5-12-2024

Examination of the Relationship Between ADHD-Related Symptoms and Pre-Attentive Auditory Processing in a Sample of Autistic Children and Adolescents

Connor K. MacKenzie
Syracuse University

Abstract

Autism Spectrum Disorders (ASD) and Attention-Deficit/Hyperactivity Disorder (ADHD) are two of the most prevalent neurodevelopmental conditions that also exhibit a high rate of co-occurrence. This co-occurrence leads to decreased efficacy of interventions and increased levels of impairments. This suggests that it might be relevant to examine the impact of ADHD symptoms on ASD research findings. Given that both these disorders have neurodevelopmental origins that share differences in sensory processing, the study of sensory neurophysiology might be a relevant avenue to explore. Neurophysiology has focused on pre-attentive auditory processing in both conditions compared to the neurotypical population by focusing on a particular ERP component called the Mismatch Negativity. The mismatch negativity is a pre-attentive ERP component in response to an unexpected event. While both groups exhibit attenuated amplitudes in the MMN, no research has examined the impact of inattention and hyperactivity symptoms on the amplitude of the MMN in autistic youth, a step taken here. Participants in this study consisted of 13 autistic and 13 typically developing children and adolescents matched by age and IQ. Participants completed a passive pure tone oddball task to elicit the MMN. Data analysis assessed MMN amplitude and *t*-scores for the Attention Problems and Hyperactivity indices of the BASC-2 across groups. Additionally, separate Spearman's ranked correlations were conducted between the BASC-2 indices and MMN amplitude for both groups and all participants together. Findings indicated moderate negative correlations between index *t*-scores and MMN amplitude when participants were not separated into ASD and TD groups. These findings may shed light on how attentional concerns and hyperactivity symptomology severity relate to pre-attentive sensory focused auditory processes in children and adolescents even in the absence of official diagnoses. This is important because it may provide

new avenues for research to examine how co-occurring neurodevelopmental conditions may affect how one experiences the world and takes in new information.

Examination of the Relationship Between ADHD-Related Symptoms and Pre-Attentive Auditory Processing in a Sample of Autistic Children and Adolescents

By

Connor MacKenzie

B.S., Otterbein University, 2020

Thesis

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Psychology.

Syracuse University

May 2024

Table of Contents

Introduction 1
EEG 3
MMN 4
MMN and Autism 5
MMN and ADHD 7
MMN in Autism and ADHD 9
Research Questions and Hypotheses 11
Methods 11
Participants 11
Hearing Examinations 12
Measures 13
Procedure 16
Data Analysis 18
Results 18
Outlier Examination 18
Discussion 21
Limitations 24
Conclusions 27

Introduction

Autism is a neurodevelopmental condition that affects 1:36 of children in the United States (Maenner et al., 2021). It is characterized by deficits in social communication (i.e., deficits in nonverbal communication, lack of social-emotional reciprocity) and the presence of restrictive, repetitive behaviors and interests (i.e., stereotyped motor movements, specific interests with abnormal intensity, rigid adherence to a routine, sensory differences; APA, 2013). Children with autism may have difficulty forming friendships with peers and engaging in the typical back-and-forth of conversation (APA, 2013). Often children and adolescents with autism prefer a consistent daily routine and unexpected changes to their schedule may be distressing to them. Autism commonly includes a sensory component that may present as hyper/hyposensitivities to different environmental stimuli. These unique sensory processing features can relate to certain textures, light sensitivity, taste, but are most noted in tactile and auditory domains, making these sensory modalities important inroads to understanding the sensory experiences of children and adolescents on the spectrum (Fernández-Andrés et al., 2015). In addition to the symptoms that compose a diagnosis of ASD, attentional challenges have been considered inherent to the disorder. In the most recent iteration of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5), these attentional challenges can, if they impede functioning in significant ways and meet the symptom requirements, be diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD).

ADHD diagnosis requires symptoms of inattention (i.e., often forgetful, difficulty with tasks requiring sustained attention) and/or hyperactivity (i.e., fidgeting, impulse control deficits) (APA, 2013). ADHD affects 9.8% of school-aged children and adolescents, making it the most common neurodevelopmental condition (Bitsko et al., 2022). In addition, it is also the most common co-occurring condition with autism. Previous research indicates that 37-87% of autistic individuals also have an ADHD diagnosis (Goldstein & Schwebach, 2004; Stevens et al., 2016). A review conducted by Hartman and colleagues (2016) that consisted of individuals 0-84 years of age found that the strongest co-occurrence of ASD and ADHD is in adolescence (approximately 12-18 years of age). While there is a large overlap between autism and ADHD at the diagnostic level, there is likely an even larger overlap at the symptom level (Van Der Meer et al., 2012). This symptom-level focus may help identify the impact of ADHD symptomatology with co-occurring autism and will be the focus of this study.

Because of the overlap between ADHD symptoms and ASD, there has been an increased interest in the commonalities and differences between these two neurodevelopmental conditions, and the interactions of symptoms of one on the other, in order to ameliorate diagnostic assessments, treatment, and identify neurophysiological underpinnings that are unique to each condition. Additional research in this area is warranted since intervening earlier with autistic children is associated with a better prognosis (Remington et al., 2007), and receiving an ADHD diagnosis can delay an ASD diagnosis in children (Kentrou et al., 2019; Stevens et al., 2016). Further, having a co-occurring ADHD diagnosis can negatively impact the efficacy of treatments for both conditions (Antshel & Russo, 2019). One direction that might aid in our comprehension of similarities, differences, and phenotypic overlap in ADHD and autism is to examine the neurophysiological underpinnings of auditory processing, which has been shown to be atypical in both populations (Chen et al., 2020; Cheng et al., 2016; Schwartz et al., 2018; Yamamuro et al., 2016) and to assess the role of symptoms of inattention and hyperactivity on neurophysiology.

There are multiple levels at which sensory processing can be examined. For example, it can be studied through behavior, via direct observation or parent report, or through studies of structure and function, with each method having advantages and disadvantages. Although it is not currently a diagnostic feature of ADHD, several studies have identified atypical sensory processing in individuals with ADHD. For example, a meta-analysis conducted by Ghanizadeh (2011) found that children and adolescents with ADHD are more likely to exhibit sensitivities to auditory and tactile stimuli compared to neurotypical peers. This suggests that sensory differences may provide an avenue for understanding the intersection of ASD and ADHD. In addition to behavioral measures, one method that provides important information regarding how the brain processes information as it unfolds over time is electroencephalography (EEG). While this approach lacks spatial resolution (i.e., where in the brain information processing occurs) compared to other brain mapping tools, it has several advantages that are useful to the study of sensory processes in autistic children and adolescents. This technique is non-invasive, temporally sensitive, and can demonstrate differences even in the absence of behavioral differences or even in the absence of behavioral responses at all (Luck, 2014).

EEG

EEG is a common tool used in neuroscientific research. A cap lined with electrodes is placed on the participant's head which measures ongoing electrical activity in the brain that reflects post-synaptic potentials firing perpendicularly to the recording electrode (Luck, 2014). Event-related potentials (ERPs) are electrical responses that are caused by a definable event (Luck, 2014). They are an ideal tool for examining information processing as it unfolds as it can provide detailed temporal information regarding brain activity with millisecond temporal resolution.

When using Event Related Potentials (ERPs) researchers attempt to isolate the electrical response to a specific stimulus, hence event-related. To do so, all electrical responses that are not related to the presented stimulus must be removed. This is crucial as, in general, the brain's signals are minuscule relative to the noise from external sources such as electrical noise, eye movements, blinking, and even sweat. To combat this noise, trials are repeated multiple times and averaged together such that the random noise fades while the signal gets amplified.

Different experimental tasks reveal different aspects of information processing that include aspects of bottom-up sensory processes that occur early in the processing stream and are considered to be pre-attentive (before 250ms or so) to more top-down, later emerging cognitive aspects of processing that include for example semantic processing or decision making. (post 250ms or so). Once a particular cognitive operation has been linked to an ERP and replicated, it becomes known as an ERP component. While there are many components that could be the focus of any experimental study, here we focus on a well-established component that has been used to study sensory-attentional processing known as Mismatch Negativity, or MMN

MMN

The MMN is an ERP component that is generally elicited in the auditory domain and was originally discovered by Näätänen and colleagues (1978). This component is typically elicited through an oddball paradigm which involves the presentation of a repetitive stimulus, referred to as the standard (presented around 80% of the time), and a different stimulus that is played less frequently, (e.g., 20% of the time), and is referred to as the deviant. When the brain's response to the standard and deviant are subtracted from one another, they yield a component that is referred to as the MMN. The unexpected deviant stimulus elicits a unique response relative to the standard stimulus in the brain between latencies of 160 and 220 milliseconds post-stimulus reflecting an individual's auditory discrimination. Two different subcomponents comprise the auditory MMN, the supratemporal subcomponent, and the frontal MMN component. The supratemporal subcomponent is correlated with perceptual change detection and requires similar effort/activity from both hemispheres. In contrast, the frontal component is associated with involuntary attention switches and almost exclusively occurs in the right hemisphere (Garrido et al., 2009).

