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Spanning the Auditory System: Subcortical and Cortical Auditory Processing of Speech Sounds in Autistic and Typically Developing Children

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Abstract

Autistic individuals often report atypical sensory processing, particularly in the auditory domain. However, the neural mechanisms that produce such symptoms are poorly understood. The Speech Auditory Brainstem Response (speech-ABR) and the Mismatch Negativity (MMN) are neurophysiological measures that capture different levels of auditory processing, such that the speech-ABR reflects processing at the subcortical level and the MMN measures cortical processing. The present study integrated both techniques in a multimethod approach, which spans both subcortical and cortical processing of speech sounds in a group of autistic children (n = 11) matched on chronological age and non-verbal IQ to their typically developing (TD) peers (n = 11). Results suggest that both groups are similar in their speed of speech processing, as measured via the interpeak V-O latency of the speech-ABR and the MMN latency. Additionally, while the subcortical auditory processing did not predict cortical auditory processing, an interesting pattern of preliminary group differences emerged. These findings, which require replication in a larger sample, suggest that there may be important nuances in auditory processing among autistic youth that are enriched by employing a multimethod design and highlight the importance of a developmental framework in research with individuals with neurodevelopmental disabilities.

Keywords: speech auditory brainstem response, mismatch negativity, autism

SPANNING THE AUDITORY SYSTEM: SUBCORTICAL AND CORTICAL AUDITORY PROCESSING OF SPEECH SOUNDS IN AUTISTIC AND TYPICALLY DEVELOPING CHILDREN

By

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Introduction

Autism Spectrum Disorder (ASD) is defined by deficits in social communication and restricted, repetitive patterns of behaviour (RRBs; American Psychiatric Association, 2013). As of 2013, atypical sensory features have been included as part of the diagnostic criteria for ASD. This criterion may be a highly sensitive and specific symptom, as approximately 90-94% of autistic individuals report atypical sensory behaviours, which is a higher rate compared to other neurodevelopmental disorders (Crane et al., 2009; Gomes et al., 2008; Leekam et al., 2007; Tomchek & Dunn, 2007). Sensory features in the auditory domain may be the most common and can include placing one's hands over one's ears to protect from sounds or a preoccupation with particular sounds (Gomes et al., 2008). However, the neurobiological underpinnings of such behaviours are not yet fully understood. It has also been posited that early, fundamental differences in auditory processing may impact later downstream neural mechanisms that contribute to speech and communication skills (Boets et al., 2008; Russo et al., 2009). In this way, both cardinal symptoms of ASD (i.e., social communication and RRBs) can be understood via differences in auditory processing (O'connor, 2012). Thus, understanding the neurophysiology of this sensory pathway may improve our clinical conceptualization and be leveraged to inform the testing of potential biomarkers for ASD (for a review, see Jones & Lord, 2013; Walsh et al., 2011). Here, I assess two components of the auditory system, such that we may gain a deeper understanding of how the functioning of the areas may differ by group, are connected, and are related to external behaviours relevant to autism. However, before approaching such research questions, one must take a step back to understand the workings of

the human auditory system. Though a full description detailing all complexities is beyond the scope of this paper, below I present a summary of the afferent auditory pathway in the brain.

The Auditory System

When a sound is played, the process of hearing begins in the peripheral auditory system, which consists of the ear (comprised of the outer, middle, and inner) and auditory nerve (Musiek & Baran, 2018). The outer ear (pinna, auditory canal, and tympanic membrane) aids in catching and collecting sound waves from the environment. These sound waves are then transmitted to the middle ear, which is made up of three small bones called ossicles (i.e., the malleus, incus, and stapes) and the oval window. The main functions of the middle ear are to amplify the energy of the acoustic stimuli before it is sent to the cochlea and to serve as a protective mechanism to defend the ear from sounds that are too loud. After the sound vibrations travel through the oval window, they reach the inner ear, which is made up of the cochlea and vestibular organs. The anatomy of the cochlea is complex, containing three canals separated by the tectorial and basilar membranes. Cochlear fluid within the canals causes the basilar membrane to move, rubbing small hair cells against the tectorial membrane. This creates a shearing force which triggers a chemical reaction called depolarization, allowing for neurotransmitters to be released. This crucial step is called transduction, which occurs when a physical stimulus (i.e., vibrational frequencies of a sound) is transformed into chemical energy (i.e., neurotransmitters) that allows for communication in the brain (Musiek & Baran, 2018). The final step of the peripheral auditory system occurs when the auditory nerve transmits the electrical impulses generated in the cochlea to the brainstem for further processing.

Next is the central auditory system, which spans from the brainstem to the cortex. Most structures here follow a tonotopic and hierarchical representation, meaning that areas are organized by frequency and an increasing level of processing as you ascend the system. The cochlear nucleus receives input from the auditory nerve and is then sent to the superior olivary complex (SOC), which is in the pons of the brainstem (Musiek & Baran, 2018). The SOC has a bilateral representation of acoustic stimuli, which aids in determining the source location of a sound (i.e., left or right ear), as well as acoustic integration. The SOC then sends input along the lateral lemniscus to the inferior colliculus (IC). The IC is in the midbrain and receives input from most of the lower auditory brainstem structures (Oliver & Morest, 1984). Similar to the SOC, the IC aids in sound localization and lateralization (Litovsky et al., 2002). The IC sends outputs primarily ipsilaterally but also contralaterally to the medial geniculate body (MGB) in the thalamus, which is known as the sensory relay of the brain. The MGB sends output to the auditory cortex along the thalamocortical pathway. The auditory cortex is located along the Sylvian fissure and includes Heschl's gyrus (the primary auditory cortex or A1), the planum temporale (also known as Wernicke's Area), the posterior inferior frontal lobe, the inferior parietal lobe, the angular gyrus, the supramarginal gyrus, the superior temporal gyrus, and the insula. The auditory cortex communicates with the rest of the brain via both inter- and intra-hemispheric tracts and is crucial for speech perception, localization, and lateralization (Musiek & Baran, 2018).

The auditory system is a complex and multi-step process, which requires involvement from both subcortical and cortical areas of the brain (Musiek & Baran, 2018). Within these complex pathways are many opportunities for differences to emerge that may impact

downstream processing and behaviour. For example, previous magnetic resonance imaging (MRI) research has found differences in the morphology of SOC neurons, hemispheric asymmetry of the planum temporale, and grey matter volume of the superior temporal gyrus between autistic and typically developing (TD) individuals (van Rooij et al., 2018), which may represent biological underpinnings of auditory atypicalities in autism. Thus, to fully understand the neural mechanisms which may contribute to auditory behaviours seen in autistic individuals, it may be beneficial to account for both the brainstem and the cortex.

Despite the comprehensive understanding of the neuroanatomy in the auditory system and the well-documented behavioural auditory atypicalities in autistic individuals, there is very limited research that spans the entirety of the auditory process. This may be because studies of the auditory system are often siloed into subcortical (under the domain of Communication Sciences and Disorders) and cortical (i.e., Psychology/Neuroscience) groups. Thus, while past research has found subcortical and cortical auditory differences in autism, less attention has been devoted to neurophysiological measures examining both processes together. Here, I begin to fill this gap by using Auditory Brainstem Responses (ABRs) to assess subcortical auditory processing and Electroencephalography (EEG) to measure cortical auditory processing in the same sample of autistic and TD children.

Auditory Brainstem Response (ABR)

ABR studies originated in the 1970s (Jewett, 1970) and are considered an effective way of assessing auditory processing at the level of the brainstem. Though ABRs have been studied in response to a multitude of stimuli, the click-ABR and speech-ABR are the most common. Click stimuli are brief and have a more rapid onset, whereas speech stimuli are longer and more

complex in their spectral content (Russo et al., 2009). Additionally, the click- and speech-ABRs call on different encoding and processing mechanisms in the brain (Johnson et al., 2005), as well as follow different developmental trajectories (Johnson et al., 2008). Differences in how speech is processed at the level of the brainstem may help to explain difficulties with language/social communication among autistic individuals (Russo et al., 2009) and may also be a viable differential marker between clinical and TD populations, as previous research has found that the speech- but not the click-ABR differentiated between autistic and TD children (Kamita et al., 2020; Russo et al., 2009). Lastly, some research suggests that the speech-ABR may be sensitive to intervention, as the latencies shortened and amplitudes increased after training (Russo et al., 2010), further positioning the speech-ABR as a useful clinical tool. Given its clinical utility (Kamita et al., 2020; Russo et al., 2009) and extremely high temporal resolution, the speech-ABR was selected to measure subcortical auditory processing.

