THE ELECTROPHYSIOLOGICAL CORRELATES OF AUDITORY DISTRACTION

by

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Dedication

To Martina: my inspiration, my motivation, my hope, my friend, my sister.

Abstract

This thesis used the electroencephalogram (EEG) to measure the electrophysiological correlates of auditory distraction. Chapter One determined that relative to broad-band noise, the presence of a continuous speech signal impaired task performance, attenuated the N1 peak and reduced theta/alpha band inter-trial phase coherence around the latency of the N1. Chapter Two found that reductions of inter-trial phase coherence during distraction were related to both disruptions of gain and the temporal fidelity of evoked responses. Chapter Three found that post-secondary adults with ADHD are not characterized by greater levels of distraction and that this population may be responding to sensory events with abnormally high phase locking. Chapter Three also found that Un-medicated ADHD adults had significantly more N1 latency, theta/alpha band evoked power than Medicated ADHD or Control groups. These results extend the literature on distraction by using time-frequency measures to assess how distraction modulates early sensory processing of stimulus events.

Preface

This thesis balances between a de novo document and a collection of papers. One of the research studies included in this thesis has been published previously (see Ponjavic-Conte, Dowdall, Hambrook, Luczak, & Tata, 2012 for a reference to Chapter 2) and the research study included in Chapter 3 is currently under press (see Ponjavic-Conte, Hambrook, Pavlovic & Tata. Dynamics of Distraction: Competition Among Auditory Streams Modulates Gain and Disrupts Inter-trial Phase Coherence in the Human Electroencephalogram. PLOS ONE. Forthcoming 2013). Note that these papers are not included in the following thesis in their entirety so please see the above references for supplemental information.

In recognizing that modern neuroscience is a team effort and that this work could not have been accomplished without the substantial contributions in particularly of that of my co-authors: Matthew Tata, Dillon Hambrook, Jarrod Dowdall, Sebastian Pavolvic, Artur Luczak, and Noëlla Piquette, you'll notice that I consistently use the word "we" instead of the word "I" throughout the body of the entire thesis in order to honor their contributions to this work.

The work included in this thesis began in collecting data from post-secondary adults with and without Attention Deficit Hyperactivity Disorder (ADHD). After analyzing the Control data (see Chapter 2) we realized that we needed to develop a deeper understanding of the electrophysiological correlates of auditory distraction in a control population before we could develop specific hypotheses about auditory distraction in a post-secondary adult ADHD population.

In Chapter 3 we explored in detail the electrophysiological correlates of auditory distraction in neurologically normal participants. In this study we found a unique correlate of auditory distraction, that is that distraction may be an active process that breaks down the phase coherence between sensory events and the neuro-electric dynamics of the brain; we termed this phenomenon *Distraction Decoherence*. Provided that people with ADHD are described as being easily distracted by extraneous stimuli and that stimulant medications are routinely reported to ameliorate the symptoms of ADHD, in Chapter 4 we predicted that adults with ADHD, in particularly those that are un-medicated would show the most evidence of distraction and Distraction Decoherence. As you will see in Chapter 4, we report data that is contrary to our predictions, that is that greater levels of distraction or Distraction Decoherence do not characterize ADHD in our task and in our sample of participants. The findings in this thesis have important implications about distractibility in ADHD and about the underlying mechanisms of auditory distraction in general. I hope that this work may offer you some deeper insights into the phenomeon that we typically describe as "distraction."

Acknowledgements

The page you are about to read is likely the most important of this entire thesis for without the immeasurable support and help of my family and colleagues, this work could not be accomplished.

Firstly I would like to my supervisor, Matthew Tata. Thank you for snatching me up many years ago and introducing me to the world of research. You have fostered in me both a love of knowledge and an inquisitive mind, two gifts of which I will be forever grateful. Furthermore, you deserve special thanks for dealing with not only a very stubborn graduate student but also one who decided to get married and have a child during her graduate degree. Thank you for your patience, support and for putting up with me. I would also like to thank my co-supervisor Noëlla Piquette and committee members Rob Sutherland and Fangfang Li. Thank you for your guidance and for supporting me along the way.

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support in my life. Thank you for always encouraging me and for all the tears you've dried, the meals you've cooked, the dishes you've washed and the diaper's you've changed. To my son Benedict, thank you for being such a good baby. I especially want to thank you for all your giggles and for motivating me to finish my degree. I'd also like to thank my parents and parents in law for their countless hours of babysitting and all my family and friends for their constant support. A special thank you goes out to my sister, Martina Ponjavic. Despite all the hardships throughout the years it was your unique mind and divine assistance that inspired me to enter this career path and will inspire me to continue on in this path all my days.

Thank you to you all.

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List of Abbreviations

ADHD	Attention-Deficit/Hyperactivity Disorder
ANOVA	Analysis of Variance
ASRS	Adult Attention Deficit Hyperactivity Disorder Self-report Scale
CCBN	Canadian Centre for Behavioural Neuroscience
CPT	Continuous Performance Test
d'	Sensitivity Index (pronouced "dee-prime")
EEG	Electroencephalography / electroencephalogram
ERP	Event-Related Potential
FDR	False Discovery Rate
fMRI	functional Magnetic Resonance Imaging
LSD	Least Significant Difference
MEG	Magnetoencephalogram
MMN	Mismatch Negativity
Nd	Negative difference
PET	Positron Emission Tomography
RON	Reorienting Negativity
TSE	Time Spectral Evolution

"Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called distraction, and Zerstreutheit in German."

William James. (1890). The Principles of Psychology. New York: Henry Holt, Vol. 1, p. 403-404.

Chapter 1: Introduction

1.1 Distraction and Selective Attention

The ability to focus attention on a single source of input amongst the presence of irrelevant information is a process broadly referred to as "selective attention." The process of selective attention undoubtedly requires that certain information be "attended" and other information "ignored." What information is attended or ignored at any given moment is likely a function of the interplay between endogenous and exogenous attentional control, feature salience, individual ability and environmental complexity. Consider the famous cocktail party effect that refers to the problems that arise when of one must attend to a source of sound input while simultaneously ignoring all others. Selective auditory attention is the process by which one overcomes these problems and perceives the selected input. But what are "these problems" that selective attention must overcome? "These problems" are most often associated with the familiar perceptual phenomenon of "distraction." Although the phenomenon of distraction is familiar to most, defining the term perceptually, behaviourally and neurophysiologically is much more difficult.

The Oxford English Dictionary[1] defines distraction as "a thing that prevents someone from concentrating on something else." The dictionary even goes as far as describing distraction as "an extreme agitation of the mind." As a verb, the definition of "distract"[2] is "to prevent (someone) from concentrating on something" or to "divert attention from something." The term distraction/distract is regularly

[1] http://oxforddictionaries.com/definition/english/distraction?q=distraction
[2] http://oxforddictionaries.com/definition/english/distract?q=distract

defined as being opposed to the processes of attention. William James (1980) to defines distraction in this way:

> "Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called distraction, and Zerstreutheit in German."[3]

In his quote (see above) William James states, "Everyone knows what attention is." This statement also indirectly suggests that everyone must then know what distraction is. And indeed if one were stop and ask a someone at random what distraction is, they would likely explain the term as opposed in some way to the processes of attention. In fact, the vast majority of people believe that the term "distraction" is so intuitive that it is used as symptom criterions in mental disorders (DSM-IV; American Psychiatric Association, 1994) and even to formulate laws.[4] The widespread implications of the word "distraction" is unnerving given that there is no generally accepted operational definition of the term. Given that the word "distraction" is routinely defined as being opposed to the processes of attention, understanding the processes of selective attention may help serve to develop insight into the mechanisms of distraction.

What is selective attention? Broadly speaking, selective attention is the ability to focus on a sensory input or subset of inputs while simultaneously ignoring all others (Gazzaniga, Ivry, & Mangun, 2009). The human brain, while marvelous, has a

[3] William James. (1980). The Principles of Psychology. New York: Henry Holt, Vol.1, p. 403-404.
[4] Title: 2010 (27th, 3rd) Bill 16, Traffic Safety (Distracted Driving) Amendment Act, 2010

limited capacity for the selective and conscious processing of sensory inputs (Broadbent, 1958). Entry into this limited capacity system is likely governed by the interplay of top-down (voluntary/goal-directed/endogenous) and bottom-up (stimulus-driven/reflexive/ exogenous) attentional processes (Tamber-Rosenau, Esterman, Chiu, & Yantis, 2011). Top-down attention reflects our ability to focus on an input or train of action and is particularly important for goal-directed behavior. Bottom-up attention is the capturing of attention by sensory inputs outside the locus of attentional selection; it is important for things such as the evaluation of potentially important inputs (Gazzaniga, et al., 2009). For example, presumably you are using top-down attentional control to focus on the words as you read them on this page. However, it would not be advantageous for you if you were so focused at reading that you missed a knock on the door. Balance between top-down and bottom-up attentional control are particularly important. Imbalances of top-down and/or bottom-up attentional control are often characterized in terms of distractibility and are manifested in people with psychiatric disorders such as Attention-Deficit Hyperactivity Disorder (ADHD). Escera and colleagues (Escera, Alho, Schroger, & Winkler, 2000) describe the relationship between distraction and top-down/bottom-up attentional control nicely:

> "Distraction denotes the involuntary redirection of ones attention from some goal-oriented behavior to other aspects of the environment. Lack of distractibility points to the dominance of top- down control of attention whereas increased distractibility suggests an abnormally low threshold for the breakthrough of the unattended (in most cases irrelevant) information."

For the purposes of this work, distraction will be referred to phenomenologically as a feeling of being disturbed in the ongoing mental activities

of a goal-directed behavior by task irrelevant events and behaviourally by deteriorations in task performance (Schroger, Giard, & Wolff, 2000). Electrophysiologiaclly, the correlates of distraction remain to be elucidated.

1.2 EEG Methodology

Neuroimaging techniques such as the human electroencephalogram (EEG) and its magnetic counterpart, the magnetoencephalogram (MEG) have been used extensively to study the mechanisms of selective attention (EEG mostly because of the relative inexpensive cost). Given that the processes of attention (e.g. orienting and re-orienting) can occur within seconds, these measures are particularly well suited for studying attention because of their high-temporal resolution (on the order of milliseconds).

EEG measures the scalp-recorded electrical activity of the brain. More specifically, EEG measures the combined activity of millions of pyramidal cells that span the layers of the cortex. The cell bodies of pyramidal cells are arranged parallel to each other and perpendicularly to the scalp. The post-synaptic potential (neurotransmitter induced changes in transmembrane voltage) of a single pyramidal cell is too small to be measureable at the scalp but the combined extracellular fields (local field potentials) of millions of spatially aligned, synchronous pyramidal cells are. Modern EEGs use multiple electrodes (dense array) to measure the distribution of voltage across the scalp. Typically differences of voltage are compared between a single reference electrode and an electrode(s) of interest; however, this can make the

EEG particularly sensitive to noise (i.e. random electrical activity such as the electrical hum at 60 Hz).

The high-temporal resolution of EEG and MEG measures comes at the cost of poor spatial resolution. A dense array EEG is able to create a topographic map of the distribution of voltage across the scalp that allows one to estimate neural sources of activity. However, because electrical fields are prone to distortion as they propagate through the scalp (due to different electrical resistances of cerebral spinal fluid, the skull etc.), these topographic maps of voltage are blurred and diffuse consequently making it difficult to estimate neural generators. MEG is better suited than EEG at estimating neural generators of activity because magnetic fields are not prone to distortion like electric fields are. Although EEG and MEG can be used in some capacity for source localization, neuroimaging techniques such as the functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET) are better suited for resolving cortical and sub-cortical activity of the brain.

Although the EEG is continuously recorded during an experiment, often researchers are more interested in the cognitive activity occurring moments slightly before and slightly after an event of interest. Capturing event related activity of the scalp-recorded EEG can be done in a variety of ways, the most popular being the event-related potential (ERP) technique. In creating the ERP, multiple intervals of time that share the same experimental condition are averaged within participants and then across participants to create a grand-averaged ERP waveform. The process of averaging isolates evoked activity related to the stimulus of interest and minimizes the background noise (i.e. activity unrelated to the evoked response). Thus ERPs are useful in visualizing cognitive processes related to a given experimental manipulation.

ERPs are typically described in terms of their components, which are a series of positive and negative deflections clearly visible in the ERP waveform. For example, the N1 or N100 component is a negative component of the ERP occurring at approximately 100 ms post-stimulus; this component will be discussed extensively throughout this work.

The ongoing-recorded EEG is compromised of numerous overlapping sine waves, each with their own frequency (wavelength), amplitude (power) and instantaneous phase (location within the wavelength). In order to visualize the oscillatory activity of a given frequency at a given time a complex demodulation is necessary to transform the EEG into time-frequency space. First the EEG signal is demodulated using a discrete algorithm that separates and computes power or phase at separate frequencies over a particular interval of time. This time-frequency decomposition is applied to each trial and then subsequently averaged across trials and ultimately participants. Subsequently, cortical activity can then be categorized by phase (e.g. inter-trial phase coherence) or power (e.g. total power, evoked power, induced power) and visualized in a time-frequency plot.

Time-frequency decompositions of power compute power changes relative to a pre-stimulus baseline (a frequency specific measure of ongoing activity (noise) typically 200 ms or 100 ms before stimulus onset) (Makeig, 1993). Total power is a composition of both evoked and induced power. Evoked power and induced power differ in their phase relationship to an eliciting stimulus. Evoked power is phase-locked to a stimulus (evoked activity is what compromises the ERP). Induced power is time-locked but not phase locked to a stimulus, thus induced power can be considered background activity that is modulated by not evoked by a stimulus.

Induced power is believed to reflect higher-order cognitive operations such as interactions within and between different cortical structures (Bastiaansen & Hagoort, 2003). In order to reveal power that is induced, evoked power is subtracted from total power. Therefore induced power is the power that cannot be explained by evoked or baseline power. Further discussion of total, evoked and induced power is taken up in Chapter 3. The work in this thesis also makes substantial use of the time-frequency decomposition of phase in a measure known as inter-trial phase coherence. Inter-trial phase coherence measures the similarity of the phases of signals over many repetitions. The values of inter-trial phase coherence range from 0 to 1 with 1 meaning perfect phase consistency across trials. The synchronization of phase is believed to play a substantial role in neuronal communication and even selective attention (Womelsdorf & Fries, 2007b).

The frequency spectra of the EEG can be divided into different frequency bands: Delta (0-4 Hz); Theta (4-8 Hz); Alpha (8-12 Hz); Beta (12-30 Hz) and Gamma (>=30 Hz). The role of theta, alpha and gamma frequency bands will be discussed routinely in subsequent chapters. Theta oscillations have been associated with a variety of cognitive tasks such as declarative memory, successful memory encoding, and virtual navigation. Alpha oscillations are involved in cortical inhibition as well as processes associated with attention and memory. Gamma oscillations are implicated in a variety of cognitive processes such as the encoding, retention and retrieval of sensory information. For an overview of theta, alpha and gamma oscillations see (Bastiaansen & Hagoort, 2003; Sauseng & Klimesch, 2008). Also see (Luck, 2005) for an overview of EEG methodology.

1.3 Indices of Selective Attention as revealed by the EEG

Decades of research have used the EEG in the study of selective attention. Research has revealed that the brain processes attended and unattended inputs differentially at early stages of cortical processing. Some of the first pioneering work on selective attention was done in the auditory modality using the EEG. In their study, Hillyard, Hink, Schwent & Picton (1973) presented a stream of randomized tone pips simultaneously to each ear (Hillyard, Hink, Schwent, & Picton, 1973). Subjects were instructed to attend to one of the two ears in order to detect the presence of a slightly higher pitched deviant tone amongst standard tones in that ear. They found that the N1 component evoked by tones in the attended ear were substantially larger than the N1 evoked by tones in the unattended ear; in other words, they found that the N1 was enhanced by attention. The amplitude of the N1 appeared to be an index of how much attention was being allotted to the processing of the selected channel. In their interpretation they suggested that the attention effect observed in the N1 represented a selective facilitation of the processing of a stimulus set or a to-be attended channel.

The N1 component of the ERP is generated by bilateral dipoles in the auditory cortices of the supratemporal plane (Giard et al., 1994; M. G. Woldorff et al., 1993) and is maximal at central electrode sites. The N1 is considered to be a stimulus-driven/exogenous component of the ERP. The general consensus is that the N1 represents an "attention capturing signal" that triggers the conscious perception of incoming external stimuli. Although the N1 informs the brain that some stimulus is occurring it does not appear to have a role in the discrimination of or response to the eliciting stimulus. However, it may have a role in facilitating

related sensory and motor processes (Naatanen, 1988, 1990; Näätänen, 1992). As previously stated, the effects of attention modulate the auditory N1; however, the mechanisms by which the brain is able to augment attended inputs and attenuate unattended inputs remains to be clarified.

Hillyard et al. (1973) proposed that attentional enhancement of the exogenous N1 was due to a sensory amplification of attended inputs. This sensory amplification has also been referred to as a "gain control" or "gating" mechanism that regulates the magnitude of neural activity of the generator cells in the auditory cortex according to the amount of attention being allocated to a specific input (Hillyard, Vogel, & Luck, 1998). Accordingly, unattended sensory inputs are thus inhibited or "gated" at the sensory periphery (Hillyard, 1985). A sensory gain amplification mechanism (as reflected in the N1 attentional enhancement) is suggested to result in an improved signal-to-noise ratio of attended inputs that is associated with improvements in signal detection and behavioural performance (Hawkins et al., 1990).

Hillyard's view was soon challenged. Using a similar paradigm to Hillyard et al., (1973) but presenting tones with a constant inter-stimulus interval (ISI), Naatanen and colleagues (Naatanen, Gaillard, & Mantysalo, 1978; Naatanen & Michie, 1979) suggested that early preferential processing of attended inputs and associated augmentation of the N1 due to selective auditory attention were due not to an amplification of attended inputs but to a prolonged endogenous attentional related component (which he termed the processing negativity) that overlaps with the exogenous N1. Naatanen (Naatanen, 1982, 1990) proposed that a matching process that selected stimuli for further analysis, of which he referred to as an

"attentional trace," generates the processing negativity. Thus in this view, modulation of the exogenous N1 and the selection of attended inputs for further processing is not solely due to an exogenous modulation of sensory gain but due partly to an endogenously originating attentional trace.

The "processing negativity" or otherwise referred to as the "negative difference," (Hansen & Hillyard, 1988) is elicited by attended tones, occurs as early as 20 to 50 ms post-stimulus (M. Woldorff, Hansen, & Hillyard, 1987) and has a pronounced negative deflection occurring around the latency of the N1 component (100 ms) termed the "early negative difference" or the "early Nd" (Hansen & Hillyard, 1988). The early Nd is the earliest ERP modulation associated with the sustained focusing of auditory attention (Donald & Young, 1982) and is a factor of both sustained attention and time. Donald & Young (1982) presented trains of auditory sequences concurrently to both ears while subjects attended to target stimuli in a particular ear. Analysis of ERPs to individual tones of each train showed that the early Nd and consequently, augmentation of the N1, needed approximately 30 to 45 seconds to develop. Similar results indicating that the attentional enhancement of the N1, is a factor of both sustained attention and time have been reported elsewhere (Hansen & Hillyard, 1988). Further support for this notion is that the earliest modulations of the ERP due to sustained auditory attention differ in both latency and topography from that of the earliest ERP correlates of transient auditory attention (Schroger & Eimer, 1993; Tata & Ward, 2005).

Other work has emphasized the role of oscillatory dynamics in the generation and modulation of the ERP. A prominent theory about the neurophysiological mechanisms underlying the generation of an ERP is that a

sensory event can "reset" and transiently lock the phase of various oscillating neural ensembles (Fuentemilla et al., 2009; Klimesch, Sauseng, Hanslmayr, Gruber, & Freunberger, 2007; Makeig et al., 2002; Sauseng et al., 2007). This model is often referred to as the oscillatory model of ERP generation. As follows, any process that interferes with the temporal fidelity of phase resetting will have the effect of reducing ERP peak amplitudes. The oscillatory model of ERP generation is in contrast to the classical view of ERP genesis that states that the ERP arises due to an additive fixed-latency, fixed polarity evoked potential (Fuentemilla, Marco-Pallares, & Grau, 2006; Sauseng, et al., 2007). In either case, an increasingly prevalent view of the role of oscillatory dynamics in attention is that synchronization of oscillating ensembles at various frequencies provides the means to differentially select one representation of sensory input, memory, or response selection (Borisyuk, Chik, & Kazanovich, 2009; Breve, Zhao, Quiles, & Macau, 2009; Fries, 2005; Fries, Womelsdorf, Oostenveld, & Desimone, 2008; Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Schroeder & Lakatos, 2009; Womelsdorf & Fries, 2006, 2007b). For example, recent EEG and MEG studies have shown increased gamma-band synchronization for attended versus unattended stimuli in auditory and visual cortices (Womelsdorf & Fries, 2007b).

Top-down cortical processes such as that of selective attention are hypothesized to be mediated by the small-scale or large-scale coherence of neuronal ensembles. Coherence requires a high temporal fidelity of the instantaneous phase of EEG oscillations, the phase of which can be modulated both by extrinsic and intrinsic signals (Engel, Fries, & Singer, 2001). Modulations of phase are suggested to be a mechanism by which the brain can control neuronal firing patterns and

communication; consequently such modulations of phase are suggested to be crucial for the processing of sensory stimuli (Klimesch, Sauseng, & Hanslmayr, 2007; Sauseng & Klimesch, 2008; Womelsdorf & Fries, 2007b). Sensory selection has also been proposed to be due to the entrainment of low-frequency oscillations to stimuli presented in a selected input channel. Stimuli occurring outside the focus of attention (such as distracter events) are consequently left to wander off in random phase thereby degrading their perception (Schroeder & Lakatos, 2009).

Phase coherence can be measured and described in a variety of ways such as the phase coherence between different brain regions, the phase coherence between different frequency oscillations and the phase coherence to stimulus presentation. For the purposes of this thesis, descriptions of phase coherence or synchronization refer to the phase coherence to stimulus presentation, otherwise known as inter-trial phase coherence. Understanding how inter-trial phase coherence is modulated in various conditions can offer insights into neural correlates of cognitive processes such as that of selective attention.

1.4 Attention Deficit Hyperactivity Disorder (ADHD)

As stated previously, imbalances of top-down and/or bottom-up attentional control are often characterized in terms of distractibility and are manifested in people with psychiatric disorders such as ADHD. ADHD is generally thought of as a childhood disorder but it is estimated that 36 percent of people diagnosed with ADHD as a child continue to meet diagnostic criteria in adulthood (Kessler, Adler, Barkley, et al., 2005). Inattention and Hyperactivity/Impulsivity are two domains of major symptom impairments in ADHD; however, the symptom most commonly

associated with people with ADHD is their tendency to be "easily distracted by extraneous stimuli" (American Psychiatric Association, 1994). Although a predisposition towards distraction is regularly exhibited in people with ADHD, such symptoms are likely a manifestation of a larger disturbance in top-down cortical control which includes executive functions such as goal-directed behavior, response planning, working memory and selective attention; all which have been reported to impaired in ADHD (Barkley, 1997; Sergeant, 2000).

Cognitive impairments in the ADHD population have been reported to be due to disturbances in the frontal-striatal network and a hypofunctioning dopaminergic system (Bush, Valera, & Seidman, 2005; Holroyd, Baker, Kerns, & Muller, 2008). Catecholamines, such as dopamine, have a strong influence on cortical function specifically on the pre-frontal cortex which plays a strong role in executive functioning (Arnsten & Li, 2005). Several lines of research have linked disturbances of the dopaminergic system to ADHD. Genetic studies have revealed polymorphisms of dopamine transporter (DAT1) and dopamine receptor (DRD4) genes that alter dopamine transmission and lead to lower levels of synaptic dopamine (Swanson et al., 2000). Further support for the link between ADHD and the catecholaminergic system comes from the general observation and pharmacological evidence that medications with strong dopaminergic action (e.g. methylphenidate) ameliorate core symptoms (inattention and hyperactivity/impulsivity) of ADHD and improve overall executive functioning (Solanto, 2002). However, drug associated improvements in cognitive functioning are not limited to the ADHD population but have also been observed in the general population (Maher, 2008).

Several studies have investigated the effects of stimulant medications using the human electroencephalogram (EEG) (Barry, Johnstone, & Clarke, 2003), however these studies predominantly address the effects of stimulant medications in children and adolescents with ADHD. Coagulating the literature between children and adults with ADHD is difficult given that their psychological and clinical profiles differ from one another (Downey, Stelson, Pomerleau, & Giordani, 1997). Very few EEG studies to date have investigated the effects of stimulant medications in adults with ADHD (Bresnahan, Anderson, & Barry, 1999; Bresnahan & Barry, 2002; Bresnahan, Barry, Clarke, & Johnstone, 2006). Moreover, these studies tend to use eyes-open or eyes-closed resting state EEG to examine differences between ADHD and control groups (Bresnahan, et al., 1999; Bresnahan & Barry, 2002; Koehler et al., 2009; Lazzaro et al., 1999). Thus a goal of this thesis was to explore differences in event-related activity as measured by the EEG between Medicated and Un-medicated adult ADHD groups.

The tasks used in this thesis resemble that of a continuous performance test (CPT). CPTs have traditionally been used to study attention in both control and clinical populations such as the ADHD population (e.g. (Wu, Gau, Lo, & Tseng, 2012)). In typical CPTs, target and non-target stimuli are presented randomly over an extended period of time; participants are instructed to make responses to target stimuli and inhibit responses to non-target stimuli. Various indexes of attention can be measured in a CPT such as errors of omission or commission, hit rate, accuracy, d' and reaction times (Riccio, Waldrop, Reynolds, & Lowe, 2001). Although CPTs are commonly used to study attention, our tasks were used to study distraction both behaviourally and electrophysiologicaly in the auditory modality.

1.5 Research Goals

In this thesis there are three studies investigating the neural correlates of auditory distraction. Emphasis is placed on ERP and oscillatory activity occurring at or around the N1 latency during distraction. Various EEG investigations have revealed that the N1 is attenuated in the presence of competing auditory streams, however modulations of time-frequency measures such as power or inter-trial phase coherence due to distraction is relatively unknown. Since the magnitude of a peak in the ERP waveform can be modulated by differences in inter-trial power but also by differences in the stability of EEG phase across trials, in Chapter 2 we sought to characterize the effect of distraction on inter-trial power and inter-trial phase coherence around the latency of the N1. The goal of Chapter 3 was to replicate the effects of distraction reported in experiment one, in particular the reduction of inter-trial phase coherence in the theta-band at the N1 latency. Given that the inter-trial phase coherence measure is sensitive to both modulations in sensory gain (amplitude) and the phase consistency across trials, we reconsidered whether reductions of inter-trial phase coherence during distraction are related to sensory gain, phase inconsistency or a combination of both mechanisms by separately evaluating spectral changes in both evoked and induced power. Given the premise that certain groups of people are differentially suseptible to distraction, in Chapter 4 we sought to charaterize the elctrophysiological correlates of distraction in the auditory modality in post-secondary adults with and without ADHD. We tested the hypothesis that people with ADHD (in particular those that are un-medicated) would show the most evidence of distraction. Specifically we tested the hypotheisis

that they would show more evidence of phase instability (distraction decoherence) across trials around the N1 latency than Control or Medicated ADHD groups.

Chapter 2 : Neural Correlates of Auditory Distraction revealed in theta band EEG

2.1 Abstract

Selective attention involves the exclusion of irrelevant information in order to optimize perception of a single source of sensory input; failure to do so often results in the familiar phenomenon of distraction. The term "distraction" broadly refers to a perceptual phenomenon. In the present study we attempted to find the electrophysiological correlates of distraction using an auditory discrimination task. EEG and ERP responses to identical stimuli were compared under two levels of distraction (continuous broad-band noise or continuous speech). Relative to broad-band noise, the presence of a continuous speech signal in the unattended ear impaired task performance and also attenuated the N1 peak evoked by non-target stimuli in the attended ear. Since the magnitude of a peak in the ERP waveform can be modulated by differences in inter-trial power but also by differences in the stability of EEG phase across trials, we sought to characterize the effect of distraction on inter-trial power and inter-trial phase coherence around the latency of the N1. The presence of continuous speech resulted in a prominent reduction of theta EEG band inter-trial phase coherence around the latency of the N1. This suggests that distraction may act not only to disrupt a sensory gain mechanism but also to disrupt the temporal fidelity with which the brain responds to stimulus events.[5]

[5] This chapter is adapted from is adapted from Ponjavic-Conte, K.D., Dowdall, J.R., Hambrook, D.A., Luczak, A. & Tata, M.S., 2012. Neural correlates of auditory distraction revealed in theta-band EEG. *NeuroReport* 23(4), 240-245.

2.2 Introduction

Selective attention entails the focus of sensory and perceptual mechanisms on a single source of input despite the presence of irrelevant information. In the auditory modality these sources of input are often referred to as streams (Bregman, 1990). Focusing on one stream of auditory information while ignoring others is known as auditory selective attention and the failure to maintain this selection is known as the perceptual phenomenon of distraction. Early research in auditory selective attention (Broadbent, 1952; Treisman, 1964) revealed that selection is sometimes incomplete such that competing information can become incorporated into the contents of auditory awareness and disrupt perception of the selected stream. Elucidating the neural correlates of attentional selection became a foundational goal of cognitive neuroscience, however the concept of distraction has gone relatively unstudied.

Investigations of auditory selective attention using the electroencephalogram (EEG) and Event-Related Potential (ERP) revealed that the responsiveness of sensory systems depends on the attentional state of the perceiver. One prominent effect is an increase in the N1 component of the auditory ERP evoked by attended relative to ignored stimuli (Hillyard, et al., 1973; Näätänen, 1992 for review). Although the perceptual effects of attention are manifested within a few 100 ms of orienting, the augmented sensory response occurs only after attention is focused on the target stream for tens of seconds (Donald & Young, 1982; Hansen & Hillyard, 1988), but not when attention is frequently reoriented (Schroger & Eimer, 1993; Tata, Prime, McDonald, & Ward, 2001; Tata & Ward, 2005) as would be expected in conditions of high distraction. Recent work has confirmed that the presence of

competing auditory streams attenuates components of the auditory ERP in the 100 – 200 ms latency range; (Ahveninen et al., 2011; De Chicchis, Carpenter, Cranford, & Hymel, 2002; Hymel, Cranford, Carpenter, & Holbert, 2000; Hymel, Cranford, & Stuart, 1998; Krumm & Cranford, 1994) however, the neurophysiological basis for this effect remains unclear.

Modulations of the N1 in selective attention experiments (Hillyard, et al., 1973) has lead to the theory that attention acts to modulate the "gain" of both the auditory (M. G. Woldorff, et al., 1993) and also visual (Hillyard, et al., 1998) systems. The "gain control" theory of attention holds that the neural responses of sensory stimuli are potentiated relative to physiological noise (e.g. neural responses to task-irrelevant events). For example, cells encoding the features of attended objects might be the target of a biasing signal enabling pre-selected cells to evoke a larger response than cells that encode features that do not match the attentional template (Luck, Chelazzi, Hillyard, & Desimone, 1997).

Other work has emphasized the effect of selective attention on oscillatory signals in the EEG. Substantial effort has attempted to link oscillatory phenomena – particularly phase locking of signals between two or more neural assemblies - to perceptual processes such as binding features into objects, attentional selection of objects from a complex scene, and entry of sensory input into consciousness (Doesburg, Green, McDonald, & Ward, 2009; Doesburg, Kitajo, & Ward, 2005; Doesburg, Roggeveen, Kitajo, & Ward, 2008; Engel, et al., 2001; Fries, 2005; Fries, et al., 2008; Ward, Doesburg, Kitajo, MacLean, & Roggeveen, 2006; Womelsdorf & Fries, 2006, 2007b; Womelsdorf, Vinck, Leung, & Everling, 2010).

Importantly, in the context of oscillatory dynamics measured in the scalp-

recorded EEG, a reduction in the N1 component of the auditory evoked potential due to distraction would appear as a reduction in sensory gain if there were a decrease in power or amplitude relative to a pre-stimulus baseline. However, distraction may manifest in other ways. For example, distraction might disrupt the temporal fidelity of brain responses relative to the events that triggered them. The notion that distraction or unfocused attention might "jitter" brain responses in time, rather than modulate sensory gain, was suggested to explain the influence of attention on the 40-hz auditory response (Tiitinen et al., 1993). If this were the case, the effect of distraction would appear as a reduction of inter-trial phase coherence of EEG oscillations when considered over successive trials.