There has been a recent increase in MMN popularity among researchers interested in early auditory discrimination. Although there are other mismatch-sensitive components, they are task-oriented which means the individual must be actively engaged in the discrimination task. The MMN is unique because participants do not need to be actively engaged in the task; they can engage in other irrelevant tasks like watching a silent movie while passively listening to the auditory stimuli. This helps conduct auditory discrimination tasks with autistic and ADHD populations because participants are not required to sustain their attention on the task. In addition, a passive version of the MMN also reduces the contamination from other attentional components such as the slightly later P300 response which reflects more post-attentive processes.

MMN and Autism

The MMN is frequently studied in autism because it can be elicited passively, and many trials can be collected quickly. In addition, previous iterations of the diagnostic criteria for autism included criteria related to language and because the MMN can be elicited using speech sounds, several studies focused on whether the MMN could predict autism symptoms or the language outcomes of autistic children. Contradictory findings have plagued the field; however, more recent meta-analyses suggest that participant characteristics, stimulus selection, and choices related to comparison groups can shed light on some of these discrepancies.

Schwartz and colleagues (2018) conducted a meta-analysis of the MMN in autistic individuals. Their analysis included 22 different studies that utilized a mixture of speech and nonspeech (pure tone and complex tone) experiments with a total of 857 ASD and 831 typically developing participants ranging from childhood to adulthood. Results indicated no overall significant difference between MMN amplitude and latency between ASD and TD groups, but there was a trend of attenuated amplitudes in autistic participants compared to their neurotypical peers. After categorizing studies by speech and nonspeech stimuli, however, there were significant differences. Analysis of nonspeech studies revealed significantly attenuated amplitudes in autistic individuals compared to neurotypical peers. They also found that autistic children tended to have attenuated MMN amplitudes compared to typically developing peers, but autistic adults tended to display larger amplitudes than typically developing adults.

A more recent meta-analysis conducted by Chen et al (2020) investigated MMN amplitude and latency for speech and non-speech sounds in ASD. Analysis of speech studies indicated that phoneme deviants resulted in reduced MMN amplitude and latency in ASD compared to TD controls. In nonspeech studies, ASD participants had reduced MMN amplitude to duration deviants. After dividing the ASD group by diagnosis (ASD; Asperger's), ASD children and adolescents had shorter latencies in response to deviations in frequency compared to controls while their peers with Asperger's exhibited the opposite. Children and adolescents with Asperger's had significantly longer latencies than neurotypical peers. Other researchers have also noted differences in early sensory processing in ASD and Asperger's populations (Bonnel et al., 2010; Madsen et al., 2015).

Some studies focusing on pure tone pitch discrimination in ASD have found evidence that a percentage of the ASD population has elevated discrimination abilities. In a study conducted by Mottron and colleagues (2000), an ASD and control group were tasked with discriminating different tonal melodies. Groups were matched on age, IQ, and literacy, and no participants had five or more years of experience with musical instruments. They found that a subgroup of the ASD participants had remarkable pitch discrimination. Higher IQ and a later onset of verbal language were all positively correlated with better pitch discrimination abilities. Jones et al (2009) also identified an ASD subgroup with significantly better pitch discrimination. Seventy-two ASD and 48 TD adolescents were instructed to listen to a pair of pure tones that could differ in pitch, duration, or intensity. Their objective was to select the tone that they perceived as higher, louder, or longer than the other. There were no significant differences between the ASD and TD groups, but a subgroup comprised of 20% of ASD participants demonstrated elevated pitch discrimination abilities. Average IQ and later onset of verbal language were both associated with superior pitch discrimination. Together, these findings suggest differences in pre-attentive auditory processing for pure tones in autistic individuals compared to neurotypical peers. Accordingly, this study will focus on a pure tone MMN task that examines the mean amplitude of the MMN response between children with and without autism.

MMN and ADHD

Although the MMN in autism has been extensively explored, there is considerably less research examining the MMN in populations with ADHD and only one study has examined the relationship of ADHD symptom severity and the MMN within a sample of children and adolescents with ADHD and typically developing peers. As such, I review the ADHD and MMN literature here as a starting point for developing relevant hypotheses. Similar to the literature on MMN in ASD, there are conflicting findings for MMN in ADHD. Some studies have reported no significant difference between ADHD and control groups (Kemner et al., 1996; Winsberg et al., 1997; Yang et al., 2015) while others have identified significant differences in amplitude and/or latency (Cheng et al., 2016; Yamamuro et al., 2016). For example, Yamamuro and colleagues (2016) examined the relationship between the MMN and symptom severity for children with ADHD. Participants included 51 treatment-naïve, that is children who are not on any medications, children with ADHD, and 15 neurotypical peers. These two groups did not differ significantly by age, sex, or full-scale IQ. Researchers implemented a passive non-speech oddball paradigm with a standard stimulus of 1,000Hz and a deviant of 1,100Hz. Stimuli were presented for 50ms with 500ms intervals at 80dB. Results indicated that the ADHD group produced significantly smaller amplitudes and longer latencies compared to the control group. Additionally, MMN amplitude was negatively correlated with symptom severity for all subscales of the ADHD Rating Scale, Fourth Edition – Japanese Version (ADHD-RS-IV-J) while latency was positively correlated with hyperactivity/impulsivity subscales. In other words, greater severity of ADHD symptomology predicted attenuated MMN amplitudes which indicates differences in pre-attentive sensory perception. This was the first study to focus on the relationship between MMN performance and symptom severity in ADHD.

A meta-analysis conducted by Cheng et al (2016) compiled the current literature on MMN in ADHD. Six studies met the criteria for this analysis, consisting of 10 experiments. In total, there were 75 children and adolescents with ADHD, and 73 neurotypical controls, ranging from 8-11 years of age. Speech and nonspeech conditions were included and seven experiments used frequency deviants, two used duration deviants, and one used phoneme deviants. Overall, there was a significantly reduced amplitude in the MMN of participants with ADHD compared to neurotypical controls.

MMN in Autism and ADHD

Research examining the MMN across individuals with ASD or ADHD is complicated by differences across studies in how the amplitude of a participant's response is measured. The two most common methods of measurement are peak amplitude and mean amplitude. Peak amplitude is recorded as the largest voltage of the wave form in a particular timeframe whereas mean amplitude is identified by calculating the average voltage in a specific timeframe (Luck, 2014). Historically, peak amplitude was utilized, although advancements in measurement techniques led to a shift towards using mean amplitude. As stated by Luck (2014), the highest voltage point on a waveform carries no meaning or significance because peaks are distinct from components. Another concern to note with peak amplitude is that it is highly prone to distortion from high frequency noise. In contrast, mean amplitude is less affected by high frequency noise and it is generally unaffected by higher levels of variance in waveforms.

Literature examining the MMN in autistic populations is split between using peak amplitude and mean amplitude. Interestingly, results vary within studies utilizing the same amplitude measurement. For example, studies utilizing mean amplitude and frequency deviants have found that autistic children and adolescents have significantly attenuated, larger, or no significant difference in MMN amplitude compared to typically developing peers (Huang et al., 2018; Weismüller et al., 2015; Yu et al., 2015).

Although there is literature focused on MMN in ASD and ADHD, these literature bases are still separate, and during preparation for this study, only one article was identified to have examined the overlap of Pervasive Developmental Disorder, Not Otherwise Specified (PDD-NOS) and ADHD symptomology (Sawada et al., 2008). It is important to note that this previous study provides minimal details regarding the methods, procedures, and analyses conducted. Additionally, another study conducted by Sawada and colleagues in 2010 has figures depicting positive waveforms for the MMN and it is unclear why that is the case. Due to this confusion and its implications for understanding the correlations presented, the study conducted by Sawada and colleagues in 2008 does not adequately examine how the co-occurrence of ADHD-related symptomology in autism affects the MMN, which is a missed opportunity given the high rates of ADHD in this population. Given previous literature demonstrating ASD and ADHD both exhibit attenuated amplitudes and longer latencies relative to neurotypical populations on non-speech oddball tasks, in addition to the presence of sensory differences in both conditions and the high degree of co-occurrence of ASD and ADHD, it is unclear to what degree the MMN response in ASD is due to symptoms related to inattention and or hyperactivity/impulsivity. To begin to disentangle the relationship between pre-attentive auditory discrimination, ASD and ADHD, the main purpose of the present study is to examine the relationship between symptoms of hyperactivity/impulsivity and inattention as measured by the BASC-2, and the mean amplitude of the MMN component in a sample of autistic and typically developing children and adolescents.

In this study, participants were matched across groups (i.e., ASD and TD) on chronological age and IQ to limit potential confounding variables (Mottron et al., 2000; Weismüller et al., 2015). It is important to note that instead of using the Full-Scale IQ (FSIQ-4) of the *Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II;* Wechsler & Hsiao-pin, 2011), the Perceptual Reasoning Index (PRI) was used as the matching variable. Previous research has demonstrated that cognitive measures with verbal demands may result in significantly lower mean scores compared to nonverbal cognitive measures for autistic individuals (Grondhuis et al., 2018). Additionally, Burack and colleagues (2004) recommend matching on nonverbal IQ for experimental tasks related to attention and perception, as it is a closer construct to what is being studied.

Research Questions and Hypotheses

The present study addressed the following two questions:

How does the ASD group perform on the pure tone oddball task compared to the TD group, as measured by mean amplitude? The purpose of this comparison is to determine if the predominant pattern present in the literature (i.e., attenuated amplitudes) is noted for mean amplitude, rather than peak amplitude, which is crucial for assessing the veracity of MMN differences in autism. Based on previous research, it was hypothesized that the ASD group would exhibit an attenuated grand average amplitude compared to the TD group on the pure tone oddball task.