The Speech-ABR. The speech-ABR is generated by the brainstem nuclei and the IC's response to a repeated consonant vowel (CV) syllable (White-Schwoch et al., 2019). The CV syllable /da/ is the most used stimulus due to its ubiquity across languages (Moossavi et al., 2019). The speech-ABR onsets about 6-10ms after presentation of the CV syllable, which accounts for the transmission time to the brainstem (Galbraith et al., 1998; Hall, 2007; Krishnan, 2007). Notably, there is a striking resemblance to the /da/ syllable characteristics (i.e., amplitude and latency) and its neural representation (i.e., the speech-ABR) after accounting for this delay, suggesting acoustic preservation in the brainstem (Johnson et al., 2005). The speech-ABR is broken down into seven peaks labelled V, A, C, D, E, F, and O (for a review, see Sansfins, 2016). Both waves V and A represent the onset of the speech syllable (Chandrasekaran & Kraus,

2010). Wave C represents the transition between the consonant and the vowel (Madrid et al., 2021). Waves D, E, and F represent the sustained frequency-following response (FFR), which reflects the transition between the consonant burst and the onset of the vowel, as well as the vowel itself (Chandrasekaran & Kraus, 2010). Lastly, wave O is the transient response to the offset of the speech stimulus (Chandrasekaran & Kraus, 2010). The speech-ABR is highly reliable and can be identified in nearly 100% of TD children (Russo et al., 2004), as well as incredibly temporally sensitive, such that latency variability of less than 1ms can be used to determine differences in performance (Chandrasekaran & Kraus, 2010).

The Speech-ABR Latency in Autism. Speech-ABR research has most consistently found that autistic children have a later wave V and A latency when compared to TD peers matched on chronological age (Chen et al., 2019, 2021; Ramezani et al., 2019; Russo et al., 2009). While some studies comparing autistic and TD individuals have also found different latencies for waves D, E, F, or O (Chen et al., 2019; Jones et al., 2020; Ramezani et al., 2019; Russo et al., 2009), the results are more divergent, likely due to methodological differences between studies on key variables including age and developmental level of the participants. In addition to reporting the latency of individual peaks in the speech-ABR, some researchers elect to report a combined measure of interpeak latency, which is calculated by taking the difference of the two individual peaks (Anderson et al., 2015; Madrid et al., 2021; Malayeri et al., 2014; Russo et al., 2004). Previous research has used this measure to examine the relationship between interpeak A-O latency and age in TD infants (Anderson et al., 2015; Madrid et al., 2021; Russo et al., 2004), but also in clinical populations, as Malayeri et al. (2014) found that children with learning problems demonstrated a longer interpeak V-A latency of the speech-ABR compared to

their non-learning disabled counterparts of the same age and IQ. Other interpeak latencies (e.g., V-O) have yet to been explored, despite theoretical support that this method of characterizing the speech-ABR may represent the entire neural conduction time of the CV syllable (Gorga et al., 1989; Salamy, 1984).

Electroencephalography (EEG)

Hans Berger was the first individual to examine electrical activity in the human brain by amplifying the signal through an electrode placed on the scalp and then tracing the changes in voltage over time (Berger, 1929). Though initially controversial, psychologists soon showed that Berger's methods were a valid depiction of brain activity and EEG became accepted in the field as a sound neurophysiological technique (Adrian & Matthews, 1934; Gibbs, 1935; Jasper & Carmichael, 1935). To collect EEG data, electrodes are placed on the surface of the scalp to record voltage changes occurring as a result of the electrical activity generated by postsynaptic potentials in the brain (Luck, 2014). This voltage change can be plotted over time and across different electrodes to create a continuous EEG signal.

Because continuous EEG recordings do not allow for the study of specific neural mechanisms, in the 1960's, researchers developed Event-Related Potentials (ERPs) as a way of indexing brain activity (Luck, 2014). An ERP is the brain's response to a specific stimulus and is typically characterized by its latency and amplitude. Latency refers to the onset of the ERP relative to zero in milliseconds (ms) after the presentation of the stimulus and amplitude refers to the microvolts (μv) of the ERP waveform relative to zero. By presenting the same stimulus over repeated trials, the brain's response to that stimulus can be averaged and its signal can emerge from the noise (i.e., brain responses not specifically associated with the stimulus of interest). A

grand average can be created by averaging average waveforms across participants, which allows us to assess the brain's response to a specific stimulus and make comparisons between groups (e.g., age, diagnosis; Ward, 2016).

The Mismatch Negativity (MMN)

Perhaps one of the most widely studied ERP components is the Mismatch Negativity (MMN). In 1975, Näätänen conducted a study in which participants listened to two interleaved tones. One of these tones, the 'standard' was presented 80% of the time and the second tone, the 'deviant' was presented 20% of the time. Näätänen found that irrespective of whether or not participants were paying attention to the stimuli, the standards and deviants produced different neural responses at the scalp. In particular, he found that when the ERP to the standard sound was subtracted from the ERP to the deviant sound, it produced a difference wave, referred to as the MMN, a negative waveform that onset around 150ms (Näätänen et al., 1978). Further studies on the MMN in adults show that the ERP typically peaks at 150-250ms at frontocentral and central scalp electrodes and is supported by two areas in the brain: the bilateral supratemporal regions and right-hemispheric frontal processes (Näätänen, 1995; Näätänen et al., 2007; Näätänen & Alho, 1995). The former is associated with pre-perceptual change detection and the latter frontal process is related to the involuntary attentional switch occurring in response to the auditory discrimination (Näätänen et al., 2007).

The Speech MMN. Similarly to the ABR, the MMN can also be elicited from speech or non-speech stimuli (for a review, see Chen et al., 2020; Schwartz et al., 2018). The MMN to speech sounds does not differ by gender (Kasai et al., 2001) and has been used to investigate processing of native versus unfamiliar languages (Cheour et al., 1998), dyslexia (Kujala &

Näätänen, 2001), and more. The neural response to speech sound discrimination may be particularly relevant to autism, given deficits in social communication (American Psychiatric Association, 2013) and the highly co-occurring specific language impairment (Conti-Ramsden et al., 2006; Tager-Flusberg, 2006). In line with this, research has noted a consistent deficit in the amplitude and latency of the MMN to speech sounds among autistic individuals (Chen et al., 2020). Thus, the present study focuses on the latency of the MMN to speech sounds to 1) leverage the high temporal resolution of EEG methodology and 2) remain consistent in measurement to the speech-ABR.

The MMN Latency in Autism. Similar to the literature on the speech-ABR in autism, research surrounding the latency of the MMN is quite diffuse, likely due to the many variations in experimental design that are employed. Despite these challenges, a recent meta-analysis by Chen et al. (2020) synthesized 22 articles examining the MMN in autistic participants (mean age 17.5) published between 2000 and 2018. The authors found no significant differences in the MMN latency to speech sounds when the deviant speech sounds differed in frequency or duration. However, when deviants in the oddball paradigm were different phonemes entirely (e.g., /ba/ vs /da/), the autistic group demonstrated significantly longer MMN latencies compared to their TD peers (*Hedge's g* = -0.33, $p = 0.041$) across nine different studies. Three of 9 those studies did not find significantly longer MMN latencies in autism (Kujala et al., 2010; Lepistö et al., 2005, 2007), which are understood via the following differences in methodology.

Lepistö et al. (2005, 2007) may not have found differences in the MMN latency because of the language and cognitive abilities in their sample. Lepistö et al. (2007) examined the MMN in children with Asperger syndrome, which differs from ASD, as children with Asperger

syndrome do not have atypical language or cognitive development. Though Asperger syndrome was collapsed into ASD in the DSM-5 (American Psychiatric Association, 2013), research suggests that the MMN latency differs by diagnosis (Chen et al., 2020). Thus, by looking exclusively at children with Asperger syndrome, this study may be ungeneralizable to the full spectrum of autistic individuals. Similarly, Lepistö et al. (2005) found no differences between autistic and TD participants in the MMN response to phoneme-deviant speech sounds, however, their autistic participants had significantly lower scores on measures of both Verbal IQ and Performance IQ. While the impact of cognitive ability on the MMN in autistic individuals is unknown, previous research shows that the cognitive abilities such as working memory (Bonetti et al., 2018) and processing speed (Hermens et al., 2010) are associated with a larger MMN in TD individuals. Lastly, Kujala et al. (2010) found no differences in the latency of the MMN in response to phoneme-deviant speech sounds, despite matching groups on age, gender, handedness, Verbal IQ, and Full-Scale IQ. However, their auditory oddball paradigm contained five alternating deviants that each occurred 10% of the time with the standard appearing only 50% of the time. Research in TD individuals has shown that the MMN is impacted by the probability of the deviants and while it has yet to be directly assessed in autism, this may explain the lack of group differences in their MMN (Kujala et al., 2010). Taken together, these three studies highlight the nuances and considerations necessary in experimental design with atypically developing populations, but also suggest that there are many more avenues to explore in autism research, as the consensus can quickly become complicated by different methodological choices.

Taken together, these findings suggest that both the speech-ABR and the MMN latencies are longer in autistic individuals (Chen et al., 2019, 2021; Chen et al., 2020; Ramezani et al., 2019; Russo et al., 2009). This similarity suggests there might be not only differences in neural processing between groups, but also a potential continuity in the neurophysiology of the subcortical and cortical auditory system. Research examining this relationship may further inform our understanding of the auditory system as a whole for autistic individuals and their TD peers.

Multimethod Approaches. Though some researchers have studied the click-ABR and the MMN together to examine non-speech processing (e.g., Althen, 2014; Schochat et al., 2002), less have focused on the speech-ABR and the MMN (El-Beltagy et al., 2019; Fu et al., 2015). Further, previous research has examined the speech-ABR and the MMN to speech-sounds in other neurodevelopmental disorders like ADHD (Azzam & Hassan, 2010), learning disabilities (Banai et al., 2005), and language problems (Wible et al., 2005), but none has been conducted in autism. Research connecting measures of the brain and behaviour are also lacking, though there is emerging evidence to suggest an association between ERPs, autistic traits, and sensory features (Cary et al., 2021; Kadlaskar et al., 2021; Kaplan-Kahn et al., 2021; Ruiz-Martinez, 2020). For example, Cary et al. (2021) found that an earlier MMN latency was associated with a higher endorsement of autistic traits using the Autism Quotient (AQ; (Baron-Cohen et al., 2001, 2006) in a sample of autistic children (mean age 12.8) matched on age and non-verbal IQ to their TD peers.