The dynamics of oscillations in neuronal networks has come under intense scrutiny with respect to the notion of attention and selection (Fries, 2005; Womelsdorf & Fries, 2007a). In this study we investigated the neural correlates of distraction by considering the relationship between the auditory ERP and measures of brain oscillatory activity. In particular, we considered whether distraction modulates sensory gain, inter-trial phase coherence or both. Attenuation of early ERP components due to distraction might reflect a reduction of sensory gain afforded by attentional processes. We also considered whether distraction disrupts inter-trial phase coherence. Put another way, we asked whether distraction introduces temporal jitter into the time-locking of brain responses relative to the events in a task-relevant target stream. Thus, we measured the effect of distraction on inter-trial power, inter-trial phase coherence and on the classical auditory ERP. We found not only that distraction attenuated the N1 peak but that this was associated with reduced inter-trial phase coherence in the theta EEG band.

2.3 Methods

Twenty-two undergraduates participated for course credit. Participants were excluded if they screened positive for Attention Deficit Hyperactivity Disorder, (Kessler, Adler, Ames, et al., 2005) did not follow task instructions, or made excessive eye movements. Thus 14 participants contributed data to the analysis (9 female; 1 left-handed; average age: 23.6). Participants provided informed written consent. Procedures were in accordance with the Declaration of Helsinki and were approved by the University of Lethbridge Human Subjects Review Committee.

Stimuli were presented on a desktop computer with sound attenuating ear-bud headphones. The OpenAL audio library was used to render sounds to 90 degrees left or right of midline. Volume was individually adjusted. Trials were presented in 28 1-minute long blocks following a practice session. In each block participants heard target and non-target noise bursts on one side and a distracting sound on the other side. Targets and non-targets were each 60 ms in duration and consisted of two brief noise bursts separated by a 20 ms or 40 ms silent gap, respectively. Ten target and 20 non-target stimuli were pseudorandomized and inter-trial intervals were randomly distributed over 1750 to 2250 ms. The distracting sound was either a "low-distraction" continuous broad-band noise or a "high-distraction" condition consisting of randomly selected segments of an audio book. The root mean square amplitude of each low-distraction stream was matched to that of each high-distraction stream. Participants were instructed to attend to the target stream, press the "space" key when a target sound occurred and to ignore the distraction.

Mean response times, accuracy, proportion of hits and false alarms and sensitivity to detect the target sound (d') were collapsed across blocks and the side of

presentation such that we tested the prediction that distraction (high vs. low) impaired perception by one-tailed t-tests.

The EEG was recorded with 128 Ag/Ag-Cl electrodes in an Electrical Geodesics Inc., (Eugene, OR, USA) system. The sampling rate was 500 Hz and impedances were maintained under 100 kilo-ohms. Data were analyzed using the BESA software package (Megis Software 5.3, Grafelfing, Germany). The EEG was visually inspected for bad channels and a small number of electrodes (8 or fewer) were replaced with an interpolated signal. Event related potentials (ERPs) were time locked to presentation of target and non-target sounds with a 200 ms pre-stimulus baseline (high-pass (0.5 Hz, 12dB/octave); low-pass (30Hz, 48 dB/octave) zero-phase Butterworth filters; re-referenced and interpolated to a standard 10-10 average-reference montage). Epochs containing artifact (amplitude >+/- 120 μV, gradient >+/- 75 μV/ms, or SD of gradient < 0.001 μV/ms) were rejected. Participants with less than 30 epochs remaining in each condition after artifact rejection were excluded from further analysis. Below we present data only for the 14 participants who met criteria on correct rejections of non-target trials (average number of trials: low-distraction 149.7; high-distraction 135.4). A small subset of these subjects (n=9) also met criteria for hits on target present trials (Please see Chapter 4 for hit analysis). When data from these 9 subjects were analyzed all of the effects reported below for correct rejections appeared as non-significant trends in the same direction.

The N1 peak (92 ms latency) for correct rejections in both distraction conditions was identified at electrode Cz (Fig 1a). Mean amplitudes of the N1 (+/- 6 ms window spanning the peak) in each condition were compared using a two-tailed t-test. Inter-trial phase coherence and total power were computed using BESA and

MATLAB.

Inter-trial phase coherence (ITC) was calculated by the following:

$$ITC_{t,f} = \left| \frac{1}{N} \sum_{k}^{N} e^{i\theta_{k,t,f}} \right|$$

where N is equal to the number of trials, and θ is the phase of trial k at a given frequency (f) and time (t). Inter-trial phase coherence is a measure of the similarity of the phases of signals over many repetitions. The values of inter-trial phase coherence range from 0 to 1 with 1 meaning perfect phase consistency across trials. Lower values of ITC suggest temporal heterogeneity of brain responses across trials.

Time-spectral evolution (TSE) of power is defined as:

$$TSE = \frac{A(t,f) - A_{baseline}(f)}{A_{baseline}(f)} * 100\%$$

where A(*t, f*) is the activity (in power) at time *t* and frequency *f* and is the mean activity over the baseline epoch at frequency *f*. TSE of power ranges from [-100% to +∞], is relative to baseline for a given frequency at time *t* and is relatively insensitive to phase.

The EEG was transformed into time-frequency space by complex demodulation (Hoechstetter et al., 2004) between 4 and 46 Hz from -200 to 800 ms in 2 Hz/25 ms steps. This implementation of complex demodulation applies a zero-phase Gaussian filter thereby blurring power in time. Grand averaged inter-trial

phase coherence and TSE of power plots under low and high-distraction conditions at electrode Cz (Fig 2a; Fig 2b) were computed in MATLAB using the Fieldtrip (F.C. Donders) toolbox.

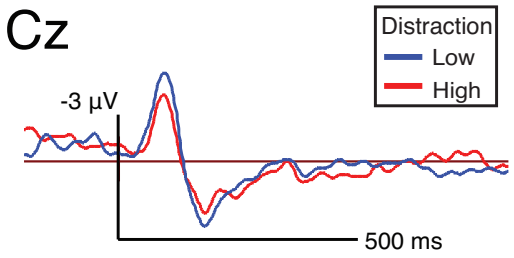
To compare the two distraction conditions, we used a non-parametric random-sample permutation method and applied a Bonferroni-like false-discovery rate (FDR) correction method to control for multiple comparisons across time and frequency bins (Benjamini & Hochberg, 1995). A surrogate distribution was built for each participant by randomly shuffling trials between low- and high-distraction conditions (thus preserving the original number of trials in each condition) and then by re-computing the difference between conditions. This process was repeated 40 000 times for each participant to create a surrogate distribution of differences. The surrogate distributions were then averaged to produce a grand-average surrogate distribution of differences. The original grand-average difference was then compared to this surrogate distribution of differences, and a two-tailed P-value (2 x the proportion of surrogate differences that fell beyond the observed difference) for each time/frequency bin was obtained. Differences between low- and high-distraction conditions in inter-trial phase coherence and TSE of power at electrode Cz were compared using the same procedure.

2.4 Results

Distraction (high vs. low) reduced sensitivity to detect the target (d') (t_{13}= 2.171; p=0.025) and increased the rate of false alarms (t_{13}=2.766; p=0.008). Participants made more hits in the low-distraction condition, and responded more slowly in the high-distraction condition, however these effects were not significant.

ERP analysis revealed a prominent N1 peak in the low-distraction condition and an attenuation of this N1 peak in the high-distraction condition (t_{13}=3.463; p=0.004) (Figure 2-1A). The N1 was maximal at electrode Cz with a peak latency of 92 ms. The isopotential map of the N1 difference across distraction conditions at 92 ms (Figure 2-1B) revealed a fronto-central focus.

A)



B)

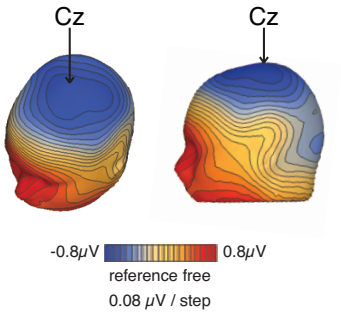


Figure 2-1: ERP waveforms evoked by target-absent correct-rejections. 2-1A) ERP waveform evoked by non-target correct rejections under low and high-distraction conditions at Cz. N1 is maximal at 92 ms and is attenuated in the high-distraction condition [t_{13}=3.463; p=0.004]. 2-1B) An isopotential map of the N1 peak difference across distraction conditions reveals a fronto-central focus.

High-distraction had a pronounced effect on theta-band inter-trial phase coherence and a smaller effect on theta-band TSE of power (Figure 2-2; Figure 2-3). Also evident was a trend of more gamma power in the low-distraction condition at the N1 latency (Figure 2-3 (iii)). We observed no significant differences in the absolute amplitudes of the baselines between the low and high-distraction conditions.

Twenty-six time-frequency bins around the N1 latency/theta frequency (4 to 8 Hz) range for inter-trial phase coherence reached significance with fifteen out of the twenty-six bins having a p value of less than 0.0001. Unlike inter-trial phase coherence, none of the time-frequency bins for TSE of power passed the FDR threshold (Figure 2-2(iv); Figure 2-3(iv)) and none of the time-frequency bins around the N1 latency/theta frequency for TSE of power reached significance when unthresholded p-values were considered (i.e. not corrected for multiple comparisons and thus much less conservative).

In a further analysis we chose a time-frequency bin (100 ms/6 Hz) that was closest to our N1 peak and in the middle of the theta frequency range. For every participant, this time-frequency bin exhibited greater inter-trial phase coherence on low-distraction trials. However, in contrast to inter-trial phase coherence, only eight of the 14 participants showed greater theta-band power at the 100 ms/6 Hz time-frequency bin in the low relative to high-distraction condition. Across participants there was a positive correlation between inter-trial phase coherence and N1 mean amplitude in the low-distraction condition [$r=0.63$; $p=0.016$] and in the high-distraction condition [$r=0.77$; $p=0.001$]. There was also a positive correlation between TSE of power and N1 mean amplitude in both low [$r=0.63$; $p=0.015$] and

high [r=0.66; p=0.010] distraction conditions. We therefore do not rule out the possibility that theta-band power was modulated by high-distraction at the N1 latency, however the distraction effect seems to be primarily manifested in theta-band inter-trial phase coherence rather than TSE of power.

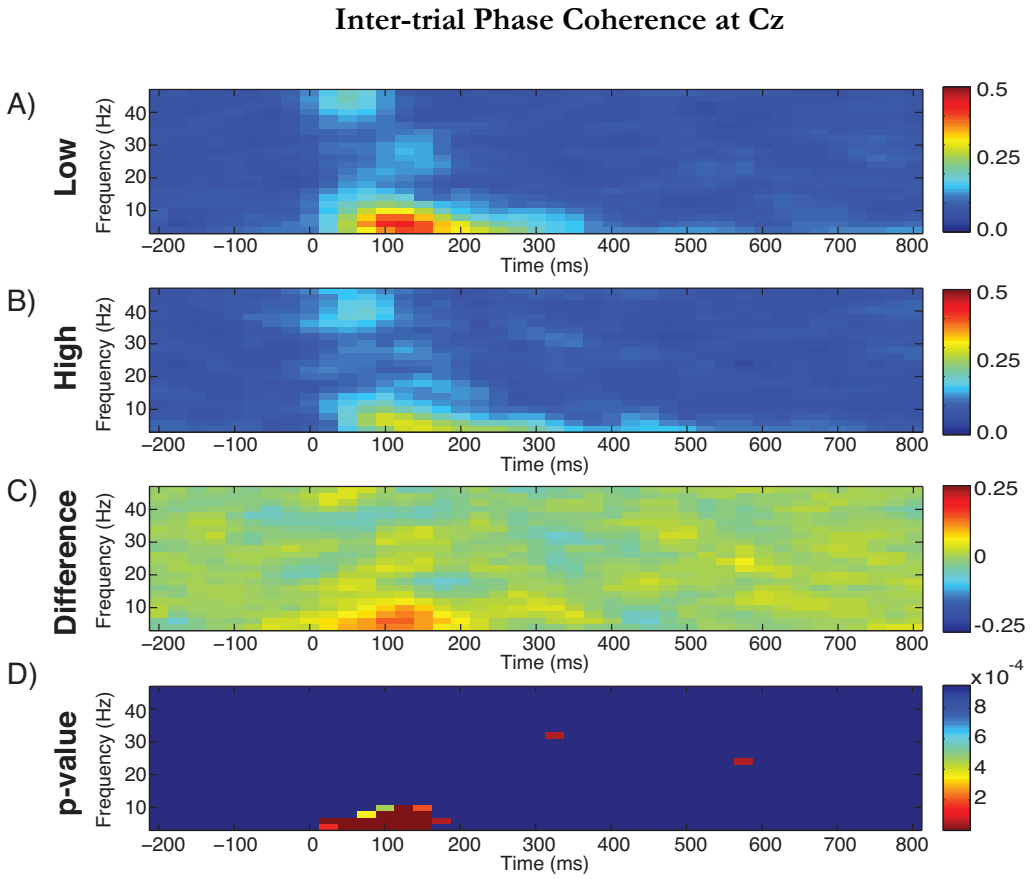


Figure 2-2: Time-frequency plot of inter-trial phase coherence at electrode Cz in low 2-2A) and high 2-2B) distraction conditions and a time-frequency plot of the inter-trial phase coherence distraction difference 2-2C). Note the substantial increase in theta inter-trial phase coherence in the low-distraction condition around the latency

of the N1. 2-2D) FDR thresholded p-values for the inter-trial phase coherence difference generated by the non-parametric test described in Methods.

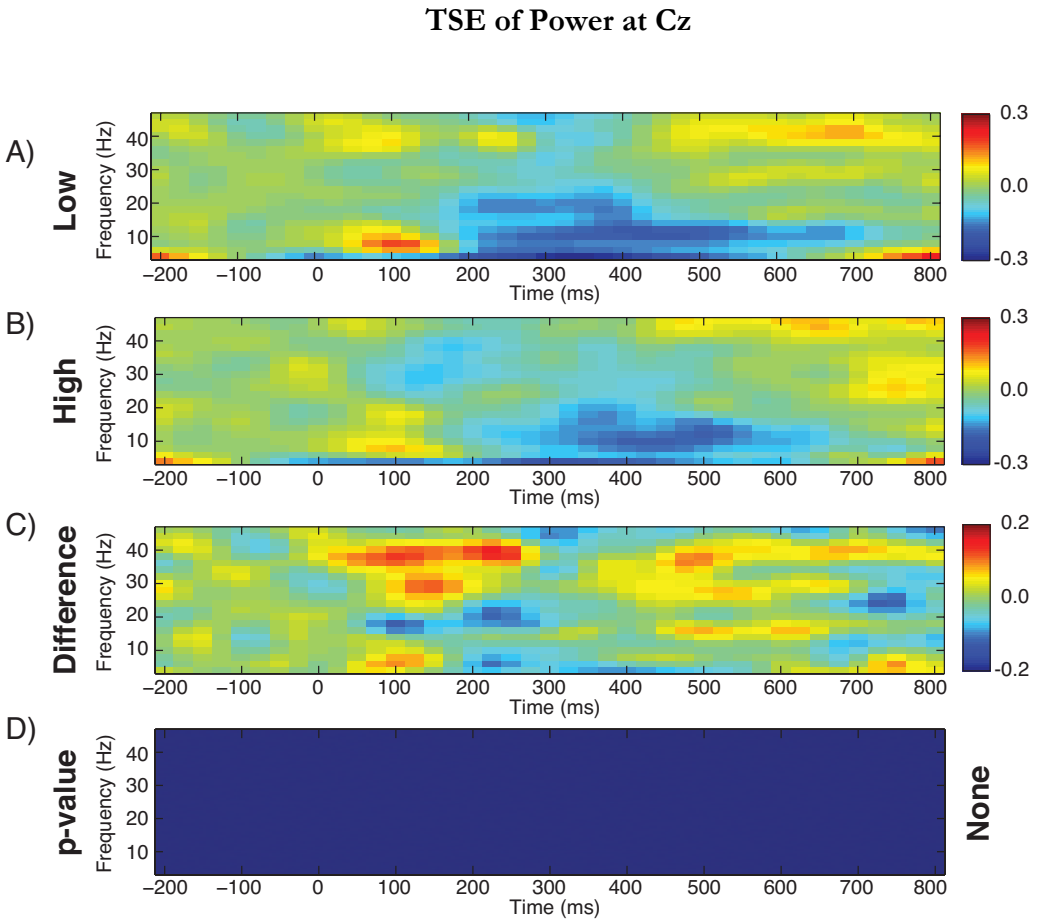


Figure 2-3 Time-frequency plot of TSE of power at electrode Cz in low 2-3A) and high 2-3B) distraction conditions and a time-frequency plot of the TSE of power distraction difference 2-3C). Note the increases in theta and gamma power occurring around the N1 peak latency in the low-distraction condition. 2-3D) No time-frequency bins exceeded the FDR threshold for TSE of power difference.

2.5 Discussion

In this study we compared the EEG and ERP responses to identical auditory stimuli under two levels of distraction. We found that the presence of distracting speech reduced the N1 peak evoked by non-target stimuli in the attended stream relative to broad-band noise. This finding is consistent with previous investigations of the effect of auditory masking on the auditory ERP (Ahveninen, et al., 2011; De Chicchis, et al., 2002; Fisher, Hymel, Cranford, & DeChicchis, 2000; Hymel, et al., 1998; Krumm & Cranford, 1994). The reduction in N1 amplitude reported here is similar to previous reports of N1 attenuation, with the difference in N1 components between low and high-distraction resembling the difference between attended and unattended stimuli respectively (Hillyard, et al., 1973; Näätänen, 1992). There are, however, important differences between the present study and that previous work. Presumably, our participants maintained a top-down attentional set on target stream stimuli in both conditions. These stimuli were "unattended" in the high-distraction condition only in that attention was likely captured away from the target stream by the distractor.

In addition, we found that attenuation of the N1 in high-distraction seemed to reflect both a reduction in the theta phase consistency across trials and, to a lesser degree, reduced theta power. Two mechanisms could account for this distraction effect: a reduction of sensory gain afforded by attentional processes, and jitter in the timing of brain responses to stimulus events.

Time-Spectral Evolution (TSE) of power is highly sensitive to changes in the magnitude of signal embedded in noisy EEG and should therefore effectively capture modulations of sensory gain. By contrast, inter-trial phase coherence is sensitive to

modulations of sensory gain, but is also highly sensitive to inter-trial jitter of any embedded signal. The effect of distraction in our study was mainly found in modulations of inter-trial phase coherence rather than TSE of power: the reduction in theta TSE of power due to distraction was marginally significant whereas the reduction of theta inter-trial phase coherence was highly significant. Furthermore, theta phase (de)coherence across trials accounted for more of the variance of the N1 amplitude in high-distraction than did theta power at the same latency. Thus, our data suggest that auditory distraction acts to primarily disrupt inter-trial phase coherence and perhaps also the temporal precision of brain responses in the theta band.

Two hypotheses that account for the observed data are considered below: in one view the injection of an additional signal in the high distraction condition scatters the phase of the scalp-recorded EEG without actually affecting activity related to events in the target stream. In the other view, which we call *Distraction Decoherence*, the process of distraction itself disrupts the temporal fidelity with which the brain responds to events in the target stream.

Scalp-recorded EEG necessarily sums the electrical signals from simultaneously active ensembles of neurons. In our study, the distraction conditions differed not only in their information content (broad-band noise versus continuous speech), but also in their time-varying amplitude envelope. Speech has an envelope of amplitude modulation that fluctuates approximately at the theta frequency, and this envelope can be tracked in the auditory EEG signal (Luo & Poeppel, 2007). Therefore epochs time-locked to events in the target stream could reasonably be expected to reflect different superposition's of underlying neural signals in the two conditions: in the low distraction condition only ensembles responding to the target-

stream events would be active whereas in the high distraction condition, ensembles responding to both target-stream events and competing speech would be active. The theta band of the superposed EEG signal recorded at the scalp would thus contain one signal time-locked to the events in the attended stream and another time-locked to the phase of the distracting speech. This second set of neural activities would thus not be time-locked to the events in the attended stream. This injection of non-phase-locked signal could lead to the reduced inter-trial phase coherence we observed in the high distraction condition. However, it is not clear that this effect would also attenuate the N1 amplitude in the ERP. Injection of new signal that is at random phase relative to time zero of the ERP waveform should drop out of the grand-averaged ERP due to averaging. Furthermore, the injection of signal in the theta band during high distraction should have incremented the absolute induced (i.e. non-phase-locked) amplitude of theta during the baseline. Since TSE of power is measured relative to the pre-stimulus baseline, it should also have been reduced if the auditory system was tracking two different signals throughout the block of trials. In fact, over noise levels common to scalp-recorded EEG, TSE of power is more sensitive to changes in noise than is inter-trial phase coherence. We found no modulation of theta power during the pre-stimulus baseline and only a small reduction in theta TSE of power around the N1 peak due to distraction. Thus we suggest that an account based on the injection of non-phase-locked signal in the high-distraction condition is untenable and an account based on the introduction of temporal jitter in the brain's response to events in the target stream is warranted.

A critical feature of the ERP is that the signals captured in the ERP waveform reflect neural processes that are tightly time-locked to the sensory event of

interest. We suggest the term *Distraction Decoherence* to convey the notion that the presence of a distracting stimulus reduces this time locking between auditory events and subsequent brain response(s). Such a process would give rise to the pattern of data we have observed: prominent reduction of the N1 amplitude coupled to reduced inter-trial phase coherence, without a prominent modulation of TSE of power. Such inter-trial jitter might occur for one or more reasons: A prominent theory about the neurophysiological mechanisms underlying the generation of an ERP is that a sensory event can "reset" and transiently lock the phase of various oscillating neural ensembles (Fuentemilla, et al., 2009; Klimesch, Sauseng, Hanslmayr, et al., 2007; Makeig, et al., 2002; Sauseng, et al., 2007). Thus any process that interferes with the temporal fidelity of phase resetting across trials will have the effect of reducing ERP peak amplitudes and also causing phase decoherence across trials relative to another condition. For example, if participants reflexively and rapidly oriented to the speech distractor during the intervals of silence between target-stream events, resetting the theta phase at the onset of events in the target stream might be disrupted.

Another possibility is that distraction breaks an attentive mechanism that would otherwise tighten the temporal resolution of early perceptual systems. This view requires no prerequisite commitment to a "phase reset" model of ERP generation and applies equally well in a "additive fixed-latency evoked potential" model of ERP generation (Sauseng, et al., 2007). In either case, an increasingly prevalent view of the role of oscillatory dynamics in attention is that synchronization of oscillating ensembles at various frequencies provides the means to differentially select one representation of sensory input, memory, or response planning (Borisyuk,

et al., 2009; Breve, et al., 2009; Fries, 2005; Fries, et al., 2008; Lakatos, et al., 2008; Schroeder & Lakatos, 2009; Womelsdorf & Fries, 2006, 2007b). It follows that phase-accurate tracking of to-be-attended stimulus onsets is important. Variability of theta-phase across trials might reflect transiently reduced synchronization of the required task-relevant ensembles within each trial. Ahveninen et al. (Ahveninen, et al., 2011) have proposed that attention acts to sharpen the frequency-tuning characteristics of auditory neurons. Here we suggest that attention may also have a similar effect on the temporal fidelity of auditory neurons and distraction the opposite effect. Future studies will help to elucidate the relationship of inter-trial phase coherence to the temporal fidelity of evoked responses.

2.6 Conclusion

Relative to broad-band noise, the presence of a continuous speech signal in the unattended ear impaired task performance, attenuated the N1 peak evoked by non-target stimuli in the attended ear and reduced theta EEG band inter-trial phase coherence around the latency of the N1. This suggests that distraction may act not only to disrupt a sensory gain mechanism but also to disrupt the temporal fidelity with which the brain responds to stimulus events.

2.7 Acknowledgements

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Chapter 3: Dynamics of Distraction: Competition Among Auditory Streams Modulates Gain and Disrupts Inter-Trial Phase Coherence in the Human Electroencephalogram

3.1 Abstract

Auditory distraction is a failure to maintain focus on a stream of sounds. We investigated the neural correlates of distraction in a selective-listening pitch-discrimination task with high (competing speech) or low (white noise) distraction. High-distraction impaired performance and reduced the N1 peak of the auditory Event-Related Potential. We explored two theories to account for this effect: disruption of sensory gain or a disruption of inter-trial phase consistency. Distraction reduced the gain of the auditory evoked potential and disrupted the inter-trial phase consistency with which the brain responds to stimulus events. Tones at a non-target, unattended frequency were more susceptible to the effects of distraction than tones within an attended frequency band.

3.2 Introduction

In complex acoustic environments, listening selectively to one out of many sources of input can present a significant challenge to the human auditory system. In the auditory modality these sources of input are often referred to as streams, and parsing the environment for such streams has been referred to as auditory scene analysis (Bregman, 1990). Occasionally, attentional focus on a selected stream may become disrupted by competing information and impair perception of the selected stream (Broadbent, 1952, 1958). This phenomenon has been conceptualized as a

failure of attentional selectivity (Broadbent, 1952; Treisman, 1964), but also in the context of auditory masking (Carhart, Tillman, & Greetis, 1969). Here we adopt the use of the broad but intuitive term *distraction* (Durlach, Mason, Shinn-Cunningham, et al., 2003) to describe perceptual competition among auditory streams. Several decades of psychophysical research has described the consequences of distraction, yet very little is known about the physiological correlates. The present study reveals that distracting speech attenuates the gain and disrupts the temporal fidelity of cortical responses to sounds in the auditory scene.

Probably the best example of real-world distraction is the "two-talker" problem. In the two-talker problem, speech perception is impaired when another stream of speech is mixed into the signal. The extreme case is the canonical "cocktail party" in which many independent streams are mixed. The "two-talker" problem differs markedly from paradigms commonly used to study auditory distraction in the laboratory. Such paradigms study the physiological correlates of unusual/discrete events happening in the auditory scene (Schroger, et al., 2000) but the objective of our study was to investigate the physiological correlates of distraction when there is a continuously competing stimulus in the auditory scene.

The decrement in perception observed in the two-talker problem has been called auditory informational masking (Pollack, 1976). Information masking occurs when a target signal is embedded in a competing signal that impairs target detection, discrimination or intelligibility of speech even when the target and masker do not overlap in frequency (Leek, Brown, & Dorman, 1991). Informational masking has been associated with the phenomenon of distraction. For example, Durlach et al. (2003) stated: "listeners are severely distracted by the masker and find it difficult to

perform well even though there is little masker energy in the frequency region of the target" (Durlach, Mason, Kidd, et al., 2003). Thus informational masking in the two-talker situation is therefore an excellent context in which to study attention and distraction.

The presence of task-irrelevant speech or music in the auditory scene is well-known to attenuate and delay the N1 component of the auditory Event-Related Potential, or its magnetic counterpart the N1m, which are evoked by transient probe stimuli (R. Hari & J. P. Makela, 1988; Hymel, et al., 2000; Hymel, et al., 1998; Krumm & Cranford, 1994; D. L. Woods, S. A. Hillyard, & J. C. Hansen, 1984). For example, Hari & Makela (1988) showed that music, speech, and to a lesser degree intermittent noise, presented to the ipsilateral ear, delayed and attenuated the N1m response to 25 ms broadband pulses. The reason for this effect in the presence of a competing auditory stream is unknown, however the phenomenon is well-aligned with studies of selective attention: The N1 component evoked by attended stimuli is typically larger relative to ignored stimuli (Hillyard, et al., 1973; Näätänen, 1992). This effect only develops after listeners have maintained selection of the target stream for a period of many seconds (Donald & Young, 1982; Hansen & Hillyard, 1988). It does not occur when attention is reoriented on a moment-by-moment basis as would be expected when a competing stream is present (Schroger & Eimer, 1993; Tata, et al., 2001; Tata & Ward, 2005). Thus, there is a consistent picture of attenuation of early ERP components in both informational masking and attention orienting paradigms, but the mechanism underlying such attenuation remains unknown.

Ponjavic-Conte et al. (2012) (see Chapter 2) replicated the attenuation of the

N1 ERP due to distraction (Ponjavic-Conte, et al., 2012). They proposed two theories to account for this effect. One theory is that distraction transiently captures attention away from the target stream, thereby reducing the boost in sensory gain afforded by sustained attention. This account follows from the "sensory gain-control" theory, which holds that attention modulates the gain of fixed-latency responses in sensory systems (Hillyard, et al., 1998). That is, cells that encode to-be-attended stimuli show a larger response than cells that encode features of unattended stimuli (Luck, et al., 1997; M. G. Woldorff, et al., 1993). Thus, by breaking sustained attention, a distracting stream could attenuate and delay early ERP components evoked by target stimuli. Importantly, in this theory of distraction, the fixed-latency ERP remains time-locked to the evoking stimuli, but it is attenuated in amplitude and delayed by a constant latency in time.

In contrast, Ponjavic-Conte et al. (2012) (see Chapter 2) suggested that distraction might disrupt the temporal fidelity of evoked responses, such that their phase consistency over successive trials is reduced. Here we suggest the term *Distraction Decoherence* and describe it as a phenomenon of signal jitter. Ponjavic-Conte et al. (2012) (see Chapter 2) based their idea on the observation that inter-trial phase coherence in the theta EEG band was reduced when a speech masker was present in the scene, relative to when a broadband noise masker was present. Inter-trial phase coherence is a measure of the temporal similarity of brain electrical signals over successive trials. Thus the measure can, in principle, reveal differences in the degree of phase consistency across different stimulus configurations and cognitive tasks.

Other work is broadly consistent with the theory of *Distraction Decoherence*.

For example, Tiitinen et al. (1993) suggested that selective attention could sharpen the temporal fidelity of the 40 Hz steady-state response. Low & Strauss (2009) showed that responses to auditory targets exhibit more inter-trial phase consistency than responses to non-targets. Substantial literature has recently emphasized the effect of selective attention on oscillatory signals in the EEG (Doesburg, et al., 2008; Engel, et al., 2001; Fries, et al., 2008; Tallon-Baudry, Bertrand, Delpuech, & Permier, 1997; Womelsdorf & Fries, 2007b); in addition, the phase dynamics of cortical oscillations is thought to be a critical factor in the computational architecture of the cortex (Fries, 2005). The possible disruption of the inter-trial phase consistency of early auditory responses due to distraction is therefore of particular theoretical importance.

Ponjavic-Conte (2012) (see Chapter 2) found that continuous speech in the auditory scene attenuated the N1 and reduced inter-trial phase coherence in the theta band. In the current study we sought to replicate these results in a pitch-discrimination task (Ponjavic-Conte, et al., 2012). However, since the inter-trial phase coherence measure is sensitive to changes in the signal-to-noise ratio, a reduction in sensory gain might also appear as a reduction in inter-trial phase coherence.

The goal of the present study was to replicate the N1 attenuation and inter-trial phase coherence effects previously observed during distraction (Ponjavic-Conte, et al., 2012) (see Chapter 2) and to reconsider whether these effects are related to sensory gain, distraction decoherence, or a combination of both mechanisms. We reasoned that temporal jitter of a normally fixed-latency component would not reduce total EEG power but would instead redistribute that power across more

phases (David, Kilner, & Friston, 2006). In other words, if distraction decoherence were to occur, it should shunt power from the evoked to the induced power signal; therefore we measured the distraction effect separately for evoked and induced power. We also considered whether distraction shifts the phase of theta-band EEG, which would possibly account for any latency shifts observed in the N1. A secondary goal was to test whether top-down attentional selection of a target stream would protect brain responses evoked by that stream from the effects of distraction. We found that early correlates of distraction in the EEG appear to be independent of a top-down attentional set, however the effects of distraction appear to be prevented by focused attention at later phases of the auditory ERP. We also found that the electrophysiological mechanisms of distraction involve both a disruption of sensory gain control and a disruption and phase-shift of early EEG responses. Our data is of interest more broadly because it shows that, in principle, any apparent attenuation of an evoked signal averaged over successive trials can be explained by phase decoherence and/or gain modulation.

3.3 Experiment One

Ponjavic-Conte et al. (2012) (see Chapter 2) used a temporal discrimination task in which participants discriminated the duration of a brief silent gap in a burst of noise. We considered that the temporal effects of distraction evident in the EEG might be unique to this duration-discrimination task so in the present study we instead used a pitch-discrimination task. We also included an "off-band" unattended non-target tone to investigate the role of top-down attentional set. Our first goal was to establish whether speech distraction has a measureable effect on task performance

in a pitch-discrimination task.

3.3.1 Methods

Fifteen undergraduates from the University of Lethbridge were recruited and participated for course credit. Participants were screened with the World Health Organization Adult Attention-Deficit Hyperactivity Disorder (ADHD) self-report scale (ASRS) (Kessler, Adler, Ames, et al., 2005). Three participants were excluded from the analysis for not following task instructions (their false alarm rate was 3 standard deviations outside the mean in both low- and high-distraction). Thus, 12 participants contributed to the data analysis (9 females; one left-handed; average age: 21.3). All participants provided informed written consent. Procedures were in accordance with the Declaration of Helsinki and were approved by the University of Lethbridge Human Subjects Review Committee.

Stimuli were presented on an Apple Mac Mini with sound attenuating headphones (approx. 30 dB attenuation); volume was individually adjusted to a comfortable volume. Auditory stimuli were created using MATLAB (MATLAB version 7.10.0; The Mathworks Inc., 2010, Natick, Massachusetts, USA) and controlled by a program custom coded using Apple Computer's Core Audio framework (Mac OS 10.6). Sounds were panned equally to both left and right ears such that they were localized to the midline.