How do the Hyperactivity and Attention Problem indices on the BASC-2, independently correlate with MMN mean amplitude on a pure tone MMN task relative to ASD and TD group performance? Children and adolescents with ASD and those with ADHD symptomology exhibit a similar pattern of attenuated grand average amplitudes for MMN performance on pure tone oddball tasks relative to typically developing peers. Based on the findings of Yamamuro and colleagues (2016), it is hypothesized that higher scores for both the Hyperactivity and Attention Problems indices will be associated with attenuated MMN amplitudes at the FCz electrode.

Methods

Participants

Twenty-six children and adolescents from the Syracuse area were recruited for this study. There were 13 autistic (11 male, 2 female) and 13 typically developing (TD) participants (6 male, 7 female). Regarding race, 25 of the participants identified as white while one participant in the ASD group identified as biracial (black and white). The ASD and TD groups did not significantly differ in age [$t(24)= 0.27$, $p= 0.78$, CI 95% = (-1.81, 2.37)] nor nonverbal IQ [$t(24)= 0.08$, $p= 0.9$, CI 95% = (-12.94, 14)] as measured by the *Wechsler Abbreviated Scale of Intelligence- Second Edition* (WASI-II; Wechsler & Hsiao-pin, 2011). Comparisons of participant characteristics across ASD and TD groups are displayed in Table 1. While no participants in the typically developing group reported a previous diagnosis of ADHD, five participants in the autism group noted a diagnosis of ADHD. Seven participants in the ASD group reported prescriptions for psychotropic medication. Medications included guanfacine, methylphenidate, clonidine, clonazepam, aripiprazole, risperidone, and fluoxetine. Participant medication status and demographic information are displayed in Table 2. Diagnoses of autism were made via gold standard assessment tools that include the ADOS-2, ADI-R and clinical judgment. Participants were recruited via flyers, which were distributed across Syracuse University. Upon enrollment, participants completed auditory examinations at Central New York Medical Center to ensure that no participant in this study had clinically impaired hearing.

To provide additional context regarding the autistic and typically developing groups, a t-test with a Welch's correction was performed for the BASC-2 Adaptive Skills Composite. Results of the t-test indicated significant differences in the Adaptive Skills Composite between the autistic and typically developing groups ($t(20.65) = -3.78$, $p = 0.001$). The *t*-scores for the typically developing group had a mean score of 44.77 which falls within the average range. In contrast, the autistic group's mean t-score of 33.58 resides within the *at-risk* range.

Hearing Examinations

The audiological examinations identified four participants, two from each diagnostic group, with hearing outside the typical range. For the TD group, the first participant's behavioral threshold at 0.250 kHz was 25 dB HL while the second participant demonstrated atypical middle ear function in their left ear with increased thresholds at 2,000 and 4,000 Hz. Regarding the ASD group, the first participant's behavioral threshold at 8 kHz was 25 dB HL while the second participant demonstrated atypical middle ear function in their left ear with increased thresholds at 250 and 6,000 Hz. These participants were not excluded from the study because none exhibited elevated thresholds within the frequency range of the stimuli used and their ERP waveforms did not deviate from their respective group norms. Audiological examination results for all other participants were within the typical range.

Measures

Autism Diagnostic Observation Schedule-Second Edition (ADOS-2)

The ADOS-2 (Lord et al., 2012) is a semi-structured, standardized assessment of autistic traits and may be used for individuals 12 months and older. The five modules (Modules 1-4 and the Toddler Module) utilize various materials and activities to evaluate communication, social interaction, play/ imagination, and restricted and repetitive behaviors. Behaviors are coded on a scale from 0 to 3 with higher scores correlating more with autistic symptoms. Specific items for each module are transferred to a diagnostic algorithm and summed to calculate the calibrated severity score (CSS) and determine a diagnosis. For this study, 12 autistic participants were administered Module 3, and one participant completed Module 4. Research on module 3 indicates strong test-retest reliability (SA = 0.81, RRB = 0.82, Total Score = 0.87) and interrater reliability (SA = 0.92, RRB = 0.91, Total Score = 0.94) in addition to increased sensitivity and specificity compared to the ADOS (Lord et al., 2012). When the ADOS-2 manual was released, no changes were made to the module 4 algorithm. However, Hus and Lord (2014) introduced a revised algorithm that demonstrated increased sensitivity and specificity compared to the original algorithm from the ADOS based on their sample. In addition to increased validity, Hus and Lord (2014) demonstrated greater than 80% agreement on all items.

Autism Diagnostic Interview-Revised (ADI-R)

The Autism Diagnostic Interview-Revised (ADI-R; Rutter et al., 2003) is a semi-structured parent interview designed to discriminate autism from other developmental conditions for individuals with a mental age of two years and older. It consists of 111 questions coded by a trained examiner and takes approximately 90 to 150 minutes to complete. Three domains are assessed by this measure including a) language/communication, b) reciprocal social interaction, and c) restricted, repetitive, and stereotyped behaviors and interests, in addition to an autism cutoff score. Items are scored on a scale of zero through three, with no impairment to severe impairment, respectively. Specific items are transferred to a diagnostic algorithm and used to determine diagnosis. Regarding test-retest reliability, all domains and subdomains have correlation coefficients between 0.93 and 0.97. Additionally, a study conducted by Pilowsky et al. (1998) found 86% agreement between the ADI-R and the Childhood Autism Rating Scale (CARS; Schopler et al., 1988).

Wechsler Abbreviated Scale of Intelligence-Second Edition (WASI-II)

The Wechsler Abbreviated Scale of Intelligence-Second Edition (WASI-II; Wechsler & Hsiao-pin, 2011) is an abbreviated, norm-referenced measure of cognitive ability for individuals 6 to 99 years of age. It consists of two verbal subtests (i.e., Vocabulary and Similarities) and two perceptual subtests (i.e., Block Design and Matrix Reasoning). The Vocabulary subtest provides participants with a series of words, and they must provide the definition, while Similarities introduces pairs of words and the participant is instructed to identify how the words are similar (e.g., in what way are grass and trees alike?). During the Block Design subtest, participants are provided with multicolored blocks and must construct designs presented to them. Matrix Reasoning requires participants to identify which item best completes a pattern. Performance on these subtests yields a Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), and Full-Scale Intelligence Quotient 2 and 4 (FSIQ-2; FSIQ-4) scores with a mean of 100 and a standard deviation of 15. Compared to the *Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV)*, the corrected correlation coefficients are all above 80% (VCI = 0.84, PRI = 0.82, FSIQ-4-FSIQ = 0.91) (Wechsler & Hsiao-pin, 2011). Regarding test-retest reliability, index scores between the first and second testing have corrected correlation coefficients of 0.85 or greater for all age groups.

Behavior Assessment System for Children- Second Edition (BASC-2)

The Behavior Assessment System for Children- Second Edition (BASC-2; Reynolds & Kamphaus, 2004) is a standardized multi-dimensional questionnaire consisting of 150 items that assess various skills, adaptive behaviors, and challenging behaviors. Self-, parent, and teacher rating forms are available. For this study, the inattention and hyperactivity t-scores were utilized as a measure of ADHD symptomology. For these indices, *t*-scores of 60 to 69 are considered in the at-risk range while scores of 70 and above are clinically significant. Regarding test-retest reliability, the child and adolescent median corrected correlation coefficients are 0.84 and 0.81, respectively. Additionally, compared to the *Achenbach System of Empirically Based Assessment* Child Behavior Checklist for ages 6 to 18 (ASEBA; Achenbach & Rescorla, 2000), the corrected correlation coefficients for attention problems indices, attention problems-ADHD indices, and Hyperactivity-ADHD indices are 0.75, 0.61, and 0.61, respectively.

MMN task

Stimuli consisted of pure tones with a standard stimulus of 1,000Hz and a deviant stimulus of 1,200Hz. The standard stimulus comprised 80% of the stimuli displayed and 20% of the stimuli were deviant. 1000 trials were presented (800 standards and 200 deviants). The stimuli were presented in a randomized order with the exception that two deviant stimuli could not be presented consecutively. Stimulus onset was 600ms, they were presented for 360ms, and the interstimulus interval was 240ms. All tones were elicited from the dual speakers at 60dB, and the task took 10 minutes to complete.

During the experiment, participants watched a show or movie of their choice silently with subtitles. Participants were also instructed to ignore the tones playing in the background. The purpose of this distractor was to eliminate contamination of the N200 and P300 which are related to attentive discrimination.

Procedure

This research project was approved by the institutional review board at Syracuse University and written parental consent was obtained, in addition to assent from child and adolescent participants. After families provided written consent and assent, participants completed the ADOS-2 and IQ testing on the first visit while parents completed the ADI-R. For the one participant who was administered the ADOS-2 Module 4, the revised algorithm developed by Hus and Lord (2014) was used for scoring. During a second visit, children completed the experimental tasks, while parents completed the Sensory Profile (Brown & Dunn, 2002), Social Responsiveness Scale, Second Edition (SRS-2; Constantino & Gruber, 2012), Autism Spectrum Quotient (AQ; Baron-Cohen et al., 2001), and the BASC-2 (Reynolds & Kamphaus, 2004). Before completing the experimental tasks, the head circumference of each participant was measured to determine the HCGSN Net size. After the electrode cap was adjusted, participants were instructed to get comfortable and to minimize movement including blinking during the tasks. After receiving instructions, the participant's electrode cap was then connected to the amplifier before initiating the tasks. Participants completed a non-speech oddball paradigm in a sound-insulated room with two speakers, one on their left side and one on the right of a computer screen. Participants watched a silent movie on an iPad during the presentation of the MMN task. Participants were paid $10 per hour.

