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Multisensory Integration in ADHD: A Behavioral and EEG Investigation in Youth and Adults

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Abstract

In daily life, we are constantly bombarded with sensory information from multiple sources. Our ability to combine these cues into a single perceptual experience is known as multisensory integration. This process can be disrupted in neurodevelopmental conditions, such as autism spectrum disorder and dyslexia, affecting cognitive functions and language. Multisensory integration may be affected in attention-deficit/hyperactivity disorder (ADHD), though findings are conflicting. To explore these discrepancies, we conducted a meta-analysis to appraise the current state of the literature, elucidate observed inconsistent findings, and identify gaps in ADHD research. Then, we conducted studies to investigate multisensory integration in youth and adults with and without ADHD using behavioural tests and electroencephalography (EEG).

In the first study, youth (ages 6-17) with ADHD (*n*=53) and without ADHD (*n*=60) completed tasks such as the Sound-Induced Flash Illusion (SIFI), McGurk task, and a speech-in-noise task. No group differences were found in the SIFI, but ADHD youth showed reduced susceptibility to the McGurk illusion compared to neurotypical (NT) youth. The speech-in-noise task revealed no differences in multisensory gain, though hyperactive-impulsive traits were negatively related to phoneme accuracy.

In the second study, youth (ages 8-17) with ADHD (*n*=30) and without ADHD (*n*=23) performed a speeded-response time task while EEG recorded their responses to auditory, visual, or combined stimuli. No differences in multisensory gain were found, but ADHD youth showed delayed integration in occipital regions.

In the third study, adults (ages 18-59) with ADHD (*n*=32) and without ADHD (*n*=32) completed perception-matched and stimulus-matched detection tasks. ADHD adults showed higher response-time gain in the perception-matched task but no differences in the stimulus-matched task. EEG revealed differences in multisensory integration in frontal and occipital regions, more pronounced in the perception-matched task, possibly due to task difficulty or controlled unisensory perception.

Overall, our findings suggest that ADHD affects multisensory integration, influenced by task demands and age. This is important because multisensory integration supports the development of higher-order cognitive functions and language, and challenges with multisensory integration may impact these processes. Future research in ADHD should investigate multisensory integration across development, the relationship between attention and integration, and multisensory integration and cognitive functioning.

Keywords

Attention-deficit/hyperactivity disorder, neurodevelopmental disorder, sensory perception, audiovisual, multisensory integration, EEG

Summary for Lay Audience

In everyday life, we are presented with a vast amount of sensory information from different sources like sights and sounds. Our ability to combine cues from multiple senses into a single perceptual experience is called multisensory integration. Multisensory integration can be affected in different neurodevelopmental conditions, such as autism spectrum disorder and dyslexia. When multisensory integration is affected, it can have downstream effects on higher-order cognitive functions and language functioning. Increasing evidence shows that multisensory integration might be affected in people with attention-deficit/hyperactivity disorder (ADHD), but results have been conflicting. This led us to first analyze the current research to understand the conflicting results and identify gaps in literature. Then, we conducted studies to investigate multisensory integration in youth and adults with and without ADHD using behavioural tests and electroencephalography (EEG).

Our most consistent finding was a reduced neural response to multisensory integration in ADHD, especially in adults compared to youth and while using a task controlling for unisensory differences in sensory perception. This meant that their brains responded less to combining sensory information from different sources. In line with previous studies on adults with ADHD, our behavioral results showed a larger multisensory gain for response times when using basic stimuli (e.g., patches of lines and beeps) but reduced integration when dealing with more complex stimuli, such as speech. Adults with ADHD showed differences in multisensory integration for the response time measure compared to adults without ADHD, whereas youth with ADHD did not differ from youth without ADHD. This suggests people with ADHD might respond faster when combining basic sensory inputs, but their brains have a harder time integrating more complex information.

Overall, our findings suggest that people with ADHD show differences in how they integrate sensory information. This is important because multisensory integration is a building block for the development of higher-order cognitive functions and language and challenges with multisensory integration may impact the development of these processes. Future research should investigate how these differences develop over time in people with

ADHD, how attention affects multisensory integration, and the impact of altered multisensory integration on cognitive functions in ADHD.

