, those with and without deviants, being played and the participant anticipating and acknowledging when a series of tones was played without a deviant. In other words, the participant might be anticipating a series of tones that has a deviant tone even when there is no deviant. If true, this has important clinical implications. It would mean that even adult brains anticipate changes to occur in the stimulus world and focus on (albeit subconsciously) when the changes do not occur.

If one has deficits in sensory processing, he or she might either 1) not anticipate any changes to occur in his or her sensory world, therefore becoming overwhelmed when they do occur, or 2) might over-anticipate changes and become obsessed with the anticipation of change, again subconsciously. We see these behaviors often in people with autism. For example, the author is good friends with an adult with autism who becomes easily obsessed at the thought of a glass container falling on the floor when it is too close to the edge of a surface. This adult over-anticipates change (the glass shattering on the floor) and waits for it to occur, unable to think of anything else. Occupational therapists need to be adept at helping people overcome these anticipatory sensory challenges.

Our study also demonstrated that when there is a deviant sound to the overall pattern, shown as a deviant tone, a neurotypical adult brain responds with an increase in consistent responses to this new sound; however, this finding needs to be replicated as this was a strong pattern for one of the deviant tones, but not the other. It is interesting that the series with the deviant in the 4th position had a more consistent response than the series with the deviant in the 5th position. One possible explanation for this is that when the deviant is in the 5th position, the 4th position had already passed, thus the participant is unsure as to whether or not this series is going to have a deviant or not. Thus, the participant may be second guessing which could cause inconsistency in the responses. When the deviant occurs in the 4th position, there is less uncertainty and the brain can respond accordingly, in a more consistent manner. Measuring the consistency of the brain's response in certain frequencies, or phase-locking, is important for optimal functioning. When time-frequency measures are linked to behavior, as was done in the current study, these measures may be able to identify individuals that have particular behaviors. As mentioned in Chapter 1, particular diagnoses have differential behaviors associated with them. For example, many groups with sensory processing behavioral difficulties, notably those with schizophrenia, have been shown to have deficits in phase-locking (Winterer et al., 2000), as shown by lower PLF values. When these brain-behavior associations are established, then measures such as PLF can become neurological markers for particular diagnoses.

The brain-behavior association can help professionals better understand the neurological underpinnings of behavior. If we understand the neural mechanisms, our treatments can be directed to those specific behaviors associated with the neural deficits. If we are careful to target these behaviors, we are more likely to facilitate lasting changes. These lasting, positive behavioral changes are more likely to be consistently demonstrated throughout life activities, which can lead to increased participation.

In this current study, after testing the neurological changes that occur in response to auditory tones, the results were compared to self-reported scores on the AASP. Our study found that even within neurotypical adults, there is a spectrum of sensory experiences and behaviors, which follow normal distribution patterns. Those with better phase-locking were generally found to have lower neurological thresholds for incoming sensory information, as shown by the correlations between PLF and the Sensory Sensitivity quadrant on the AASP. This means that the better the phase-locking a person has, the lower the amounts of a given stimulus needed necessary for their brains to respond to it. This helps describe the behaviors of certain populations, such as children and adults with autism, that are considered to be sensory sensitive –

it is possible that their brains are better at responding consistently to stimuli than typically developing brains, although this hypothesis should be directly tested.

The last important implication of our findings was that sensory processing is cross-modal in theory, rather than unimodal. Cross-modality was supported via many relationships found between phase-locking factor measured during an auditory task and self-report of visual processing, taste/smell processing, movement processing, and touch processing (categories from the AASP). Implications for therapy include incorporation of many types of sensory stimuli into one therapeutic modality, which could lead to better integration of multi-sensory modalities which could be reflected in EEG measures such as phase-locking.

Our study highlights that examining neurological activity in the brain can, and should be, related back to behavioral differences. This is one of the first studies that related time-frequency, specifically phase-locking factor, to self-reported assessments of responses to sensory stimuli that are often used in occupational therapy. Linking PLF to behavior is a step towards establishing PLF as a neurological marker that could be used both to identify people with sensory processing difficulties and as evidence of treatment effectiveness.

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