One notable multimethod study has connected subcortical, cortical, and behavioural systems in autism by using the speech-ABR, structural magnetic resonance imaging (sMRI), and

the Gesell Developmental Diagnosis Scale (GDDS) in a sample of autistic children matched on chronological age to their TD peers (mean age around 4 years old; Chen et al., 2021). Researchers found significant correlations between the speech-ABR (i.e., wave V and A latency, wave V amplitude) and the surface area of the left rostral middle frontal gyrus (lRMFG), which is involved in language and complex sentence construction (Chapman et al., 1992, 1998). This suggests a relationship between the subcortical speech processing and cortical language systems in autistic children using speech-ABR and sMRI. Further, there was a significant indirect mediation effect in which surface area of lRMFG predicted GDDS language outcomes via wave V amplitude, which provides preliminary evidence to suggest that combining subcortical and cortical indices of auditory processing of the brain can aid in predicting behavioural outcomes.

Theoretical Considerations

Autism research requires the consideration of several theoretical and methodological issues. The lens one uses to approach research impacts the questions they ask, how they go about testing such questions, and the interpretation of the subsequent findings. Many theories have attempted to unify the interesting and heterogenous pattern of abilities in autism (for a review, see Fletcher-Watson & Happé, 2019). The Enhanced Perceptual Functioning Theory (EPF; Mottron et al., 2006) posits that autistic individuals have relative strengths in processing early, simple, perceptual stimuli but are poorer at higher-order, complex cognitive information compared to their TD peers. In line with this, research has found that autistic individuals demonstrate enhanced pitch perception, identification, and discrimination for simple pure tones, but not complex stimuli (for a review, see Jones et al., 2009; O'Connor, 2012). Because this model recognizes both strengths and weaknesses, it offers a different way of conceptualizing

autism. This is especially important as research focused exclusively on deficits and impairments in autism may limit the scope of the research questions to those that confirm but not challenge negative beliefs, further contributing to stigma and an inaccurate representation of autistic ability in research (for a review, see Bottema-Beutel et al., 2021).

Second, between-subjects research designs with atypically developing individuals requires one to consider the importance of a developmental approach and a careful selection of the comparison group, as both carry large implications when interpreting results. One such consideration is the importance of matching autistic participants on the basis of developmental level as opposed to just chronological age (Russo et al., 2020), so that we can control for differences in cognitive ability. Further, given that autistic individuals often demonstrate an uneven cognitive profile with lower verbal compared to non-verbal IQs (Joseph et al., 2002), how researchers operationalize cognitive ability can impact matching and the following results. Taken together, these nuanced considerations demand open-minded research questions, methodological rigor, and a careful interpretation of findings to ensure our science striving to better understand auditory processing in autism is conducted accurately and justly.

In accordance with previous evidence suggesting slower latencies in the speech-ABR and the MMN (Chen et al., 2019, 2021; Chen et al., 2020; Ramezani et al., 2019; Russo et al., 2009) and associations between subcortical and cortical measures of the auditory system (Chen et al., 2021), the primary aims of the present study were twofold. First, I sought to assess whether there were differences between autistic and TD children in the subcortical and cortical auditory processing of speech sounds. To do this, the latency of the speech-ABR and the MMN in response to speech sounds were compared between a group of autistic and TD children matched

on chronological age and cognitive ability. In line with previous research (Chen et al., 2019, 2021; Chen et al., 2020; Ramezani et al., 2019; Russo et al., 2009), I hypothesized that the interpeak V-O latency of the speech-ABR and the latency of the MMN would be longer for the autistic group compared to their TD peers. Second, given the importance of understanding the full span of the auditory system, I sought to connect subcortical and cortical measures of auditory processing. To do so, I examined whether the interpeak V-O latency of the speech-ABR predicted the latency of the MMN across participants, hypothesizing that a longer interpeak V-O latency would lead to a later MMN. Lastly, in an effort to replicate Chen et al. (2021) and learn about the relationship between the brain and behaviour, an exploratory analysis using scores from the Sensory Profile (SP; Dunn, 1997) and AQ (Auyeung et al., 2008; Baron-Cohen et al., 2001, 2006) was conducted to provide a preliminary characterization of the relationship between the neurophysiology of the subcortical-cortical alignment to external sensory behaviours and autistic traits.

Methods

Participants. G-power analyses were used to prospectively determine the necessary sample size for each aim. In line with Chen et al. (2020), an expected effect size of -0.33 was used for the MMN latency. No published effect size measurements for the speech-ABR or the relationship between the speech-ABR and the MMN were available. As such, we conservatively used a similar effect size of 0.3. With the conventional α error probability of 0.05, an independent samples t-test required a sample size of 230 and a linear regression required 26. We recruited 42 participants for this project, of whom 31 (20 TD and 11 ASD) completed all components necessary for this study. Acknowledging that verbal measures of IQ tend to

underestimate autistic intelligence (Joseph et al., 2002), 11 autistic children aged 9-16 years old (91% male) were matched on both chronological age and the Perceptual Reasoning Index (PRI) of the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011) to 11 TD children (36% male). There were no significant differences between groups on age ($t(20) = 0.362$, $p = 0.783$), the PRI ($t(20) = 0.356$, $p = 0.080$), or the Full Scale IQ ($t(20) = 1.718$, $p = 0.102$) but groups differed on the Verbal Comprehension Index (VCI) of the WASI-II ($t(20) = 3.435$, $p = .003$), such that the TD individuals scored significantly higher than their age and PRI-matched autistic peers (see Table 1). 100% of participants reported that they identified as White and non-Hispanic/Latinx.

The WASI-II is a standardized cognitive assessment for children aged 6 to 16 years old (Wechsler, 2011). It is comprised of four subtests (Block Design, Vocabulary, Matrix Reasoning, and Similarities) and computes three composite indices (FSIQ, VCI, and PRI). The average split half reliability of the WASI-II composite scores range from .92-.96 (Wechsler, 2011), which is in the High range. Test-retest reliability has also been assessed, with adequate stability coefficients ranging from .87 to .95 on composite scores. The WASI-II has convergent validity with the WISC-IV (Wechsler Intelligence Scale for Children – Fourth Edition; WISC-IV), with correlations between .82 and .91 across composites, and moderate-to-high correlations to the Kaufman Brief Intelligence Test – Second Edition (KBIT-2; Kaufman & Kaufman, 2004). Lastly, the WASI-II has also been used to assess the cognitive abilities of a diverse sample, including autistic individuals and those with Intellectual Disabilities (Minshew et al., 2005; Wechsler, 2011).

ASD diagnoses were confirmed using DSM-5 criteria, the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; (Lord et al., 2012), the Autism Diagnostic Interview – Revised (ADI-R; Rutter et al., 2003), and clinical judgement. Assessments were administered by graduate students trained and certified in the ADOS-2 and the ADI-R was conducted by a licenced psychologist. Autistic participants had to score 7 or higher on the ADOS-2 and meet criteria on the ADI-R. TD participants had no previous psychiatric diagnoses. Participants were excluded if they had an FSIQ below 80, or a history of epilepsy, neurological, genetic, psychiatric, and learning disorders. To control for hearing ability, all participants passed an audiology assessment, which including otoscopy, behavioural audiometric threshold evaluation, distortion product otoacoustic emissions (DPOAEs), transient click evoked otoacoustic emissions, and wide band absorbance. Hearing and cochlear functioning was considered normal if the behavioural thresholds were < 25 dB HL (hearing level).

Procedure. This study was approved by the Institutional Review Board (IRB) at Syracuse University. Caregivers provided written informed consent and children provided written assent to participate. In total, the experiment took around four hours to complete, which was broken up into at least two sessions. Participants first completed the hearing screen and two ABR tasks (i.e., the click- and speech-ABR) at the Pediatric Audiology Laboratory. They then scheduled another appointment at the Center for Autism Research and Electrophysiology (CARE) lab, where they completed the cognitive assessment, two MMN tasks (i.e., a speech and non-speech MMN), and questionnaires. Only results from the experiments focused on speech processing are reported here.

ABR

ABR Experimental Task. The Intelligent Hearing Systems SmartEP system was used to present the stimuli and record the ABR data. Speech-ABRs were elicited using 40ms /da/ syllables with an alternating polarity of 11.1/s at 63 dB nHL (normal hearing level). Stimuli were presented binaurally and recorded in both the left and right hemispheres. Electrodes were placed on the mastoids, upper forehead, and lower forehead for the ground. Impedences were maintained below 3kΩ and within 1kΩ of each other. Data was amplified using a gain of 100, 000 and bandpass filtered from 100-3000Hz.