Each session consisted of 26 blocks of 1.2 minute duration in which two different streams of sound (a target stream and a distraction stream) were presented simultaneously to both ears. The target stream consisted of two target tones (target-high: 1000 Hz; target-low: 975 Hz) that were to be attended and one non-target tone

(600 Hz) that was to be unattended; all tones were 200 ms in duration. In each block, nine target-high, nine target-low and 18 non-target tones were presented in a randomized order with an inter-stimulus interval of 1.94 seconds +/- 250 ms of jitter. The distraction stream consisted of one of two types of stimuli. The low-distraction condition was continuous broad-band noise. The high-distraction condition was randomly selected segments of audio books consisting only of the voice of a single reader (i.e. no sound effects). The root mean square amplitude of each low-distraction stimulus was matched to that of a high-distraction stimulus. In each session, 13 low-distraction and 13 high-distraction blocks were presented pseudorandomly.

Participants were instructed to attend to the target-high and target-low tones so that they could discriminate between them, while ignoring the much lower non-target tone along with the distracting noise or speech. The required response was to press the up arrow key for the target-high tone and press the down arrow key for the target-low tone, and to withhold response for the non-target tone. Maximum response time allotted per trial was 750 ms. A response was considered an accurate hit if the participant discriminated correctly between the target-low and target-high tones. Thus, discrimination accuracy was measured as a percentage of correct target-present trials. Possible behavioural data outcomes are depicted in Table 3-1. The effect of distraction (high vs. low) on mean response times, discrimination accuracy, false alarms, correct rejections and misses were assessed by two-tailed t-tests.

Table 3-1: Behavioural Data Outcomes**.** Possible behavioural data outcomes are depicted. Discrimination accuracy between the two tones within the target frequency band (975 Hz and 1000 Hz) was calculated as the number of correct responses divided by the total number of hits.

	Participant's Response		
Auditory Stimulus	**Up Arrow**	**Down Arrow**	**None**
High-Pitch Target	Accurate Hit	Inaccurate Hit	Miss
Low-Pitch Target	Inaccurate Hit	Accurate Hit	Miss
Non-Target	False Alarm	False Alarm	Correct Rejection

3.3.2 Results

High-distraction decreased listener ability to discriminate accurately between the target-low and target-high tones (Mean low-distraction: 0.771, SD = 0.202; Mean high-distraction: 0.728, SD = 0.199; $t_{11} = 2.426$; P = 0.034). Participants tended to make more "false alarm" responses to the low-pitch non-target tone (Mean low-distraction: 0.010, SD = 0.010; Mean high-distraction: 0.030, SD = 0.027) and were more likely to miss the high-pitched target tones in the high-distraction condition (Mean low-distraction: 0.250, SD = 0.157; Mean high-distraction 0.270, SD = 0.173); but these effects were not significant. There was also no effect of distraction condition on response times (Mean low-distraction: 548.6, SD = 44.6; Mean high-distraction: 552.3, SD = 48.6).

3.3.3 Discussion

Experiment One confirmed that the experimental paradigm of distraction used by Ponjavic-Conte et al. (2012) (see Chapter 2) extends also to pitch discrimination and is consistent with a large body of literature in the domain of information masking. The presence of task-irrelevant speech in the auditory scene impaired performance of a difficult pitch discrimination. Experiment Two considers the neurophysiological correlates of distraction.

3.4 Experiment Two

Distraction in Experiment One had the effect of impairing discrimination of two similar target pitches while also disrupting attentional selection of the target frequency bands. Experiment Two considers the neurophysiological basis for these distraction effects.

3.4.1 Methods

Task parameters were as in Experiment One except that sounds were presented in free field by a Mac Pro with a firewire audio interface (M-Audio Firewire 410). Participants sat in front of two near-field studio monitors (Mackie HR624 MK-2) arranged vertically (one monitor played the target stream; the other played the distraction stream). Participants were seated in a dimly lit and sound attenuated room.

Nineteen undergraduates participated in the study for course credit. Two were excluded due to excessive artifact in the EEG and two because they screened

positive for ADHD on the ASRS; thus 15 were included in the analysis (11 female; all right-handed; average age: 22.5). Procedures were in accordance with the Declaration of Helsinki and were approved by the University of Lethbridge Human Subjects Review Committee; all participants gave written informed consent.

The EEG was recorded with 128 Ag/Ag-Cl electrodes in an elastic net (Electrical Geodesics Inc., Eugene, OR, USA). Scalp voltages were recorded with a 500 Hz sampling rate and impedances were maintained under 100 kilo-ohms. Data were analyzed using the BESA software package (Megis Software 5.3, Grafelfing, Germany). The EEG was first visually inspected for bad electrodes and a small number of electrodes (10 or less) per participant were replaced with an interpolated signal.

ERP waveforms were time locked to target and non-target tones [high-pass (0.5 Hz, 12 dB/octave); low-pass (30 Hz, 24 dB/octave) zero-phase Butterworth filters; re-referenced to a standard 10-10 average-reference montage with a 200 ms pre-stimulus baseline]. Epochs containing artifact (deflections of greater than +/- 120 μV) were rejected. Participants had few miss and false alarm trials, thus after artifact rejection only accurate responses to targets (i.e. "hits") and correct-rejection of non-targets (i.e. "correct-rejections") had enough epochs (> 25) to be analyzed across all participants. We refer to these conditions below as "Attended Hits" and "Unattended Correct-rejections". The average number of trials per participant per condition after artifact rejection were as follows: Attended Hits under low-distraction: 118; Attended Hits under high-distraction: 117; Unattended Correct-rejections under low-distraction: 165; Unattended Correct-rejections under high-distraction: 169.

The N1 peak was identified at electrode Cz for all conditions at latencies ranging from 118-122 ms (Attended Hits low-distraction: 118 ms; Attended Hits high-distraction: 120 ms; Unattended Correct-rejections low-distraction: 120 ms; Unattended Correct-rejections high-distraction: 122 ms). For statistical comparisons, the mean amplitude of the N1 peak for all conditions was computed within a window spanning 6 ms on either side of 120 ms (without filtering) and by using an average reference. A repeated-measures ANOVA with two levels of the factor Distraction (low/high distraction) and two levels of the factor Frequency Selection (target/non-target) was performed on N1 mean amplitudes. Difference waves were computed for differences due to distraction and viewed in an isopotential map by subtracting the ERP waveforms in the high-distraction condition from waveforms in the low-distraction condition.

In order to assess the possibility that differences in evoked responses during low- and high-distraction could be due to increased energetic masking by the speech distractor relative to the broad-band noise distractor, high-distraction trials were reclassified as being high-energy or low-energy based on the spectrogram of the speech distractor during a given trial. The power spectral density of the speech distractor was calculated using a short Fourier transform for the duration of each target tone, at the tone frequency. If the power spectral density of the of the speech distractor for a particular trial was greater than the grand mean power spectral density for the broad-band noise distractor at that frequency, then that trial was reclassified as being high-energy/high-distraction; if the power spectral density for a trial was less than the grand mean power spectral density of the broad-band noise distractor, the trial was reclassified as being low-energy/high-distraction. The

proportion of trials classified as being high-energy/high-distraction for Attended Hits was 16.3 and 28.2 for Unattended Correct-rejections. Reclassifying trials in this way allows the effect of distraction to be dissociated from the possibly confounding factor of increased energetic masking by the speech distractors. Grand-averaged ERP waveforms for Attended Hits and Unattended Correct-rejections in high-energy/high-distraction, low-energy/high-distraction and low-distraction were created for visualization [high-pass (0.5 Hz, 12 dB/octave); low-pass (30 Hz, 24 dB/octave) zero-phase Butterworth filters; re-referenced to a standard 10-10 average-reference montage with a 200 ms pre-stimulus baseline]. For statistical comparisons, two-tailed t-tests were performed on N1 mean amplitudes (within a window spanning 6 ms on either side of 120 ms (without filtering) and by using an average reference).

The raw EEG was transformed into time-frequency space using complex demodulation as implemented in BESA 5.3 (Hoechstetter, et al., 2004) between 4 and 46 Hz, from -200 to 800 ms, and exported in 2 Hz/25 ms sample bins. The time-spectral data for each participant for Attended Hits and Unattended Correct-rejections in both low- and high-distraction conditions was then exported from BESA and imported into Matlab. Grand-averaged inter-trial phase coherence, Total Power, Induced Power and Evoked Power at electrode Cz were calculated for Attended Hits and Unattended Correct-rejections in low- and high-distraction conditions.

Inter-trial phase coherence (ITC) was calculated by the following:

$$ITC_{t,f} = \left| \frac{1}{N} \sum_{k}^{N} e^{i\theta_{k,t,f}} \right|$$

where N is equal to the number of trials, and θ is the phase of trial k at a given frequency (f) and time (t). Inter-trial phase coherence is a measure of the similarity of the phases of signals over many repetitions. The values of inter-trial phase coherence range from 0 to 1 with 1 meaning perfect phase consistency across trials.

Total power, induced power and evoked power were calculated by the following. First the total power in the pre-stimulus (-200 ms to -100 ms) baseline was computed:

$$Z_{k,t,f} = A_{k,t,f} \cdot e^{i\theta_{k,t,f}}$$

$$B_f = \frac{1}{n_t} \sum_{t_{prestimulus}}^{t_0} \frac{1}{N} \sum_{k}^{N} \left| A_{k,t,f} \right|^2$$

Where n_t is the number of time bins before t = -100 ms, $A_{k,t,f}$ is the coefficient of the complex valued result ($Z_{k,t,f}$) of the complex demodulation for trial k, frequency f, and time t; B_f is the baseline power for a given frequency f. Power was then computed relative to the baseline:

$$TP_{t,f} = \frac{\frac{1}{N} \sum_{k}^{N} \left| A_{k,t,f} \right|^2}{B_f}$$

$$EP_{t,f} = \frac{\frac{1}{N} \left| \sum_{k}^{N} A_{k,t,f} \right|^2}{B_f}$$

$$IP_{t,f} = TP_{t,f} - EP_{t,f}$$

Where $TP_{t,f}$ is the total power percent change from baseline for a given time t, and frequency f; $EP_{t,f}$ is the percent change in power that is evoked (i.e. phase-locked) and $IP_{t,f}$ is the non-phase locked change in power from the baseline. Both evoked and induced power represent changes in power that are time locked to the onset of a stimulus but evoked power and induced power differ in their phase relationship to the stimulus. Evoked power is phase locked to stimulus onset, thereby capturing phase-consistent power across trials. By contrast, induced power does not capture phase-locked power. Instead, it is a measure of the power of oscillatory activity with no phase consistency across trials. Both evoked power and induced power were calculated to determine what proportion of the total change in power in single trials was phase-locked to the stimulus. Since by definition evoked power and induced power sum to equal total power, given a constant total power, evoked power and induced power must vary inversely.

We compared the difference between low- and high-distraction for inter-trial phase coherence for Attended Hits and Unattended Correct-rejections with a random-sample permutation method and applied a False-Discovery Rate (FDR) correction method to control for multiple comparisons across time and frequency bins (Benjamini & Hochberg, 1995). A surrogate distribution was built for each participant by randomly shuffling trials between low- and high-distraction conditions (thus preserving the original number of trials in each condition) and then by re-computing the difference between conditions. This process was repeated 40 000 times for each participant to create a surrogate distribution of differences. The surrogate distributions were then averaged to produce a grand-average surrogate

distribution of differences. The original grand-average difference was then compared to this surrogate distribution of differences, and a two-tailed P-value (2 x the proportion of surrogate differences that fell beyond the observed difference) for each time/frequency bin was obtained. Differences between low- and high-distraction conditions in total, evoked and induced power were compared using the same procedure.

In order to further investigate the inter-trial phase coherence difference at the N1 latency between low- and high-distraction for Attended Hits and Unattended Correct-rejections, we chose to focus our analysis on the 150 ms/6 Hz time-frequency bin. This time-frequency bin was chosen because it captured most of the inter-trial phase coherence difference between low- and high-distraction for both Attended Hits and Unattended Correct-rejections. Since the raw EEG was transformed into time-frequency space in 25 ms/2 Hz samples, the 150 ms/6 Hz time-frequency bin also captures activity occurring around the observed N1 latency (118 – 122 ms). Radial histogram plots of phase angle (in degrees) and the proportion of trials that fell within each phase angle bin were constructed for the 150 ms/6 Hz time-frequency bin. These were computed separately for each subject and then averaged across subjects. In order to examine the distribution of mean phases for low- and high-distraction at the 150 ms/6 Hz time-frequency bin, a Watson-Williams test was performed to compare the mean phase angles of low- vs. high-distraction trials. This was followed by a Kruskal-Wallis one-way analysis of variance that tested the concentration factor of phase between low- and high-distraction conditions (Berens, 2009).

Simulations done by David et al. (2006) and Ponjavic-Conte et al. (in press; Forthcoming 2013) suggest a novel approach to detecting the signature of signal jitter in the ERP. Signal jitter is uniquely indicated by a directional cross-over interaction between evoked and induced power. We use the term '*directional cross-over interaction'* below to describe the specific characteristic changes in power that occur when a signal is jittered across successive trials. It is 'directional' in the sense that increasing jitter causes evoked and induced power to change in specific directions. It is a 'cross-over interaction' in that these quantities vary inversely. For example, increasing jitter causes evoked power to decrease while causing induced power to increase. Thus a directional statistical test for time/frequency bins that exhibit both a significant reduction in evoked power and a significant increase in induced power should reveal the presence of signal jitter without being confounded with amplitude modulation. To this end we applied a Wilcoxon signed-rank test across the time-frequency bins of grand averaged evoked and induced power. In this way we independently compared both evoked power and induced power in low- and high-distraction. For visualization, we masked time/frequency bins that did not fulfill the following criteria: 1) both induced and evoked power changed significantly according to the Wilcoxon test and 2) induced and evoked power change oppositely and in the predicted direction (i.e. increasing jitter reduces evoked power and increases induced power). Figure 3-3 shows the results of applying the directional cross-over interaction test to Attended Hits and Unattended Correct-rejections conditions. Note that baseline correction was performed for visualizing power changes in Figure 3-3 as percent change from baseline, but the cross-over interaction is computed

without baseline correction to avoid potentially confounding effects of temporal blurring of power from post- to pre-stimulus bins.

Mean values of evoked and induced power for 4 time-frequency bins (125 to 150 ms and from 6 to 8 Hz) that passed criteria for the directional cross-over interaction for both Attended Hits and Unattended Correct-rejections were averaged to create a grand average of evoked and induced power in both low- and high-distraction for each condition. This was done in order to visualize the directional-cross over interaction in a different way (see Figure 3-4).

3.4.2 Results

As in Experiment One, high-distraction significantly reduced listener accuracy in discriminating between the two tones within the target frequency band (975 Hz and 1000 Hz) (Mean low-distraction: 0.784, SD = 0.194; Mean high-distraction: 0.732, SD = 0.170) as was assessed by a two-tailed t-test ($t_{14} = 2.421$; P = 0.030). There was a non-significant trend for participants to make more misses during high-distraction (Mean low-distraction: 0.296, SD = 0.118; Mean high-distraction: 0.315, SD = 0.106). There was no effect of distraction on response times (Mean low-distraction: 579.4, SD = 48.0; Mean high-distraction: 575.3, SD = 46.1).

We observed a prominent N1 peak in the low-distraction condition and attenuation of this peak in the high-distraction condition for both Attended Hits (Mean low-distraction: -2.810, SD = 1.235; Mean high-distraction: -1.982, SD = 1.251) and Unattended Correct-rejections (Mean low-distraction: -3.253, SD = 1.293; Mean high-distraction: -2.285, SD = 1.331) (Fig. 3-1A(i) and Fig. 3-1B(i)). A two-way

repeated measures ANOVA on N1 mean amplitude revealed a main effect of frequency selection (i.e. Attended Hits vs. Unattended Correct-rejections) ($F_{(1,14)}$ = 5.730; P = 0.031; ε = 1.000) as well as a main effect of distraction (i.e. high vs. low) ($F_{(1,14)}$ = 8.404; P = 0.012; ε = 1.000), but no interaction ($F_{(1,14)}$ = 0.142; P = 0.712; ε = 1.000). The isopotential maps revealed a fronto-central focus of the N1 difference (Fig. 3-1A(ii) and 3-1B(ii)) with a polarity reversal at temporal sites consistent with generator(s) on the supratemporal plane. This was apparent for both Attended Hits and Unattended Correct-rejections.

Grand-averaged ERP waveforms for Attended Hits and Unattended Correct-rejections in high-energy/high-distraction, low-energy/high-distraction and low-distraction and be viewed in Figure 3-1C(i and ii). There was no difference of N1 mean amplitudes between high-energy and low-energy high-distraction trials for either Attended Hits (t_{14} = -1.033; P = 0.319) or Unattended Correct-rejections (t_{14} = 0.022; P = 0.983). However, the distraction effect is still evident when low- and high-distraction are equated for energy (low-energy/high-distraction and low-distraction) for Attended Hits (t_{14} = 1.935; P = 0.073) and Unattended Correct-rejections (t_{14} = 2.336; P = 0.035).

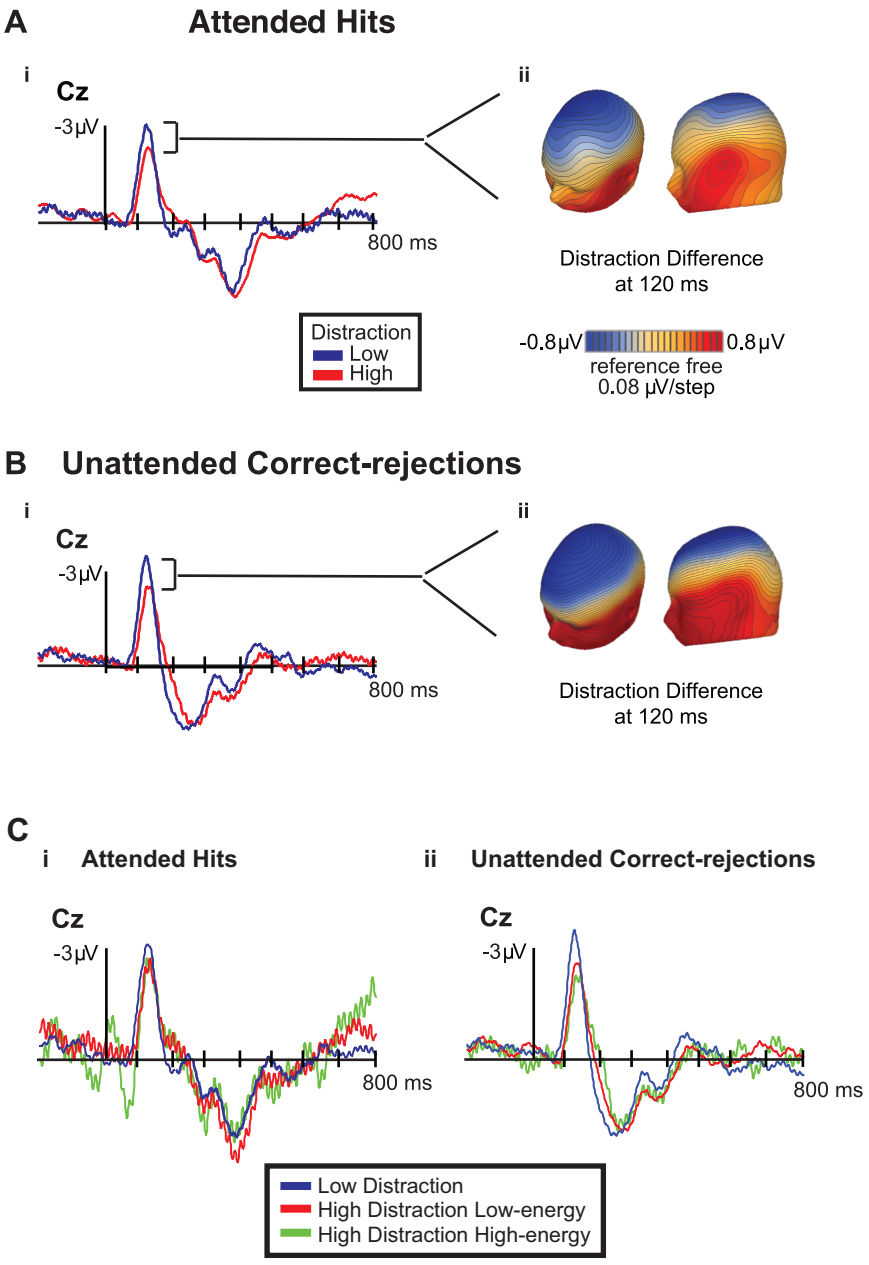

Figure 3-1: ERP waveforms evoked by target-present hits (Attended Hits) and by target-absent correct-rejections (Unattended Correct-rejections). 3-1A) (i) ERP waveforms evoked by Attended Hits in low- and high-distraction conditions. The N1 was maximal at Cz in low-distraction at 118 ms and in high-distraction at

120 ms. It was attenuated in high-distraction (t_{14} = 2.649; P = 0.019). (ii) Isopotential maps of Attended Hits N1 peak difference between low- and high-distraction at 120 ms. 3-1B) (i) ERP waveforms evoked by target-absent correct rejections (Unattended Correct-rejections) in low- and high-distraction conditions. The N1 was maximal at Cz in low-distraction at 120 ms and in high-distraction at 122 ms. It was attenuated in high-distraction (t_{14} = 2.387; P = 0.032). (ii) Isopotential map of Unattended Correct-rejections N1 peak difference between low- and high-distraction at 120 ms. 3-1C) (i) ERP waveforms evoked by target present hits in high-energy/high-distraction, low-energy/high-distraction and low-distraction at electrode Cz. No difference was found between high-energy and low-energy high-distraction trials (t_{14} = -1.033; P = 0.319). Comparisons between low-energy/high-distraction and low-distraction revealed a near significant difference (t_{14} = 1.935; P = 0.073). (ii) ERP waveforms evoked by target absent correct-rejections in high-energy/high-distraction, low-energy/high-distraction and low-distraction at electrode Cz. No difference was found between high-energy and low-energy high-distraction trials (t_{14} = 0.022; P = 0.983). Comparisons between low-energy/high-distraction and low-distraction revealed a significant difference (t_{14} = 2.336; P = 0.035).

As predicted, distraction (high vs. low) significantly reduced theta/alpha band inter-trial phase coherence around the N1/P2 latency for Attended Hits; this effect was also evident for Unattended Correct-rejections (Fig. 3-2A; Fig. 3-2B). High-distraction also reduced evoked power around the N1 latency (Fig. 3-3A(ii); Fig. 3-3B(ii)). In addition to reduced inter-trial phase coherence and reduced evoked power around the N1 latency, we also observed a later reduction in inter-trial phase

coherence approximately 300 to 400 ms post-stimulus in the theta/alpha EEG band (4 to 12 Hz) but only for Unattended Correct-rejections (Fig. 3-2A(iv); Fig. 3-2B(iv)). A similar effect was observed in evoked power (Fig. 3-3A(ii); Fig 3-3B(ii)). This later reduction of inter-trial phase coherence for Unattended Correct-rejections also passed FDR correction for multiple paired comparisons (Fig 3-2B(iv)). Eight time-frequency bins (between 300 to 400 ms and 8 to 12 Hz) passed FDR correction for inter-trial phase coherence of Unattended Correct-rejections with p-values ranging from 0.00005 to 0.00085, whereas no time-frequency bins passed FDR correction of inter-trial phase coherence for Attended Hits (p-values ranged from 0.4076 to 0.8944).

As evidenced by the radial histogram phase plots of the 150 ms/6 Hz time-frequency bin (Fig. 3-2C; Fig. 3-2D), Attended Hits and Unattended Correct-rejections exhibited different phase distributions at this frequency and latency depending on the level of distraction. The Watson-Williams test for different mean phase angles across distraction conditions found that the theta (6 Hz) phase distribution on high-distraction trials was significantly lagged (rotated counter-clockwise) ($F_{1,14} = 12.35$; $P = 0.0015$) for Unattended Correct-rejections at the 150 ms latency. This effect was marginally significant for Attended Hits ($F_{1,14} = 3.06$; $P = 0.09$). Kruskal-Wallis one-way analysis of variance on the concentration of phase at the 150 ms/6 Hz time-frequency bin for low- and high-distraction conditions found a significant effect of distraction for both Attended Hits ($c^2(1, n=15) = 4.56$; $P = 0.03$) and Unattended Correct-rejections ($c^2(1, n=15) = 5.11$; $P = 0.02$). The effect of distraction (high vs. low) on mean concentration factor was larger for the Unattended Correct-rejection condition (Attended Hits low-distraction: 1.1005;

Attended Hits high-distraction: 0.7732; Unattended Correct-rejections low-distraction: 1.345; Unattended Correct-rejections high-distraction: 0.902).

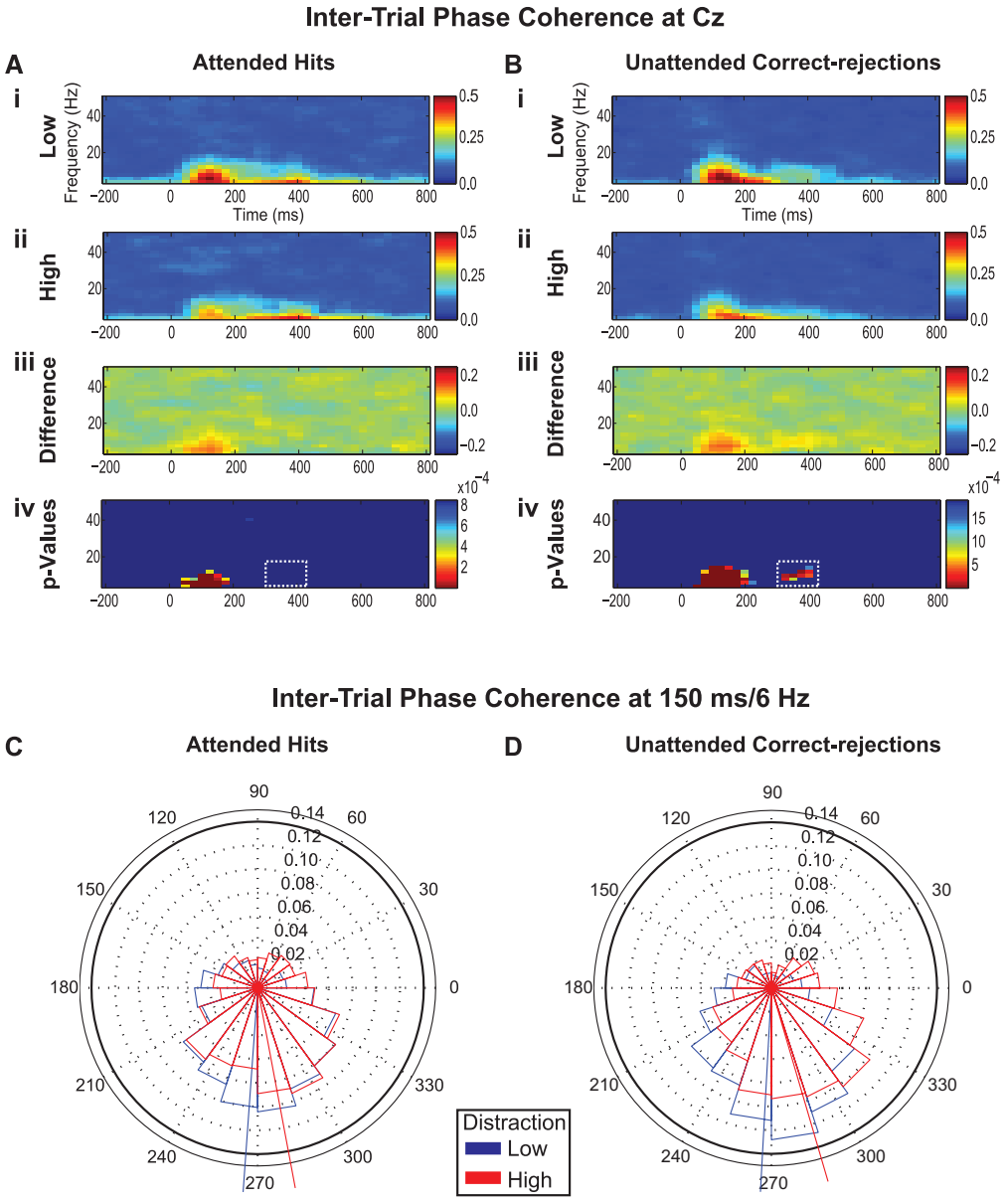

Figure. 3-2: Inter-trial phase coherence and Phase Distributions. 3-2A) Time-frequency plots of grand-averaged Inter-trial phase coherence at electrode Cz for

Attended Hits in low (i) and high (ii) distraction. (iii) Time-frequency plot and (iv) FDR thresholded map of the differences between distraction conditions (low minus high) in Inter-trial phase coherence 3-2B) Time-frequency plots of grand-averaged Inter-trial phase coherence at electrode Cz for Unattended Correct-Rejections in low (i) and high (ii) distraction. (iii) Time-frequency plot and (iv) FDR thresholded map of the differences between distraction conditions (low minus high) in Inter-trial phase coherence. There was a decrease of theta/alpha inter-trial phase coherence around the N1 latency in high-distraction for both Attended Hits and Unattended Correct-rejections. There was a decrease of theta and alpha inter-trial phase coherence for Unattended Correct-rejections (but not Attended Hits) at approximately 300 to 400 ms post-stimulus in high-distraction. 3-2C) Grand-averaged radial histograms of phase angle distributions in the 150 ms/6 Hz time-frequency bin in low- and high-distraction for Attended Hits; mean phase angles for low- and high-distraction are indicated by the blue and red lines, respectively. The distribution of phase angles was rotated (delayed) by distraction. The difference in mean phase angles was marginally significant ($F_{(1,14)} = 3.06$; $P = 0.09$) and the difference in phase concentration was significant ($c^2(1, n=15) = 4.56$; $P = 0.03$) . 3-2D) Grand-averaged radial histograms of phase angle distributions for the 150 ms/6 Hz time-frequency bin in low- and high-distraction for Unattended Correct-rejections. The difference in mean phase angles and phase concentrations were both significant ($F_{(1,14)} = 12.35$; $P = 0.0015$) and ($c^2(1, n=15) = 5.11$; $P = 0.02$), respectively, for Unattended Correct-rejections. Note that high-distraction in both Attended Hits and Unattended Correct-rejections appears to both broaden and shift the distribution of phases of 6 Hz theta band signals.

Figure 3-3 shows the results of applying the directional cross-over interaction test to Attended Hits and Unattended Correct-rejections. Note that in both cases total power and evoked power are reduced under high relative to low-distraction (Fig 3-3A(i); Fig 3-3B(i); Fig 3-3A(ii); Fig 3-3B(ii)). Also, substantial alpha suppression is evident for the Attended Hit condition (Fig 3-3A(i); Fig 3-3B(i)). Importantly, a directional crossover interaction is evident in the theta/alpha band at a latency range spanning the N1 and P2 components, particularly for Unattended Correct-rejections at the non-target (ignored) frequency (Fig 3-3A(iv); Fig 3-3B(iv)), thereby indicating the presence of signal jitter in the ERP.