ERP Measurement

Data were collected using a Geodesic SensorNet 128-channel cap and were recorded with NetStation at a sampling rate of 1,024Hz. Data were filtered between .1-30Hz with a 2nd-order Butterworth filter and were referenced to Cz during data collection. During offline processing, the data was re-referenced to the average of the mastoids as is common practice for the MMN (Yamamuro et al., 2016). ERP segments were extracted -50 to 650ms of stimuli presentation. Baseline corrections were implemented from -50 to 0ms and epochs with artifacts of more than 100 microvolts were removed. Visual inspection identified invalid channels to interpolate with spline interpolation techniques. All post-collection processing and data extraction was performed using EEGLAB v14.1.2 (Delorme & Makeig, 2004) and ERPLAB v7.0.0 (Lopez-Calderon & Luck, 2014) toolboxes in MATLAB R2017a.

To isolate the ERP averages are made for the standard stimulus and deviant stimulus for each participant, and then their MMN waves are averaged, resulting in the grand average. The grand average of the deviant stimulus was then subtracted from the grand average of the standard stimulus to calculate the difference wave. This process was completed separately for ASD and TD groups. In this study, the mean amplitude was utilized as the MMN amplitude measurement.

Data Analysis

Data analysis and figures were completed with SPSS, in addition to the EEGLAB v14.1.2 (Delorme & Makeig, 2004) and ERPLAB v7.0.0 (Lopez-Calderon & Luck, 2014) packages in MATLAB R2017a. Firstly, three independent two-tailed *t*-tests were conducted across the autistic and typically developing groups for MMN mean amplitude, the Attention Problems index, and the Hyperactivity index. These *t*-tests included a Welch correction as the autistic and typically developing groups are not expected to have equal variance. Additionally, six Spearman's Ranked Correlations were conducted. Four of the correlations were between the BASC-2 indices and MMN Mean amplitude within the autistic and typically developing groups. Given the small sample size of this study, two additional correlations were calculated across groups (i.e., everyone together; not separated into groups).

Results

Power analyses were conducted for t-tests and Spearman's correlations. Given the small sample size of this study, all power analyses indicated inadequate power for these analyses. Regarding the *t*-tests, results indicated that to detect a medium effect of .5, given a significance of $\alpha = .05$ and power = .80, the minimum number of participants required per group is 64, or 128 total participants. Additionally, for the Spearman's ranked correlations, to detect an effect size of .3 at a power of .80 given $\alpha = .05$, 84 total participants are required.

Outlier Examination

The mean amplitude of one participant in the ASD group was significantly discrepant from all other participants in the group. Their mean amplitude of –7.99 microvolts is 2.85 standard deviations away from the grand average amplitude of the autistic group. It is important to address that this participant may skew the results in favor of the autistic group; however, there are arguments to include the participant. Firstly, it is unclear if removing this participant would be unrepresentative of the general autism population. As previously discussed in the introduction, previous behavioral and ERP studies have identified a subgroup of autistic individuals with exceptional pitch discrimination. Removing this participant may remove the proportion of the spectrum that falls within this subgroup as this individual might be more likely to have a genuine pitch discrimination ability, especially for an ERP component that does not require active attention or behavioral responses. To assess the role of this participant in the data, data analysis was conducted while removing and retaining this participant. This did not impact the findings; accordingly, this participant was retained in the analysis.

It is also important to note that a different participant in the ASD group completed the MMN task, but their guardian failed to complete the BASC-2. In an effort to include this participant and preserve the match between groups on age and nonverbal IQ, the mean *t*-scores for the Attention Problems and Hyperactivity indices of the autistic group replaced this participant's missing data. While mean imputation may be used when minimal values are missing, it underestimates outliers and given the size of this study's sample, it is more prone to the influence of outliers or skewed data (Zhang, 2016).

The grand average MMN amplitude for the autistic group was -2.8054 microvolts and -1.7246 microvolts for the typically developing group. Based on the results of a two-sample independent *t*-test with a Welch correction, there is no statistically significant difference in grand average amplitude between groups ($t(20.61) = -1.51$, $p = 0.147$). This indicates that autistic and typically developing groups had similar mean amplitudes.

The mean *t*-score for the Attention Problems index was 61.58 for the autistic group and 49.54 for the typically developing group. There was a strong statistically significant difference in mean *t*-scores between the autistic and typically developing group, as demonstrated by an independent-samples *t*-test with a Welch correction ($t(23.95) = 3.596$, $p = .001$). While the mean *t*-score for the typically developing group is within the average range, the mean *t*-score for the autistic group is within the at-risk range. The relationship between Attention Problems *t*-scores and MMN amplitude for both groups is displayed in Figure 1.

The mean *t*-score for the Hyperactivity index was 64.00 for the autistic group and 52.00 for the typically developing group. Based on the results of an independent-samples *t*-test with a Welch correction, there is a significant difference in *t*-scores between the autistic and typically developing groups ($t(19.85) = 2.29$, $p = .033$). Similar to the Attention Problems index, the mean *t*-score for the typically developing group was within the average range while the ASD group's mean *t*-score is within the at-risk range. The relationship between Hyperactivity *t*-scores and MMN amplitude for both groups is displayed in Figure 2.

The first series of Spearman's rank correlations assessed the relationship between MMN amplitude and the BASC-2 Attention Problems index within the ASD and TD groups and across all participants. The results of this analysis suggest that there is not a significant relationship between Attention problems *t*-scores and MMN amplitude for the ASD [r (11) = -0.45, $p = .13$] nor TD [r (11) = -0.30, $p = .32$] groups individually; however, there is a significant negative correlation between MMN amplitude and Attention Problems *t*-scores across all participants [r (24) = -0.44, $p = .026$] with a moderate effect size. In other words, when participants are not separated into different groups, higher *t*-scores on the Attention Problems index were associated with more negative amplitudes.

The second series of Spearman's rank correlations assessed the relationship between MMN amplitude and the BASC-2 Hyperactivity index within the ASD and TD groups and across all participants. In line with the findings for the Attention Problems index, results do not indicate a significant relationship between Hyperactivity index *t*-scores and MMN amplitude for the ASD [r (11) = -0.40, p = .18] and TD [r (11) = -0.37, p = .22] groups; although there was a significant negative correlation between MMN amplitude and Hyperactivity *t*-Scores across all participants [r (24) = -0.44, p = .026] with a moderate effect size. When participants were not separated into different groups, higher Hyperactivity *t*-scores were associated with more negative amplitudes.

Discussion

Before discussing the results of this study, it is important to note that although symptoms of hyperactivity, impulsivity, and attentional concerns are core diagnostic criteria for ADHD and its subtypes, these symptoms are not exclusive to ADHD. Since a comprehensive evaluation was not conducted to rule out the potential influence of trauma, anxiety, depression, or other co-occurring conditions/symptomology in this sample, the *t*-scores for the Hyperactivity and Attention Problems indices may in part reflect aspects of co-occurring psychopathology. This is particularly salient given the high proportion of autistic individuals who report experiences of anxiety, trauma, and depression (Griffiths et al., 2019). Given that this study relies on parent report, it is difficult to know what behaviors parents are imagining when responding to items on the BASC-2. Further, it is clear that parent-reported symptoms of hyperactivity and inattention are not the same as a diagnosis of ADHD. The goals of this study are to begin the process of understanding the relationship between neural variability in auditory processing among autistic youth and symptoms of inattention and hyperactivity as a steppingstone to understanding the impact of the co-occurrence of ADHD and autism on neural processing through future studies that include participants with autism and no ADHD, autism and ADHD and ADHD alone.

Despite high rates of co-occurring ASD and ADHD in addition to differences in pre-attentive auditory processing in both neurodevelopmental conditions compared to the neurotypical population, minimal research has explored how a dual diagnosis of these conditions affects auditory processing. The goal of this study is to take a step in this direction by examining how symptoms associated with ADHD affect the MMN response in autistic and neurotypical children and adolescents to expand our knowledge on how overlapping/co-occurring symptomology affects pre-attentive auditory processing, especially in autistic children and adolescents.

Two research questions were asked: 1) Is there a significant difference in MMN amplitude between the ASD and TD groups? and 2) How do symptoms of hyperactivity/impulsivity and inattention independently correlate with MMN mean amplitude for ASD and TD groups? It was hypothesized that the grand average MMN amplitude for the ASD group would be attenuated (i.e., closer to zero microvolts) compared to the TD group. Additionally, it was hypothesized that there would be a negative correlation between the BASC-2 indices (i.e., Hyperactivity and Attention Problems Indices) and MMN amplitude.