ABR Data analysis. Latencies were extracted using Smart EP software. Two 1500 sweep runs were averaged together, resulting in a speech-ABR that contained 3000 sweeps. The latencies for waves V, A, C, D, E, F, and O were independently picked using visual inspection by an experienced doctoral student. To calculate the interpeak V-O latency of the speech-ABR, wave V latency was subtracted from wave O latency for each participant. A paired t-test was conducted to determine whether there were significant differences in the interpeak V-O latency based on recording site because the speech stimuli that elicited the ABR were presented binaurally but recorded from one hemisphere at a time. No significant differences were found ($t(1,21)=0.098$, $p = .923$). As such, the interpeak V-O latency data across both hemispheres were averaged together for the remainder of the analyses.

EEG

EEG Experimental Task. Stream (Hahsler et al., 2017) and MATLAB (MATLAB, 2010) were used to control the presentation of the stimuli and elicit the MMN. Participants were presented with a typical oddball paradigm in which the speech syllable /da/, designated as the standard, was presented 80% of the time, and a second syllable /ba/, designated as the deviant

was interspersed among the standards 20% of the time. Stimuli were presented in a random order, with the exception that two deviants were not play consecutively. There were 1000 trials of speech stimuli at a stimulus onset asynchrony of 600ms, with each stimulus playing for 360ms followed by an interstimulus interval of 240ms. Stimuli were presented via two speakers to the left and right of the computer screen at 60 dB SPL. To mitigate interference from other cognitive ERP components that require active attention (Näätänen et al., 2007), a distraction task was employed, such that participants watched a silent movie or television show of their choice and were instructed to ignore the auditory stimuli.

EEG Recording. Net Station Software from Electrical Geodesics, Inc. (EGI; Electrical Geodesics, 2003) was used to record the EEG data. A high-density 128-channel Geodesic SensorNet cap was fitted to each participant's head using the nasion, inion, and jawbone as landmarks to help standardize fit. To increase the signal to-noise ratio, electrode impedences were maintained below 50kΩ and recorded at a sampling rate of 1024 Hz. Data was referenced to the Cz electrode during recording.

EEG Data Analysis. The MMN is typically quantified relative to the mastoids (Näätänen et al., 2007), which are the bones behind the ears. As such, the resulting EEG data was re-referenced to the right and left mastoids. Data was band-pass filtered using a 0.1Hz high-pass and 30Hz low-pass criteria from a 2nd order Butterworth filter to reduce noise (Luck, 2014). High-pass filtering removes large gradual voltage changes which are most often caused by skin potentials, while low-pas filtering removes noise generated by electrodes at the scalp, typically from cellphones and computers (Luck, 2014). Next, the EEG data was segmented, beginning 50ms before the presentation of the stimulus and continuing for 650ms after. This created

segments or *epochs* of 700ms each. Following segmentation, the data was baseline corrected such that each epoch of data had a near zero voltage at the onset of the stimulus, allowing for the epochs to be compared across trials. To control for any movement or noise, a semi-automatic artefact rejection process was conducted in which epochs greater than 100 microvolts (μV) were removed. Lastly, visual inspection of the remaining data was conducted by a graduate student to identify any outstanding noisy channels. Identified channels were replaced using the surface spline interpolation method, which takes the activity from electrodes across the 3D scalp surface to inform the prediction of the missing data (Perrin et al., 1987).

MMN Latency Extraction. Previous research suggests that the MMN typically peaks primarily in the fronto-central midline approximately 150-250ms after presentation of the stimulus (Luck, 2014, Näätänen et al., 2007). Thus, after artefact rejection was complete, data from the FCz electrode across similar trials were averaged together. To quantify the MMN, a difference wave was calculated by subtracting the standard from the deviant (Näätänen et al., 2007), such that each participant had their own averaged waveform for the standard, deviant, and difference wave. Grand averages for the standard, deviant, and differences waves were created by aggregating all participants' average waveforms together by group (Figures 2-4). Though there are many methods of calculating latency, fractional area latency was chosen because it is less sensitive to noise (Luck, 2014). Fractional area latency extracts the moment in time in which a percentage of area under the curve has been accrued. In this way, fractional area latency allows for more flexibility, as one can specify an exact percentage that is in line with their research question. For the present study, 30% fractional area latency was selected to capture the onset of the discrimination between sounds in the brain (i.e., the speed in which the brain recognizes the

difference between the standard and the deviant). Time windows were selected by a graduate student, blind to group, who selected the onset time for each participant's MMN by identifying the point in which the waveform deviated from 0μv. These time windows were approved by a second ERP expert, also blind to group membership. Consistent with previous research, a 200ms window was standardized across participants (Lepistö et al., 2006). After visual inspection of the difference waves, two participants were removed from the analysis because their MMN could not be identified. One participant had a very small and noisy difference wave, which did not demonstrate a salient peak nor return to 0μv. The second participant's waveform also demonstrated no clear peak, nor a return to baseline. The remainder of the MMN waveforms were acceptable and retained for analysis. As such, the final sample for all EEG analyses consisted of 11 TD and 9 autistic participants. Lastly, the fractional area latency was calculated using ERPLab (Lopez-Calderon & Luck, 2014), which identified the point at which 30% of the area under the curve was accrued for each individual's time window at the FCz electrode.

Questionnaires

The AQ is a 50-item questionnaire used to assess autistic traits and contains five subscales, including Social Skills, Attention Switching, Attention to Detail, Communication, and Imagination, with higher scores indicating a greater endorsement of autistic traits (Baron-Cohen et al., 2001, 2006). There are three different versions of the AQ with consistent item content but adapted for developmental level: a parent-reported Child AQ (Auyeung et al., 2008) was given to participants aged 4-11 years old, the Adolescent AQ for ages 12-15 years old (Baron-Cohen et al., 2006), and a self-report Adult AQ to participants 16 years or older (Baron-Cohen et al., 2001). All three forms of the AQ have acceptable psychometric properties, with Cronbach's

alpha coefficients ranging from .63- .97 across the subscales, which is in the Moderate to High range (Auyeung et al., 2008; Baron-Cohen et al., 2001, 2006). Additionally, research suggests that the AQ has good convergent validity with ASD diagnosis and excellent test-retest reliability (Auyeung et al., 2008; Baron-Cohen et al., 2001, 2006). Because this task required auditory discrimination and speech processing, the Attention to Detail and Communication subscales were selected for analysis.

The SP (Dunn, 1999) is a 125-item parent-report questionnaire that assesses sensory processing and behaviours, with higher scores indicating a greater endorsement of sensory features. There are four quadrants on the SP: Seeking, Registration, Avoidance, and Sensitivity. Additionally, previous research has established an additional composite of Sensory Overresponsivity, which is comprised of 14 items to examine tactile, auditory, and visual sensitivity (Green et al., 2015; McKernan et al., 2020). The SP has acceptable psychometric properties with Moderate to High internal consistency, as estimated from Cronbach's alpha coefficients ranging from .47-.91 across subscales (Dunn, 1999), moderate convergent validity to other validated measures of sensory processing (i.e., Sensory Processing Measure; (Miller-Kuhaneck et al., 2007) and discriminant validity between clinical (e.g., Attention Deficit Hyperactivity Disorder, Asperger Syndrome, Fragile X Syndrome) and TD children (Brown et al., 2010). Given the interest in sensory features in autism, the Sensitivity quadrant and Overresponsivity composite were selected for analysis.

Statistical Analyses

All statistical analyses including descriptives were conducted using Rstudio (RStudio Team, 2020). Two independent samples two tailed t-tests were conducted to determine if there

were significant differences between autistic and TD groups on the interpeak V-O latency and the MMN latency. A linear regression was conducted to determine whether the interpeak V-O latency in the speech-ABR could predict the latency of the MMN. Due to the temporal sequence of events, the speech-ABR was selected as the predictor and the MMN as the outcome variable. Lastly, an exploratory analysis was conducted to examine the associations between the subcortical-cortical relationship to autistic traits and sensory features using the AQ (Baron-Cohen et al., 2001) and the SP (Dunn, 1999), respectively.

To characterize the subcortical-cortical relationship, a ratio of *z*-scores ($z = x - \mu \square \sigma \square$) was computed, such that the *z*-score for the interpeak V-O latency was divided by the *z*-score for the MMN latency. Creating a ratio of *z*-scores put both variables in common terms, which allowed for an interpretation of how well aligned the subcortical and cortical auditory latencies were per participant (i.e., scores closer to 1 are better aligned).

Results

Descriptive Statistics

Descriptive analyses depicting the means and standard deviations for the latencies of the speech-ABR and MMN data by group are listed in Table 2. The latencies were largely comparable, but the autistic group demonstrated larger variance in their MMN latency compared to the TD group. The speech-ABR between groups appeared similar, starting around 7ms and ending around 50ms. The grand average MMN for the autistic group (n = 9) peaked at an amplitude of -1.82μv, which occurred at a latency of 204ms, while the peak amplitude for the TD group (n = 11) peaked at -2.06μv at 216ms, both of which fall within the previously

established time window of the MMN (Näätänen et al., 2007). Grand averages by group for the speech-ABR and MMN can be found in Figures 1 and 2.

Aim 1: Do autistic participants have longer V-O speech-ABR and MMN latencies?