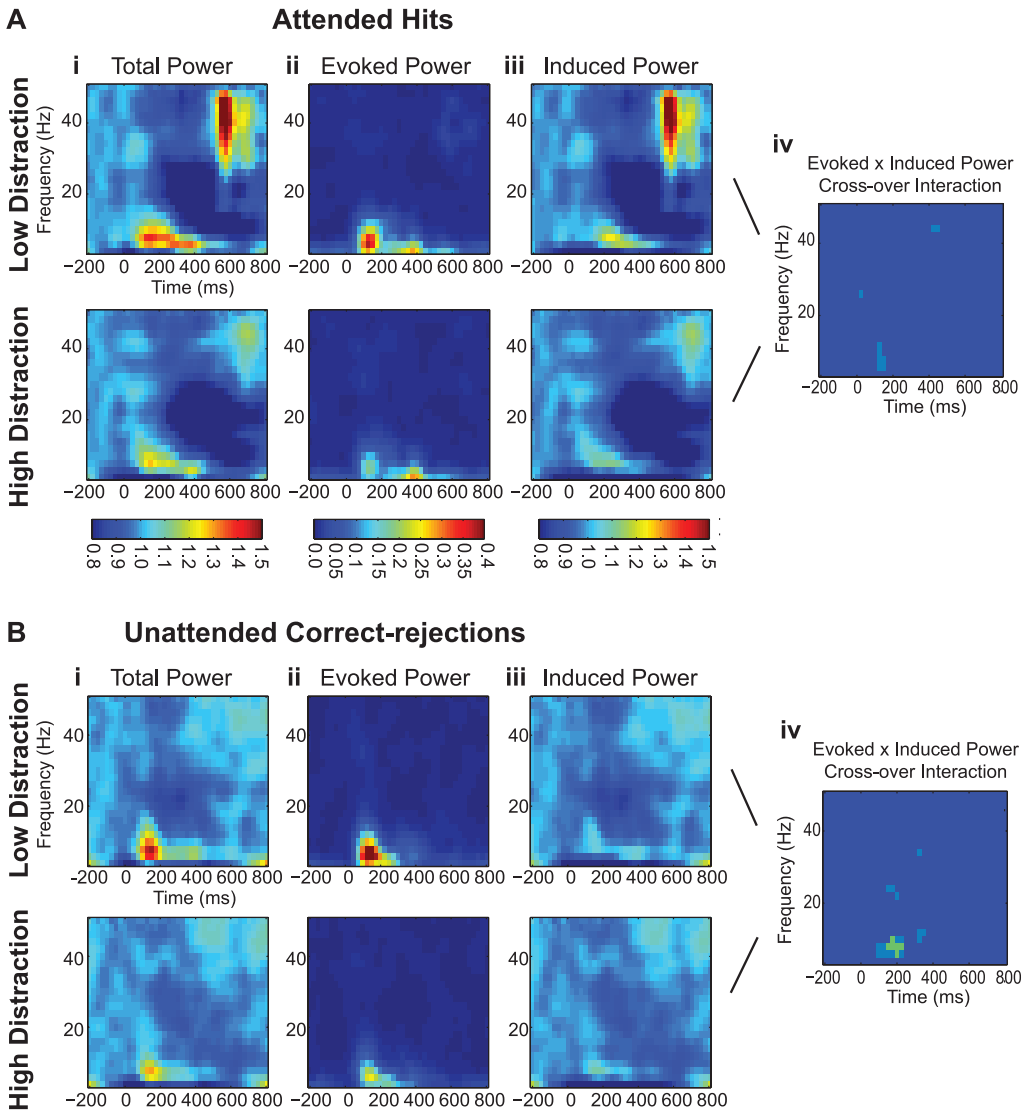

Figure 3-3: Decoherence Due to Distraction. 3-3A) Time frequency plots of (i) total power (ii) evoked power and (iii) induced power for Attended Hits in low (above) and high (below) distraction. (iv) Wilcoxen Rank Sum maps masked to show bins exhibiting a significant directional cross-over interaction between evoked and induced power. Light blue indicates time/frequency bins with p-values between 0.05 and 0.01 and green indicates bins with p-values less than 0.01. 3-3B) Time frequency

plots of (i) total power (ii) evoked power and (iii) induced power for Unattended Correct-rejections in low (above) and high (below) distraction. (iv) Wilcoxen Rank Sum maps masked to show bins exhibiting a significant directional cross-over interaction between evoked and induced power. Note the significant crossover interaction in the theta/alpha band at the N1 latency range, particularly for Unattended Correct-rejections.

Grand-averaged mean values of evoked and induced power (125 to 150 ms and from 6 to 8 Hz) for both Attended Hits (Fig. 3-4A) and Unattended Correct-rejections (Fig. 3-4B) showed that evoked power decreased and induced power increased in the high relative to low-distraction conditions, respectively. Figure 3-4 provides clear evidence of a directional cross-over relationship between evoked and induced power.

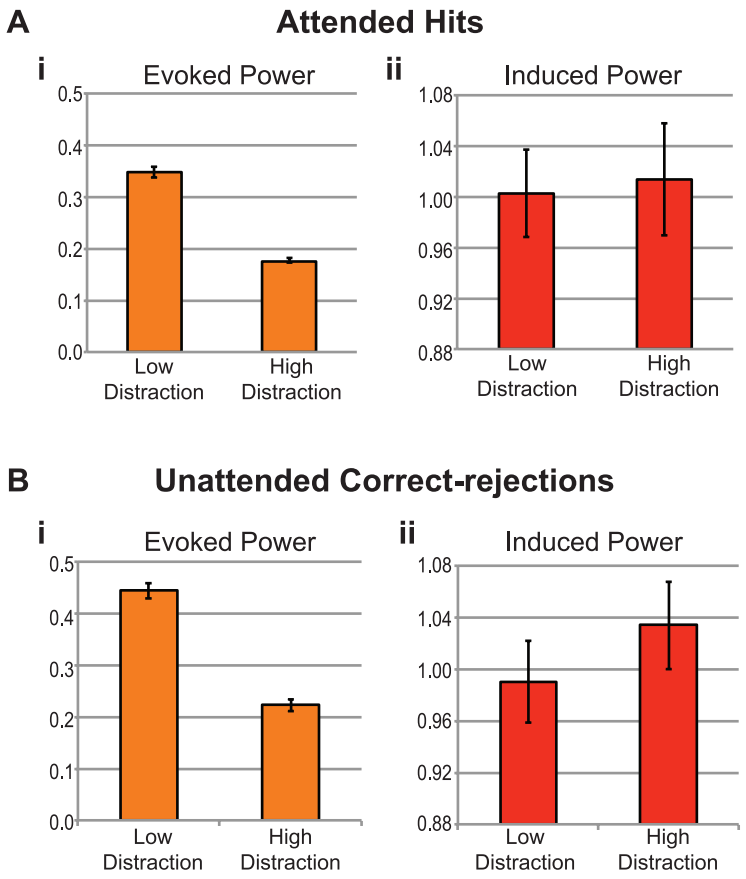

Figure 3-4. Evoked by Induced Directional Cross-over Interaction due to Distraction. 3-4A) Grand-averaged evoked (i) and induced (ii) power in low- and high-distraction for Attended Hits at time-frequency bins: 125 to 150 ms; 6 to 8 Hz; error bars indicate the standard error of the mean. 3-4B) Grand-averaged evoked (i) and induced (ii) power in low- and high-distraction for Unattended Correct-rejections at time-frequency bins: 125 to 150 ms; 6 to 8 Hz. Note that both Attended Hits and Unattended Correct-rejections show evidence of a directional evoked by induced cross-over interaction.

3.4.3 Discussion

In this study we sought to replicate the results of Ponjavic-Conte et al. (2012) (see Chapter 2) using a selective-attention pitch-discrimination task that assessed task performance, EEG and ERP responses under two levels of distraction. In Experiment One we found that relative to broadband noise, the presence of continuous speech significantly reduced listener accuracy in discriminating between target tones. In Experiment Two high-distraction had a similar effect on pitch discrimination. Thus both experiments confirm that the experimental paradigm of distraction used by Ponjavic-Conte et al. (2012) (see Chapter 2) extends also to pitch discrimination.

Previous investigations of competition among auditory streams have revealed that ERP components such as the N1 peak are attenuated and delayed by task-irrelevant distraction (R. Hari & J.P. Makela, 1988; Hymel, et al., 2000; Hymel, et al., 1998; Ponjavic-Conte, et al., 2012; D.L. Woods, S. A. Hillyard, & J.C. Hansen, 1984). The modulation of the N1 component apparent in Figure 3-1 is consistent with this work. Furthermore, the reduction in inter-trial phase coherence evident in Figure 3-2, replicates the results reported by Ponjavic-Conte et al. (2012) (see Chapter 2). The counterclockwise rotation of phase at the 6 Hz theta band during high-distraction (Fig 3-2C; Fig 3-2D) is also reflected in the latency shift of the N1 peak (Fig 3-1A(i); Fig 3-1B(i)). Reduced inter-trial phase coherence and broadening of the phase distribution evident in the phase histograms suggests that temporal jitter across trials might account for the attenuation of the N1 component.

A secondary goal was to test whether attention on a target stream would protect brain responses from the effects of distraction. We found that high-

distraction reduced inter-trial phase coherence and evoked power at the theta and alpha EEG bands at latencies beyond the N1 (300 to 400 ms), but only for Unattended Correct-rejections. The effect of distraction on phase variability appears to be stronger for tones occurring at an unattended frequency suggesting that focused attention may prevent Distraction Decoherence. Responses to attended targets appear to be protected from this later distraction effect, but it is possible that our test simply lacked the statistical power to find these effects in the Attended Hit condition. Our data therefore suggest that one effect of top-down attentional selection is to protect the phase stability of theta/alpha responses under high-distraction. We speculate that maintenance of good temporal-fidelity might be critical for early sensory systems to contribute information to response-planning and memory processes in other brain regions (Fries, 2005). Alternatively, it is possible that the presence of a phase-locked P300 component in the ERP for Attended Hits but not Unattended Correct-rejections might have masked a difference in inter-trial phase coherence and evoked power at the 300 to 400 ms post-stimulus latency range.

When designing the stimuli and task for the present study, we adjusted the root mean square amplitude of each noise distractor to match one of the speech distractors. This resulted in the speech and noise stimuli being approximately matched in apparent loudness. However, speech and broadband noise have very different spectrotemporal properties. Speech is characterized by a high degree of spectrotemporal dynamics such as sharp discontinuities in energy and pitch, whereas broadband noise is relatively constant. Speech also tends to have power concentrated below approximately 1000 Hz. As a consequence, over the entire block of trials, on average our speech distractor contained more power at the

frequencies of the target (975 Hz and 1000 Hz) and non-target (600 Hz) tones than did the noise distractor. Moreover, this difference was more pronounced at the frequency of the non-target tone than at the frequency of the target tones.

A second analysis on N1 mean amplitudes was done to assess whether the N1 attenuation during high-distraction was due to increased energetic masking by the speech distractor. Energetic masking occurs when a tone or noise acts as a masker because of its spectral overlap with the target; it is distinct from informational masking in which masking occurs when a target signal is embedded in a competing signal that impairs target detection, discrimination or intelligibility of speech even when the target and masker do not overlap in frequency (Leek, et al., 1991) (see Durlach, Mason, Kidd, et al., 2003 for discussion of the distinction). To address this confound, high-distraction trials were reclassified as being high-energy/high-distraction or low-energy/low-distraction. The N1 mean amplitude analysis revealed that even when equated for energy, distraction (high vs. low) still attenuated the N1 (Fig. 3-1C (i); Fig. 3-1C(ii)). Thus N1 attenuation observed in high-distraction can be dissociated from the energetic masking confound and instead the present results can likely be considered in the context of auditory informational masking.

The present results can also be interpreted in the context of selective attention. The gain-control theory of attention holds that attention acts to modulate the gain of fixed-latency responses in sensory systems (Hillyard, et al., 1998; Luck, et al., 1997; M. G. Woldorff, et al., 1993). The earliest effects of auditory attention (the early negative difference or "early ND") require that attention be *sustained* at a given frequency or location for several tens of seconds (Donald & Young, 1982; Hansen &

Hillyard, 1988). The early ND is maximal at fronto-central sites and is believed to reflect modulation of auditory cortex on the supratemporal plane (M. G. Woldorff, et al., 1993). When attention is re-oriented on a moment-by-moment basis, as in cue-target (Schroger & Eimer, 1993; Tata & Ward, 2005) or target-target (Tata, et al., 2001) paradigms, the earliest effect of attention occurs after the N1 peak; thus later than in the sustained attention case. The differences between the effects of sustained and transient attention on the ERP suggest that top-down attentional set takes time to deploy, at least at early stages of auditory processing.

If distraction transiently and repeatedly captures one's attention away from a stream of target tones, then attention would be operating in a transient rather than sustained mode, and the boost of early ERP components due to attention would be prevented. In this sense, distraction is conceptually the opposite of attention. This is possibly why "low" compared to "high" distraction ERP waveforms in the present study qualitatively resemble "attended" and "unattended" stimuli in previous attention studies (e.g. Hillyard, et al., 1973). Note however that there is a fundamental difference between the distraction paradigm employed here and the sustained-attention paradigm used by Hillyard and colleagues. In the present study, the target and non-target tones never changed in pitch or location throughout the session. Only the kind of distractor was changed across blocks of trials. That is, the top-down goal of the listener was to maintain a constant attentional set with respect to the target stimuli. The differences in ERP waveforms can be seen as reflecting an involuntary breakdown of attentional set under high compared to low-distraction. However, our data show no evidence of a reorienting negativity (RON), (Schroger & Wolff, 1998) which might be expected if attention is being shifted and re-shifted

during distraction. It is possible that some activity related to reorienting may not have been clearly visible because of signal jitter due to distraction. Furthermore, because our distractor stimuli consisted of continuous speech rather than discrete stimuli, we were unable to extract ERP waveforms associated with distractors.

As stated previously, attenuation of amplitude in the ERP does not unequivocally indicate gain modulation. Likewise, inter-trial phase coherence is a sensitive but not specific indicator of signal jitter. By contrast, an evoked by induced directional cross-over interaction does seem specific to signal jitter (David, et al., 2006). Our data exhibited an evoked by induced directional cross-over interaction thereby indicating the presence of signal jitter and suggesting that Distraction Decoherence is an important consideration in understanding the effects of distraction. However, our data also showed a reduction of total power suggesting that gain attenuation (Hillyard, et al., 1998) is also a correlate of distraction.

Accounts of sensory gain suppression under sub-optimal attentional focus date back to the earliest work with the ERP technique (e.g. Hillyard, Hink, Schwent & Picton, 1973), whereas the notion of Distraction Decoherence is a relatively new electrophysiological correlate of distraction. Thus, we next consider some possible mechanisms of Distraction Decoherence. One possibility is that Distraction Decoherence arises because a subset of neural ensembles becomes phase locked to amplitude modulation of the speech signal in the high-distraction condition. Speech has an envelope of amplitude modulation that fluctuates approximately at the theta frequency, and this envelope is known to be tracked in the auditory EEG signal (Luo & Poeppel, 2007). A simple explanation might be that this extra activity injects phase noise into the ERP. However this is unlikely because the baselines did not differ in

induced power across conditions as would be expected if additional signal was present throughout high-distraction blocks.

Another view of distraction decoherence considers that it may not be possible for the auditory system to both track the phase of a competing speech signal and respond consistently to occasional events such as our target tones. One view of the ERP signal is that it reflects transient phase reorganization and consolidation of ongoing oscillations in the EEG (Klimesch, Sauseng, & Hanslmayr, 2007; Kruglikov & Schiff, 2003; Makeig, Debener, Onton, & Delorme, 2004; Makeig, et al., 2002; Min et al., 2007; Sauseng, et al., 2007) although some reported data are also found to be more consistent with an additive fixed-latency view of ERP generation (e.g. Mazaheri & Jensen, 2006). It may be that distraction disrupts the timing of such phase resetting that would normally exhibit high inter-trial coherence. Inter-trial phase coherence might reflect a mechanism that attempts to entrain to a periodic environmental stimulus as a means of attentional selection (Fries, 2005; Womelsdorf & Fries, 2007a). For example, Schroeder & Lakatos (2009) proposed that the brain might act in two modes with respect to attention: a "vigilance" mode characterized by readiness to respond to discrete events in time, and a "rhythmic" mode characterized by phase entrainment with a to-be-attended periodic signal. The brain cannot effectively be in both modes at once. Distraction decoherence might occur because the high-distraction speech signal causes the brain to enter a rhythmic mode. To respond to the temporally unpredictable occurrence of the probe tones, the brain would need to escape this rhythmic mode and switch to the vigilance mode. Since the distracting speech, and therefore any entrained oscillation in the auditory system, could have any phase at the moment of target onset, this switching might take

slightly different amounts of time on different trials, thereby jittering the subsequent ERP response.

3.5 Conclusion

Distraction is a common occurrence in any complex sensory environment. Although much is known about related attentional processes and their physiological correlates, little is known about the consequences of distraction itself. The present study showed that distraction leads to attenuation of the gain with which the auditory system responds to stimulus events. We also showed that distraction disrupts the time-locking of neural responses relative to acoustic events in the environment. We propose the term *Distraction Decoherence* to describe the resulting breakdown in coherence of the EEG signal across successive trials. In general, the concept of inter-trial phase decoherence could account for a wide variety of situations in which a cognitive or perceptual manipulation leads to an apparent attenuation of a component in the averaged ERP waveform. The exact reasons why Distraction Decoherence occurs, and the mechanistic significance of inter-trial phase coherence in general, remain to be explored in both general and special populations.

3.6 Acknowledgments

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Chapter 4: The Neural Correlates of Auditory Distraction in Post-secondary Adults with ADHD: A Pilot Study

4.1 Abstract

A failure to maintain selective attentional control in the presence of irrelevant or competing information is typically described as the phenomenon of distraction. Certain populations of individuals such as those with Attention Deficit Hyperactivity Disorder (ADHD) are observed to be easily distracted by extraneous stimuli. In the present study we used a selective-listening duration-discrimination task with high (competing speech) or low (white noise) distraction to investigate the electrophysiological correlates of auditory distraction in post-secondary adults with ADHD. EEG and ERP responses were compared across low-and high-distraction conditions and across three groups: Un-medicated ADHD, Medicated ADHD and Controls. Chapter Three found that distraction both attenuates the gain and disrupts the temporal fidelity of evoked responses (i.e. Distraction Decoherence). In the present study we tested the hypothesis that those with ADHD who were un-medicated would show greater levels of distraction and Distraction Decoherence than other groups. All groups exhibited a reduction in behavioural performance, an attenuation of the N1, reduced theta/alpha inter-trial phase coherence and a reduction of the gain of the auditory evoked potential in high-distraction. However, our analyses indicated that adults with ADHD are not characterized by greater levels of distraction and that this population may be responding to transient sensory events with abnormally high phase locking. This chapter also found that Un-medicated

ADHD adults had significantly more N1 latency, theta/alpha band evoked power than Medicated ADHD or Control groups.

4.2 Introduction

ADHD is predominantly considered a childhood disorder, however, it is estimated that 36 percent of people diagnosed with ADHD as a child continue to meet diagnostic criteria in adulthood (Kessler, Adler, Barkley, et al., 2005). In the current clinical view of adult ADHD, (DSM-IV; American Psychiatric Association, 1994) there are two major dimensions of symptom impairments: Inattention and Hyperactivity/Impulsivity, and three subtypes of the disorder: Predominately Inattentive, Predominately Hyperactive-Impulsive and Combined Type (Barkley, 1997). Propensity towards distractibility in individuals with ADHD is widely reported and has been suggested to be due to poor response inhibition, under arousal, a lack of motivation, or a lowered threshold to irrelevant stimuli (van Mourik, Oosterlaan, Heslenfeld, Konig, & Sergeant, 2007). Although people with ADHD are described as easily distracted by extraneous stimuli (DSM-IV; American Psychiatric Association, 1994) the phenomenon of stimulus-driven distraction and its underlying mechanisms remain relatively unexplored in the ADHD literature. The present study sought to investigate the electrophysiological correlates of auditory stimulus-driven distraction in post-secondary adults with and without ADHD.

Our study investigated a population of university students who had previously been diagnosed with ADHD. Although these students are relatively high functioning, the university environment can present profound challenges for the

student with ADHD. Post-secondary students with ADHD exhibit poorer academic functioning in comparison to their non-ADHD college peers (DuPaul, Weyandt, O'Dell, & Varejao, 2009). Academic problems in students with ADHD may include disorganization, difficulties sustaining and focusing attention, poor time management skills, poor organization and deficient test taking strategies (Norwalk, Norvilitis, & MacLean, 2009). It is estimated that only 5 percent of post-secondary students with ADHD are expected to graduate (Barkley, 2002). Despite the academic challenges facing the post-secondary ADHD population, this population represents a unique subset of individuals with ADHD. Individuals with ADHD who experience significant impairments due to the disorder are likely never to pursue a post-secondary education (Shaw-Zirt, Popali-Lehane, Chaplin, & Bergman, 2005). Adults with ADHD that pursue a post-secondary education likely have higher cognitive abilities, a greater history of success in academics, experience less cognitive and adaptive impairment and have developed a unique set of coping strategies necessary to adapt to the academic demands of a post-secondary education (Weyandt & Dupaul, 2008).

Cognitive impairments in the ADHD population have been most powerfully correlated with disturbances of brain catecholamines, specifically in dopaminergic function (Bush, et al., 2005; Castellanos & Tannock, 2002; Holroyd, et al., 2008). Several lines of research have linked a hypo-functioning dopaminergic system to ADHD. For example, genetic studies have revealed polymorphisms of dopamine transporter (DAT1) and dopamine receptor (DRD4) genes that alter dopamine transmission and lead to lower levels of synaptic dopamine (Swanson, et al., 2000). Perhaps the strongest link between ADHD and the catecholaminergic system is the

effective treatment of the core symptoms of inattention, hyperactivity and impulsivity in people with ADHD using drugs with strong dopaminergic action. Such drugs are typically referred to as "stimulants" and include for example, methylphenidate (e.g. Ritalin, Concerta) and dextroamphetamine (e.g. Dexedrine) (Zahn, Rapoport, & Thompson, 1980). Although individual mechanisms differ between medications, they act to facilitate the actions of the catecholaminergic neurotransmitters either by preventing their reuptake and/or facilitating their release (Solanto, 2002).

Spencer et al. (1996) systematically reviewed 155 studies of nearly 6000 children, adolescents and adults with ADHD of which the efficacy of stimulant medications was documented in approximately 70 percent of participants. The efficacy of stimulant medications was reflected in decreased symptoms of ADHD but also in improvements in self-esteem, cognition and social functioning. Several studies have investigated the effects of stimulant medications using the human electroencephalogram (EEG) (Barry, Johnstone, et al., 2003), however these studies predominantly address the effects of stimulant medications in children and adolescents with ADHD; very few EEG studies to date have investigated the effects of stimulant medications in adults with ADHD (Bresnahan, et al., 1999; Bresnahan & Barry, 2002; Bresnahan, et al., 2006). Although stimulant medications are associated with the amelioration of ADHD symptomatology, the mechanisms by which stimulant medications exert their effects as revealed by measures such as the EEG are less understood, specifically in adults with ADHD.

The scalp-recorded EEG and the associated Event-Related Potential (ERP) have been extensively used to study the effects of attention across both healthy and

clinical populations; thus these techniques can be useful in studying a population of people that demonstrate symptoms of inattention and heightened distractibility. Decades of research using EEG have revealed that the brain processes attended and unattended inputs differentially. A prominent effect of sustained attention in the ERP is an increase in the N1 component of the ERP evoked by attended relative to unattended stimuli (Hillyard, et al., 1973). The augmented N1 response occurs only after attention is focused on the task-relevant target stream for several tens of seconds (Donald & Young, 1982; Hansen & Hillyard, 1988), but not when attention is frequently reoriented (Schroger & Eimer, 1993; Tata, et al., 2001; Tata & Ward, 2005) as would be expected in situations when an individual is distracted. The general consensus is that the N1 represents an "attention capturing signal" that triggers the conscious perception of incoming external stimuli (Naatanen, 1988, 1990; Näätänen, 1992). The quality of early sensory processing, for example as reflected in modulations of the N1, is likely to impact later processes that make perceptual decisions, which are then reflected in behavior. Thus, observations of how the N1 is modulated in conditions of distraction in groups with and without ADHD may help to elucidate the neural underpinnings of the disorder particularly in regards to distractibility.

Chapter 3 discussed how, in healthy controls, attenuation of the N1 and associated reduction in inter-trial phase coherence under high-distraction could result from gain modulation and/or jittering of that component across trials. A reduction of theta/alpha total power at the N1 latency was indicative of sensory gain modulation and a theta/alpha band evoked by induced power directional cross-over interaction was indicative of signal jitter (a phenomenon of which we termed,

Distraction Decoherence). In the present study we used a selective listening task in low (broad-band noise) or high (continuous speech) distraction as in Chapter 2. The EEG was recorded to examine three adult groups: Controls, Un-medicated ADHD and Medicated ADHD. We predicted that the Un-medicated ADHD group would show more evidence of distraction both behaviourally and electrophysiologically than Medicated ADHD or Control groups. More specifically, we predicted that the Un-medicated ADHD group would show the most evidence of Distraction Decoherence at the N1 latency. We found that all groups exhibited a reduction in behavioural performance, an attenuation of the N1, reduced inter-trial phase coherence and reduced gain of the auditory evoked potential under high- relative to low-distraction. However, unlike what we predicted, the Un-medicated ADHD group did not show more evidence of Distraction Decoherence. Our results indicate that ADHD groups show differential patterns of phase synchronization then Controls at early stages of stimulus processing. Phase dynamics of cortical oscillations are thought to play a crucial role in attentional control (Fries, 2005), thus the interplay of oscillatory dynamics particularly at low frequencies may play a role in ADHD treatment and symptomatology.

4.3 Experiment One (Behavioural Measures)

In the present study we used a selective-listening duration-discrimination task with high (competing speech) or low (white noise) distraction to investigate the electrophysiological correlates of distraction in the auditory modality in post-secondary adults with ADHD. Our first goal was to establish whether speech

distraction has a measureable effect on task performance in Control, Medicated ADHD and Un-medicated ADHD groups.

4.3.1 Methods

Sixty undergraduates from the University of Lethbridge were recruited and participated for course credit. Of these participants, 25 were recruited as a control population and 45 were recruited on the basis of a prior diagnosis of ADHD. Participants provided informed written consent. Procedures were in accordance with the Declaration of Helsinki and were approved by the University of Lethbridge Human Subjects Review Committee. The data from the Control group are reported in Chapter 2 and in Ponjavic-Conte et al. 2012. Note also that Control and ADHD group data were collected at the same time.

All participants were screened with the World Health Organization adult ADHD self-report scale (ASRS) (Kessler, Adler, Ames, et al., 2005). The ASRS was used to validate a diagnosis of ADHD and to screen out any controls that met ASRS criteria for ADHD. This scale is a short 18-question questionnaire with two subscales that measure symptoms of inattention and symptoms of hyperactivity/impulsivity. Separate scores for symptoms of inattention, hyperactivity/impulsivity and total ASRS, with reliabilities of 0.75, 0.77 and 0.82 (Kessler et al. 2005) can be obtained. Scores in each category can be summed, and the higher the score, the higher the symptom severity. If the scored sum of either category is between 0 and 16, the individual is considered unlikely to have ADHD; if the scored sum is between 17 and 23, then the individual is considered likely to have

ADHD and if the scored sum is 24 or higher then the individual is considered highly likely to have ADHD.

Participants diagnosed with ADHD were not differentiated by subtype but were separated into "Medicated" and "Un-medicated" ADHD groups. Criteria for the Medicated ADHD group included: 1) the participant had to be currently taking a stimulant-based drug (i.e. primarily dopaminergic acting – this precluded Atomoxetine/Straterra) and 2) the participant had to be regularly medicated for at least 4 weeks prior to testing. Medication dosage was not monitored and the time at which the medication was taken was individually variable. To be included in the Un-medicated ADHD group, participants had to be un-medicated for at least four weeks prior and up to the day of testing. Note that participants with ADHD were not screened for co-morbidities, but participants in the control group were.

Of the participants recruited for the control group, four were excluded because they screened positive for ADHD on the ASRS. Thus 21 participants (15 female; 1 left-handed; average age: 22.8) contributed to the data analysis for controls. Three participants with a diagnosis of ADHD did not screen positive for ADHD on the ASRS and thus were excluded from the analysis. In addition, 5 participants with ADHD were also excluded from the analysis because they were medicated with a primarily noradrenergic drug (Strattera). Thus 22 participants contributed to the analysis for the Medicated ADHD group (13 female; 2 left-handed; average age: 22.6). Medication types varied among individuals were as follows: Dexedrine (n=9), Concerta (n=6), Adderall (n=4), Ritalin (n=2) and Vyvanse (n=1). Data from 15 participants were included in the Un-medicated ADHD group (4 female; 3 left-

handed; average age: 21.5). See Table 1 for mean Inattentive, Hyperactive-Impulsive and Total ADHD ASRS scores for participants included in the analysis.

Stimuli were presented on a desktop computer with sound attenuating ear-bud headphones. The OpenAL audio library was used to render sounds to 90 degrees left or right of midline. Volume was individually adjusted. Trials were presented in 28, 1-minute long blocks following a practice session. In each block participants heard target and non-target noise bursts on one side and a distracting sound on the other side. Targets and non-targets were each 60 ms in duration and consisted of two brief noise bursts separated by a 20 ms or 40 ms silent gap, respectively. Ten target and 20 non-target stimuli were pseudorandomized and inter-trial intervals were randomly distributed over 1750 to 2250 ms. The distracting sound was either a "low-distraction" continuous broad-band noise or a "high-distraction" condition consisting of randomly selected segments of an audio book. The root mean square amplitude of each low-distraction stream was matched to one of the high-distraction streams to roughly equate the average subjective loudness of the two distractor conditions. Participants were instructed to attend to the target stream and to press the "space" key when a target sound occurred, while trying to ignore the distraction. While participants did the task their EEG was recorded; discussion of the EEG methods and analysis is taken up in Experiment Two (Electrophysiology).

Mean response times, accuracy, proportion of hits and false alarms and d' were collapsed across blocks and the side of presentation. A repeated measures ANOVA with 3 levels of the factor Group (Control, Medicated ADHD and Un-medicated ADHD) and 2 levels of the factor Distraction (high vs. low) was conducted. As discussed in the results, the 3 by 2 ANOVA did not reveal any

differences of group or distraction by group on the above behavioural measures. Since this was a pilot project and the goal of this study was to explore differences between groups, a two-way repeated-measures ANOVA with two levels of the factor Distraction (high vs. low) and two levels of the factor Group (Control vs. Un-medicated ADHD; Control vs. Medicated ADHD and Medicated ADHD vs. Un-medicated ADHD) was performed on all the behavioural outcomes listed above. Since we had a strong a priori hypothesis that behavioural performance would be impaired by high-distraction, Tukey LSD post-hoc pairwise comparisons were divided by two to show directionality.

4.3.2 Results

The goal of the present study was to make a preliminary investigation of exogenous distraction in ADHD, with the specific aim of testing the prediction that Un-medicated ADHD individuals will exhibit more signs of exogenous distraction. Given the pilot nature of the study, we report here all of the data and statistical comparisons, including a comprehensive set of post-hoc pairwise comparisons. It should be noted that no attempt was made to control for experiment-wise Type I error rate. We report all of these data in the hopes that they will provide a priori guidance to future studies.

Mean Inattentive, Hyperactive-Impulsive and Total ADHD ASRS scores for participants included in the analysis can be viewed in Table 4-1. The Un-medicated ADHD and Medicated ADHD groups did not differ significantly from each other for rated symptoms of Inattention ($t_{35} = 0.652$; $P = 0.519$) and Hyperactivity/Impulsivity ($t_{35} = -0.863$; $P = 0.394$). However, both ADHD groups

differed significantly from the Control group for rated symptoms of inattention (Control vs. Medicated ADHD: $t_{41} = -8.846$; $P < 0.001$; Control vs. Un-medicated ADHD: $t_{34} = -9.717$; $P < 0.001$) and for rated symptoms of Hyperactivity/Impulsivity (Control vs. Medicated ADHD: $t_{41} = -7.883$; $P < 0.001$; Control vs. Un-medicated ADHD: $t_{34} = -7.515$; $P < 0.001$).

Table 4-1: Experiment One ASRS Scores. Mean Inattentive, Hyperactive-Impulsive and Total ADHD ASRS scores for participants included in the Experiment One Behavioural Analysis. Standard deviations are shown in brackets. For all 3 measures (Inattentive, Hyperactive-Impulsive and Total ADHD symptoms), the Control group scored unlikely to have ADHD. Un-medicated ADHD and Medicated ADHD groups score likely to have ADHD for Hyperactive-Impulsive and Total ADHD symptoms and score highly likely to have ADHD for Inattentive symptoms. Un-medicated ADHD and Medicated ADHD group ASRS scores did not differ significantly from each other for symptoms of Inattention or Hyperactivity/Impulsivity; however both ADHD groups differed significantly from Controls for both categories of symptoms.

Group	ASRS DSM-IV Inattentive	ASRS DSM-IV Hyperactive-Impulsive	ASRS DSM-IV Total ADHD
Controls	12.9 (4.0)	10.2 (4.2)	11.5 (4.3)
Un-medicated ADHD	24.9 (3.1)	20.6 (4.0)	22.8 (4.2)
Medicated ADHD	24.1 (4.3)	22.0 (5.6)	23.1 (5.0)

The 3 by 2 repeated measures ANOVA with 3 levels of the factor Group (Control, Medicated ADHD and Un-medicated ADHD) and 2 levels of the factor Distraction (high vs. low) revealed a main effect of distraction for correct-rejections ($F_{(1,55)} = 8.473$; $P = 0.005$), d' ($F_{(1,55)} = 18.886$; $P < 0.001$) and accuracy ($F_{(1,55)} = 23.248$; $P < 0.001$) but not for reaction times ($F_{(1,55)} = 0.319$; $P = 0.575$)) or hits ($F_{(1,55)} = 2.071$; $P = 0.156$). The 3 by 2 repeated measures ANOVA revealed no main effects of group or of group by distraction. The three 2 by 2 repeated measures ANOVA results are described below.

4.3.2.1 Control vs. Medicated ADHD

The two-way repeated measures ANOVA with two-levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Medicated ADHD) revealed main effects of distraction (high vs. low) for correct-rejections, d' and accuracy but not for hits or reaction times. There was no main effect of group or interaction between group and distraction for any of the behavioural measures (see Table 4-2).