The first hypothesis, that the autistic group would exhibit attenuated amplitudes was not supported. The MMN amplitude for ASD and TD groups did not significantly differ; however, numerically, the amplitude of the group of children with autism was more negative (i.e., larger than comparison participants). As previously discussed, the literature is inconsistent with various studies indicating attenuated amplitudes (Abdeltawwab & Baz, 2015; Dunn et al., 2008), greater amplitudes (Ferri et al., 2003), or no significant difference for autistic children and adolescents compared to typically developing peers (Jansson-Verkasalo et al., 2003; Weismuller et al., 2015). A myriad of factors may account for the discrepancies in the literature including the stimuli used, participant age, diagnostic presentation (i.e., DSM-IV classifications vs. DSM-5 classification of ASD), how amplitude is measured (i.e., mean vs. peak amp), how participants were matched, and small sample sizes. Here we minimize some of these confounds by matching on nonverbal IQ, confirming autism diagnoses with gold standard tools, and using measurements that are based on best practice approaches to ERP analysis (Luck, 2014).

The second set of hypotheses focused on brain-behavior relations with the expectation that attention and hyperactivity symptoms would be negatively associated with MMN amplitude. In line with high rates of co-occurrence between ADHD and autism, the ASD group reported significantly higher levels of attentional concerns and hyperactivity/impulsivity compared to the control group. Further, the parents of five participants in the autistic group also reported a previous diagnosis of ADHD on the ADI-R. The key finding of this study is that the amplitude of the MMN was moderately negatively correlated with both Hyperactivity and Attention Problems indices on the BASC-2. In other words, higher reported levels of attention problems and hyperactivity separately are associated with larger (more negative) MMN amplitudes.

Previous research indicates that larger MMN amplitudes are associated with better discrimination of the deviant stimulus (Pakarinen et al., 2015). Although there was no correlation between MMN amplitude and either BASC-2 index when participants were divided into the autistic and control groups, this may have been due to the small sample size of this study. The power analyses that were conducted revealed that the statistical methods implemented were significantly underpowered. Doubling the sample size by conducting the analyses across all participants may have provided a more accurate depiction of the relationship between ADHD symptomology and auditory processing. When participants were not divided into autistic and typically developing groups, there was a moderate negative association between MMN performance and ADHD symptomology. Given the results of this study, we may infer that higher levels of attentional concerns and hyperactivity/impulsivity are associated with better pitch discrimination abilities in children and adolescents.

The findings from this study may have critical clinical applications for understanding the symptomology and behaviors of children and adolescents with higher levels of hyperactivity/impulsivity and attentional concerns, without requiring an official diagnosis of ADHD. For example, this may provide additional insight into distractibility related to auditory stimuli. Alternatively, there may be a connection between MMN amplitude and inattention as more cognitive resources are being used for unexpected/background auditory stimuli instead of the current task at hand such as sustaining one's attention on an assignment or listening to instruction. It is also important to note that the results of this study provide evidence that parental ratings of attentional difficulties and hyperactivity/impulsivity are associated with an ERP component that is thought to be pre-attentive. Understanding auditory processing in individuals with higher levels of ADHD symptomology may inform interventions and classroom/environmental modifications to cater to being respectful of students' sensory sensitivities and reduce distractions.

Limitations

Similar to an overwhelming majority of the current literature regarding the MMN in autism, one significant limitation of the present study is the small sample size. This is a recurring limitation for research in this area. For example, of the 15 non-speech studies with a frequency deviant in the meta-analysis conducted by Chen and colleagues (2020), seven of the studies contained 15 or fewer participants per group. Similarly, Cheng et al. (2015) included six studies in their meta-analysis and five of the studies contained 14 participants or less per group. A small sample size with limited diversity is important to keep in mind when thinking about the validity and generalizability of the findings. Analyses were underpowered due to the small sample size and generalization of these findings should be done cautiously.

It is important to note that this study did not account for the role of trait anxiety and its relationship with MMN performance. Future research in this area should account for anxiety, as it is a frequent co-occurring diagnosis with autism and previous research has demonstrated that higher self-reported ratings of trait anxiety are associated with larger (i.e., more negative) MMN amplitudes (Ioakeimidis et al., 2023).

Another limitation of this study is related to psychotropic medications. Of the 13 autistic participants, seven reported current prescriptions and three were prescribed more than one psychotropic medication. Although most studies examining the effects medications have on the MMN focus on individuals with schizophrenia and other psychiatric disorders, there have been findings that psychotropic medications like clozapine and osmotic-release methylphenidate may affect MMN amplitude (Horton et al., 2011; Sawada et al., 2010). However, it is important to note that the effects of medications that target dopamine or serotonin should be considered minimal (Todd et al., 2013).

There were several significant limitations that related to the diversity of the participants in this sample. The first is that individuals with a PRI of 80 or below were excluded from the study. Some research indicates that Intellectual Developmental Disorder (IDD) is associated with attenuated MMN amplitudes and greater N1 latency (Ikeda et al., 2009). This exclusionary criterion resulted in no representation for a significant portion of the autism spectrum, as recent prevalence rates from the CDC indicated that 37.9% of autistic children with cognitive testing available met criteria for an intellectual disability (Maenner, 2023). Additionally, the inclusion of individuals with intellectual disabilities brings with it unique challenges to matching participants as they cannot be matched on both chronological and developmental age. While there are methodological reasons for excluding individuals with intellectual disabilities, there are also systemic barriers to their inclusion in this area of research including ableist presumptions and expected obstacles of completing all the necessary tasks, and the small laboratory where this study took place had limited resources. Due to this limitation, the results of this study should not be generalized to autistic individuals with below average cognitive functioning.

Participants in this study also lacked diversity across several other modalities as well. While the typically developing group had a balanced representation of male and female participants (i.e., 6 male, 7 female), the autism group consisted of 11 males and only two females. A male-skewed autism group is consistent with current prevalence rates of ASD being 3.8 times more prevalent in males compared to females (Maenner et al., 2021). Further, this study sample as a whole contained minimal racial and ethnic diversity. All 26 participants reported non-Hispanic backgrounds, 25 identified as white, and only one participant identified as biracial (i.e., white and black). While there are multiple potential barriers stifling the representation of individuals from diverse backgrounds, a critical systemic barrier is the technological designs of the tools used. EEG functions by measuring the brain's electrical impulses through the scalp; however, the design of most caps is not as effective at establishing strong connectivity with the scalp for persons with course or curly hairstyles (Krishnan et al., 2018). While new tools and techniques are being developed, such as *Sevo* electrodes (Etienne *et al.,* 2020), the lack of racial and ethnic diversity in psychophysiological research has only recently been highlighted. To provide context regarding the state of this area of research, of studies published in *Psychophysiology* from 2010-2020, only 17.3% of studies reported racial and ethnical information of participants (Kissel & Friedman, 2023).

One final limitation regarding the diversity of this sample is the age of participants. In this study, participants ranged from eight to 16 years of age. Previous research has identified differences in MMN amplitude/latency in autistic adults compared to children with autism (Schwartz et al., 2018; Chen et al., 2020). Taken as a whole, the generalizability of this study is limited given the lack of diversity in cognitive functioning, age, sex, race, and ethnicity.

Conclusions

Together the findings from this study suggest that the overlapping symptomatology of autism and ADHD may be obscuring findings of early pre-attentional auditory processing in autism. Future research should further examine the intersectionality of ASD and ADHD-related symptomology and its relation to MMN.

Table 1

Means, Standard Deviations, and Two-Tailed t-Test Statistics for Diagnostic Groups

Variable	ASD		TD		Two-Tailed t-Test	
	M	SD	M	SD	t	Sig
Age	12.9	2.73	12.5	2.52	-0.35	.73
Nonverbal IQ (PRI)	111.5	20.63	109.5	10.78	-0.31	.76
Verbal IQ (VCI)	98.54	13.17	116.54	11.22	3.46	.002
Total IQ (FSIQ-4)	103.69	14.95	115.08	10.76	1.93	.07
ADOS-2 Total	14.0	3.14	--	--	--	--
ADOS-2 Severity Score	8.08	1.66	--	--	--	--
Attention Problems Index *t*-Score	61.58	8.35	49.54	8.72	3.40	.001
Hyperactivity Index *t*-Score	64	16.14	52	9.85	2.29	.033
Adaptive Composite *t*-Score	32.72	13.08	49.08	8.54	-3.78	.001

Table 2

Demographic Information and Medication Status of Participants

	ASD	TD
	N	N
Sex		
Male	11	6
Female	2	7
Ethnicity		
Hispanic	0	0
Non-Hispanic	13	13
Race		
White	12	13
Biracial	1	0
Medications		
Aripiprazole	2	0
Clonazepam	1	0
Clonidine	1	0
Fluoxetine	3	0
Guanfacine	2	0
Methylphenidate	1	0
Risperidone	1	0

Note. Three participants in the ASD group reported multiple current psychotropic prescriptions: one participant was prescribed guanfacine and aripiprazole, one participant was prescribed methylphenidate and clonazepam, and one participant was prescribed clonidine and aripiprazole.