Two independent samples t-tests were conducted to determine whether there were significant differences between the autistic and TD groups on both the speech-ABR and MMN latency. First, the assumptions of independence, equal variance, and normality were assessed. Each participant was only represented once in their respective group. Levene's test was conducted to examine the assumption of equal variance, with results suggesting that the variance between groups did not differ. Lastly, visual inspection of the histogram suggested that the assumption of normality was not violated. Given that all necessary assumptions were met, the analyses were run and the results found non-significant differences between groups on both the interpeak V-O latency ($t(1, 20) = 0.151$, $p = 0.955$) and the MMN latency ($t(1,16) = -0.287$, $p = 0.778$).

Aim 2: Does interpeak V-O latency of the speech-ABR predict latency of the MMN?

Before conducting the linear regression, the assumptions of linearity, zero mean, homoscedasticity, and normality were checked. The assumption of independence was examined by creating a graph with the interpeak V-O latency on the *x*-axis and the MMN latency on the *y*-axis. The data were not clearly linear, however no other better pattern emerged. To assess the zero mean assumption, residuals were calculated by subtracting the predicted value from the observed value derived from the regression equation (residuals = $y - \hat{y}$) and averaged together. The mean of all residuals was near zero at 2.22912e-17. The assumption of homoscedasticity was examined by plotting the residuals on the *y*-axis and the predictor variable (interpeak V-O

latency) on the *x*-axis. Visual inspection showed that the data had constant variance around 0 and were independent of each other, though two potential outliers were noted. The assumption of normality was assessed by creating a histogram and Q-Q plot, both of which suggested that the data were generally normally distributed with the presence of at least two outliers. These data points were confirmed as outliers after applying the *a priori* criteria of residuals greater than two standard deviations away from the predicted regression equation. As such, these two points were removed and the assumptions were rechecked, leaving a final sample of 18 participants (10 TD and 8 ASD). Neither the results of the initial regression before outlier correction ($F(1, 18) = 0.0$, $p = .9771$), nor the final regression model ($F(1, 16) = 0.7376$, $p = .4031$) were statistically significant, suggesting that the speech-ABR latency did not predict MMN latency across participants.

Given the limited sample size, I was underpowered to model the relationship between subcortical and cortical auditory processing by group. However, as a first step towards this later goal, I created a plot to examine patterns of data by group with the interpeak V-O latency on the *x*-axis and the MMN latency on the *y*-axis. Visual inspection suggests there may be group differences in the relationship between the interpeak V-O latency and MMN latency (see Figure 5). The graph suggests that the autistic participants followed a negative trend (dashed red), suggesting that a longer interpeak V-O latency is associated with an earlier MMN onset. Conversely, while there was less variance in the MMN latency for the TD group, they followed a slightly positive trend (solid black), suggesting that a shorter interpeak V-O latency led to a faster MMN onset. This potential group difference in the subcortical-cortical relationship may be investigated and replicated with further research and larger sample sizes.

Exploratory Analyses

One participant did not complete the SP for the exploratory analyses (TD = 10, ASD = 11), but all other questionnaire data was completed in full. The majority of participants had a parent-report AQ (n =19). A series of Pearson Correlations were conducted to examine the subcortical-cortical relationship (i.e., the ratio of z-scores) to autistic traits and sensory behaviours. Results of the correlations were not statistically significant for the ratio of z-scores and the Attention to Detail ($r(1,18)$ = -0.30 p = .1955) or Communication ($r(1,18)$ = 0.23, p = .3235) subscales of the AQ, nor the sensitivity ($r(1,17)$ = -0.08, p = .7409) and overresponsivity composite of SP ($r(1,17)$ = -0.08, p = .7481).

Discussion

The present study utilized an interdisciplinary and multimethod approach to characterize the latency of the auditory system in a sample of autistic and typically developing children. The speech-ABR and the MMN were used to examine auditory processing of speech sounds in the subcortical and cortical auditory systems, respectively. Both groups evinced the expected speech-ABR and MMN latencies, which did not differ between groups. While the interpeak V-O latency of the speech-ABR was not found to significantly predict the latency of the MMN, there appeared to be a pattern of preliminary group differences in the latency relationships between measures.

In line with previous research, wave V of the speech-ABR occurred at approximately 7ms and wave O was at 50ms in both the autistic and TD groups (Chen et al., 2019, 2021; Jones et al., 2020; Ramezani et al., 2019; Russo et al., 2004, 2009). Visual inspection of the speech-ABR suggests very minimal differences in the latency of each wave, however, groups do seem to

differ on amplitude, such that the autistic group demonstrated smaller waves V, A, D, E, F, and O, though this was not statistically assessed. In line with previous research, the MMN demonstrated a two-humped pattern (Bishop, 2007), peaking between 150-250ms in both groups (Näätänen et al., 2007). Similarly to previous studies, the autistic participants appeared to have a smaller MMN amplitude compared to their TD peers (Chen et al., 2020), though this was not statistically examined. Taken together, these results suggest that the speech-ABR and the MMN were validly elicited from both groups of children.

Notably, the MMN latencies of the autistic children were more variable than the TD group. This notion of increased variability or neural instability in autism fits both theoretically and empirically. Autism is a highly heterogeneous disorder, and while auditory atypicalities are very common (Gomes et al., 2008), they vary in the direction of effects (i.e., hyperresponsivity vs hyporesponsivity). Cortical variability in autistic but not TD children may also be an important group differential, as previous research has demonstrated increased variability for the P1 (Milne, 2011), N170 and N200 (Magnuson et al., 2020), and other cortical oscillation patterns (David et al., 2016). Thus, the consistent inconsistency found in autistic individuals may help to explain the somewhat discordant literature and aid in diagnosis, as informed by neuroscience.

The present study failed to find significant differences between groups on both the interpeak V-O latency of the speech-ABR and the MMN latency. This represents a departure from the majority of research (Chen et al., 2019, 2021; Ramezani et al., 2019; Russo et al., 2009), however, may not be mutually exclusive with previous findings (Kujala et al., 2010; Lepistö et al., 2005, 2007). That is, no studies in autism to date have quantified the speech-ABR using the interpeak V-O latency and the MMN via 30% fractional area latency. Research on the

speech-ABR mostly reports the latency of each individual wave (i.e., V, A, C, D, E, F, O) or the interpeak A-O latency (Anderson et al., 2015; Madrid et al., 2021), but not the interpeak V-O latency. As previous research suggests that autistic individuals demonstrate delayed latencies of individual waves (Chen et al., 2019, 2021; Jones et al., 2020; Ramezani et al., 2019; Russo et al., 2009), the failure of the present study to find differences in the interpeak latency indicates that while onset of particular aspects in the processing of speech sounds (e.g., processing the vowel) may be delayed in autism, the overall speed of processing as captured by the interpeak V-O latency is similar to their neurotypical peers. This interpretation is in line with a "different but not deficit" perspective, which posits that while there may be differences in how autistic individuals process information, it is not necessarily worse or impaired (Burack et al., 2016). Future research to extend and replicate these findings may provide a valuable shift in the narrative and demonstrate that autistic individuals are similar to their neurotypical peers in their speed of speech processing at the subcortical level.

Most autism research uses the peak latency to operationalize the latency of the MMN, which extracts the moment of time in which the amplitude of the waveform is the largest (Luck, 2014). This method is beneficial as it collapses both amplitude and latency into one variable. However, it rests on the fundamental assumption that peak amplitude reflects the greatest magnitude of neural processing in the brain, when in reality there is nothing informative or meaningful about the point at which the voltage reaches a local maximum (Luck, 2014). Additionally, given that the absolute peak of the MMN is difficult to identify, particularly for more complex stimuli such as speech (Bishop, 2007), peak latency can be significantly different depending on *which* peak is identified as the largest in the specified time window. Therefore, this

failure to find group differences in the latencies of the speech-ABR and the MMN may not be in opposition with existing research and emphasizes the importance of carefully selecting how we quantify neurophysiological responses given such methodological implications so that we can best represent the specific research questions.

Lastly, the majority of past research on the speech-ABR and the MMN has focused on matching participants on chronological age (Chen et al., 2019, 2021; Lepistö et al., 2005; Ramezani et al., 2019; Russo et al., 2009) but have failed to account for developmental level. This consideration may be important as some research has demonstrated that the latency of the MMN decreases with age in TD children (Shafer et al., 2000). Similarly, research suggests that the wave V latency of the speech-ABR decreased over time for autistic but not TD children (Chen et al., 2019). The takeaway is clear: in research with atypically developing populations, whom by definition do not follow the typical developmental trajectory as their peers, the group that is selected for comparison has implications in the interpretation of the findings. Therefore, in studies which involve perceptual (i.e., attention) and cognitive (i.e., speech-processing) abilities such as this, matching autistic and TD groups only on the basis of chronological age may not be sufficient to capture the nuances in developmental level for these individuals. Conversely, accounting for developmental level (and specifically using cognitive assessments that do not focus the weaknesses of autistic individuals, such as verbal IQ measures; Joseph et al., 2002) allows us to control for these differences in IQ. In so doing, we can be more confident that any group differences that remain are the result of true fundamental differences in neural processing and not simply a by-product of cognitive abilities.

Despite similarities across systems and adjacent neuroanatomical structures, the present study did not find a significant relationship between the interpeak V-O latency of the speech-ABR and the latency of the MMN. This may be explained, in part, by the temporal sequence of auditory processing in the brain. As previously indicated, the interpeak V-O latency of the speech-ABR was about 41ms and the MMN latency was about 170ms. Though a seemingly short temporal gap, this leaves around 130ms of auditory processing unaccounted for in our model. The P1 is an earlier ERP component that may fill this gap, as it peaks around 100ms (Luck, 2014). Though the MMN was originally selected for analysis because of its ubiquity in the literature for both TD and autistic groups, future research may seek to examine whether the speech-ABR predicts the P1 or other earlier ERP components.