Table 4-2: Experiment One behavioural results of the two-way repeated-measures ANOVA between Control and Medicated ADHD groups. F and significance values (P) for effects of distraction, group, and distraction by group are shown for correct-rejections, hits, d', accuracy and reaction times. Blocks with an asterisk indicate p-values of <0.05. There was a main effect of distraction for correct-rejections, d' and accuracy but no main effects of group or interactions between group and distraction.

Controls vs. Medicated ADHD						
Behavioural Measure	Distraction		Group		Distraction by Group	
	$F_{(1,41)}$	P	$F_{(1,41)}$	P	$F_{(1,41)}$	P
Correct-rejections	9.014	0.005 *	0.733	0.397	0.000	0.989
Hits	1.245	0.271	0.003	0.953	0.013	0.908
d'	17.017	< 0.001 *	0.130	0.720	0.794	0.378
Accuracy	16.732	< 0.001 *	0.566	0.456	0.002	0.966
Reaction Time	0.063	0.804	0.071	0.792	0.475	0.494

4.3.2.2 Control vs. Un-medicated ADHD

Like the two-way repeated measures ANOVA between the Control and Medicated ADHD group, the two-way repeated measures ANOVA with two-levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Un-medicated ADHD) revealed main effects of distraction (high vs. low) for

correct-rejections, d' and accuracy but no main effects of group or interaction between group and distraction (see Table 4-3).

Table 4-3: Experiment One behavioural results of the repeated-measures ANOVA between Control and Un-medicated ADHD groups. F and significance values (P) for effects of Distraction, Group, and Distraction by group are shown for correct-rejections, hits, d', accuracy and reaction times. Blocks with an asterisk indicate p-values of <0.05. There was a main effect of distraction for correct-rejections, d' and accuracy but no main effects of group or interactions between group and distraction.

Controls vs. Un-medicated ADHD						
Behavioural Measure	Distraction		Group		Distraction by Group	
	$F_{(1,34)}$	P	$F_{(1,34)}$	P	$F_{(1,34)}$	P
Correct-rejections	6.564	0.015 *	3.350	0.076	0.221	0.641
Hits	1.288	0.264	0.121	0.730	0.138	0.713
d'	12.211	0.001 *	0.430	0.517	0.187	0.668
Accuracy	19.392	<0.001 *	1.553	0.221	0.000	0.998
Reaction Time	0.107	0.746	1.974	0.169	0.424	0.519

4.3.2.3 Medicated ADHD vs. Un-medicated ADHD

The two-way repeated measures ANOVA with two-levels of the factor Distraction (high vs. low) and two levels of the factor group (Medicated ADHD vs.

Un-medicated ADHD) revealed main effects of distraction (high vs. low) for d' and accuracy but no main effects of group or interaction between group and distraction (see Table 4-4).

Table 4-4: Experiment One behavioural results of the repeated-measures ANOVA between Medicated ADHD and Un-medicated ADHD. F and significance values (P) for effects of distraction, group, and distraction by group are shown for correct-rejections, hits, d', accuracy and reaction times. Blocks with an asterisk indicate p-values of <0.05. There was a main effect of distraction for d' and accuracy but no main effects of group or interactions between group and distraction.

Medicated ADHD vs. Un-medicated ADHD						
Behavioural Measure	Distraction		Group		Distraction by Group	
	$F_{(1,35)}$	P	$F_{(1,35)}$	P	$F_{(1,35)}$	P
Correct-rejections	3.379	0.075	0.823	0.371	0.108	0.744
Hits	1.546	0.222	0.135	0.716	0.083	0.776
d'	10.098	0.003 *	0.152	0.699	0.091	0.765
Accuracy	12.566	0.001 *	0.350	0.558	0.001	0.973
Reaction Time	0.492	0.488	1.088	0.304	0.014	0.906

4.3.2.4 Post-hoc pairwise comparisons

Means, standard deviations, and significance values of Tukey Least Significant Difference (LSD) post-hoc pairwise comparisons between low- and high-

distraction for all behavioural measures (correct-rejections, hits, d', accuracy and reaction times) and all groups (Control, Medicated ADHD and Un-medicated ADHD) can be viewed in Table 4-5. Also see Fig 4-1A for behavioural data. Distraction (high vs. low) significantly reduced d' and accuracy in all groups (Fig. 4-1A(iii); Fig. 4-1A(iv)). The rate of correct-rejections was significantly reduced in high-distraction but only for the Control group (Fig. 4-1A(i)). High-distraction had no significant effect on hit rate (Fig. 4-1A(ii)) although all groups tended to make fewer hits in high-distraction. No group showed an effect of distraction (high vs. low) on reaction times (Fig. 1A(v)); however, the Un-medicated group tended to make faster responses in both low- and high-distraction as compared to Control or Medicated ADHD groups.

Table 4-5: Experiment One Behavioural Data**.** Means, standard deviations, and significance values of Tukey LSD post-hoc pairwise comparisons between low- and high-distraction for all behavioural measures (correct-rejections, hits, d', accuracy and reaction times) and all groups (Control, Medicated ADHD and Un-medicated ADHD) are shown. Blocks with an asterisk indicate p-values of <0.05. High-distraction significantly reduced listener sensitivity to detect the target (d') and to discriminate between target and non-target noise bursts (Accuracy) in Controls, Un-medicated ADHD and Medicated ADHD groups. The rate of correct-rejections was significantly reduced in high-distraction for the Control group.

Behavioural Measure	Group	Low Distraction	High Distraction	P
Correct-rejections (mean %)	Controls	91.1 (6.9)	88.8 (7.8)	0.001*
	Un-medicated ADHD	83.1 (16.2)	81.5 (18.5)	0.165
	Medicated ADHD	88.2 (13.5)	85.8 (15.3)	0.055
Hits (mean %)	Controls	59.7 (15.2)	58.3 (18.0)	0.247
	Un-medicated ADHD	62.6 (21.1)	59.9 (26.3)	0.210
	Medicated ADHD	59.5 (17.8)	57.8 (22.0)	0.194
d'	Controls	1.77 (0.80)	1.57 (0.67)	0.003 *
	Un-medicated ADHD	1.56 (1.10)	1.40 (0.99)	0.04 *
	Medicated ADHD	1.66 (0.76)	1.53 (0.70)	0.008 *
Accuracy (mean %)	Controls	80.6 (7.77)	78.6 (7.74)	0.001 *
	Un-medicated ADHD	76.2 (13.3)	74.3 (13.3)	0.008 *
	Medicated ADHD	78.6 (10.4)	76.5 (10.2)	0.009 *
Reaction Time (ms)	Controls	596.1 (67.5)	593.7 (64.1)	0.317
	Un-medicated ADHD	554.3 (104.9)	561.6 (92.0)	0.331
	Medicated ADHD	586.2 (84.3)	591.4 (91.1)	0.299

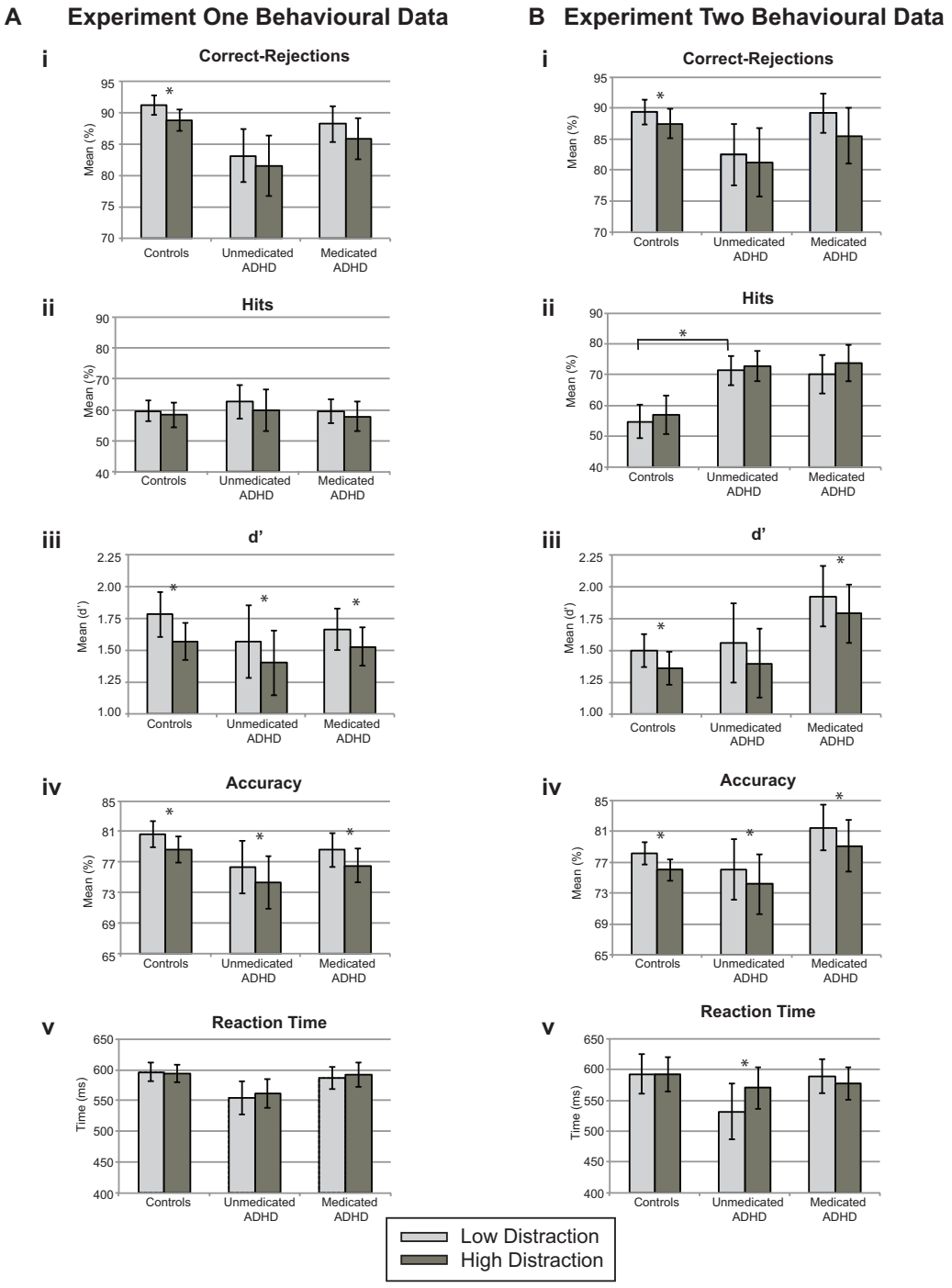

Figure 4-1: Behavioural Data Outcomes for Experiment One and Experiment Two.

4-1A) Behavioural Data Outcomes for Experiment One. Means and standard errors

of the means for (i) correct-rejections, (ii) hits, (iii) d', (iv) accuracy and (v) reaction times in low- and high-distraction for Control, Un-medicated ADHD and Medicated ADHD groups. Asterisks indicate within group significant differences between low- and high-distraction. High-distraction significantly reduced d' and accuracy in Controls, Un-medicated ADHD and Medicated ADHD groups. The rate of correct-rejections was significantly reduced in high-distraction but only for the Control group. 4-1B) Behavioural Data Outcomes for Experiment Two. Means and standard errors of the means for (i) correct-rejections, (ii) hits, (iii) d', (iv) accuracy and (v) reaction times in low- and high-distraction for Control, Un-medicated ADHD and Medicated ADHD groups. Asterisks indicate significant differences between low- and high-distraction and across groups (note also the significant difference in the hit condition between Controls and Un-medicated ADHD in low distraction). High-distraction significantly reduced d' in Controls and Medicated ADHD groups. High-distraction also reduced participant accuracy in discriminating between targets and non-targets across all groups. The rate of correct-rejections was significantly reduced in high-distraction but only for the Control group.

4.3.3. Discussion of Experiment One (Behavioural Measures)

Participant ASRS scores (see Table 4-1) revealed that Un-medicated and Medicated ADHD groups rated their symptoms of inattention and hyperactivity/impulsivity more severely than the Control group although they did not rate their symptoms of inattention or hyperactivity/impulsivity differently from one another. This is surprising given that stimulant medications are reported to be effective in ameliorating core symptoms of ADHD (Spencer, et al., 1996). The lack

of a difference in ASRS scores between Medicated ADHD and Un-medicated ADHD groups could be attributed to one of several reasons: 1) Participants were not instructed to fill out the ASRS on the basis of whether they were currently on or off their medication; thus Medicated ADHD participants could have been recollecting their symptoms prior to starting their medication or when they were "off" their medication. In general, future studies of ADHD should take care to be very specific about how the ASRS should be filled out. 2) The questionnaire instructed participants to rate their symptoms of ADHD over the past 6 months. Differences in the length of treatment varied amongst participants who were medicated, thus variation in ASRS scores could be reflective of this. 3) Medicated ADHD participants might still subjectively view their symptoms as severe regardless of whether they are on or off their medication. Our study was limited in that the ASRS was the only type of screening tool available on the day of the test. Perhaps differences amongst Medicated and Un-medicated ADHD groups could have been observed with comprehensive screening that included interviews, more diverse screening tools, or longitudinal measures.

A 3 by 2 repeated measures ANOVA with 3 levels of the factor group (Control, Medicated ADHD and Un-medicated ADHD) and 2 levels of the factor distraction (high vs. low) revealed a main effect of distraction for correct-rejections, d' and accuracy (there were no main effects of distraction on hit rates or reaction times) but no main effects of group or group by distraction for any of the behavioural measures. Similar results were found in the 2 by 2 repeated measures ANOVAs between Control and Medicated ADHD groups and Control and Un-medicated ADHD groups. The 2 by 2 repeated measures ANOVA between

Medicated ADHD and Un-medicated ADHD groups also resulted in a main effect of distraction for d' and accuracy, but there was no main effect of distraction for correct-rejections. The results of both the 3 by 2 and the 2 by 2 repeated measures ANOVAs suggest that our task is sensitive to the effects of distraction but may not be sensitive to the effects of group or group by distraction, at least as revealed by behavioural measures in this task. The unbalanced number of subjects in each group and the heterogeneity of the group samples could explain that lack of group effect(s) and we acknowledge these limitations. Given that this was a pilot study, the pooling of behavioural data was done in an effort to get an overall picture of performance in this task across groups. Experiment Two (Electrophysiology) looks at balanced behavioural and EEG data.

Tukey LSD post-hoc pairwise comparisons revealed that distraction (high vs. low) had the effect of significantly reducing d' and accuracy across all groups. This implies that both d' and perceptual accuracy were the behavioural measures most sensitive to the effects of distraction in our task. Distraction (high vs. low) did not have a significant effect on hit rates or reaction times across all groups. Both the proportion of hits and the proportion of false alarms (1- rate of correct-rejections) are factored into the d' score. This might explain why d' appears to be more sensitive to the effects of distraction than hits or correct-rejections alone in the present task. Taken together, our results suggest that distraction (high vs. low) has a measurable effect on task performance in Control, Medicated ADHD and Un-medicated ADHD groups.

It is important to note that high-distraction reduced the rate of correct-rejections (i.e. increased the rate of false alarms) but only for the Control group. This

implies that both Medicated ADHD and Un-medicated ADHD groups made similar rates of false alarms regardless of distraction condition. This result is inconsistent with our a priori prediction that the Un-medicated ADHD group would be more sensitive to distraction than Medicated ADHD or Control groups. This result is also counter-intuitive given that people with ADHD are reported to be easily distracted by extraneous stimuli (DSM-IV; American Psychiatric Association, 1994) and thus would be expected (particularly the Un-medicated ADHD group) to make more false alarms in high-distraction. The finding that both Medicated ADHD and Un-medicated ADHD groups made similar amounts of false alarms regardless of distraction condition is in line with research that suggests that adults with ADHD have deficits in inhibition as evidence by CPT performance (Hervey, Epstein, & Curry, 2004; Woods, Lovejoy, & Ball, 2002) and is also in line with the theory that the essential impairment in ADHD is that of response inhibition (Barkley, 1997).

Overall, reports of CPT performance in adults with ADHD resemble that of ADHD child and adolescent literature and indicate that they have deficits in sustained attention and inhibition (Hervey, et al., 2004; Woods, et al., 2002). Although our task failed to differentiate Medicated ADHD or Un-medicated ADHD groups from Controls, the data suggest that the Un-medicated ADHD group had the poorest overall task performance as indicated by d' and accuracy (see Fig. 4-1A). The Un-medicated ADHD group also was the most variable of groups (see Table 4-5) although there were no violations of sphericity in any of the behavioural measures reported. A high degree of variability particularly in reaction times is characteristic of the ADHD population and is suggested to be an index of distractibility (Fassbender et al., 2009). Thus the data suggest that the Un-medicated ADHD group may be the

most distractible of groups in our analysis although this is only speculative.

Effects of stimulant medications have been largely studied using the continuous performance test (CPT). We did not differentiate between drug type, however research indicates that stimulant medications (e.g. methylphenidate, amphetamine, dextroamphetamine) similarly affect performance on various renditions of the CPT (Kavale, 1982). Stimulant medications are reported to improve CPT performance in people with ADHD as evidenced by increased hit rates, decreases in omission and commission errors and less variable reaction times (Riccio, et al., 2001). In addition, stimulant medications have also been reported to slow down reaction times in ADHD groups (Epstein et al., 2006). We did not find any significant differences between Medicated ADHD and Un-medicated ADHD groups; however, there were some trends in the data that are worth noting. In comparison to the Un-medicated ADHD group, the Medicated ADHD group did not make fewer errors of commission (false alarms) or have increased hit rates; however the Medicated ADHD group had slower and less variable reaction times than the Un-medicated ADHD group (Fig. 4-1A (v); Table 4-5). Thus it appears that our task is sensitive to some but not all of the previously reported effects of stimulant medications on ADHD populations in CPT tasks. Such discrepancies could be due to the differences the type of CPT used in our study and others. Furthermore, medication was a between-groups factor in our design, which typically entails more variability in scores across groups. Future experiments may help to elucidate such discrepancies.

4.4 Experiment Two (Electrophysiology)

Experiment One found that our behavioural task showed excellent manipulation of distraction, but this distraction effect did not vary significantly across Control, Medicated ADHD and Un-medicated ADHD groups; all groups were similarly distracted by an extraneous speech distractor. Since we observed trends suggesting differences in performance across groups, irrespective the degree of distraction, in Experiment Two we considered the electrophysiological data to explore whether Medicated ADHD, Un-medicated ADHD and Control groups differ with respect to low-level auditory system responses under distraction.

4.4.1 Methods

Task parameters were the same as in Experiment One. The EEG was recorded with 128 Ag/Ag-Cl electrodes in an Electrical Geodesics Inc., (Eugene, OR, USA) system. The sampling rate was 500 Hz and impedances were maintained under 100 kilo-ohms. Data were analyzed using the BESA software package (Megis Software 5.3, Grafelfing, Germany). The EEG was visually inspected for bad channels and a small number of electrodes (8 or fewer) were replaced with an interpolated signal. Event related potentials (ERPs) were time locked to presentation of target and non-target sounds with a 200 ms pre-stimulus baseline (high-pass (0.5 Hz, 12dB/octave); low-pass (30Hz, 48 dB/octave) zero-phase Butterworth filters; re-referenced and interpolated to a standard 10-10 average-reference montage). Epochs containing artifact (amplitude >+/- 120 μV, gradient >+/- 75 μV/ms, or SD of gradient < 0.001 μV/ms) were rejected. The EEG technique is particularly

sensitive to signal-to-noise concerns and requires that data are averaged over a large number of repeated trials per individual. Performance was high on the task (see Table 4-10); thus after artifact rejection only accurate responses to targets (i.e. "hits") and correct-rejection of non-targets (i.e. "correct-rejections") had enough epochs (> 30) to be analyzed across all participants.

Twelve participants in the Medicated ADHD group, 13 participants in the Un-medicated ADHD group and 14 participants in the control group had enough trials to be included in the correct-rejection analysis. In order to make all groups equal in size, participants with the highest and lowest number of accepted correct-rejection trials in the control group were excluded from further analysis and the participant with the lowest number of accepted trials was excluded from the Un-medicated ADHD group. Thus the correct-rejection analysis included 12 subjects from each of the 3 groups: Controls (9 female; 1 left-handed, average age: 23.6), Un-medicated ADHD (3 female; 2 left-handed; average age: 21.3) and Medicated ADHD (7 female; 1 left-handed; average age: 24.4; Medications: Adderall (n=4), Dexedrine (n=2), Concerta (n=4), Ritalin (n=1) and Vyvanse (n=1)). See Table 4-6 for mean Inattentive, Hyperactive-Impulsive and Total ADHD ASRS scores for participants included in the EEG analysis.

Table 4-6: Experiment Two ASRS Scores. Mean Inattentive, Hyperactive-Impulsive and Total ADHD ASRS scores for participants included in the EEG Analysis for correct-rejections. Standard deviations are shown in brackets. For all 3 measures (Inattentive, Hyperactive-Impulsive and Total ADHD symptoms) Controls score unlikely to have ADHD. Un-medicated ADHD and Medicated ADHD groups score likely to have ADHD for Hyperactive-Impulsive and Total ADHD symptoms. For symptoms of Inattention the Un-medicated ADHD group score highly likely to have ADHD and the Medicated ADHD group score likely to have ADHD. Un-medicated and Medicated ADHD group ASRS scores did not differ significantly from each other for symptoms of Inattention and Hyperactivity/Impulsivity, however both ADHD groups differed significantly from Controls for both categories of symptoms.

Group	ASRS DSM-IV Inattentive	ASRS DSM-IV Hyperactive-Impulsive	ASRS DSM-IV Total ADHD
Controls	13.3 (4.4)	10.7 (4.7)	12.0 (4.7)
Un-medicated ADHD	25.1 (2.9)	20.9 (4.4)	23.0 (4.2)
Medicated ADHD	23.8 (4.1)	20.3 (5.7)	22.1 (5.2)

Nine participants in the control group and 8 participants in both the Medicated and Un-medicated ADHD groups had enough trials to be included in the analysis for hits. To make the groups equal, the control subject that was excluded in the correct-rejection analysis for having the highest amount of trials was also excluded from the hit analysis for having the highest amount of trials. Thus participants included in the analysis of hits were as follows: Controls (6 female; 1

left-handed; average age: 24.6), Un-medicated ADHD (3 female; 2 left-handed; average age: 22.3) and Medicated ADHD (3 female; 0 left-handed; average age: 25.9; Medications: Adderall (n=3), Dexedrine (n=1), Concerta (n=3) and Vyvanse (n=1)).

As in Chapters 2 and 3, the N1 peak of the auditory evoked potential was identified at electrode Cz. Peaks for the correct rejection condition ranged from 84 ms to 94 ms across groups (Controls low-distraction: 92 ms; Controls high-distraction: 92 ms; Un-medicated ADHD low-distraction: 84 ms; Un-medicated ADHD high-distraction 84 ms; Medicated ADHD low-distraction: 94 ms; Medicated ADHD high-distraction: 90 ms). Peaks for the hit condition also ranged from 84 to 94 ms across groups (Controls low-distraction: 94 ms; Controls high-distraction: 92 ms; Un-medicated ADHD low-distraction: 90 ms; Un-medicated ADHD high-distraction 84 ms; Medicated ADHD low-distraction: 92 ms; Medicated ADHD high-distraction: 92 ms). For statistical comparisons, the mean amplitude of the N1 peak for all conditions and all groups was computed from 80 to 100 ms (without filtering) and by using an average reference. Three repeated-measures ANOVAs were used to compare N1 amplitudes across groups. These ANOVAS had two levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs.Un-medicated ADHD; Control vs. Medicated ADHD and Medicated ADHD vs. Un-medicated ADHD).

The raw EEG was transformed into time-frequency space using complex demodulation as implemented in BESA 5.3 (Hoechstetter, 2004) between 4 and 46 Hz, from -200 to 800 ms, and exported in 2 Hz/25 ms sample bins. The time-spectral data for each participant for correct-rejections and hits in both low- and high-distraction conditions was then exported from BESA and imported into

Matlab. Grand-averaged inter-trial phase coherence, Total Power, Induced Power and Evoked Power at electrode Cz were calculated for hits and correct-rejections in low- and high-distraction conditions. Please see Chapter 3 for inter-trial phase coherence, total power, induced power and evoked power calculations.

We compared the difference between low- and high-distraction for inter-trial phase coherence for correct rejections and hits with a random-sample permutation method and applied a method for controlling False-Discovery Rate (FDR) across time and frequency bins (Benjamini 1995). A surrogate distribution was built for each participant by randomly shuffling trials between low- and high distraction conditions (thus preserving the original number of trials in each condition) and then by re-computing the difference between conditions. This process was repeated 40 000 times for each participant to create a surrogate distribution of differences. The surrogate distributions were then averaged to produce a grand-average surrogate distribution of differences. The original grand-average difference was then compared to this surrogate distribution of differences, and a two-tailed P-value (2 x the proportion of surrogate differences that fell beyond the observed difference) for each time/frequency bin was obtained. Differences between low- and high-distraction in total, evoked and induced power were compared using the same procedure. This procedure was also used to compare differences across groups in inter-trial phase coherence, total power, evoked power and induced power.

As discussed in Chapter 3, decoherence of signals across successive trials is uniquely indicated by a directional cross-over interaction between evoked and induced power. It is 'directional' in the sense that increasing jitter causes evoked and induced power to change in specific directions. It is a 'crossover interaction' in that

these quantities vary inversely. Increasing jitter causes evoked power to decrease and induced power to increase (David 2006; see also Chapter 3). Thus a directional cross over interaction between evoked and induced power should reveal the presence of signal jitter without being confounded with amplitude modulation. In Chapter 3 a directional cross-over interaction between evoked and induced power (as evidenced by a significant decrease in evoked power and a significant increase in induced power) occurred in the theta/alpha and N1 latency range. To examine whether a directional cross-over interaction was evident in the current data set, mean values of evoked and induced power for 6 time-frequency bins around the N1 latency and theta range (100 to 150 ms and from 6 to 8 Hz) for both hits and correct-rejections were averaged to create a grand average of evoked and induced power in both low and high-distraction for each group. Two-way repeated measures ANOVAs on grand-averaged evoked and induced power with two-levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Medicated ADHD; Control vs. Un-medicated ADHD; Medicated ADHD vs. Un-medicated ADHD) were conducted to test for between group differences in evoked and induced power. Tukey LSD post-hoc comparisons assessed within group differences in grand-averaged evoked and induced power.

4.4.2 Results

Mean Inattentive, Hyperactive-Impulsive and Total ADHD ASRS scores for participants included in the analysis can be viewed in Table 4-6. Like experiment one, the Un-medicated ADHD and Medicated ADHD group did not differ significantly from each other for rated symptoms of Inattention ($t_{22} = 0.860$; P =

0.399) and Hyperactivity/Impulsivity (t_{22} = 0.280; P = 0.782). Once again both ADHD groups differed significantly from the Control group for rated symptoms of inattention (Control vs. Medicated ADHD: t_{22} = -6.014; P <0.001; Control vs. Un-medicated ADHD: t_{22} = -7.723; P < 0.001) and for rated symptoms of Hyperactivity/Impulsivity (Control vs. Medicated ADHD: t_{22} = -4.514; P <0.001; Control vs. Un-medicated ADHD: t_{22} = -5.481; P < 0.001).

4.4.2.1 Behavioural Results

4.4.2.1.1 Control vs. Medicated ADHD

The two-way repeated measures ANOVA with two-levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Medicated ADHD) revealed a main effect of distraction for correct-rejections, d' and accuracy but not for hits or reaction times. There were no main effects of group or interactions between group and distraction for any of the behavioural measures (see Table 4-7).

Table 4-7: Experiment Two behavioural results of the repeated-measures ANOVA between Control and Medicated ADHD groups. F and significance values (P) for the effects of distraction, group, and distraction by group are shown for correct-rejections, hits, d', accuracy and reaction times. Blocks with an asterisk indicate p-values of <0.05. There was a main effect of distraction for correct-rejections, d' and accuracy but no main effects of group or interactions between group and distraction.

Controls vs. Medicated ADHD						
Behavioural Measure	Distraction		Group		Distraction by Group	
	F	P	F	P	F	P
Correct-rejections	$F_{(1,22)} = 5.531$	0.028 *	$F_{(1,22)} = 0.064$	0.802	$F_{(1,22)} = 0.591$	0.450
Hits	$F_{(1,14)} = 2.914$	0.110	$F_{(1,14)} = 3.789$	0.072	$F_{(1,14)} = 0.199$	0.662
d'	$F_{(1,22)} = 9.198$	0.006 *	$F_{(1,22)} = 2.625$	0.119	$F_{(1,22)} = 0.000$	0.995
Accuracy	$F_{(1,22)} = 10.735$	0.003 *	$F_{(1,22)} = 0.909$	0.351	$F_{(1,22)} = 0.043$	0.838
Reaction Time	$F_{(1,14)} = 1.010$	0.332	$F_{(1,14)} = 0.051$	0.825	$F_{(1,14)} = 0.854$	0.371

4.4.2.1.2 Control vs. Un-medicated ADHD

The two-way repeated measures ANOVA with two-levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Un-medicated ADHD) revealed a main effect of distraction for d', accuracy and reaction times, a main effect of group for hits and an interaction of group by distraction for reaction times (see Table 4-8).

Table 4-8: Experiment Two behavioural results of the repeated-measures ANOVA between Control and Un-medicated ADHD groups. F and significance values (P) for the effects of distraction, group, and distraction by group are shown for correct-rejections, hits, d', accuracy and reaction times. Blocks with an asterisk indicate p-values of <0.05. Note the main effect of distraction for d', accuracy and reaction time. There was also a main effect of group for hits and a significant interaction between distraction and group for reaction times.

Controls vs. Un-medicated ADHD						
Behavioural Measure	Distraction		Group		Distraction by Group	
	F	P	F	P	F	P
Correct-rejections	$F_{(1,22)} = 2.129$	0.159	$F_{(1,22)} = 1.387$	0.252	$F_{(1,22)} = 0.118$	0.735
Hits	$F_{(1,14)} = 0.651$	0.433	$F_{(1,14)} = 5.022$	0.042 *	$F_{(1,14)} = 0.019$	0.892
d'	$F_{(1,22)} = 5.623$	0.027 *	$F_{(1,22)} = 0.025$	0.876	$F_{(1,22)} = 0.027$	0.872
Accuracy	$F_{(1,22)} = 12.182$	0.002 *	$F_{(1,22)} = 0.225$	0.640	$F_{(1,22)} = 0.033$	0.858
Reaction Time	$F_{(1,14)} = 5.655$	0.032 *	$F_{(1,14)} = 0.688$	0.421	$F_{(1,14)} = 5.982$	0.028 *

4.4.2.1.3 Medicated ADHD vs. Un-medicated ADHD

The two-way repeated measures ANOVA with two-levels of the factor Distraction (high vs. low) and two levels of the factor group (Medicated ADHD vs. Un-medicated ADHD) revealed a main effect of distraction for d' and accuracy, no main effects of group and a main effect of group by distraction for reaction times (see Table 4-9).

Table 4-9: Experiment Two behavioural results of the repeated-measures ANOVA between Medicated ADHD and Un-medicated ADHD groups. F and significance values (P) for effects of distraction group and distraction by group are shown for correct-rejections, hits, d', accuracy and reaction times. Blocks with an asterisk indicate p-values of <0.05. Note the main effect of distraction for d' and accuracy as well as the significant interaction between distraction and group for reaction times.

Medicated ADHD vs. Un-medicated ADHD						
Behavioural Measure	Distraction		Group		Distraction by Group	
	F	P	F	P	F	P
Correct-rejections	$F_{(1,22)} = 2.810$	0.108	$F_{(1,22)} = 0.743$	0.398	$F_{(1,22)} = 0.766$	0.391
Hits	$F_{(1,14)} = 1.449$	0.249	$F_{(1,14)} = 0.000$	0.991	$F_{(1,14)} = 0.248$	0.626
d'	$F_{(1,22)} = 5.557$	0.028 *	$F_{(1,22)} = 1.055$	0.315	$F_{(1,22)} = 0.028$	0.868
Accuracy	$F_{(1,22)} = 8.659$	0.008 *	$F_{(1,22)} = 1.094$	0.307	$F_{(1,22)} = 0.113$	0.739
Reaction Time	$F_{(1,14)} = 1.995$	0.180	$F_{(1,14)} = 0.452$	0.512	$F_{(1,14)} = 8.066$	0.013 *

4.4.2.1.4 Post-hoc pairwise comparisons

Means, standard deviations, and significance values of Tukey LSD post-hoc pairwise comparisons for all behavioural measures (correct-rejections, hits, d', accuracy and reaction times) in low- and high-distraction in all groups (Control, Medicated ADHD and Un-medicated ADHD) can be viewed in Table 4-10. Also see Fig 4-1B for behavioural data. . High-distraction significantly reduced d' in Controls and Medicated ADHD groups; however, the Un-medicated ADHD group

also showed a similar trend (Fig 1B(iii)). High-distraction also reduced perceptual accuracy across all groups (Fig. 1B(iv)). The rate of correct-rejections was significantly reduced in high-distraction but only for the Control group (Fig. 1B(i)). High-distraction had no effect on hit rates across all groups (Fig. 1B(ii)). The reaction times of the Un-medicated ADHD group were significantly slower in high-distraction (Fig. 1B(v)) although this group tended to make faster responses in both low- and high-distraction as compared to Control or Medicated ADHD groups.