Figure 1

MMN Amplitude as a Function of Attention Problems

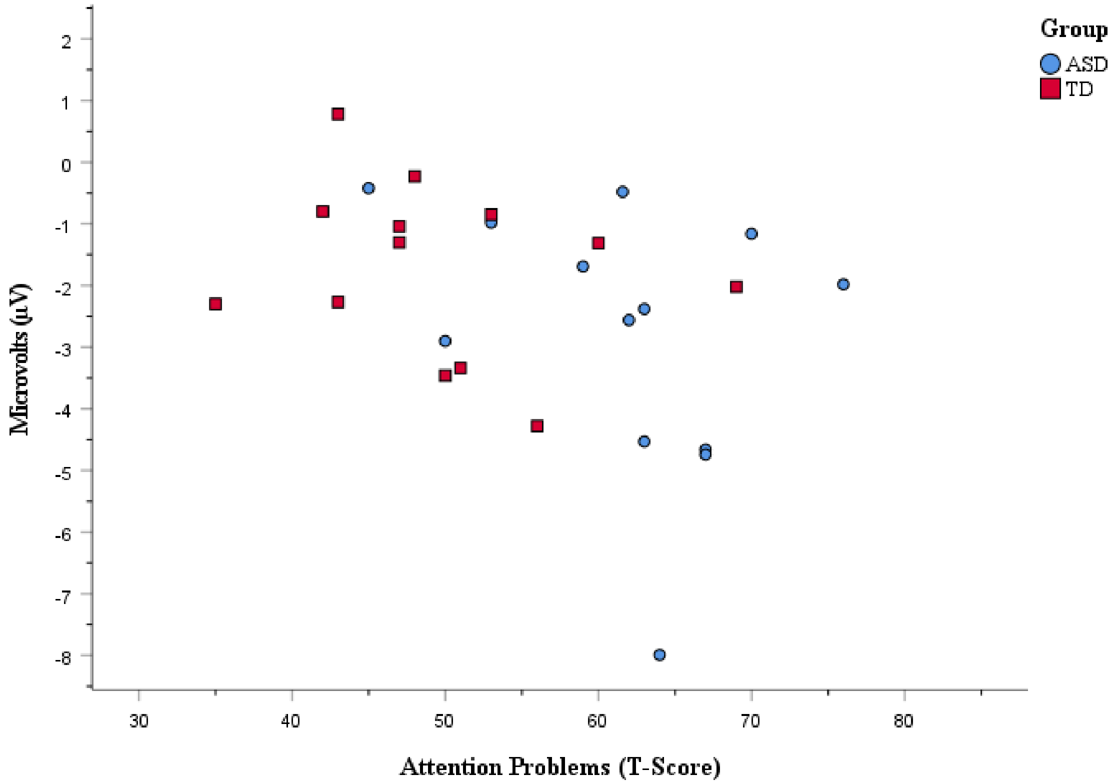
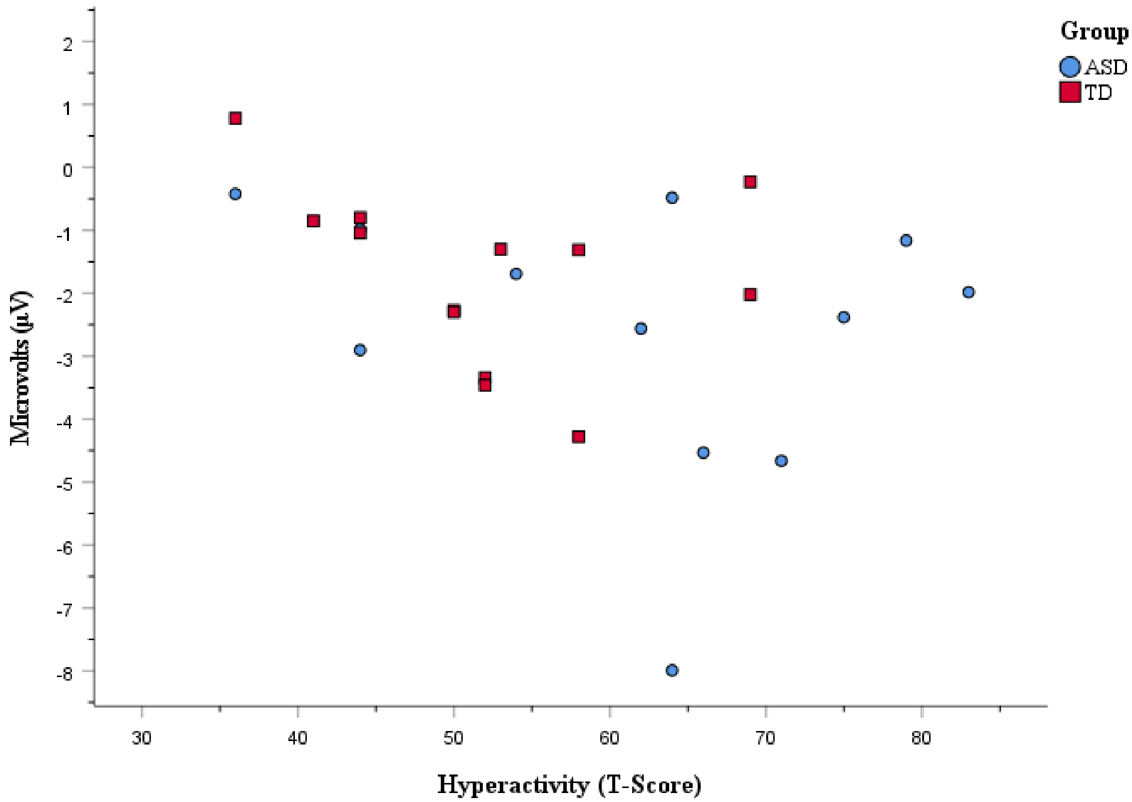


Figure 2

MMN Amplitude as a Function of Hyperactivity



References

Abdeltawwab, M. M., & Baz, H. (2015). Automatic pre-attentive auditory responses: MMN to tone burst frequency changes in autistic school-age children. J Int Adv Otol, 11(1), 36-41. https://doi.org/10.5152/iao.2014.438

Achenbach, T., & Rescorla, L. (2000). Manual for the ASEBA forms and profiles. Burlington, VT: University of Vermont.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5®)*. American Psychiatric Pub.

Antshel, K. M., & Russo, N. (2019). Autism spectrum disorders and ADHD: Overlapping phenomenology, diagnostic issues, and treatment considerations. *Current Psychiatry Reports*, *21*(5), 1-11. https://doi.org/10.1007/s11920-019-1020-5

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): Evidence from Asperger Syndrome/high-functioning autism, males and females, scientists and mathematicians. *Journal of autism and developmental disorders*, *31*(1), 5-17. https://doi.org/10.1023/A:1005653411471

Bitsko, R. H., Claussen, A. H., Lichstein, J., Black, L. I., Jones, S. E., Danielson, M. L., ... & Meyer, L. N. (2022). Mental health surveillance among children—United States, 2013–2019. *MMWR supplements*, *71*(2), 1. https://doi.org/10.15585%2Fmmwr.su7102a1

Bonnel, A., McAdams, S., Smith, B., Berthiaume, C., Bertone, A., Ciocca, V., Burack, J. A., & Mottron, L. (2010). Enhanced pure-tone pitch discrimination among persons with autism but not Asperger syndrome. *Neuropsychologia*, *48*(9), 2465-2475. https://doi.org/10.1016/j.neuropsychologia.2010.04.020

Brown, C. E., & Dunn, W. (2002). *Adolescent/ Adult Sensory Profile User's Manual.* Psychological Corporation.

Burack, J. A., Iarocci, G., Flanagan, T. D., & Bowler, D. M. (2004). On mosaics and melting pots: Conceptual considerations of comparison and matching strategies. *Journal of autism and developmental disorders, 34*, 65-73. https://doi.org/10.1023/B:JADD.0000018076.90715.00

Chen, T. C., Hsieh, M. H., Lin, Y. T., Chan, P. Y. S., & Cheng, C. H. (2020). Mismatch negativity to different deviant changes in autism spectrum disorders: A meta-analysis. *Clinical Neurophysiology*, *131*(3), 766-777. https://doi.org/10.1016/j.clinph.2019.10.031

Cheng, C. H., Chan, P. Y. S., Hsieh, Y. W., & Chen, K. F. (2016). A meta-analysis of mismatch negativity in children with attention deficit-hyperactivity disorders. *Neuroscience letters*, *612*, 132-137. https://doi.org/10.1016/j.neulet.2015.11.033

Constantino, J. N., & Gruber, C. P. (2012). *Social Responsiveness Scale-Second Edition (SRS-2)*. Western Psychological Services.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, *134*(1), 9-21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dunn, M. A., Gomes, H., & Gravel, J. (2008). Mismatch negativity in children with autism and typical development. Journal of autism and developmental disorders, 38, 52-71. https://doi.org/10.1007/s10803-007-0359-3

Dunn, W. (1999). *Sensory Profile*. Psychological Corporation.

Etienne, A., Laroia, T., Weigle, H., Afelin, A., Kelly, S. K., Krishnan, A., & Grover, P. (2020, July). Novel electrodes for reliable EEG recordings on coarse and curly hair. In *2020 42nd annual international conference of the IEEE engineering in medicine & biology society (EMBC)* (pp. 6151-6154). IEEE. https://doi.org/10.1109/EMBC44109.2020.9176067.