Despite the non-significant relationship between the speech-ABR and the MMN, an interesting pattern of group differences emerged. That is, while the TD group evinced a slightly positive relationship, the autistic group appeared to follow a negative trend, such that those with a shorter interpeak V-O latency had a longer MMN latency (Figure 5). This would suggest that faster processing duration at the level of the brainstem corresponds to slower auditory discrimination in the cortex. This trend in the subcortical-cortical relationship may be particularly notable given the lack of group differences on both interpeak V-O and MMN latency. This interesting but preliminary pattern is limited by the small sample size and should be assessed in future research.

Limitations

There were several limitations to the present study. Most notably, there was a very small sample size of only 22 participants across groups, which was reduced to 20 after MMN latency

extraction. Though such sample sizes are not uncommon for neurophysiology and autism research, I was underpowered to test other hypotheses of interest, including models that seek to replicate Chen et al. (2021) to examine whether subcortical measures (i.e., the speech-ABR) mediate the relationship between cortical (i.e., the MMN) and behavioural measures (i.e., autistic traits and sensory features). Further, participant characteristics may limit the generalizability of the present study. Though groups were matched on both chronological age and PRI, the VCI of the autistic group was significantly lower than the TD children. There was a large age range (9-16 years old) and the FSIQ across participants was also quite high (*mean* = 109.4). Additionally, all participants identified as White and non-Hispanic/Latinx. Thus, it is unknown whether these findings can generalize to individuals from historically underrepresented backgrounds and represent the full spectrum of cognitive abilities in autistic and TD children. Lastly, though we attempted to retain as much similarity as possible between the subcortical and cortical neurophysiology measures, the stimuli that elicited the speech-ABR and the MMN were inherently different in duration due to the methodological requirements. Further, the speech-ABR and the MMN tap into different aspects of the auditory system and may impact auditory processing in important but unrelated ways. Future research may address the aforementioned limitations and extend this line of work to 1) examine subcortical-cortical relationships by group, 2) assess other measures of subcortical and cortical auditory processing (e.g., amplitude), and 3) explore potential causal relationships between auditory neurophysiology and behaviours related to autism.

Conclusions

The present study used neurophysiology to understand the relationship between the subcortical and cortical auditory system in a sample of autistic and TD children. The present study identified a clear speech-ABR and MMN but did not find differences between groups in either measure, highlighting the importance of methodological considerations and accounting for developmental level. Results also suggest that the speech-ABR did not significantly predict the latency of the MMN across participants, though preliminary inspection of the data suggests that this relationship may differ between groups. Future research applying the methodology and developmental framework demonstrated here may be valuable in confirming this difference in the subcortical-cortical speech processing of autistic and TD children. Implications of this research may inform our understanding on the neural mechanisms which contribute to auditory sensory behaviours and underlie social communication, which may be leveraged to inform diagnosis and clinical conceptualization of ASD.

Table 1. Demographic information by group

	Autistic	TD	*p* Value
Age	12.8 (2.3)	12.4 (2.3)	0.78
FSIQ	103.4 (16.3)	115.3 (11.6)	0.08
PRI	112.1 (21.7)	109.5 (11.6)	0.102
VCI	96.5 (13.2)	116.8 (12.2)	0.003*

* Indicates significant group differences.

Table 2. Descriptive statistics by group

	Autistic *(SD)*	TD *(SD)*
Speech-ABR Interpeak V-O Latency	41.4 *(0.3)*	41.4 *(0.3)*
MMN Latency	169.3 *(34)*	170.5 *(24.7)*
AQ: Attention to Detail	6.4 *(3.3)*	3.5 *(2)*
AQ: Communication	7.1 *(1.4)*	3 *(2.6)*
SP: Sensitivity	51 *(13.2)*	34.7 *(9.5)*
Sensory Overresponsivity	24.1 *(8.6)*	11.2 *(9.5)*

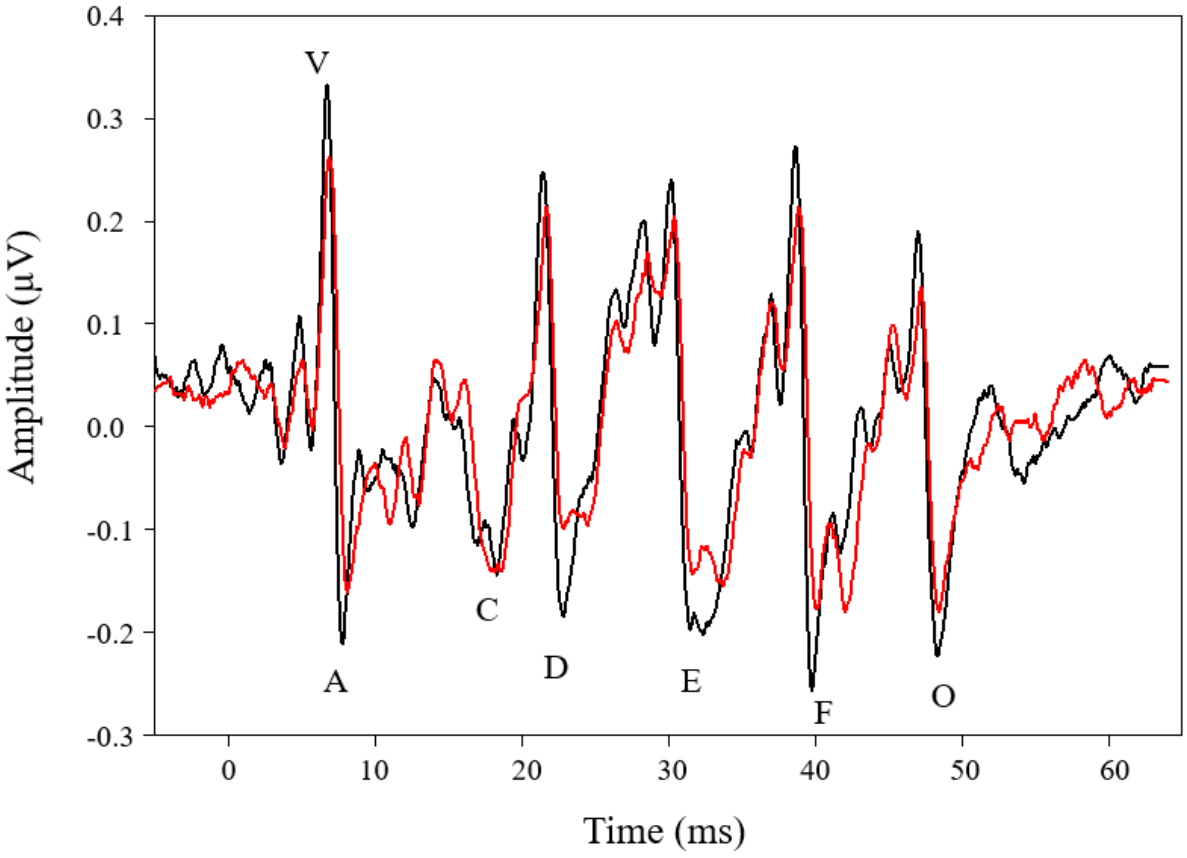

Figure 1. Speech-ABR by group with autistic (red) and TD (black) participants (*n* = 22).

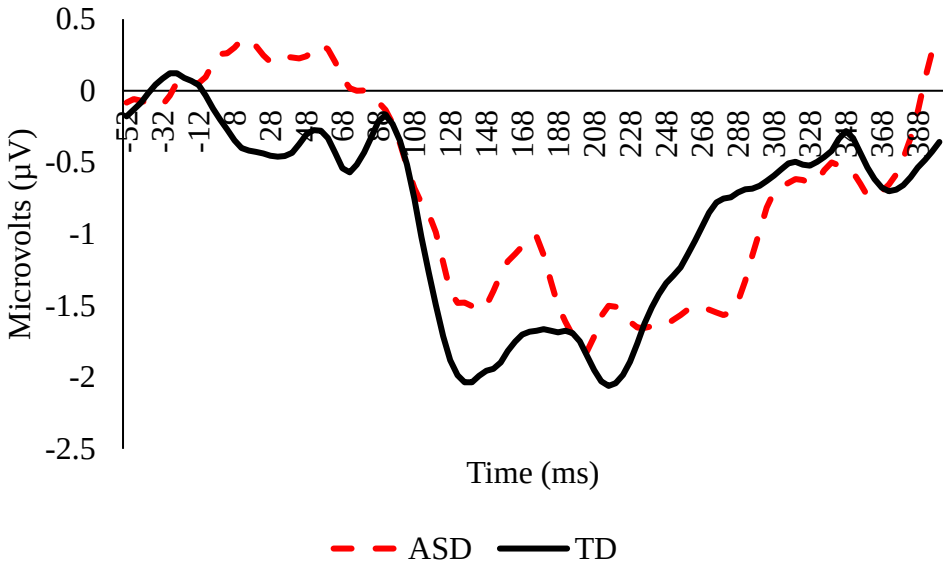

Figure 2. Grand average MMN difference waves by group with autistic (dashed red) and TD (solid black) participants (*n* = 20).