Table 4-10: Experiment Two Behavioural Data. Means, standard deviations, and significance values of Tukey LSD post-hoc pairwise comparisons between low- and high-distraction for correct-rejections, hits, d', accuracy and reaction times in all groups (Control, Medicated ADHD and Un-medicated ADHD) are shown. Blocks with an asterisk indicate p-values of <0.05. High-distraction significantly reduced d' in Controls and Medicated ADHD groups; there was a near significant effect of distraction on d' for the Un-medicated ADHD group. High-distraction also reduced listener perceptual accuracy across all groups. The rate of correct-rejections was significantly reduced in high-distraction but only for the Control group. Un-medicated ADHD group reaction times were significantly slower in high-distraction.

Behavioural Measure	Group	Low Distraction	High Distraction	P
Correct Rejections (mean %)	Controls	89.4 (7.1)	87.5 (8.2)	0.028 *
	Un-medicated ADHD	82.4 (17.0)	81.3 (19.2)	0.276
	Medicated ADHD	89.2 (11.1)	85.5 (15.5)	0.061
Hits Mean (%)	Controls	54.8 (15.2)	56.9 (17.8)	0.220
	Un-medicated ADHD	71.3 (13.5)	72.9 (14.0)	0.348
	Medicated ADHD	70.2 (17.9)	73.8 (16.9)	0.069
d'	Controls	1.50 (0.44)	1.36 (0.45)	0.014 *
	Un-medicated ADHD	1.56 (1.08)	1.40 (0.93)	0.062
	Medicated ADHD	1.92 (0.83)	1.79 (0.79)	0.043 *
Accuracy	Controls	78.1 (4.9)	76.0 (4.9)	0.008 *
	Un-medicated ADHD	76.0 (13.5)	74.1 (13.4)	0.028 *
	Medicated ADHD	81.3 (10.3)	79.1 (11.5)	0.032 *
Reaction Time (ms)	Controls	592.2 (90.7)	591.6 (77.6)	0.472
	Un-medicated ADHD	531.8 (129.3)	569.9 (96.0)	0.015 *
	Medicated ADHD	589.3 (78.9)	576.5 (74.6)	0.144

4.4.2.2 Electrophysiological Results

4.4.2.2.1 N1 Mean Amplitudes

A prominent N1 peak in the low-distraction condition and attenuation of this peak in the high-distraction condition was observed in both correct-rejections and hits for Control, Un-medicated ADHD and Medicated ADHD groups (Fig. 4-2A; Fig. 4-2B). Three two by two repeated measures ANOVAs on N1 mean amplitudes revealed main effects of distraction for both correct-rejection and hit conditions across all group comparisons (Controls vs. Medicated ADHD; Controls vs. Un-medicated ADHD; Medicated ADHD vs. Un-medicated ADHD). There were no main effects of group and no interactions of group by distraction on N1 mean amplitudes. See Table 4-11 for N1 mean amplitude repeated measures ANOVA results. ERP waveforms for correct rejections can be viewed in Fig. 4-2A for (i) Control vs. Medicated ADHD comparisons, (ii) Control vs. Un-medicated ADHD comparisons and (iii) Medicated ADHD and Un-medicated ADHD comparisons. ERP waveforms for hits can be viewed in Fig. 4-2B for (i) Control vs. Medicated ADHD comparisons, (ii) Control vs. Un-medicated ADHD comparisons and (iii) Medicated ADHD and Un-medicated ADHD comparisons. N1 mean amplitudes, standard deviations and Tukey LSD post-hoc pairwise comparisons significance values can be viewed in Table 4-12. Distraction (high vs. low) significantly reduced the N1 peak for all groups in the correct-rejection condition but only for the Medicated ADHD group in the hit condition although the N1 was attenuated in high-distraction for both Control and Un-medicated ADHD groups.

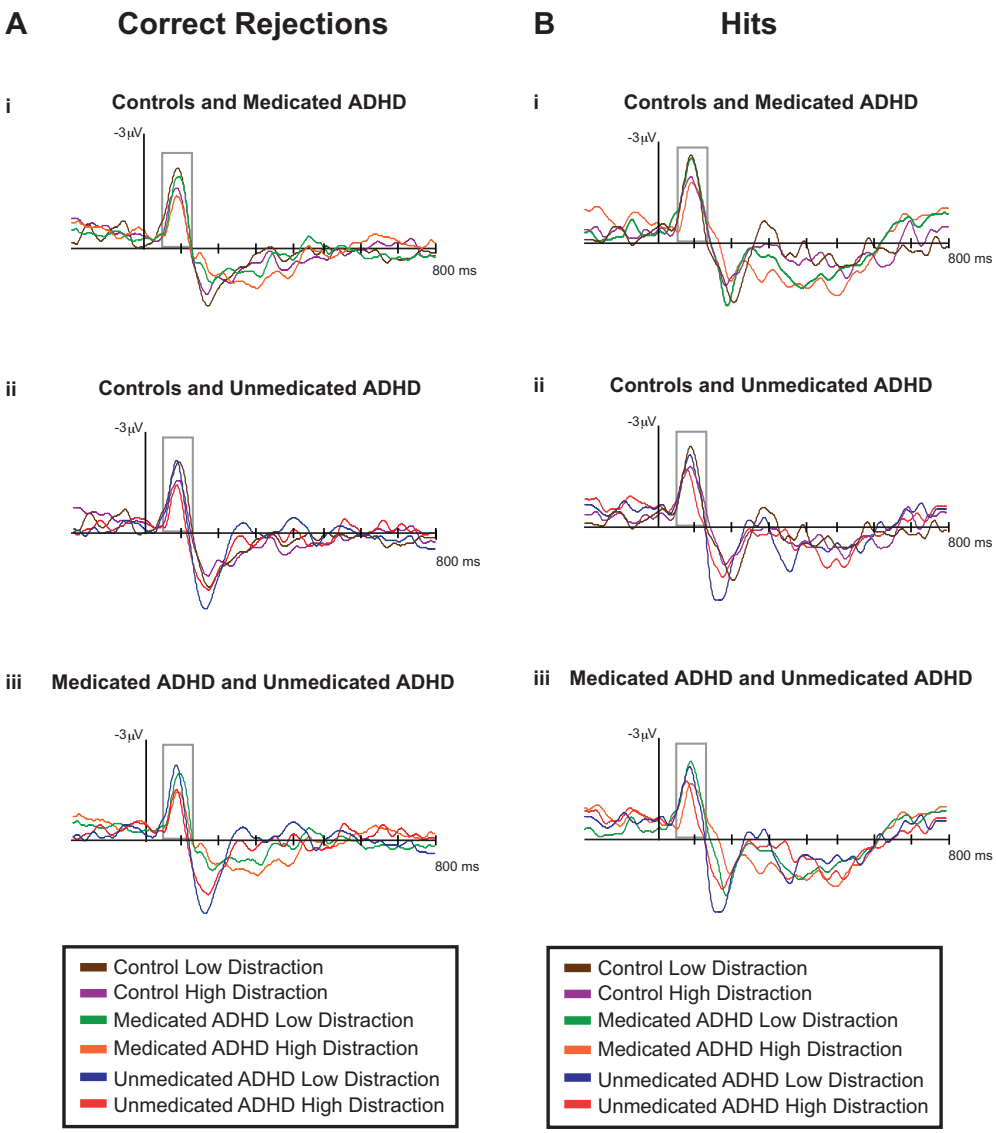

Figure 4-2: ERP waveforms evoked by target-absent correct-rejections and by target-present hits. 4-2A) ERP waveforms evoked by correct-rejections at electrode Cz in low- and high-distraction conditions for (i) Control and Medicated ADHD groups (ii) Control and Un-medicated ADHD groups and for (iii) Medicated ADHD and Un-medicated ADHD groups. Gray boxes outline the N1. Three two by two repeated measures ANOVAs on correct-rejection N1 mean amplitudes with two

levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Medicated ADHD; Control vs. Un-medicated ADHD and Medicated ADHD vs. Un-medicated ADHD) revealed main effects of distraction but no main effects of group or interactions of group by distraction on N1 mean amplitudes (See Table 4-11). Tukey LSD post-hoc pairwise comparisons revealed that distraction (high vs. low) significantly reduced the N1 peak across all groups (see Table 4-12). 4-2B) ERP waveforms evoked by hits at electrode Cz in low- and high-distraction conditions for (i) Control and Medicated ADHD groups (ii) Control and Un-medicated ADHD groups and for (iii) Medicated ADHD and Un-medicated ADHD groups. Gray boxes outline the N1. Three two by two repeated measures ANOVAs on hit N1 mean amplitudes with two levels of the factor distraction (high vs. low) and two levels of the factor group (Control vs. Medicated ADHD; Control vs. Un-medicated ADHD and Medicated ADHD vs. Un-medicated ADHD) revealed main effects of distraction but no main effects of group or interactions of group by distraction on N1 mean amplitudes (See Table 4-11). Tukey LSD post-hoc pairwise comparisons revealed that distraction (high vs. low) significantly reduced the N1 peak in the Medicated ADHD group, although the N1 was attenuated in high-distraction for both Control and Un-medicated ADHD groups (see Table 4-12).

Table 4-11: N1 mean amplitude repeated measures ANOVA results**.** N1 mean amplitude measures of the three two by two repeated measures ANOVA with two levels of the factor distraction (high vs. low) and two levels of the factor group (Controls vs. Medicated ADHD; Controls vs. Un-medicated ADHD; Medicated ADHD vs. Un-medicated ADHD). Blocks with an asterisk indicate p-values of <0.05. Note that although there was a main effect of distraction on N1 mean amplitude in all groups for both correct-rejections and hits, there were no main effects of group or interactions of group by distraction.

Groups Compared	Effects	Correct-rejections		Hits	
		$F_{(1,22)}$	P	$F_{(1,14)}$	P
Controls vs. Medicated ADHD	Distraction	13.023	0.002 *	9.990	0.007 *
	Group	0.275	0.605	2.444	0.140
	Distraction by Group	0.923	0.347	0.759	0.398
Controls vs. Un-medicated ADHD	Distraction	20.553	0.000 *	5.515	0.034 *
	Group	0.222	0.642	1.220	0.288
	Distraction by Group	0.352	0.559	0.002	0.968
Medicated ADHD vs. Un-medicated ADHD	Distraction	15.219	0.001 *	18.438	0.001 *
	Group	0.001	0.977	0.000	0.995
	Distraction by Group	0.299	0.590	1.570	0.231

Table 4-12: Tukey LSD post-hoc pairwise comparisons of N1 mean amplitudes in low- and high-distraction. N1 mean amplitudes in low- and high-distraction with standard deviations (in brackets), and Tukey LSD post-hoc pairwise comparison significance values for Control, Un-medicated ADHD and Medicated ADHD groups are shown. Blocks with an asterisk indicate p-values of <0.05. Distraction (high vs. low) significantly reduced the N1 peak for all groups in the correct-rejection condition and significantly reduced the N1 peak in the hit condition for the Medicated ADHD group, although the peak was attenuated in high-distraction for both Control and Un-medicated ADHD groups.

Group	Correct-rejections			Hits		
	Low	High	P	Low	High	P
Controls	-1.59 (1.11)	-0.97 (0.70)	0.013 *	-2.39 (1.47)	-1.68 (0.96)	0.212
Un-medicated ADHD	-1.88 (1.23)	-1.08 (1.18)	0.006 *	-1.75 (1.04)	-1.07 (1.52)	0.052
Medicated ADHD	-2.02 (1.68)	-0.96 (0.70)	0.027 *	-2.03 (0.87)	-0.79 (0.50)	0.008 *

4.4.2.2.2 Time-frequency Analysis

4.4.2.2.2.1 Distraction Differences

As predicted, high-distraction significantly reduced theta/alpha band inter-trial phase coherence and evoked power around the N1 latency for *correct-rejections* in Control, Un-medicated ADHD and Medicated ADHD groups. Distraction differences for *correct-rejections* as revealed by FDR corrected p-values can be viewed in Figure 4-3C(i) and (iii) for the Control group (top), Figure 3C(i) and (iii) for the

Medicated ADHD group (bottom) and Figure. 4-5C(i) and (iii) for Un-medicated ADHD group (bottom)). High-distraction also reduced theta/alpha band inter-trial phase coherence and evoked power around the N1 latency for *hits* in Control (Fig. 4-4A(i) and (iii)), Un-medicated ADHD (Fig. 4-6A(i) and (iii)) and Medicated ADHD (Fig. 4-4B(i) and (iii)) groups; however these effects are not as transparent in the hit data likely due to the smaller number of subjects included in the analysis for hits. Distraction differences for *hits* as revealed by FDR corrected p-values can be viewed in Figure 4-4C(i) and (iii) for Control group (top), Figure 4-4C(i) and (iii) for the Medicated ADHD group (bottom) and Figure 4-6C(i) and (iii) for Un-medicated ADHD group (bottom)). Distraction (high vs. low) did not have a significant effect on total power or induced power as revealed by FDR correction methods.

4.4.2.2.2.2 Group Differences

4.4.2.2.2.2.1 Control vs. Medicated ADHD

The time-frequency analysis between Control and Medicated ADHD groups revealed significant differences in inter-trial phase coherence and evoked power. In the *correct-rejection* condition the Control group, in comparison to the Medicated ADHD group, had greater inter-trial phase coherence in the theta/alpha band at the N1 latency in low-distraction (Fig. 4-3D (i) (top)); the Control group also showed more evoked power in low- and high-distraction than the Medicated ADHD group in this time-frequency window (Fig. 4-3D (iii)). Differences in Control and Medicated ADHD groups in the *correct-rejection* condition also occur in evoked power at approximately 400 ms; the Medicated ADHD group show more theta/alpha evoked power as compared to the Control group in both low- and high-distraction.

The difference between Control and Medicated ADHD groups in theta/alpha evoked power around 400 ms in both low- and high-distraction also occurs in the *hit* condition (Fig. 4-4D (iii)).

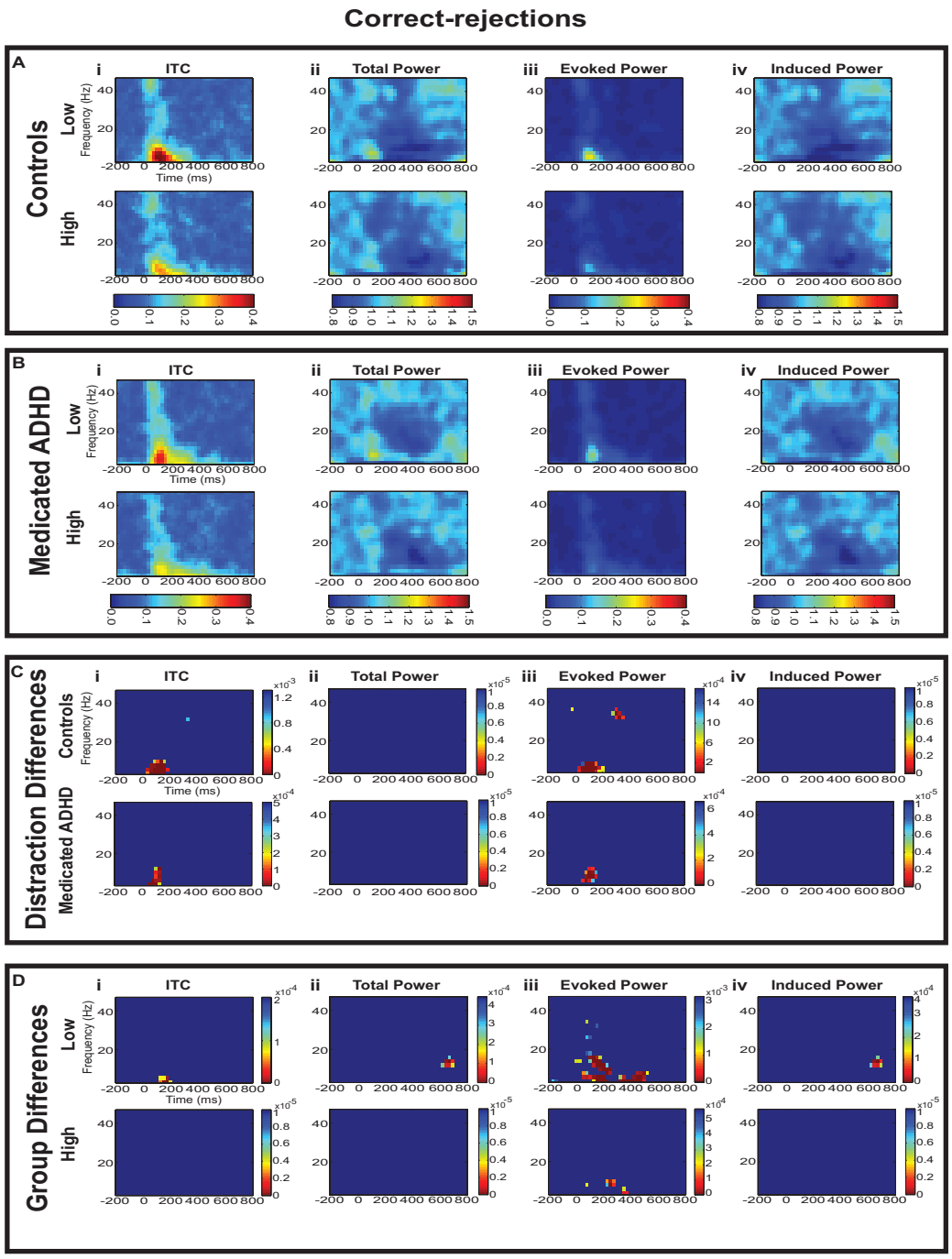

Figure 4-3: Time-frequency analysis of correct-rejections for Control and Medicated ADHD groups. 4-3A) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high

(below) distraction in the correct-rejection condition for the Control Group. 4-3B) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the correct-rejection condition for the Medicated ADHD group. 4-3C) FDR thresholded map of the differences due to distraction (high vs. low) for Control (above) and Medicated ADHD group (below) in the correct-rejection condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power. Note that both Control and Medicated ADHD groups show a reduction of Inter-trial phase coherence and Evoked power in high-distraction at the N1 latency and theta/alpha frequency range. 4-3D) FDR thresholded map of the differences between Control and Medicated ADHD groups in the correct-rejection condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction. Note the Inter-trial phase coherence difference in low-distraction and evoked power difference in low- and high-distraction in the N1 latency range; there is more Inter-trial phase coherence and evoked power in the Control group. Also note the difference in evoked power in low-distraction and to a lesser extent in high-distraction at approximately 400 ms; the Medicated ADHD group show more evoked power in the theta/alpha frequency range at this latency than the Control group.

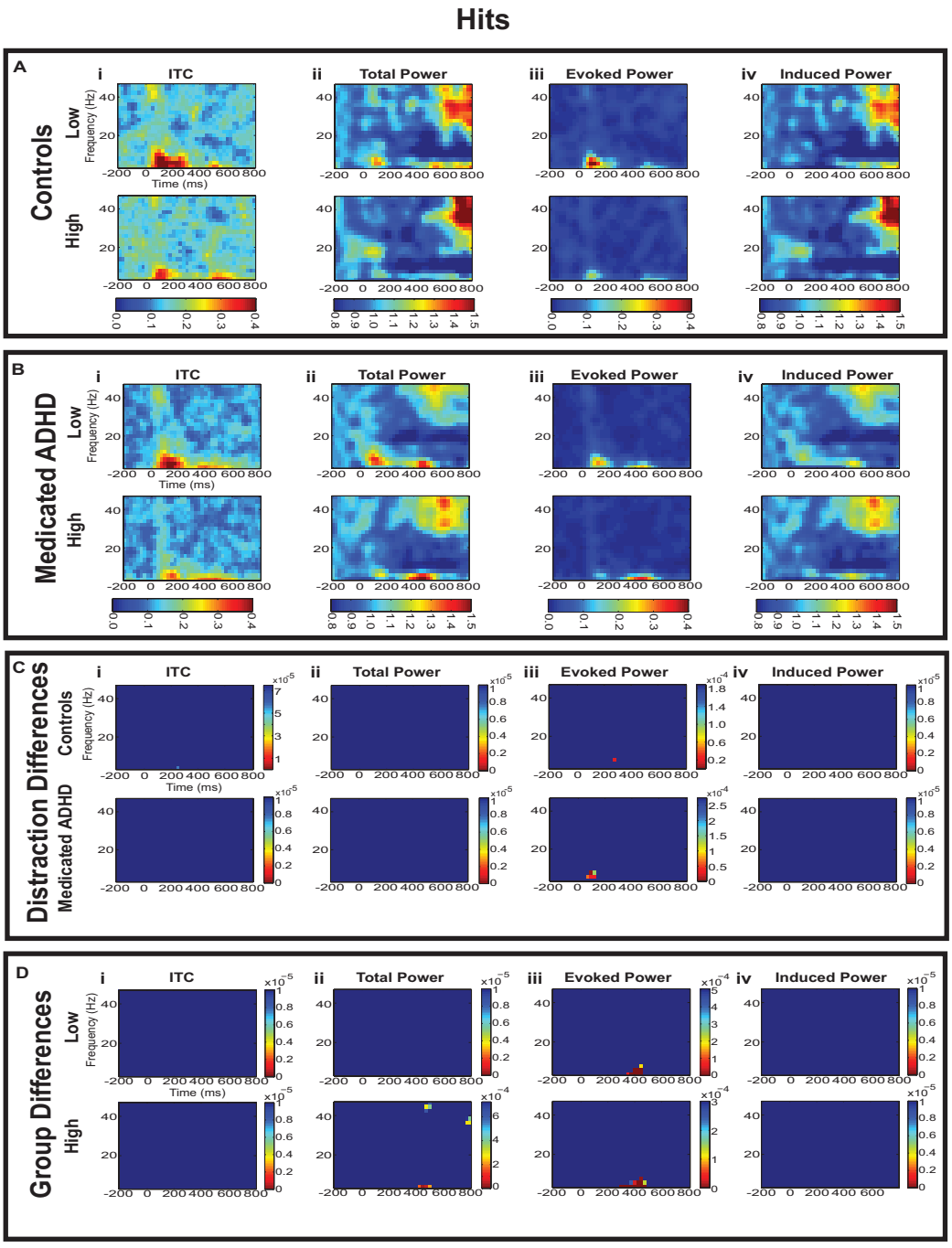

Figure 4-4: Time-frequency analysis of hits for Control and Medicated ADHD groups. 4-4A) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the hit condition for the Control Group. 4-4B) Time frequency plots

of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the hit condition for the Medicated ADHD group. 4-4C) FDR thresholded map of the differences due to distraction (high vs. low) for Control (above) and Medicated ADHD group (below) in the hit condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power. Both Control and Medicated ADHD groups showed a reduction of Evoked power in high-distraction at the N1 latency and theta/alpha frequency range although FDR thresholded differences are only clearly visible for the Mediated ADHD group. 4-4D) FDR thresholded map of the differences between Control and Medicated ADHD groups in the hit condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction. Note that the Medicated ADHD group had significantly more evoked power in low- and high-distraction than controls at approximately 400 ms post-stimulus.

4.4.2.2.2.2.2 Control vs. Un-medicated ADHD

Comparisons between Control and Unmedicated ADHD groups for correct-rejection and hit conditions revealed significant differences in theta/alpha band evoked power at the N1 latency. The Un-medicated ADHD group had significantly more evoked power in low- and high-distraction than the Control group in the *correct-rejection* condition (Fig. 4-5D (iii)) and in low-distraction for the *hit* condition (Fig. 4-6D (iii) (top)). The Un-medicated ADHD group in comparison to the Control group also showed more evoked power around the N1 latency in the 20-30 Hz range for *correct-rejections* specifically in low-distraction (Fig. 4-5D (iii) (top)).

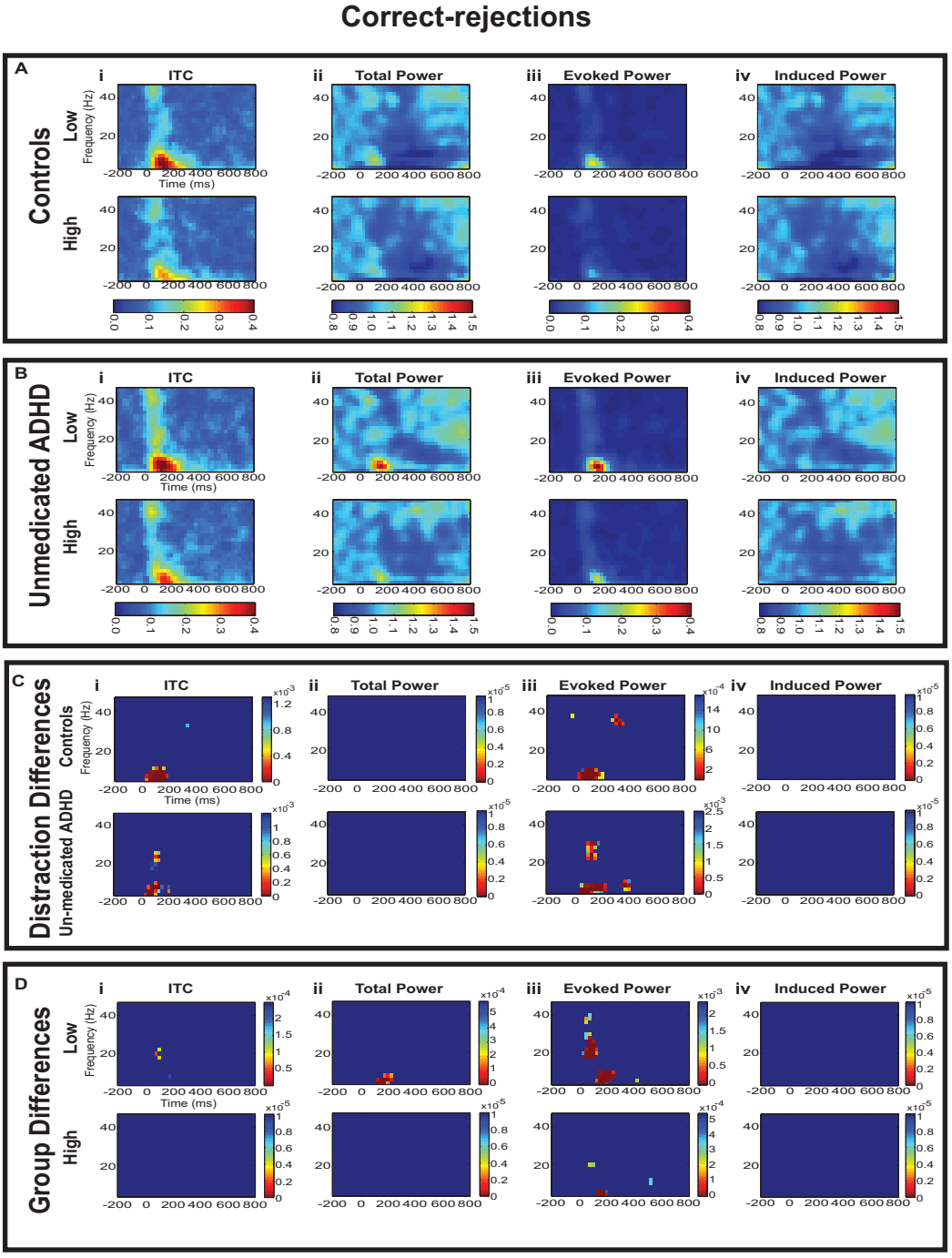

Figure 4-5: Time-frequency analysis of correct-rejections for Control and Un-medicated ADHD groups. 4-5A) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low

(above) and high (below) distraction in the correct-rejection condition for the Control Group. 4-5B) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the correct-rejection condition for the Un-medicated ADHD group. 4-5C) FDR thresholded map of the differences due to distraction (high vs. low) for Control (above) and Un-medicated ADHD group (below) in the correct-rejection condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power. Note that both Control and Un-medicated ADHD groups showed a reduction of Inter-trial phase coherence and Evoked power in high-distraction at the N1 latency and theta/alpha frequency range. 4-5D) FDR thresholded map of the differences between Control and Un-medicated ADHD groups in the correct-rejection condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction. Note that the Un-medicated ADHD group had significantly more evoked power in low- and high-distraction than controls in the theta/alpha frequency range at the N1 latency. The Un-medicated ADHD group also had significantly more evoked power around the N1 latency in the 20-30 Hz range.

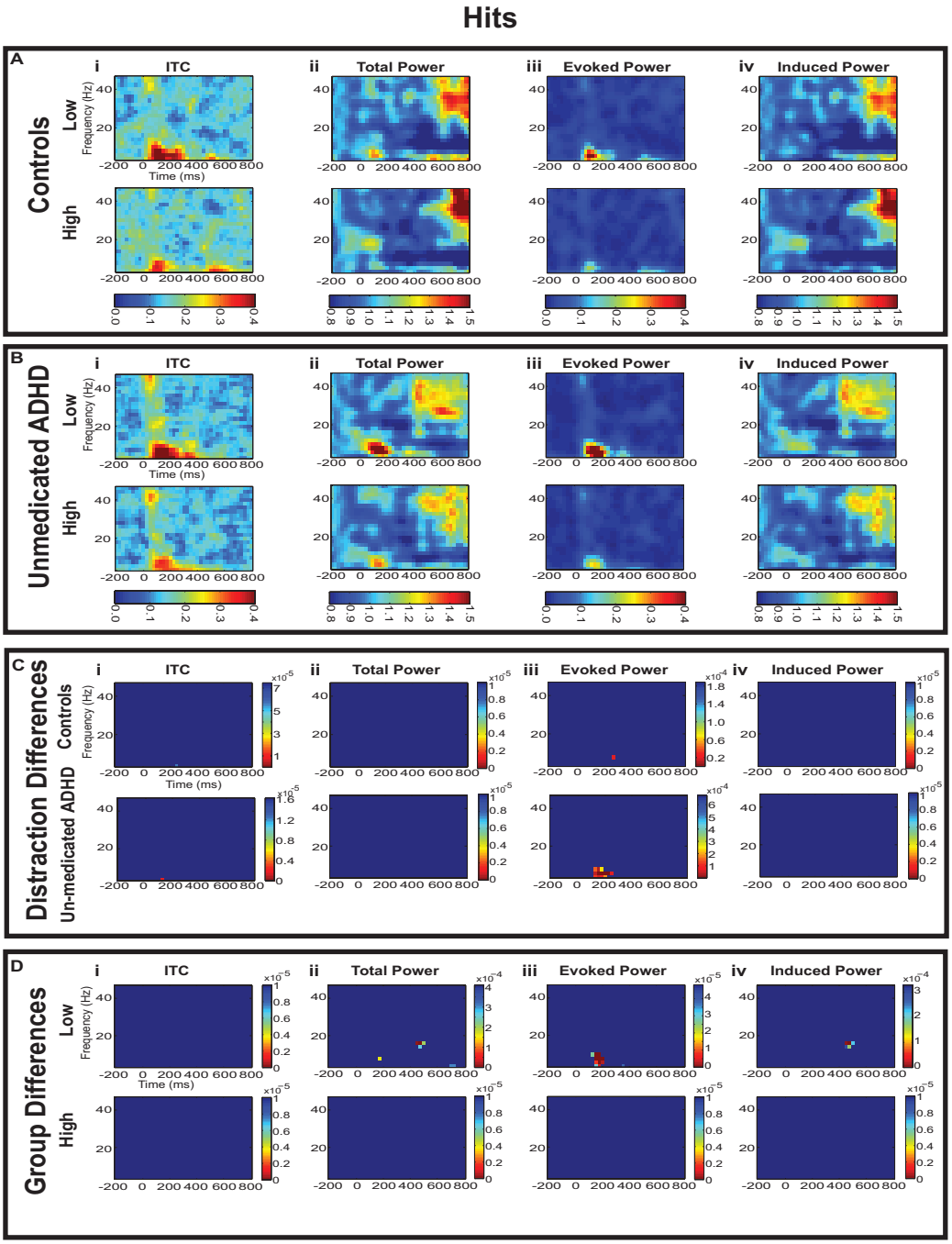

Figure 4-6: Time-frequency analysis of hits for Control and Un-medicated ADHD groups. 4-6A) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below)

distraction in the hit condition for the Control Group. 4-6B) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the hit condition for the Un-medicated ADHD group. 4-6C) FDR thresholded map of the differences due to distraction (high vs. low) for Control (above) and Un-medicated ADHD group (below) in the hit condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power. Note the significant reduction of Evoked Power in high-distraction for the Un-medicated ADHD group. 4-6D) FDR thresholded map of the differences between Control and Un-medicated ADHD groups in the hit condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction. Note that the Un-medicated ADHD group had significantly more evoked power in low-distraction in the theta/alpha frequency range at the N1 latency.