Ferri, R., Elia, M., Agarwal, N., Lanuzza, B., Musumeci, S. A., & Pennisi, G. (2003). The mismatch negativity and the P3a components of the auditory event-related potentials in autistic low-functioning subjects. Clinical neurophysiology, 114(9), 1671-1680. https://doi.org/10.1016/S1388-2457(03)00153-6

Garrido, M. I., Kilner, J. M., Stephan, K. E., & Friston, K. J. (2009). The mismatch negativity: a review of underlying mechanisms. *Clinical neurophysiology*, *120*(3), 453-463. https://doi.org/10.1016/j.clinph.2008.11.029

Ghanizadeh, A. (2011). Sensory processing problems in children with ADHD, a systematic review. *Psychiatry investigation*, *8*(2), 89. https://doi.org/10.4306%2Fpi.2011.8.2.89

Grondhuis, S. N., Lecavalier, L., Arnold, L. E., Handen, B. L., Scahill, L., McDougle, C. J., & Aman, M. G. (2018). Differences in verbal and nonverbal IQ test scores in children with autism spectrum disorder. *Research in Autism Spectrum Disorders*, *49*, 47-55. https://doi.org/10.1016/j.rasd.2018.02.001

Goldstein, S., & Schwebach, A. J. (2004). The comorbidity of pervasive developmental disorder and attention deficit hyperactivity disorder: Results of a retrospective chart review. *Journal of autism and developmental disorders, 34*(3), 329-339. https://doi.org/10.1023/B:JADD.0000029554.46570.68

Griffiths, S., Allison, C., Kenny, R., Holt, R., Smith, P., & Baron-Cohen, S. (2019). The Vulnerability Experiences Quotient (VEQ): A study of vulnerability, mental health and life satisfaction in autistic adults. *Autism Research*, *12*(10), 1516-1528. https://doi.org/10.1002/aur.2162

Harrell Jr, F. E., Lee, K. L., Califf, R. M., Pryor, D. B., & Rosati, R. A. (1984). Regression modelling strategies for improved prognostic prediction. *Statistics in medicine*, *3*(2), 143-152. https://doi.org/10.1002/sim.4780030207

Hartman, C. A., Geurts, H. M., Franke, B., Buitelaar, J. K., & Rommelse, N. N. (2016). Changing ASD-ADHD symptom co-occurrence across the lifespan with adolescence as crucial time window: Illustrating the need to go beyond childhood. *Neuroscience & Biobehavioral Reviews*, *71*, 529-541. https://doi.org/10.1016/j.neubiorev.2016.09.003

Horton, J., Millar, A., Labelle, A., & Knott, V. J. (2011). MMN responsivity to manipulations of frequency and duration deviants in chronic, clozapine-treated schizophrenia patients. Schizophrenia research, 126(1-3), 202-211. https://doi.org/10.1016/j.schres.2010.11.028

Huang, D., Yu, L., Wang, X., Fan, Y., Wang, S., & Zhang, Y. (2018). Distinct patterns of discrimination and orienting for temporal processing of speech and nonspeech in Chinese children with autism: an event-related potential study. *European Journal of Neuroscience*, *47*(6), 662-668. https://doi.org/10.1111/ejn.13657

Hus, V., & Lord, C. (2014). The autism diagnostic observation schedule, module 4: revised algorithm and standardized severity scores. *Journal of autism and developmental disorders*, *44*(8), 1996-2012. https://doi.org/10.1007/s10803-014-2080-3

Ikeda, K., Hashimoto, S., Hayashi, A., & Kanno, A. (2009). ERP evaluation of auditory sensory memory systems in adults with intellectual disability. *International Journal of Neuroscience*, *119*(6), 778-791. https://doi.org/10.1080/00207450802323842

Ioakeimidis, V., Lennuyeux-Comnene, L., Khachatoorian, N., Gaigg, S. B., Haenschel, C., Kyriakopoulos, M., & Dima, D. (2023). Trait and State Anxiety Effects on Mismatch Negativity and Sensory Gating Event-Related Potentials. Brain Sciences, 13(10), 1421. https://doi.org/10.3390/brainsci13101421

Jansson-Verkasalo, E., Ceponienè, R., Kielinen, M., Suominen, K., Jäntti, V., Linna, S. L., ... & Näätänen, R. (2003). Deficient auditory processing in children with Asperger Syndrome, as indexed by event-related potentials. Neuroscience letters, 338(3), 197-200. https://doi.org/10.1016/S0304-3940(02)01405-2

Jones, C. R., Happé, F., Baird, G., Simonoff, E., Marsden, A. J., Tregay, J., ... & Charman, T. (2009). Auditory discrimination and auditory sensory behaviours in autism spectrum disorders. *Neuropsychologia*, *47*(13), 2850-2858. https://doi.org/10.1016/j.neuropsychologia.2009.06.015

Kemner, C., Verbaten, M. N., Koelega, H. S., Buitelaar, J. K., van der Gaag, R. J., Camfferman, G., & van Engeland, H. (1996). Event-related brain potentials in children with attention-deficit and hyperactivity disorder: effects of stimulus deviancy and task relevance in the visual and auditory modality. *Biological psychiatry*, *40*(6), 522-534. https://doi.org/10.1016/0006-3223(95)00429-7

Kentrou, V., de Veld, D. M., Mataw, K. J., & Begeer, S. (2019). Delayed autism spectrum disorder recognition in children and adolescents previously diagnosed with attention-deficit/hyperactivity disorder. *Autism*, *23*(4), 1065-1072. https://doi.org/10.1177/1362361318785171

Kissel, H. A., & Friedman, B. H. (2023). Participant diversity in Psychophysiology. Psychophysiology, 60(11), e14369. https://doi.org/10.1111/psyp.14369

Krishnan, A., Kumar, R., Etienne, A., Robinson, A., Kelly, S. K., Behrmann, M., ... & Grover, P. (2018). Challenges and opportunities in instrumentation and use of high-density EEG for underserved regions. In *Innovations and Interdisciplinary Solutions for Underserved Areas: Second International Conference, InterSol 2018, Kigali, Rwanda, March 24–25, 2018, Proceedings 2* (pp. 72-82). Springer International Publishing. https://doi.org/10.1007/978-3-319-98878-8_7

Leyfer, O. T., Folstein, S. E., Bacalman, S., Davis, N. O., Dinh, E., Morgan, J., ... & Lainhart, J. E. (2006). Comorbid psychiatric disorders in children with autism: Interview development and rates of disorders. *Journal of autism and developmental disorders*, *36*, 849-861. https://doi.org/10.1007/s10803-006-0123-0

Lord, C., Rutter, M., DiLavore, P. C., Risi, S., Gotham, K., & Bishop, S. (2012). *Autism Diagnostic Observation Schedule, Second Edition*. Western Psychological Services.

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in human neuroscience*, *8*, 213. https://doi.org/10.3389/fnhum.2014.00213

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT press.

Madsen, G. F., Bilenberg, N., Jepsen, J. R., Glenthøj, B., Cantio, C., & Oranje, B. (2015). Normal P50 gating in children with autism, yet attenuated P50 amplitude in the asperger subcategory. *Autism Research*, *8*(4), 371-378. https://doi.org/10.1002/aur.1452

Maenner, M. J., Shaw, K. A., Bakian, A. V., Bilder, D. A., Durkin, M. S., Esler, A., ... & Cogswell, M. E. (2021). Prevalence and characteristics of autism spectrum disorder among children aged 8 years—autism and developmental disabilities monitoring network, 11 sites, United States, 2018. *MMWR Surveillance Summaries, 70*(11). https://doi.org/10.15585%2Fmmwr.ss7011a1

Maenner, M. J. (2023). Prevalence and characteristics of autism spectrum disorder among children aged 8 years—Autism and Developmental Disabilities Monitoring Network, 11 sites, United States, 2020. *MMWR. Surveillance Summaries*, *72*. http://dx.doi.org/10.15585/mmwr.ss7202a1

Mottron, L., Peretz, I., & Menard, E. (2000). Local and global processing of music in high-functioning persons with autism: beyond central coherence?. *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, *41*(8), 1057-1065. https://doi.org/10.1111/1469-7610.00693

Näätänen, R., Gaillard, A. W., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta psychologica*, *42*(4), 313-329. https://doi.org/10.1016/0001-6918(78)90006-9

Pakarinen, S., Takegata, R., Rinne, T., Huotilainen, M., & Näätänen, R. (2007). Measurement of extensive auditory discrimination profiles using the mismatch negativity (MMN) of the auditory event-related potential (ERP). Clinical Neurophysiology, 118(1), 177-185. https://doi.org/10.1016/j.clinph.2006.09.001

Pilowsky, T., Yirmiya, N., Shulman, C., & Dover, R. (1998). The Autism Diagnostic Interview-Revised and the Childhood Autism Rating Scale: differences between diagnostic systems and comparison between genders. *Journal of Autism and developmental Disorders*, *28*(2), 143-151. https://doi.org/10.1023/A:1026092632466

Remington, B., Hastings, R. P., Kovshoff, H., Degli Espinosa, F., Jahr, E., Brown, T., Alsford, P., Lemaic, M., & Ward, N. (2007). Early intensive behavioral intervention: Outcomes for children with autism and their parents after two years. *American Journal on Mental Retardation*, *112*(6), 418-438. https://doi.org/10.1352/0895-8017(2007)112[418:EIBIOF]2.0.CO;2

Reynolds, C. R., & Kamphaus, R. W. (2004). *Behavior Assessment System for Children Second Edition (BASC-2)*. Psychological Corporation.

Rutter, M., LeCoutier, A., & Lord, C. (2003). *The autism diagnostic interview-revised (ADI-R)*. Western Psychological Services.

Sawada, M., Iida, J., Ota, T., Negoro, H., Tanaka, S., Sadamatsu, M., & Kishimoto, T. (2010). Effects of osmotic-release methylphenidate in attention-deficit/hyperactivity disorder as measured by event-related potentials. Psychiatry and clinical neurosciences, 64(5), 491-498. https://doi.org/10.1111/j.1440-1819.2010.02134.x

Sawada, M., Negoro, H., Iida, J., & Kishimoto, T. (2008). Pervasive developmental disorder with attention deficit hyperactivity disorder-like symptoms and mismatch negativity. Psychiatry and clinical neurosciences, 62(4), 479-481. https://doi.org/10.1111/j.1440-1819.2008.01835.x

Schopler, E., Reichler, R., & Rochen Renner, B. (1988). *The childhood autism rating scale*. Western Psychological Services.