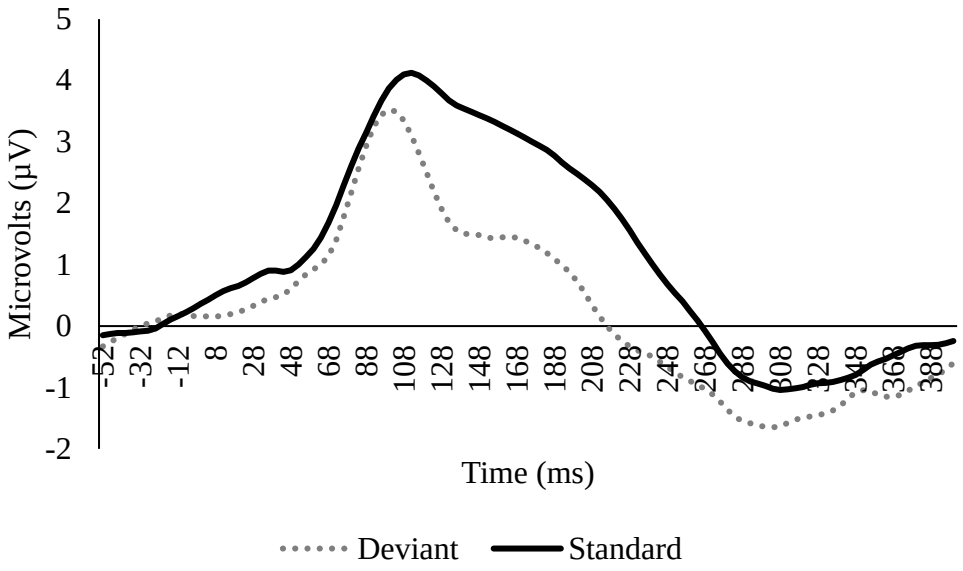

Figure 3. Grand averages for the standard (solid black) and deviant (dotted grey) ERP waveforms for TD participants (*n* = 11).

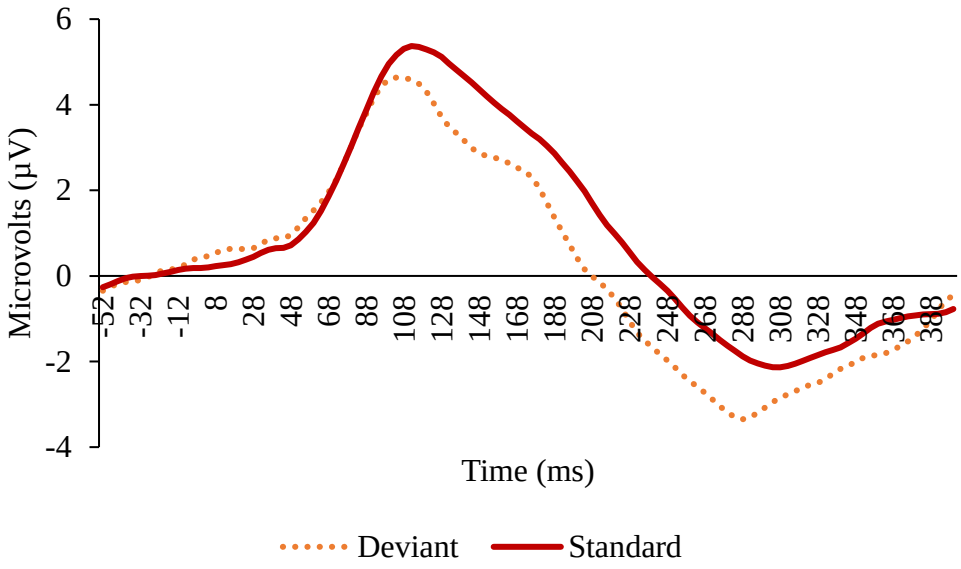

Figure 4. Grand averages for the standard (solid red) and deviant (dotted orange) ERP waveforms for the autistic participants (*n* = 9).

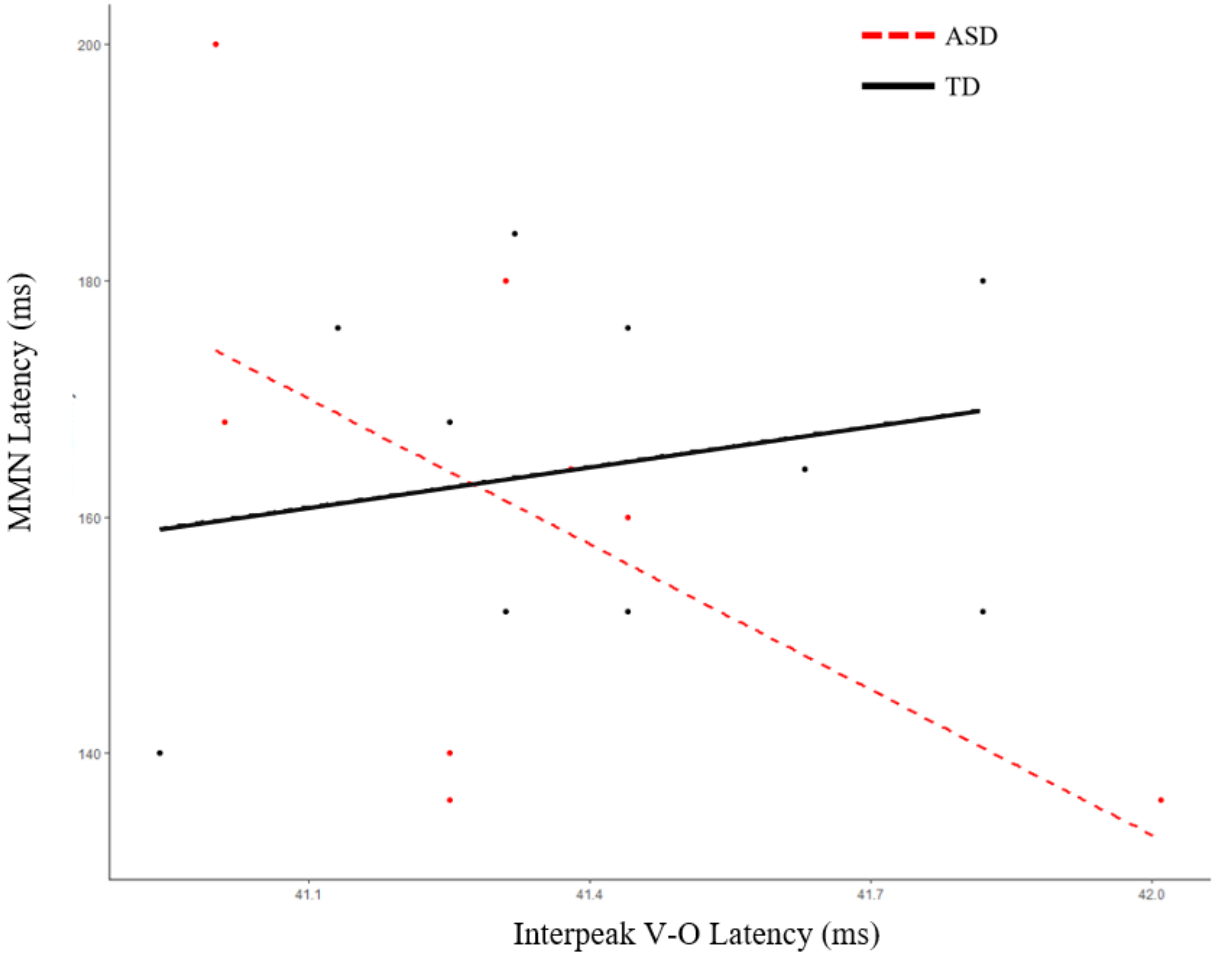

Figure 5. Speech-ABR and MMN data of autistic (dashed red) and TD (solid black) participants and linear regression lines by group (n = 19).

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EDUCATION

Syracuse University – Syracuse, New York 2019-Present
School Psychology Doctoral Program – Neuroscience Concentration
APA accredited, NASP approved
Primary Advisor: Natalie Russo, Ph.D., Licensed Psychologist
Thesis: *Bridging the gap: Connecting the subcortical and cortical auditory systems*
GPA: 4.0

McGill University – Montreal, Quebec 2015-2019
Bachelor of Arts and Science First Class Honours in Cognitive Science with a Minor in Psychology
Thesis: *Exploring the associations between the reward positivity, stress and depression*
GPA: 3.67

AWARDS

Interdisciplinary Graduate Neuroscience Concentration Travel Award – 500$
Doctoral Foreign Study Award (DFSA) – Canadian Institutes of Health Research (submitted)
Arts Research Internship Awards (ARIA) – Undergraduate Research Internship Award – 4,000$

PROFESSIONAL EXPERIENCES

Upstate Medical Hospital, Rehabilitation Psychology 2021-2022
Graduate Student Assessment Technician at the Institute for Human Performance (IHP)
Supervisors: Brian Rieger, Ph.D., Licensed Psychologist, Stephanie Barry, LMSW

- Conduct neuropsychological assessments for children in the pediatric oncology unit
- Collaborate with an interdisciplinary care team including oncologists, teachers, and psychiatrists
- Receive supervision from licensed psychologists and other mental health professionals

Syracuse University, Department of Psychology 2020-2021
Student Clinician at the Psychological Services Center (PSC)
Supervisors: Afton Kapuscinski, Ph.D., Licensed Psychologist

- Deliver weekly psychotherapy to children and adults with mental disorders
- Conduct intake evaluations
- Receive supervision from licensed psychologists and peer mentors

Syracuse University, Department of Psychology 2019-2020
Teaching Assistant for Foundations of Human Behavior (PSY205)
Supervisors: Shannon Houck, Ph.D., Meredith J Martin, Ph.D.