4.4.2.2.2.2.3 Medicated ADHD vs. Un-medicated ADHD

The time-frequency analysis between Medicated ADHD and Un-medicated ADHD groups revealed significant differences in inter-trial phase coherence and evoked power. In comparison to the Medicated ADHD group, the Un-medicated ADHD group had significantly more theta/alpha band inter-trial phase coherence and evoked power in low- and high-distraction at the N1 latency for *correct-rejections* (Fig. 4-7D(i) and (iii)) and significantly more theta/alpha band evoked power at the N1 latency for *hits* (Fig. 4-8D (iii)). Also, slightly after stimulus onset, the Un-medicated ADHD show significantly more evoked gamma activity in high-distraction in the *correct-rejection* condition than the Medicated ADHD group (Fig. 4-

7D (iii)). Differences between Un-medicated ADHD and Medicated ADHD groups in theta/alpha band evoked power also extend beyond the N1 latency to around 400 ms post-stimulus; the Medicated ADHD group exhibit more evoked power in this time-frequency range in both *correct-rejections* and *hits* in both low-and high-distraction (Fig. 4-7D(iii); Fig. 4-8D (iii)). Notice that this is a reversal of the pattern exhibited in the earlier latency window of the N1.

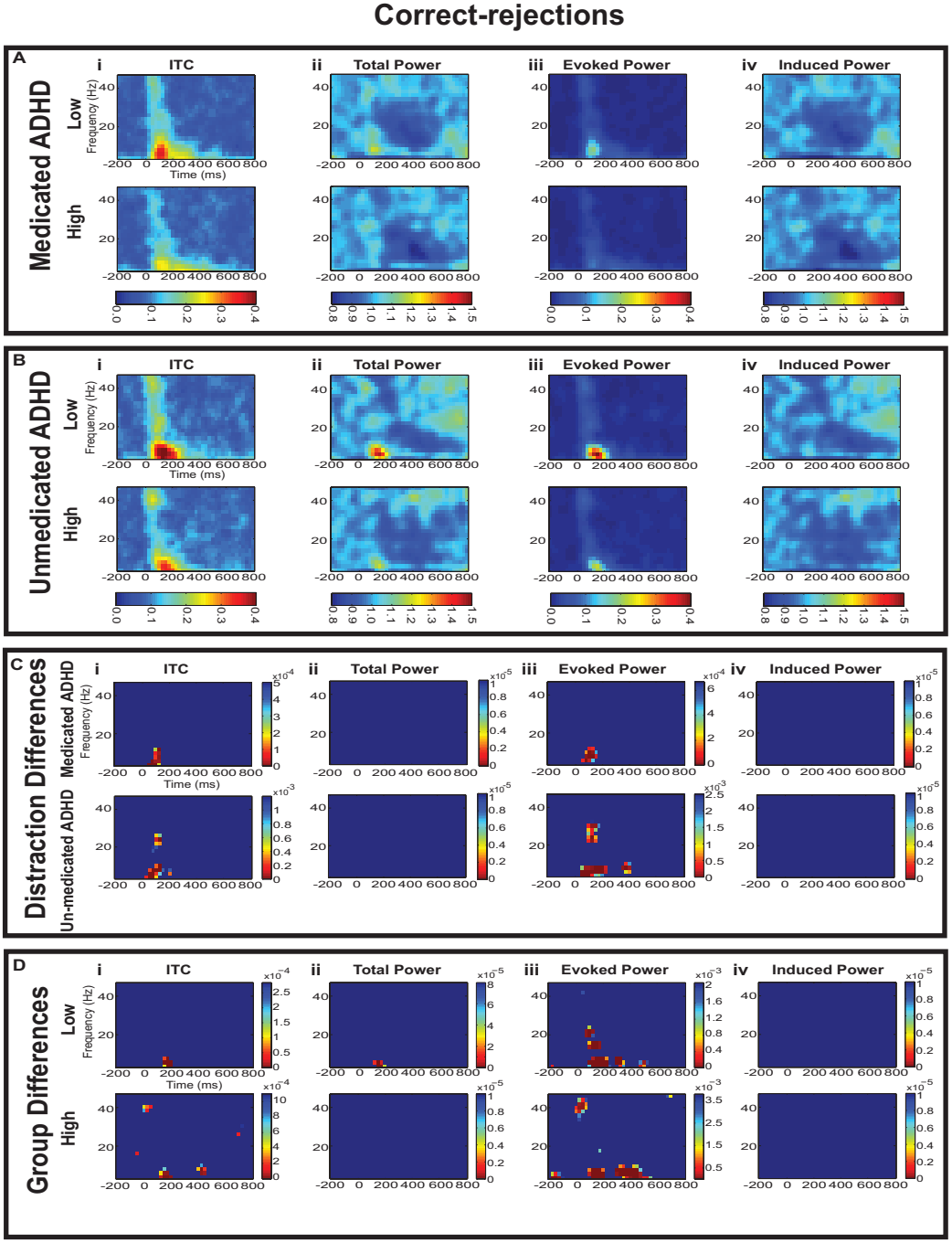

Figure 4-7: Time-frequency analysis of correct-rejections for Medicated ADHD and Un-medicated ADHD groups. 4-7A) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low

(above) and high (below) distraction in the correct-rejection condition for the Medicated ADHD group. 4-7B) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the correct-rejection condition for the Un-medicated ADHD group. 4-7C) FDR thresholded map of the differences due to distraction (high vs. low) for Medicated ADHD (above) and Un-medicated ADHD group (below) in the correct-rejection condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power. Note that both Medicated ADHD and Un-medicated ADHD groups showed a reduction of Inter-trial phase coherence and Evoked power in high-distraction at the N1 latency and theta/alpha frequency range. 4-7D) FDR thresholded map of the differences between Medicated ADHD and Un-medicated ADHD groups in the correct-rejection condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction. Note that the Un-medicated ADHD group had significantly more Inter-trial phase coherence and evoked power in low- and high-distraction in the theta/alpha frequency range at the N1 latency. Also, slightly after stimulus onset, the Un-medicated ADHD showed significantly more evoked gamma activity in high-distraction than the Medicated ADHD group. The Medicated ADHD group had significantly more evoked power at approximately 400 ms than the Un-medicated ADHD group, specifically in high-distraction.

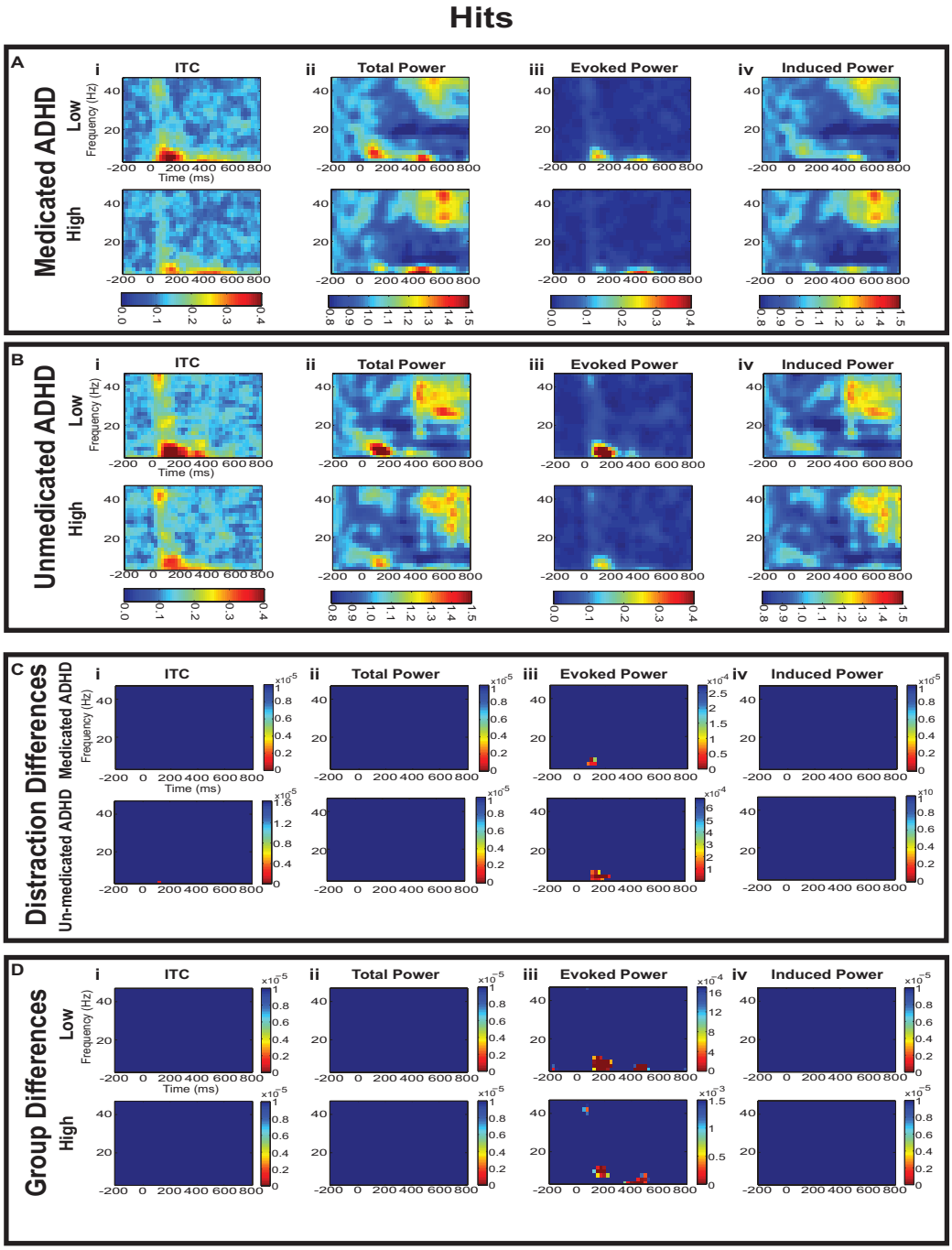

Figure 4-8: Time-frequency analysis of hits for Medicated ADHD and Un-medicated ADHD groups. 4-8A) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high

(below) distraction in the hit condition for the Medicated ADHD group. 4-8B) Time frequency plots of (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction in the hit condition for the Un-medicated ADHD group. 4-8C) FDR thresholded map of the differences due to distraction (high vs. low) for Medicated ADHD (above) and Un-medicated ADHD group (below) in the hit condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power. Note that both Medicated ADHD and Un-medicated ADHD groups show a reduction of Evoked power in high-distraction at the N1 latency and theta/alpha frequency range. 4-8D) FDR thresholded map of the differences between Medicated ADHD and Un-medicated ADHD groups in the hit condition for (i) Inter-trial phase coherence, (ii) Total Power, (iii) Evoked Power and (iv) Induced Power in low (above) and high (below) distraction. Note that the Un-medicated ADHD group had significantly more evoked power in low- and high-distraction in the theta/alpha frequency range at the N1 latency. The Medicated ADHD group showed significantly more evoked power in low- and high-distraction in the theta/alpha frequency range at approximately 400 ms.

4.4.2.2.3 Distraction Decoherence Analysis

The two-way repeated-measures ANOVA on grand-averaged evoked power (6-8 Hz; 100-150 ms) with two levels of the factor distraction (low/high distraction) and two levels of the factor group (Control vs. Medicated ADHD; Control vs. Un-medicated ADHD and Medicated ADHD vs. Un-medicated ADHD) revealed a main effect of distraction for both hit and correct-rejection conditions but no main

effects of group or interactions of group by distraction (see Table 4-13 for correct-rejections and Table 4-14 for hits). The two-way repeated-measures ANOVA on induced power revealed no main effects of distraction, group or interaction.

Table 4-13: Grand-averaged evoked and induced power (6-8 Hz; 100-150 ms) repeated-measures ANOVA results for correct-rejections**.** Blocks with an asterisk indicate p-values of <0.05. There was a main effect of distraction in evoked power in all group comparisons.

Correct-rejections					
Group	Effects	Evoked Power		Induced Power	
		$F_{(1,22)}$	P	$F_{(1,22)}$	P
Control vs. Medicated ADHD	Distraction	21.189	<0.001 *	0.135	0.717
	Group	0.484	0.494	0.624	0.438
	Distraction by Group	0.480	0.496	0.060	0.809
Control vs. Un-medicated ADHD	Distraction	27.117	<0.001 *	0.126	0.726
	Group	0.765	0.391	0.159	0.694
	Distraction by Group	0.660	0.425	0.838	0.370
Medicated ADHD vs. Un-medicated ADHD	Distraction	29.998	<0.001 *	0.658	0.426
	Group	2.085	0.163	1.671	0.210
	Distraction by Group	2.692	0.115	0.940	0.343

Table 4-14: Grand-averaged evoked and induced power (6-8 Hz; 100-150 ms) repeated-measures ANOVA results for hits. Blocks with an asterisk indicate p-values of <0.05; near significant effects are indicated in italics. There was a main effect of distraction in evoked power for all group comparisons. Note the near significant effects of group (Control vs. Medicated ADHD; Control vs. Un-medicated ADHD) for induced power.

Hits					
Group	Effects	Evoked Power		Induced Power	
		$F_{(1,14)}$	P	$F_{(1,14)}$	P
Control vs. Medicated ADHD	Distraction	10.988	0.005 *	1.999	0.179
	Group	0.251	0.624	3.817	*0.071*
	Distraction by Group	0.175	0.682	2.460	0.139
Control vs. Un-medicated ADHD	Distraction	8.645	0.011 *	2.732	0.121
	Group	0.432	0.522	4.218	*0.059*
	Distraction by Group	0.816	0.382	0.669	0.427
Medicated ADHD vs. Un-medicated ADHD	Distraction	14.752	0.002 *	0.143	0.711
	Group	1.282	0.277	0.082	0.779
	Distraction by Group	0.524	0.481	0.265	0.615

As discussed extensively in Chapter 3, Distraction Decoherence is uniquely indicated by a directional cross-over interaction between evoked and induced power in which there is both a significant decrease in evoked power and a significant

increase in induced power from low to high-distraction. Tukey LSD post-hoc pairwise comparisons on evoked and induced power (6 to 8 Hz; 100 to 150 ms) in low- and high-distraction revealed that evoked power is significantly reduced in high-distraction in Control, Medicated ADHD and Un-medicated ADHD groups for *correct-rejections* and in Medicated ADHD and Un-medicated ADHD groups for *hits*. Induced power was not significantly increased in high-distraction in either *correct-rejections* or *hits* for any of the groups (Fig. 4-9A; Table 4-15; Table 4-16). Provided that there were no significant differences in induced power, we did not reliably detect Distraction Decoherence in this sample of participants. Thus the following results will be discussed in terms of a *trend* either towards or away from Distraction Decoherence.

Modulations of induced power from low to high-distraction were inconsistent across groups. Induced power was increased in high-distraction for both hits and correct-rejections in the Control group (Fig. 4-9B(i) and (ii)). Thus the Control group showed evidence of a trend *towards* Distraction Decoherence. Induced power in the Medicated ADHD group stayed relatively the same in both low- and high-distraction for both hits and correct-rejections (4-9B(iii) and (iv)); thus the Medicated ADHD group did not show evidence of a trend either towards or away form Distraction Decoherence. Patterns of induced power from low to high-distraction are inconsistent in the Un-medicated ADHD group. In the hit condition induced power increases from low to high-distraction and in the correct-rejection condition, induced power decreases in high-distraction (4-9B(v) and (vi)); Thus, the Un-mediated ADHD group showed evidence towards Distraction Decoherence in the hit condition and evidence away from Distraction Decoherence in the correct-

rejection condition.

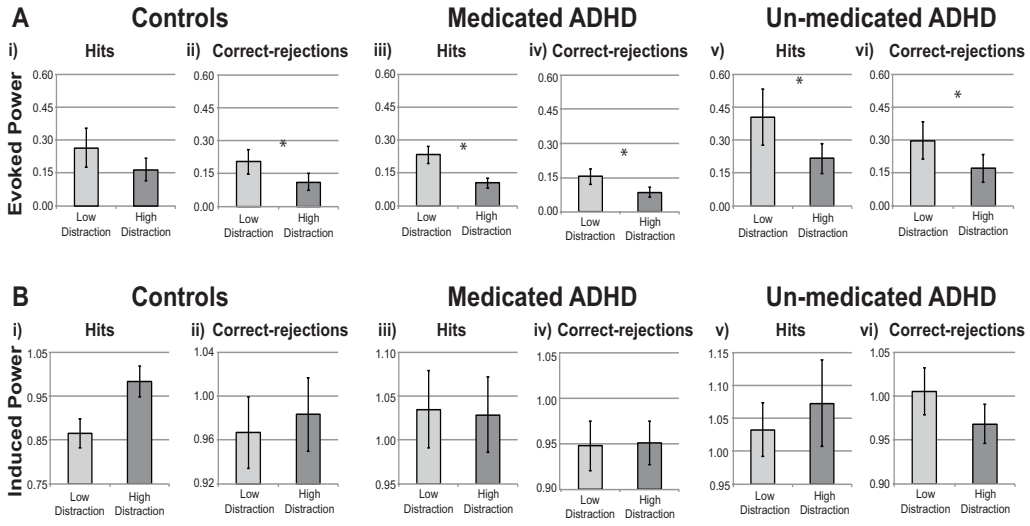

Figure 4-9: Grand-averaged evoked and induced power (6-8 Hz; 100-150 ms) in Control, Medicated ADHD and Un-medicated ADHD groups. 4-9A) Grand-averaged evoked power in low- and high-distraction for hits and correct-rejections in Control (i, ii), Medicated ADHD (iii, iv) and Un-medicated ADHD (v,vi) groups. High-distraction significantly reduced evoked power for *correct-rejections* across all groups and for *hits* in Medicated ADHD and Un-medicated ADHD groups. 4-9B) Grand-averaged induced power in low- and high-distraction for hits and correct-rejections in Control (i, ii), Medicated ADHD (iii, iv) and Un-medicated ADHD (v,vi) groups. There were no significant increases of induced power from low to high-distraction.

Table 4-15: Tukey LSD Post-hoc pairwise comparisons for grand-averaged evoked and induced power (6-8 Hz; 100-150 ms) for correct-rejections in low- and high-distraction. Correct-rejection means, standard deviations (in brackets) and Tukey LSD Post-hoc pairwise comparisons significance values (P) for grand-averaged evoked and induced power (6-8 Hz; 100-150 ms) are shown. Blocks with an asterisk indicate p-values of <0.05. Evoked power was significantly reduced in high-distraction for Control, Medicated ADHD and Un-medicated ADHD groups.

Correct-Rejections					Post-hoc Pairwise Comparisons	
	Mean Evoked Power		Mean Induced Power		Evoked Power	Induced Power
Group	Low	High	Low	High	P	P
Control	0.205 (0.196)	0.112 (0.132)	0.967 (0.113)	0.983 (0.116)	0.009 *	0.738
Medicated ADHD	0.155 (0.120)	0.087 (0.082)	0.948 (0.094)	0.951 (0.083)	0.004 *	0.895
Un-Medicated ADHD	0.297 (0.294)	0.170 (0.216)	1.005 (0.092)	0.968 (0.077)	0.001 *	0.295

Table 4-16: Tukey LSD Post-hoc pairwise comparisons for grand-averaged evoked and induced power (6-8 Hz; 100-150 ms) for hits in low- and high-distraction. Blocks with an asterisk indicate p-values of <0.05. Hit means, standard deviations (in brackets) and Tukey LSD Post-hoc pairwise comparisons significance values (P) for grand-averaged evoked and induced power (6-8 Hz; 100-150 ms). Blocks with an asterisk indicate p-values of <0.05. Evoked power was significantly reduced in high-distraction for Medicated ADHD and Un-medicated ADHD groups.

Hits					Post Hoc Pairwise Comparisons	
	Mean Evoked Power		Mean Induced Power		Evoked Power	Induced Power
Group	Low	High	Low	High	P	P
Control	0.264 (0.308)	0.165 (0.178)	0.865 (0.115)	0.983 (0.122)	0.148	0.094
Medicated ADHD	0.233 (0.136)	0.105 (0.081)	1.035 (0.153)	1.029 (0.148)	0.004 *	0.907
Un-Medicated ADHD	0.403 (0.440)	0.216 (0.240)	1.033 (0.140)	1.072 (0.227)	0.043 *	0.605

4.4.3 Discussion

Participant ASRS scores were similar to ASRS scores in Experiment One of this chapter. Self-reports were similar across the two ADHD groups, but different from controls. Thus we can infer that both Medicated ADHD and Un-medicated ADHD groups are a representative sample of the post-secondary adult ADHD population.

Behavioural results were similar to that of Experiment One in this chapter (Fig. 4-1A and 4-1B). Loss of significant effects from Experiment One to

Experiment Two for example, in d' in the Un-medicated ADHD group could be attributed to the smaller sample sizes used in Experiment Two. Differences could also be attributed to indirectly screening out participants that perhaps were more distractible because participants included for EEG analysis in Experiment Two were those who had the most trials of hits and correct-rejections out of the larger pool of participants in Experiment One above.

While there are behavioural similarities between Experiment One and Experiment Two there are some important differences: The repeated measures ANOVA between the Control and Un-medicated ADHD groups in Experiment Two revealed a main effect of group for hits. Tukey LSD post-hoc pairwise comparisons revealed that the Un-medicated ADHD group made significantly more hits than controls in the low-distraction condition (Fig. 4-1B (i)). However, the Un-medicated ADHD group also made more false alarms in low-distraction; although not significant, this indicates a shift in criterion. In other words, the Un-medicated ADHD group seemed more likely to indicate the presence of a target and the cost of responding when they should not.

Another difference between the behavioural data in Experiment One and Experiment Two was that there was main effect of distraction for reaction times and an interaction between group and distraction in reaction times in the Control vs. Un-medicated ADHD comparison. An interaction between group and distraction in reaction times was also found in the repeated measures ANOVA between Medicated ADHD vs. Un-medicated ADHD groups in Experiment Two. Tukey LSD post-hoc pairwise comparisons revealed that the Un-medicated ADHD group responded to targets significantly slower in high relative to low-distraction in Experiment Two; the

reaction times of the Un-medicated ADHD group were also more variable than other groups (Fig. 4-1B (v); Table 4-10). Slower reactions times are indicative of distraction (Broadbent, 1971). Furthermore, reaction time variability has been associated with heightened levels of distractibility (Fassbender, et al., 2009). Thus the reaction time data in the Un-medicated ADHD group suggest that Un-medicated ADHD group was more distractible than Control or Medicated ADHD groups.

Distraction (high vs. low) had the effect of attenuating the N1 peak in Control, Un-medicated ADHD and Medicated ADHD groups (Fig. 2A; Fig. 2B). The ANOVA on N1 mean amplitudes revealed a main effect of distraction for both correct-rejection and hit conditions across all group comparisons (Controls vs. Medicated ADHD; Controls vs. Un-medicated ADHD; Medicated ADHD vs. Un-medicated ADHD) but no main effects of group and no interactions of group by distraction (see Tables 4-11 and 4-12). These data indicate that high-distraction has the effect of attenuating the N1 similarly across groups. This is consistent with our behavioural finding in Experiment One and Two, that is that the ADHD groups do not seem to be substantially more distracted by exogenous speech.

In our study, N1 mean amplitudes in the Control group (in low- and high-distraction) are larger for the hit as compared to the correct-rejection condition (see Table 4-12 and Fig. 2). Conversely, the Un-medicated and Medicated ADHD groups in our study show similar N1 mean amplitudes to target and non-target stimuli in low- and high-distraction. Similar N1 mean amplitudes to target and non-target stimuli in ADHD have been previously reported (Johnstone & Barry, 1996; Zambelli, Stamm, Maitinsky, & Loiselle, 1977). Our data suggest that both Un-medicated and Medicated ADHD groups could be processing target and non-target

stimuli similarly at initial stages of processing. However, Medicated ADHD and Un-medicated ADHD groups had larger N1s than the Control group to non-targets (correct-rejection condition) particularly in low-distraction (the N1 was modulated similarly in high-distraction across all groups). This difference in N1 mean amplitude across groups (although not significant) suggests that ADHD groups even in low-distraction environments could be processing incoming sensory information more effectively in to-be unattended stimuli than Controls.

The general consensus is that early processing (e.g. N1 modulation) is not dysfunctional in ADHD (Barry et al., 2009). Previous studies of adult ADHD have found larger N1 amplitudes in patient as compared to control groups in both the auditory (Barry, et al., 2009) and visual modalities (Prox, Dietrich, Zhang, Emrich, & Ohlmeier, 2007). Such results have led to the view that adults with ADHD have additional neuronal activity that leads to a greater shifts of attention (Prox, et al., 2007). Our results are somewhat aligned with this theory, although our work clearly indicates that larger ERP amplitudes should not be unequivocally interpreted as increases in the level of neuronal activity. Instead, it is possible that ADHD is characterized by heightened phase consistency following sensory events. This would appear as increased amplitude of ERP peaks. The decrease in induced power from low to high-distraction (Fig. 9B(vi)) for non-target stimuli in the Un-medicated ADHD group may also be further evidence of better phase-resetting mechanisms, at least for non-target stimuli.

High-distraction had the effect of reducing theta/alpha band inter-trial phase coherence around the N1 latency in Control, Medicated ADHD and Un-medicated ADHD groups (Fig. 4-3 – 4-8C). This effect was previously reported in (Ponjavic-

Conte, et al., 2012) and was replicated in Chapter 3. High-distraction also reduced theta/alpha band evoked power at the N1 latency in all groups. Reductions of inter-trial phase coherence and evoked power were more apparent in the correct-rejection condition, likely because of the higher number of participants included in the correct-rejection analysis. Decreased inter-trial phase locking and evoked power in high-distraction is likely reflective of disruptions in sensory gain and/or phase consistency across trials (see Chapter 3).

The Un-medicated ADHD group showed significantly more gamma band inter-trial phase coherence and evoked power in the correct-rejection condition around the N1 latency in low as compared to high-distraction (Fig. 4-5C). Gamma band activity, in particular phase synchronization has been implicated in the effective coding of sensory stimuli (Womelsdorf & Fries, 2007b) and in attentional processes, with the degree of synchronization correlated with the degree of selective attention (Fell, Fernandez, Klaver, Elger, & Fries, 2003)for review. Increased evoked gamma band responses at approximately 100 ms have previously been reported in people with ADHD and have been suggested to reflect additional neuronal activation (Lenz et al., 2008). A reduction in gamma band inter-trial phase coherence and evoked activity from low to high-distraction in the Un-medicated ADHD group could be reflective of a breakdown of selective attention processes in this group during distraction.

The time-frequency analysis also revealed that the Un-medicated ADHD group had substantially more theta/alpha band evoked power at the N1 latency than Control or Medicated ADHD groups. Our finding is in line with recent literature. Increased theta and alpha power has been repeatedly found in adolescents and adults

with ADHD in eyes-open or eyes-closed resting state EEG (Bresnahan, et al., 1999; Bresnahan & Barry, 2002; Koehler, et al., 2009; Lazzaro, et al., 1999). Increased slow wave activity, particularly in the theta band, has been found in people with ADHD from childhood to adulthood and may be considered a diagnostic feature of ADHD (Barry, Clarke, & Johnstone, 2003). Our study is different from this previous work in that it reports event-related changes in theta power, and specifically identifies these changes as being tightly time-locked to sensory events.

Stimulant medications have been reported to normalize the EEG and to reduce theta/alpha power activity in individuals with ADHD. For example, children who demonstrate a positive response to treatment with stimulants (e.g. methylphenidate) show a reduction in theta/alpha activity (Clarke, Barry, Bond, McCarthy, & Selikowitz, 2002; Clarke et al., 2003; Loo, Teale, & Reite, 1999). Reductions of theta/alpha band power with stimulant medication use has also been reported in adolescent (Rowe, Robinson, & Gordon, 2005) and adult (Bresnahan, et al., 2006) ADHD populations. In the Bresnahan et al. (2006) study it was found that when medicated with Dexedrine, ADHD adults had significantly less absolute and relative to baseline theta power than when un-medicated, but they still had significantly more absolute and relative theta power than a control group. The Mediated ADHD group in our study showed lesser amounts of theta/alpha band evoked power at the N1 latency than the Un-medicated ADHD group. Interestingly, unlike the Bresnahan et al. (2006) study, the Medicated ADHD group in our study had significantly less theta/alpha band evoked power than the Control group at the N1 latency.

Our results indicate that that one mechanism by which certain stimulant medications may exert their effects is by selectively decreasing brain activity, at least at early stages of sensory processing. This effect might seem counter-intuitive, since the word "stimulant" implies an increase of activity. However, stimulants act to selectively decrease brain metabolic activity as evidenced by Positron-Emission Tomography, fMRI and intracranial recordings (Foote, Freedman, & Oliver, 1975; Friston et al., 1992; Mattay et al., 1996; Willson, Wilman, Bell, Asghar, & Silverstone, 2004). Decreases in brain activity due to increased levels of dopamine are hypothesized to be due to dopaminergic networks of inhibitory interneurons that selectively potentiate task-relevant regions and suppress task-irrelevant ones (Mattay, et al., 1996; Volkow et al., 2001), although the mechanisms by which this occurs remain to be elucidated. The resulting decrease in variability across the network might help to "lock down" the selection of one dominant representation, for example in working memory systems (e.g. Gruber et al., 2003, 2006). Lower amounts of theta-alpha band evoked power and inter-trial phase coherence in the Medicated ADHD group in our study may thus be associated with dopamine-related attentional tuning of the cortex.

Although stimulant medications are reported to ameliorate ADHD symptomatology, our data suggest that stimulant medications do not have the effect of equating the Medicated ADHD group to Controls with respect to brain function. In fact, the Medicated ADHD group can be differentiated from both Control and Un-medicated ADHD groups in that they have significantly more theta/alpha evoked power at approximately 400 ms (+/- 100 ms) in both low- and high-distraction in both hit and correct-rejection conditions (Fig. 4-3D; Fig. 4-4D; Fig. 4-

7D; Fig. 4-8D). It is unclear as to what is driving this effect. The Medicated ADHD group showed a trend of more theta/alpha band evoked power at 400 ms in the hit as compared to correct- rejection condition (Fig. 4-3B(iii); Fig. 4-4B(iii)). They also showed more theta/alpha band evoked power in high as compared to low distraction in the hit condition (Fig. 4-4B(iii)). This increase in theta/alpha band evoked power, particularly in high-distraction in the hit condition may be reflective of an increased gain mechanism in sensory areas involved in target discrimination and/or response preparation during conditions of distraction. Note also that the Medicated ADHD group showed the trend to out perform both Control and Un-Medicated ADHD groups in overall task performance (d') in both low-and high-distraction (Fig. 1B (iii)). It is possible that the increase in theta/alpha power at 400 ms in the Medicated ADHD group is the neural correlate of their improved task performance, however, further investigations are required.

Chapter 3 demonstrated that signal jitter in high-distraction is uniquely indicated by a directional cross-over interaction between evoked and induced power, the phenomenon of which we referred to as, Distraction Decoherence. In this experiment we sought to test the theory that an abnormally distractible population, that is the Un-medicated ADHD group, would show more evidence of Distraction Decoherence than Control or Medicated ADHD groups. The two-way repeated measures ANOVA between Control and Un-medicated ADHD groups and Medicated ADHD and Un-medicated ADHD groups did not reveal any main effects of group or interactions between group and distraction (see Tables 4-13 and 4-14). Therefore, the Un-medicated ADHD group did not show more evidence of Distraction Decoherence as predicted.

Distraction Decoherence is uniquely indicated by the directional cross-over interaction between evoked and induced power from low to high-distraction of which there is both a significant decrease in evoked power and a significant increase in induced power. All groups (Controls, Medicated ADHD, Un-medicated ADHD) did not exhibit Distraction Decoherence in the sense that there was both a significant reduction in evoked power and a significant increase in induced power; thus further discussion of the results will be taken in regards to either a trend towards or away from Distraction Decoherence.

Grand-averaged evoked power (6 to 8 Hz; 100 to 150 ms) was decreased in high-distraction across all groups in both hit and correct-rejection conditions (Fig. 4-9A) but not all groups showed an increase in induced power in high-distraction (Fig. 4-9B); that is, not all groups showed a trend towards Distraction Decoherence. The trend towards Distraction Decoherence was observed for the Control group in hit and correct-rejection conditions as predicted and in the Un-medicated ADHD group but only in the hit condition (induced power decreased in high-distraction for the correct-rejection condition in the Un-medicated group). Induced power for the Medicated ADHD group remained similar in low- and high-distraction for both hits and correct rejections (Fig. 4-9B (iii and iv)) hence this group did not show evidence either toward or away from Distraction Decoherence. Given the trend away from Distraction Decoherence in the Un-medicated ADHD group in the correct-rejection condition, it may be that phase synchronization or phase-reset processes related to selective attention (Fries, 2005; Womelsdorf & Fries, 2007b) are being deployed more strongly for non-target than target stimuli in the Un-medicated ADHD group. The Medicated ADHD and Un-medicated ADHD group data together suggest that

individuals with ADHD may have a tendency to respond to transient events with sharp temporal fidelity; an observation of which may have important implications for distractibility in ADHD.