Schwartz, S., Shinn-Cunningham, B., & Tager-Flusberg, H. (2018). Meta-analysis and systematic review of the literature characterizing auditory mismatch negativity in individuals with autism. *Neuroscience & Biobehavioral Reviews*, *87*, 106-117. https://doi.org/10.1016/j.neubiorev.2018.01.008

Stevens, T., Peng, L., & Barnard-Brak, L. (2016). The comorbidity of ADHD in children diagnosed with autism spectrum disorder. *Research in Autism Spectrum Disorders*, *31*, 11-18. https://doi.org/10.1016/j.rasd.2016.07.003

Todd, J., Harms, L., Schall, U., & Michie, P. T. (2013). Mismatch negativity: translating the potential. *Frontiers in psychiatry*, *4*, 171. https://doi.org/10.3389/fpsyt.2013.00171

Van Der Meer, J. M., Oerlemans, A. M., Van Steijn, D. J., Lappenschaar, M. G., De Sonneville, L. M., Buitelaar, J. K., & Rommelse, N. N. (2012). Are autism spectrum disorder and attention-deficit/hyperactivity disorder different manifestations of one overarching disorder? Cognitive and symptom evidence from a clinical and population-based sample. *Journal of the American Academy of Child & Adolescent Psychiatry*, *51*(11), 1160-1172. https://doi.org/10.1016/j.jaac.2012.08.024

Wechsler, D., & Hsiao-pin, C. (2011). *WASI-II: Wechsler abbreviated scale of intelligence* 2nd ed.). Psychological Corporation.

Weismüller, B., Thienel, R., Youlden, A. M., Fulham, R., Koch, M., & Schall, U. (2015). Psychophysiological correlates of developmental changes in healthy and autistic boys. *Journal of autism and developmental disorders*, *45*(7), 2168-2175. https://doi.org/10.1007/s10803-015-2385-x

Winsberg, B. G., Javitt, D. C., & Shanahan, G. (1997). Electrophysiological indices of information processing in methylphenidate responders. *Biological Psychiatry*, *42*(6), 434-445. https://doi.org/10.1016/S0006-3223(96)00429-5

Yamamuro, K., Ota, T., Iida, J., Nakanishi, Y., Kishimoto, N., & Kishimoto, T. (2016). Associations between the mismatch-negativity component and symptom severity in children and adolescents with attention deficit/hyperactivity disorder. Neuropsychiatric disease and treatment, 12, 3183. https://doi.org/10.2147/NDT.S120540

Yang, M. T., Hsu, C. H., Yeh, P. W., Lee, W. T., Liang, J. S., Fu, W. M., & Lee, C. Y. (2015). Attention deficits revealed by passive auditory change detection for pure tones and lexical tones in ADHD children. *Frontiers in Human Neuroscience*, *9*, 470. https://doi.org/10.3389/fnhum.2015.00470

Yu, L., Fan, Y., Deng, Z., Huang, D., Wang, S., & Zhang, Y. (2015). Pitch processing in tonal-language-speaking children with autism: An event-related potential study. *Journal of*

Autism and Developmental Disorders, *45*(11), 3656-3667. https://doi.org/10.1007/s10803-015-2510-x

Zhang, Z. (2016). Missing data imputation: focusing on single imputation. *Annals of translational medicine*, *4*(1). https://doi.org/10.3978%2Fj.issn.2305-5839.2015.12.38

Connor MacKenzie

350 Huntington Hall, Syracuse, NY 13244 (585) 732-3450
Syracuse, NY 13244 ckmacken@syr.edu

EDUCATION

Syracuse University, Syracuse, New York **2020-Present**
Graduate Student, School Psychology Doctoral (PhD) Program
(APA and NASP Approved)
Anticipated graduation, August 2025

Otterbein University, Westerville, Ohio **2016-2020**
Bachelor of Science in Psychology, Graduating with Honors

Maastricht University, Maastricht, Netherlands **Fall 2018**
Faculty of Psychology and Neuroscience

RESEARCH EXPERIENCE

Center for Autism Research and Electrophysiology (CARE) **2020-present**
Graduate Researcher | PI: Natalie Russo, Ph.D.

Responsibilities:
Run participants through research studies primarily focused on perception and psychophysiology in autistic children and adolescents using EEG. Complete autism evaluations for the community. Evaluations include administration of the ADOS-2, cognitive measures (SB-5, WASI-II), and language instruments (PPVT-IV). Following evaluations, comprehensive reports are written and provided to the families.

Honor's Thesis: Assessment of Perceived Workload in the Classroom **2019-2020**
Advisor: Cynthia Laurie-Rose, Ph.D.

Research Assistant | Attention Lab (Dr. Cynthia Laurie-Rose, Dr. Meredith Frey) **2016-2018**
Department of Psychology, Otterbein University

Responsibilities:
Assisted with the programming of experiments through Superlab. Recruited participants, schedule their appointments with Sona Systems. Clean, code, and analyze data. Mentored two students interested in research.

Apprentice | Substance Lab (Nadia Hutten) **Fall 2018**
Faculty of Psychology and Neuroscience, Maastricht University, Netherlands

Responsibilities:
Shadowed a study on the effects of microdosing with LSD. Observed training and live sessions. Learned how to execute the tests and methods used.

PROFESSIONAL EXPERIENCE

Intern | Horizons Clinic at the Arc of Onondaga **2023-2024**

Responsibilities:
Conduct psychological evaluations for individuals across the lifespan with developmental disorders. Evaluations primarily consisted of cognitive and adaptive testing in addition to autism evaluations. Further, sexuality assessments are conducted for individuals at residential facilities to determine their capacity to consent to sexual activity. Following an evaluation, a detailed report is written to assist with service eligibility determinations through the Office for People with Developmental Disabilities (OPWDD).

Intern | Kelberman Center **2021-2023**

Responsibilities:
Provide psychological evaluations for individuals with autism and other neurodevelopmental conditions across the lifespan. Evaluations may include but are not limited to direct and indirect assessment of intellectual functioning, adaptive skills, social-communication abilities, executive functions, mental health, and behavior. Following an evaluation, a comprehensive report is written to provide to the families to assist with service acquisition and planning for future supports.

Intern | J. D. George Elementary School **2022**

Responsibilities:
Assisted an Applied Behavior Analysis (ABA) specialist with special education and autism-specific classrooms. Conducted Functional Behavior Analyses (FBA), assisted teachers with problem-solving, collected data through direct observation and indirect measures completed by teachers and parents. Developed Behavior Intervention Plans (BIP) and completed teacher and staff training.

Intern | Nationwide Children's Hospital **2019-2020**

Responsibilities:

Assisted with literature searches, researched for individual case studies, organized data, and scored various instruments for clinical research. Observed multidisciplinary diagnostic sessions, psychological assessment, and Applied Behavioral Analysis treatment sessions.

Direct Service Professional | Lifetime Assistance Inc. **2016 – 2019**

Responsibilities:
Assist residential developmentally disabled adults reach daily goals they set for themselves. Take clients on outings into the community for work, volunteering, or leisure. Teach them job readiness skills, assist with academic work, and plan group projects. Make sure all meals meet the dietary guidelines for all clients.

Intern | Lifetime Assistance Inc. **2016**

Responsibilities:
Taught developmentally disabled adults about exercise and wellness. Showed how to use various weight machines safely.

TEACHING EXPERIENCE

Teaching Assistant | Syracuse University **2020-2021**
Supervisor: Meredith Martin
PSY 205 – Introduction to Psychology

Responsibilities:
Complete recitation lectures for students, respond to student inquiries, and evaluate student assignments. Input grades and provide feedback.

HONORS AND AWARDS

Felipe Martinez Humanitarian Award	**2020**
Student Research Fund Award	**2019; 2020**
Torch & Key Honor Society	**2019-present**
Exchange Program at Maastricht University	**2018**
Psi Chi International Honor Society in Psychology	**2018-present**
Stephen Karsko Memorial Award	**2018**
Honors Program at Otterbein University	**2018-2020**
Otterbein University Academic Dean’s List	**2017-2020**

LEADERSHIP

Professional Development Committee at Syracuse University	**2020-2021**
President of Psi Chi at Otterbein University	**2019-2020**
Teaching Assistant at Otterbein University	**2019-2020**
Senator of the Interfraternity Council at Otterbein University	**2019-2020**
Student Government Senator at Otterbein University	**2019-2020**
Academic chair of the Eta Phi Mu fraternity at Otterbein University	**2019-2020**
Vice president of Psi Chi at Otterbein University	**2018-2019**
Member of the Eta Phi Mu fraternity, house manager	**2017-2018**

COMMUNITY SERVICE

North Central Mental Health Services Suicide Prevention Hotline	**2019-2020**
Working with kids at several elementary schools in the Columbus area with the Otterbein lacrosse team	**2016-2018**

SKILLS

CITI research certified

TF-CBT certified

Data Analysis with R commander GUI software, SPSS

Subject pool management with Sona Systems, Quadratics, Mentimeter