- Create weekly lesson plans and facilitation recitations
- Evaluate academic progress of students

School of Music Montreal 2016-2018
Site Coordinator

- Manage needs and schedules for students and teachers
- Foster safe and inclusive learning environment

Seneca Summer Camps 2013-2017

Senior Staff
- Oversee operations of staff and campers
- Direct program logistics and resolve conflicts

RESEARCH EXPERIENCE

Center for Autism Research and Electrophysiology (CARE) 2019-Present
Graduate Researcher
PI: Natalie Russo, Ph.D., Licensed Psychologist
- Run participants in ERP studies examining perceptual and cognitive processes in children with autism spectrum disorders
- Observe and administer ADOS-2, intelligence (WASI-II) and language measures (PPVT-IV)
- Collect and analyze behavioral and electrophysiological (EEG and ERP) data using EGI and MATLAB

Behavioral Autism NeuroDevelopment Lab (BAND) 2017-2019
Research Assistant
PI: Eve-Marie Quintin, Ph.D.
- Run participants in behavioral studies examining language processing and cognitive abilities in children with autism spectrum disorders
- Administer intelligence (WISC-V), cognitive and verbal fluency tasks (D-KEFS)
- Input data using Q-Global

Translational Research in Affect and Cognition Lab (TRAC) 2017-2019
Honours Thesis student
PI: Anna Weinberg, Ph.D.
- Run participants in ERP studies examining the response to reward, emotional stimuli and processing of errors in relation to depression in emerging adults
- Collect and analyze behavioral and electrophysiological (EEG and ERP) data using BrainVision Analyzer 2
- Collaborate in writing scientific papers and poster presentations

PUBLICATIONS

Kaplan, E., McKernan, E., Kopec, J., **Matsuba, E**., & Russo, N. (2022). The development of attention in Down Syndrome. In J.A. Burack & J. Edgin (Eds.) The Oxford Handbook of Down Syndrome and Development. *Oxford University Press.*

Matsuba, E., Russo, N., McKernan, E. P., Miseros, M., Curl, R., & Burack, J.A. (accepted). Visual filtering over time and space for persons with Down Syndrome. *Journal of Intellectual Disabilities Research.*

Matsuba, E., Cary, E., Madrid, A., Pacheco, D., Prieve, B., & Russo, N. (submitted). Subcortical and Cortical Auditory Processing of Speech Sounds in Autistic and Typically

Developing Children. Special Issue Sensory Features in Autism and Related Conditions Developmental Approaches, Mechanisms, and Targeted Interventions. *Journal of Autism and Developmental Disorders.*

Matsuba, E., Cary, E. L., Goldstein, A., & Russo, N. (in prep). Perceptions of Autism Strengths Scale.

Kaplan, E., **Matsuba, E.,** Kates, Wyble, B., & Russo, N. (in prep). ERP correlates of the attentional blink in autism.

Russo, N., Bertone, A., **Matsuba, E.,** & Mottron, L. (in prep). Visual, auditory, and tactile detection in autism: A psychophysical approach.

Cary, E., Rodrigues, A., Masters, E., **Matsuba, E.,** & Russo, N. (in prep). Trauma Mediates the relation between Autistic Traits and Sensory Sensitivity and Avoiding in Adults.

Cary, E., **Matsuba, E.,** Rao, A., & Russo, N. (in prep). Gender Differences in Restrictive Repetitive Behaviours in Autism Spectrum Disorder.

POSTER PRESENTATIONS

Matsuba, E. S. M., Prieve, B. A., Cary, E. L., Pacheco, D., Madrid, A., McKernan, E., Kaplan-Kahn, E., & Russo, N. (2022). *Speech from the brainstem to the cortex to behaviour: Characterizing subcortical and cortical auditory processing and their relation to autistic traits and sensory features.* Poster presented at the Neuroscience Research Day, Syracuse University.

Matsuba, E. S. M., Prieve, B. A., Cary, E. L., Pacheco, D., Madrid, A., McKernan, E., Kaplan-Kahn, E., & Russo, N. (2022). *Speech from the brainstem to the cortex to behaviour: Characterizing subcortical and cortical auditory processing and their relation to autistic traits and sensory features.* Poster accepted for the International Society for Autism Research, Austin, Texas.

Cary, E. L., Rodrigues, A., Masters, E., **Matsuba, E. S. M.,** MacKenzie, C., Osborne, J., & Russo, N. (2022). *Trauma mediates the relationship between autistic traits and sensory sensitivity and avoiding in adults.* Poster accepted for the International Society for Autism Research, Austin, Texas.

Cary, E. L., Rao, A., **Matsuba, E. S. M.,** Masters, E., MacKenzie, C., Osborne, J., & Russo, N. (2022). *Barriers to an autistic identity: How RRBs may contribute to the underdiagnosis of females.* Poster accepted for the International Society for Autism Research, Austin, Texas.

Cary, E. L., Kaplan-Kahn, E., Masters, E., **Matsuba, E**., MacKenzie, C., Rodrigues, A., Prieve, B., Pacheco, D., Madrid, A., & Russo, N. (2021). *Relating ASD Traits and Sensory*

Overresponsivity to Early Electrophysiological Indices of Auditory Processing in Children with and without ASD. International Society for Autism Research, Boston, Massachusetts.

Masters, E.C., McKernan, E.P., Kopec, J., Kaplan-Kahn, E.A., Cary, E.L., **Matsuba, E**., Rodrigues, A., MacKenzie, C., & Russo, N. (2021). *The Impact of ADHD Symptoms and Age on Sensory Features in Autism.* International Society for Autism Research 2021 Annual Meeting.

Cary, E. L. Kaplan, E. A. Masters, E., **Matsuba, E.,** Prieve, B., Pacheco, D. Rodrigues, A. & Russo, N. (2020). *Early Neural Difference in Auditory Processing of Speech in Children with ASD: Is It Habituation or Discrimination*? International Society for Autism Research 2020 Annual Meeting, Seattle, Washington – Cancelled due to COVID-19 Pandemic.

Kaplan, E. A., Cary, E., Masters, E., **Matsuba, E.,** Rodrigues, A. & Russo, N. (2020). *Pathways of Perceptual Primacy: ERP Evidence for Relationships between Autism Traits and Enhanced Perceptual Functioning*. International Society for Autism Research 2020 Annual Meeting, Seattle, Washington – Cancelled due to COVID-19 Pandemic.

Matsuba, E., Banica, I., Weinberg, A. (2019, April). *Exploring the associations between the reward positivity, stress and depression.* Poster presented at the Annual Cognitive Science Research Day, McGill University, QC.

Matsuba, E., Thierry, S., Rimmer, C., Dahary, H. & Quintin, E. M. (2019, January). *How music moves us: An analysis of the effects of a musical intervention on repetitive motor behaviours of children with autism spectrum disorder.* Poster presented at the 9th Annual Faculty of Arts Undergraduate Research Event for the Arts Research Internship Award (ARIA), McGill University, QC.

Thierry, S., **Matsuba, E.,** Dahary, H., Rimmer, C. & Quintin, E. M. (2019, January). *The effect of music education on positive social skills of children with autism spectrum disorder*. Poster presented at the 9th Annual Faculty of Arts Undergraduate Research Event for the Arts Research Internship Award (ARIA), McGill University, QC.

INIVITED TALKS

Matsuba, E., (2022). Theories of Autism. Guest Lecture for Undergraduate PSY447: Autism, Syracuse University.

Matsuba, E., (2021). Neurophysiological Mechanisms of Speech and Non-Speech Sound Perception Among Preterm Infants. Presentation for the Psychology Research Initiative in Diversity Enhancement Program, Syracuse University.

Matsuba, E., (2021). Career Paths in Psychology: Graduate School. Presentation for Bayview Glen School. Toronto, ON.

TRAINING

Autism Diagnostic Observation Schedule – Second Edition (ADOS-2)	2022
Brief Observation of Symptoms of Autism (BOSA)	2020
Doctoral Student and Trainee Certificate of Clinical Excellence in Clinical Suicidology	2020
Trauma-Focused Cognitive Behavioral Therapy CE	2019

PROFESSIONAL SERVICE

Department Service

Psychology Action Committee Co-President	2021-2022
Committee for Diversity and Inclusion	2019-2022
Psychology Action Committee Events Member	2020-2021
Social Skills Group Facilitator	2019-2020

Program Service

School Psychology Justice, Equity, Diversity and Inclusion Committee	2019-2022
Graduate Student Liaison	2020-2022

MEMBERSHIPS

International Society for Autism Research (INSAR)	2021-2022
American Psychological Association Division 40 (School Psychology)	2021-2022
American Psychological Association Division 40 (Clinical Neuropsychology)	2021-2022