We speculate that individuals with ADHD (in particular those that are Un-medicated) might in general respond to transient sensory events with abnormally high phase-locking. This theory arises from the data that showed that the Un-medicated ADHD group had significantly more theta/alpha band evoked power at the N1 latency than do Control or Medicated ADHD groups (Fig. 4-5D; Fig. 4-6D; Fig. 4-7D; Fig. 4-8D). Furthermore, the Un-medicated ADHD group was the only group to show a reduction of induced power (6-8 Hz; 100-150 ms) in high-distraction. This suggests that people with ADHD particularly those that are un-medicated may have better temporal fidelity for transient sensory evoked events. As stated previously, the general consensus is that early processing (e.g. N1 modulation) is not dysfunctional in ADHD (Barry, et al., 2009). We support this theory and propose that early processing as reflected in the N1 is very functional in ADHD. Alternatively, it may be that total power was simply greater in the ADHD group and, by chance, some of that signal is time-locked to the auditory events. Since we could not measure the degree of phase-locking associated with auditory events in the distracting stream, we can only speculate that those events might also trigger a high degree of phase locking. This tendency to respond to transient events with sharp temporal fidelity might explain why ADHD is thought to entail distractibility.

4.4.4 Conclusion

The phenomenon of being "distracted" is a common occurrence for most people regardless of whether or not they have a diagnosis of ADHD. Despite this familiarity, the mechanisms by which distraction occurs remain poorly understood. The present study showed that distraction leads to decrements in behavioural preformance and attenuation of the N1 component of the auditory evoked potential in Control, Medicated ADHD and Un-Medicated ADHD post-secondary adult groups. Time-frequency analyses of theta/alpha band inter-trial phase coherence, evoked power and induced power in low- and high-distraction conditions showed that Control, Un-medicated ADHD and Medicated ADHD groups differ from one another at the N1 latency and at later stages of sensory processing. Further exploration of the effects of distraction in adults with and without ADHD is required.

4.4.5 Acknowledgements

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Chapter 5: Discussion

This thesis included three experiments that investigated the perceptual and electrophysiological correlates of auditory distraction. Participants were required to discriminate target from non-target stimuli in either a duration-discrimination or pitch-discrimination task in the presence of broad-band noise (low-distraction) or continuous speech (high-distraction) while their EEG was simultaneously recorded. Analyses focused on ERP and neuro-electric oscillatory activity occurring around the latency of the N1 component (~100 ms post-stimulus) of the auditory evoked potential. The N1 component is sensitive to selective and sustained attention; as such we predicted that it would be also be sensitive to the effects of distraction.

In Chapter 2 ERP and time-frequency measures were used to characterize the effect of distraction around the N1 latency. Results showed that relative to broad-band noise, the presence of a continuous speech signal impaired task performance, attenuated the N1 peak and reduced theta/alpha EEG band inter-trial phase coherence around the latency of the N1. However, inter-trial phase coherence is sensitive to both modulations in sensory gain (amplitude) and the phase consistency of oscillatory signals across trials. In Chapter 3 we reconsidered whether reductions of theta/alpha band inter-trial phase coherence during distraction around the N1 latency were related to sensory gain, phase inconsistency or a combination of both mechanisms. We found that distraction both attenuated the gain and disrupted the phase consistency of the brain responses to stimulus events. The term *Distraction Decoherence* was used to describe the resulting breakdown in coherence of the EEG signal across successive trials. Given the premise that certain groups of people are differentially suseptible to distraction, in Chapter 4 we sought to characterize the

elctrophysiological correlates of auditory distraction (particularly in regards to Distraction Decoherence) in post-secondary adults with and without ADHD. We found that theta/alpha band evoked power and inter-trial phase coherence were reduced by distration in Control, Medicated ADHD and Un-medicated ADHD groups. We also found significant group differences in theta/alpha band evoked power at the N1 latency. This suggests that oscillatory dynamics particularly at low-frequencies are modulated by stimulant medications and may also play a role in ADHD symptomatology.

Although the experiments in this thesis differed in task type, stimulus presentation and subject type, they all sought to investigate the effects of a continous speech distractor on behavioural performance or on electrophysiological indices. Thus this discussion chapter integrates our new understanding of distraction across all three experimental chapters.

5.1 Limitations of the Studies

Before general inferences are suggested in regards to distraction and the experiments presented in this thesis, it is worthwhile to consider some important limitations. From the outset the very definition of distraction proved problematic. We sought to investigate the electrophysiological correlates of distraction; however, distraction is a poorly defined term. It is used to describe several subtly different phenomena in the literature and in common usage. For example, distraction might refer to auditory informational masking in which there is an intrusion of a task irrelevant signal into the cognitive mechanisms of the brain. This notion stands in subtle contrast to a more intuitive idea that distraction is reflexive orienting to task-

irrelevant stimuli. The reader will notice that our operationalization of distraction has evolved to include both of these related ideas over the time-course of this thesis. These notions of exogenous or stimulus-driven distraction are quite different from an endogenous act of disengaging from the task at hand, to dwell instead on other thoughts. This alternative conceptualization of distraction might resonate better with some readers, although it is no more or less valid. In fact, distraction is probably more than one phenomenon with more than one mechanism. Only one element of distraction (i.e. exogenous/stimulus driven distraction by a continuous speech distractor) was explored in the present thesis.

The primary focus of this thesis was to characterize the effects of auditory stimulus-driven distraction on the ERP and on oscillatory activity occurring around the latency of the N1 component. Given that the N1 component occurs over a limited time window and is generated by only a subset of electrically active neurons, modulations of activity during distraction at this latency represent only some of the neural correlates of distraction. Furthermore, since the N1 is maximal at central electrode sites, our ERP and time-frequency analysis focused on the single electrode Cz, which is located at the scalp vertex. In focusing our analyses in this way, we neglected to examine cortical processes that are likely modulated by distraction at other areas and latencies. Moreover, only correct target-present or target-absent conditions had enough trials to be analyzed. This limited our interpretations even further because incorrect trials were most likely more indicative of distraction. Lastly, although there were behavioural decrements in performance during high-distraction as compared to low-distraction, we can only infer that our populations were "distracted" by the continuously presented speech stream (that is, that they

failed to maintain top-down selection of the target stream). Differences in the ERP and EEG attributed to distraction may just be modulations due to the presence of the speech stream. That is, differences may be due to increased energetic masking by the speech distractor relative to the broad-band noise distractor and not distraction at all although the results in Chapter 3 indicate otherwise.

Extending our novel findings concerning distraction to the ADHD population necessarily introduced a set of theoretical and practical complications. The participants with ADHD used in the study were those of the post-secondary ADHD population. Post-secondary ADHD adults represent a special subset of those with the disorder. Although these participants had a diagnosis of ADHD and their ASRS scores indicated higher levels of ADHD symptom severity than controls, these individuals represent a high-functioning, highly adaptive subset of those with ADHD (Weyandt & Dupaul, 2008). Individuals with ADHD who experience significant impairments due to the disorder are likely to never pursue a post-secondary education (Shaw-Zirt, et al., 2005). Furthermore, the ADHD participants used in the present EEG analysis were by definition the least distracted in our perceptual task. This was because of a need to select only those individuals who had successfully detected and discriminated the target on enough trials to provide clean EEG data. Given that we screened out participants with a low trial count and those with the most EEG artifacts due to eye blinking or saccadic movements, we indirectly screened out ADHD participants with the worst performance and greater symptom severity (Munoz, Armstrong, Hampton, & Moore, 2003).

Our ADHD work was intended merely to lay an empirical basis for further investigations. This was an unfunded pilot study. Thus there were relatively few

participants. In addition participants with ADHD were highly heterogeneous in that we did not screen out for comorbidities, differentiate by subtype or by medication type. We also used only one type of screening tool (the ASRS) to confirm a diagnosis of ADHD. Given a lack of statistical power and the relatively high-functioning, heterogeneous nature of our ADHD groups, we may have committed many Type II errors. For these reasons, generalizing our results to the general adult ADHD population is only speculative.

5.2 Strengths of the Studies

Our work differs from paradigms typically used to study auditory distraction in the laboratory. Previous investigations of distraction tended to use discrete distractor events that evoked discrete ERP waveforms. A sequence of ERP indicators of distraction has been described in the literature in this way: the elicitation of the mismatch negativity (MMN) caused by task-irrelevant deviations, followed by the P3a component which is associated with the involuntary orienting of attention, followed by the re-orienting negativity (RON) which reflects the neural processes involved in the returning attention to the target stimuli (Schroger, et al., 2000). Our data are largely equivocal with respect to these electrophysiological correlates of distraction. This is possibly due to differences in the type of distracting stimulus used in the present study – differences rooted in our conceptualization of distraction itself. Since we used a continuous speech signal as our distractor, we were unable to extract waveforms associated with the distracting events themselves. Our common experience with distraction fundamentally entails temporal overlap of auditory streams – not temporally discrete auditory blips in the auditory scene. Thus the

electrophysiological correlates of auditory distraction reported in this thesis are more reflective of the type of distraction that occurs on a moment-to-moment basis in the real world. Furthermore, there is a lack of literature exploring the neuro-electric correlates of auditory distraction. This thesis not only explored aspects of commonplace distraction but also assessed the effects of distraction using time-frequency measures of the EEG, methods of which that are not typically used to study distraction in Control or ADHD populations.

Our work featured several novel advantages that are worth considering. One advantage to the study reported in Chapter 4 was that we only used ADHD participants who were medicated or un-medicated for an extended period of time (minimum 4 weeks; however, most subjects were regularly medicated or un-medicated for years). Most studies that investigate the effects of medications in the ADHD population use regularly medicated participants. These studies differentiate between medicated and un-medicated ADHD groups on the basis of whether an individual was "on" or "off" their medication at the time of the experiment – possibly because the notion of a "drug holiday" on weekends is encountered among clinicians. In some studies a drug wash out period of as little as 24 hours was used (e.g. (Holroyd, et al., 2008; Loo, Hopfer, Teale, & Reite, 2004). Recent evidence suggests that increased striatal dopamine transporter (DAT1) is a neural correlate of ADHD (Cook et al., 1995). Prolonged treatment with methylphenidate has been found to down-regulate striatal DAT1 expression in adults with ADHD (Krause, Dresel, Krause, Kung, & Tatsch, 2000). Thus prolonged medication alters brain structure on a time scale beyond a standard 24-hour drug washout. Re-equilibration of DAT1 expression probably takes substantially more time. Consequently, previous

studies using brief drug wash-out periods may not have accurately discriminated between medicated un-medicated ADHD groups. The brain of someone acutely deprived of a regular dose of Ritalin might be quite unlike that of an un-medicated individual with ADHD in our study.

Another advantage of our work is that the experiments described in Chapter 3 made use of the virtual auditory space at the Canadian Centre for Behavioural Neuroscience (CCBN). A key feature of this system is its exceptionally good temporal precision. The EEG technique itself offers high temporal resolution, but only when neuro-electric recordings can be accurately time-aligned with visual or auditory stimulus events. The customized software that controls audio playback and EEG acquisition at the CCBN achieves latency jitter on the scale of only a few milliseconds. This was important because it allowed investigation of phase information of EEG signals across many trials.

5.3 Behavioural Correlates of Distraction

The experiments conducted indicate that several behavioural indices are sensitive to the effects of stimulus-driven distraction by speech in our continuous performance task (CPT). One behavioral measure that was prominently sensitive to the effects of distraction (i.e. significantly decreased in high vs. low-distraction) across all experiments and across all groups was perceptual accuracy in either discriminating targets from non-targets (Chapter 2 and 4) or discriminating between stimuli within a target frequency band (Chapter 3). This suggests that participants either had more difficulty discriminating between stimuli in the presence of a continuous speech signal or that they changed their criteria to favor high hit rates at

the expense of false alarms (Chapter 2 and 4) or at the expense of accuracy (Chapter 3). Other behavioural measures were sensitive to distraction in some experiments and not others or sensitive in some groups but not others.

Investigations of CPT performance in random sampled "normal" adults show that hit rates and d' are sensitive measures in this population, particularly to differences in education level and age (W. J. Chen, Hsiao, Hsiao, & Hwu, 1998). Across all experiments, distraction (high vs. low) did not have an effect on hit rates. However, d' (which incorporates both hit rate and false alarm rate in its score) was a sensitive measure to the effects of distraction in both Control and ADHD groups (Chapter 2 and 4). Measures of d' were not calculated in Chapter 3 because of the unique structure of the task. In the pitch-discrimination task a response to either stimulus within the target frequency band was considered a hit regardless of whether or not the response was correct. Thus in that task a "hit" (correct responses to or within the target frequency band) could have been either a correct or an incorrect discrimination of the target tone. The stimuli in the pitch-discrimination task were chosen so that the effects of top-down attentional set could be examined; however this could also be considered a limitation to the interpretability of hit-related data in Chapter 3.

An important result of Chapter 4 was a failure to find differential sensitivity to distraction in the ADHD groups. Neither the Medicated ADHD nor the Un-medicated ADHD group was more perceptually impaired by concurrent speech than the Control group. For example, unlike Controls, correct-rejection rate data (i.e. false alarm rate data) from both ADHD groups did suggest a heightened level of impulsivity, but this was regardless of the level of stimulus-driven distraction in the

environment. Our failure to find a difference in distractibility across groups stands in contradiction to the popularly held notion that ADHD entails heightened distractibility. Setting aside the possibility of a simple Type II error for the sake of discussion, these data suggest that the notion of distractibility in ADHD may be misapplied.

It is probably important to consider the nature of the stimuli used to measure distraction and distractibility. Both target stimuli and high-distraction speech stimuli were dynamic in that they featured large fluctuations in stimulus intensity. Our data address only the specific situation in which to-be-attended and to-be-ignored dynamic stimuli are set in competition. Distractibility in ADHD might not apply to all kinds of distraction. For example, it is possible that ADHD entails a susceptibility to stimulus-driven distraction only when the to-be-attended information is not encoded in dynamic sensory input, for example when reading a book or holding information in working memory.

5.4 Early-latency Electrophysiological Correlates of Distraction

5.4.1 N1 Mean Amplitudes

Distraction (high vs. low) had the effect of attenuating N1 mean amplitudes across all experiments and groups. The N1 ERP component in low and high-distraction resembles that of attended and un-attended stimuli respectively (Hillyard, et al., 1973). Since participants were instructed to focus attention on the target stream, differences in ERP waveforms can be seen as reflecting an involuntary breakdown of attentional set under high compared to low-distraction. In this sense

our data are consistent with the notion that speech distraction triggers occasionally reflexive reorienting of attention away from the target stream.

Our data are also consistent with previous reports that the presence of task-irrelevant speech or music in the auditory scene attenuates the N1 component of the auditory ERP or its magnetic counterpart, the N1m (R. Hari & J. P. Makela, 1988; Hymel, et al., 2000; Hymel, et al., 1998; Krumm & Cranford, 1994; D. L. Woods, et al., 1984). These studies interpreted the N1 attenuation in the context of auditory masking. In fact the literature on auditory informational masking and the literature on attention orienting exhibit little effort to interact conceptually, despite fundamental overlap of ideas. This has presented unique challenges in crafting our discussions of distraction, for example in Chapter 3. We conclude here that reduction of the N1 ERP waveform is a physiological correlate of competition between two auditory streams. It remains to be elucidated whether such attenuation occurs because of reflexive reorienting, auditory masking or a combination of both mechanisms.

5.4.2 Oscillatory Activity at the N1 latency

Distraction (high vs. low) also had a strong effect on theta/alpha band inter-trial phase coherence around the N1 latency across all experiments and groups. Although inter-trial phase coherence is not an exclusive measure of phase coherence, it nevertheless is sensitive to modulations of phase. Chapter 3 showed that modulations of inter-trial phase coherence are at least partly due to phase jitter in the theta/alpha frequency band although a sensory gain account could not be dismissed. The presence of phase jitter in high-distraction suggests that distraction is disrupting

the temporal fidelity of evoked responses to stimulus events (i.e. Distraction Decoherence). Jittering of phase at the theta/alpha border has been previously associated with reductions of N1 amplitude (Low & Strauss, 2009). Thus we are not describing a new phenomenon but only applying it to the context of auditory distraction.

All three main group comparisons (Control vs. Un-medicated ADHD; Medicated ADHD vs. Un-medicated ADHD and Control vs. Medicated ADHD) in Chapter 4 revealed differences across groups in theta/alpha band inter-trial phase coherence and evoked power around the N1 latency. Although no significant differences were found between groups in N1 mean amplitudes, the Un-medicated ADHD group had the largest amount of theta/alpha band evoked power and inter-trial phase coherence around the N1 latency followed by the Control and Medicated ADHD groups. These data suggest that the Un-medicated ADHD group could have better phase resetting mechanisms (Fuentemilla et al., 2009; Sauseng et al., 2007) or that cells generating the N1 in the auditory cortex could be responding with larger gain (Hillyard, et al., 1998) in the Un-medicated ADHD group than other groups. Either mechanism or a combination of the two would likely manifest in a larger "attention capturing signal" in the Un-medicated ADHD group as reflected by greater amounts of theta/alpha band oscillatory activity occurring around the latency of the N1 (Hillyard, et al., 1973; Naatanen, 1988, 1990; Näätänen, 1992). In line with this view is that the orienting attentional network does not seem to be impaired with those with ADHD (Berger & Posner, 2000).

The Medicated ADHD group (as compared to the Un-medicated ADHD group and the Control group) showed the least amount of theta/alpha band evoked

power and inter-trial phase coherence around the N1 latency (see Chapter 4). This indicates that one mechanism by which certain stimulant medications may exert their effects is by selectively decreasing brain activity, at least at early stages of sensory processing. This effect might seem counter-intuitive, since the word "stimulant" implies an increase of activity. However, stimulants act to selectively decrease brain metabolic activity as evidenced by Positron-Emission Tomography, fMRI and intracranial recordings (Foote, et al., 1975; Friston, et al., 1992; Mattay, et al., 1996; Willson, et al., 2004). Decreases in brain activity due to increased levels of dopamine are hypothesized to be due to dopaminergic networks of inhibitory interneurons that selectively potentiate task-relevant regions and suppress task-irrelevant ones (Mattay, et al., 1996; Volkow, et al., 2001), although the mechanisms by which this occurs remain to be elucidated. The resulting decrease in variability across the network might help to "lock down" the selection of one dominant representation, for example in working memory systems (e.g. (Gruber, Dayan, Gutkin, & Solla, 2006). Lower levels of theta-alpha band evoked power and inter-trial phase coherence in the Medicated ADHD group may thus be associated with dopamine-related attentional tuning of the cortex.

5.4.3 Distraction Decoherence

Indices of phase jitter as indicated by the directional cross-over interaction between evoked and induced power from low to high-distraction (i.e. Distraction Decoherence; see Chapter 3) are difficult to interpret. The directional cross-over interaction between evoked and induced power failed to reach significance for all groups (Controls, Medicated ADHD, Un-medicated ADHD) in the duration-

discrimination task (see Chapter 4). It is possible that this dissimilarity arose because of differences in stimuli parameters or presentation between the two tasks, or variation in the time-frequency bins chosen in the analysis. Further exploration is needed.

At first glance, the absence of both a significant decrease in evoked power and a significant increase in induced power from low-to high distraction in the duration-discrimination task seems to discredit the phenomenon of Distraction Decoherence. However it is important to note that Control subjects in the duration-discrimination task, the pitch-discrimination task and another pitch discrimination task conducted (not reported in this thesis) all showed the same trend of the directional cross-over interaction between theta/alpha band evoked and induced power from low to high-distraction around the N1 latency (evoked power went down, induced power went up). The only group(s) that did not show this trend was the Medicated ADHD group (induced power stayed the same in both low- and high-distraction conditions) and the Un-medicated ADHD group in the correct-rejection condition (induced power decreased in high-distraction). This suggests that Distraction Decoherence is a real phenomenon and that the temporal fidelity of evoked responses may be differentially modulated in ADHD.

We speculate that individuals with ADHD might in general respond to transient sensory events with abnormally high phase-locking. For example, unlike the trend of data that was observed in the pitch discrimination task (Chapter 3), the Un-medicated ADHD group in the duration discrimination task showed more evidence of Distraction Decoherence for hit than correct-rejection conditions (induced power decreased in high-distraction for correct-rejections in the Un-

medicated ADHD group) (Chapter 4). It may be that phase synchronization or phase-reset processes related to selective attention (Fries, 2005; Womelsdorf & Fries, 2007b) are being deployed more strongly for non-target than target stimuli in the Un-medicated ADHD group. This tendency to respond to transient events with sharp temporal fidelity might explain why ADHD is thought to entail distractibility.

Conversely, it has been proposed that a degree of phase decoherence is beneficial for sensory processing and target detection. For example, Chen et al. (2008) demonstrated using an Bayesian ideal observer that assessed neural responses in reaction time tasks, that a high degree of temporal phase coherence can actually limit the quality of sensory processing and task performance (Y. Chen, Geisler, & Seidemann, 2008). Furthermore, it has been suggested that neuronal networks need an optimal level of synchronization among nodes on the network; too little or too much can be detrimental to performance. An optimal level of phase synchronization could allow for more flexibility in responses; for example, neural networks could be better able to reconfigure to changing task demands (Moioli, Vargas, & Husbands, 2012). Thus an alternative hypothesis is that people with ADHD display non-optimal amounts of phase locking (i.e. too much) between neuro-electric events in the brain and sensory events in the environment. In this view, too much phase coherence to task relevant events could interfere with their processing. Alternatively, too much phase synchronization to task-irrelevant events could also be associated with improper processing of task-relevant stimuli. Either mechanism could be related to a tendency towards distraction in people with ADHD.

5.5 Distraction

The experiments in this thesis showed that distraction decreases both the gain and the temporal fidelity with which the brain responds to stimulus events. This thesis emphasizes the temporal effects rather than the sensory gain effects. Whereas the notion of Distraction Decoherence is a relatively new electrophysiological correlate of distraction, accounts of sensory gain suppression under sub-optimal attentional focus date back to the earliest work with the ERP technique (e.g. Hillyard, Hink, Schwent & Picton, 1973).

We used the term Distraction Decoherence to describe the breakdown of the temporal fidelity of evoked responses associated with a stimulus event. One view of the ERP signal is that it reflects transient phase reorganization and consolidation of ongoing oscillations in the EEG (Klimesch, Sauseng, & Hanslmayr, 2007; Kruglikov & Schiff, 2003; Makeig, et al., 2004; Makeig, et al., 2002; Min, et al., 2007; Sauseng, et al., 2007). Distraction Decoherence might occur because of disrupted phase resetting processes that (in the absence of distraction) would otherwise exhibit high inter-trial phase coherence. Another possibility is that Distraction Decoherence arises because a subset of neural ensembles becomes phase locked to amplitude modulation of the speech signal in the high-distraction condition. It is not possible for the auditory system to track both the phase of a competing speech signal and respond consistently to target stream events. Thus, if a distracting stream is capturing attention away from the target stream, inaccurate tracking of target stream stimuli could result in Distraction Decoherence.

The concept of distraction has traditionally been described as opposed to the processes of selective attention, that is, as a process that directs attention towards

task-irrelevant stimuli and disrupts the selection of task-relevant stimuli (Tecce, Savignano-Bowman, & Meinbresse, 1976). However, distraction can also be considered in the context of auditory informational masking. Speech is characterized by a high degree of spectrotemporal dynamics such as sharp discontinuities in energy and pitch, whereas broadband noise is relatively constant. In the present experiments the differences we observe between high- and low-distraction and between target and non-target stimuli might be associated with different levels of energetic masking, different levels of informational masking, or both. However, our analysis in Chapter 3 showed that even when equated for energy, distraction (high vs. low) still attenuated the N1. Thus it appears that N1 attenuation in high-distraction can be dissociated from the energetic masking confound and instead can be considered in the context of auditory informational masking. Future experiments should explore whether the electrophysiological correlates of distraction reported here (i.e. gain modulation or signal jitter) is a phenomenon associated with one particular type of auditory masking.

5.6 Summary

Although the concept of distraction is commonplace, in reality little is known about distraction and its electrophysiological correlates. The experiments in this thesis showed that the presence of a continuous speech stream in comparison to broad-band noise, deteriorates task performance, attenuates the N1 and decreases the gain and the temporal fidelity of which the brain responds to stimulus events (Distraction Decoherence). Comparisons between post-secondary adults with and without ADHD revealed that low-frequency oscillatory activity around the N1

latency is differently modulated across groups thereby implicating their role in ADHD symptomatology and treatment. However the prediction that ADHD should be characterized by greater levels distraction and Distraction Decoherence was unsupported. Due to the importance and complexity of the phenomena that comprise "distraction", further research is essential. The reports described in this thesis represent a step toward a better operationalization of distraction phenomena and suggest one route toward understanding the underlying mechanisms.

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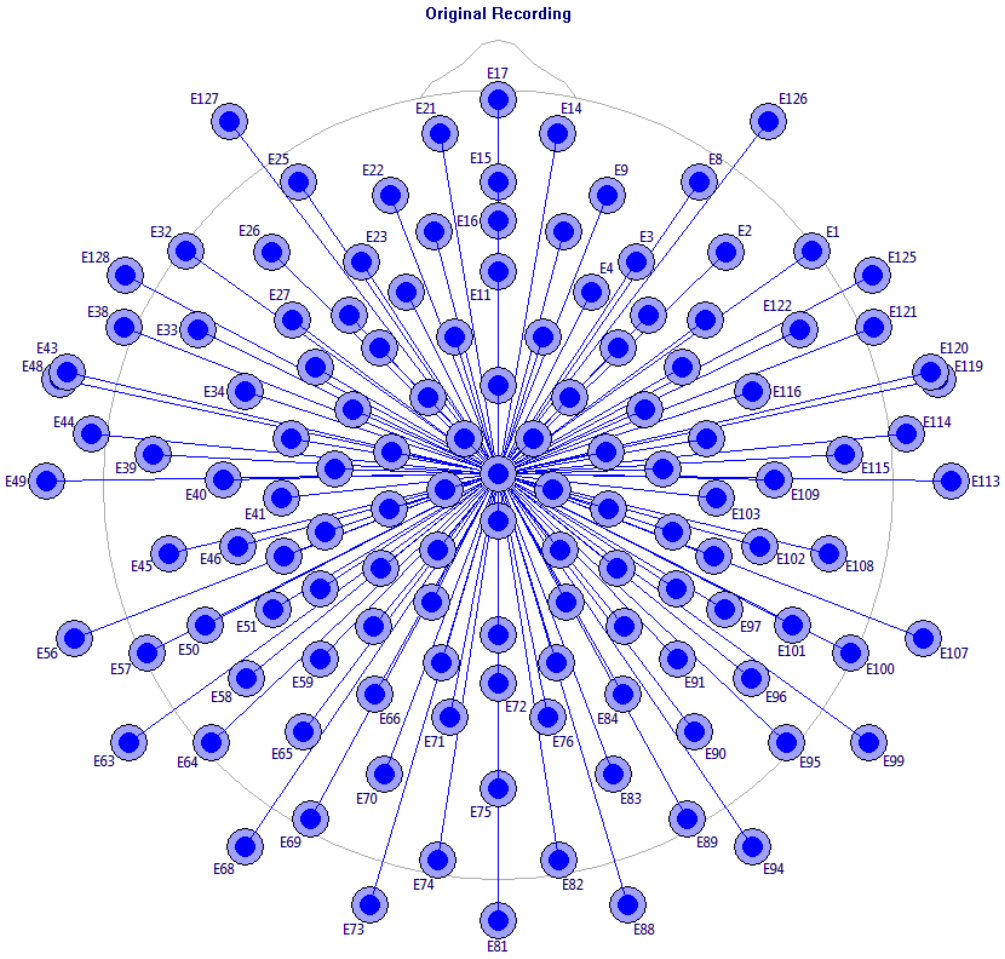
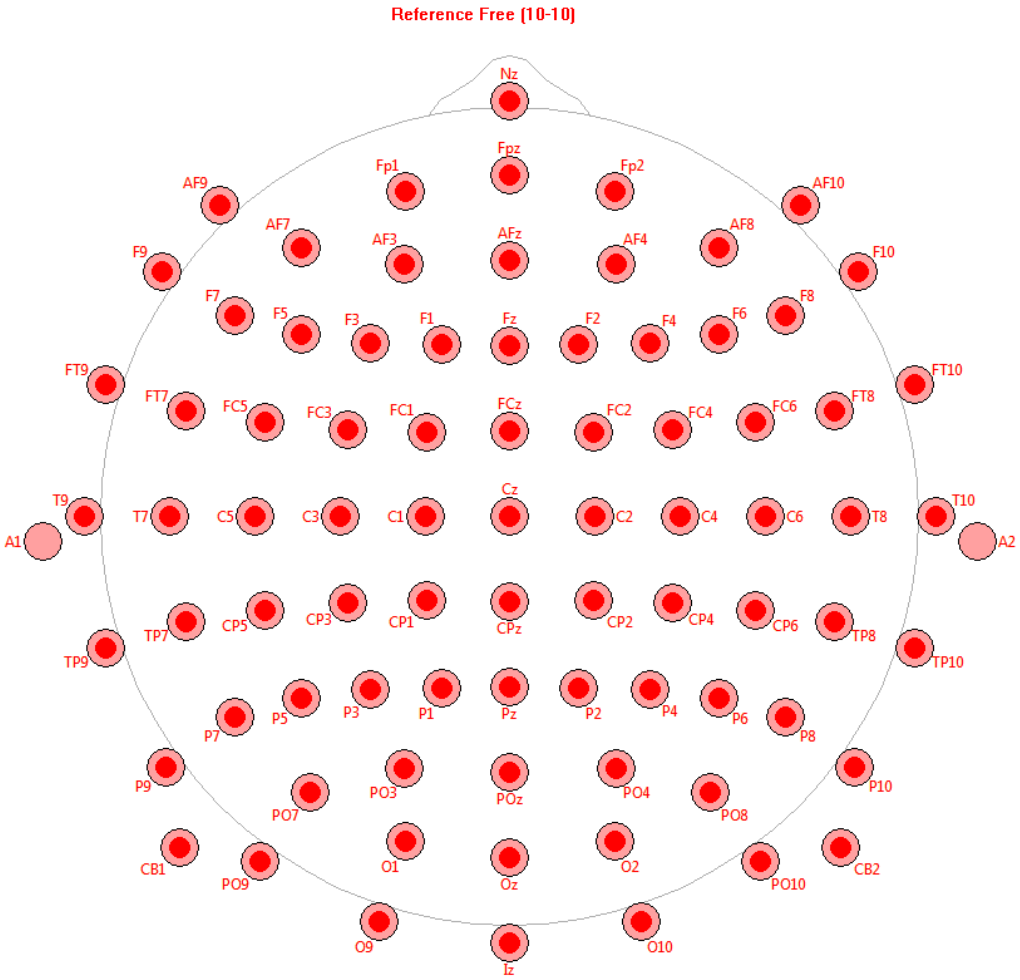
Appendix A: EGI HydroCel Geodesic Sensor Net Electrode Locations



Appendix B: International 10-10 Electrode Placement Locations



Appendix C: Adult Attention Deficit Hyperactivity Disorder Self-report Scale

Please place an X in the box that best describes your conduct over the previous six months.	Never	Rarely	Sometimes	Often	Very Often
1. How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?					
2. How often do you have difficulty getting things in order when you have to do a task that requires organization?					
3. How often do you have problems remembering appointments or obligations?					
4. When you have a task that requires a lot of thought, how often do you avoid or delay getting started?					
5. How often do you fidget or squirm with your hands or feet when you have to sit down for a long time?					
6. How often do you feel overly active and compelled to do things, like you were driven by a motor?					
7. How often do you make careless mistakes when you have to work on a boring or difficult project?					
8. How often do you have difficulty keeping your attention when you are doing boring or repetitive work?					

9. How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?					
10. How often do you misplace or have difficulty finding things at home or at work?					
11. How often are you distracted by activity or noise around you?					
12. How often do you leave your seat in meetings or other situations in which you are expected to remain seated?					
13. How often do you feel restless or fidgety?					
14. How often do you have difficulty unwinding and relaxing when you have time to yourself? 15. How often do you find yourself talking too much when you are in social situations?					
16. When you're in a conversation, how often do you find yourself finishing the sentences of the people you are talking to, before they can finish them themselves?					
17. How often do you have difficulty waiting your turn in situations when turn taking is required?					
18. How often do you interrupt others when they are busy?					