Co-Authorship Statement

For all chapters, Carolynn Hare is the primary author, and Dr. Ryan A Stevenson was co-author.

Chapter 2 was co-authored by Elim Chan.

Chapter 3 data collection was assisted by Bernice Leung, Glenda Zhai, and YuHe (Rainey) Li.

Chapter 4 was co-authored by Michelle Luszawski who led collection in autistic youth (not included in this dissertation). Data collection was assisted by Rainey Li, Julia Shannon, Bernice Leung, Megan Ho. Data cleaning was assisted by Rainey Li.

Chapter 5 was co-authored by Michelle Luszawski who led collection in autistic adults (not included in this dissertation). Data collection was assisted by Carol Atta, Glenda Zhai, Rainey Li, Julia Shannon, Kathleen McCombe.

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Chapter 1

Introduction

In our day-to-day environments, we are presented with a vast amount of sensory information originating from various modalities. For example, imagine you are at a coffee shop with your friend and trying to listen to a story they are telling you while blocking out the sounds of people ordering, the smells of the coffee, and the movement of people around the coffee shop. Watching your friends' facial articulations while they are speaking help you to make out what they are saying since they are hard to hear in this busy coffee shop. Our ability to use these cues from multiple senses in parallel and combine them into a single perceptual experience is an essential process referred to as multisensory integration. As important as it is to integrate information that should be combined, it is also important to accurately dissociate sensory information coming from different sources and events, then segregate these into discrete percepts.

Multisensory integration is achieved through low-level influences, such as the physical characteristics of the incoming sensory signals, and higher-level learned associations. Key physical characteristics include the spatial and temporal coincidence of paired inputs and the intensity or effectiveness of the signals. Temporal coincidence is a strong cue to bind, and sensory streams that are temporally synchronous are more likely to be integrated (Dixon & Spitz, 1980; Miller & D'Esposito, 2005; Powers et al., 2009; Stevenson et al., 2016; Wallace & Stevenson, 2014). Similarly, spatial congruency also plays a key role in multisensory integration as sensory inputs that are presented close together in space are more likely to be integrated than signals that are spatially disparate (Delong & Noppeney, 2021; Meredith & Stein, 1996; Stevenson, Fister, et al., 2012; Teder-Sälejärvi et al., 2005; Wallace et al., 1992). Also, the less effective the unisensory components of a multisensory pairing are, the greater the multisensory benefit, a principle known as *inverse effectiveness* (Meredith & Stein, 1986). These spatial, temporal, and inverse effectiveness factors interact with one another at both the behavioral (Fister et al., 2016; Nidiffer et al., 2016) and neural levels (Cappe et al., 2012; Royal et al., 2009). The processing of these fundamental aspects of multisensory integration are learnt early in development.

In both animal and human models, it is well-documented that sensory systems appear prenatally. Further, rudimentary multisensory processes appear early in post-natal life and improve over development (Ernst, 2008; Gori et al., 2008; Murray et al., 2016; Stevenson et al., 2018). These sensory systems develop far in advance of higher-order cognitive and communicative processes and provide a strong foundation for these skills (Bremner et al., 2012). With communication skills, past research has shown that in neurotypical (NT) children attend to and integrate the visual cues that correspond with auditory speech very early in postnatal life (Lewkowicz & Hansen-Tift, 2012; Patterson & Werker, 2003). NT infants and toddlers tend to look at the mouth during pivotal periods in early language learning, such as when they are acquiring their native language and when they are experiencing an acceleration in word learning (de Boisferon et al., 2018; Lewkowicz & Hansen-Tift, 2012). Looking at the mouth while someone is speaking enhances early speech perception, prelinguistic vocal development, and overall language learning (e.g., Bahrick et al. 2018, Teinonen et al. 2008, Tenenbaum et al. 2015). In some cases, such as in children with neurodevelopmental conditions (NDCs), sensory processing and integration can be affected which has downstream effects when they are learning these higher-order cognitive and communicative processes.

Altered sensory and multisensory processing have been found in different NDCs, such as autism spectrum disorder (ASD; Collignon et al., 2013; Foxe et al., 2015; Ostrolenk et al., 2019; Segers et al., 2020; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014; Stevenson, Baum, et al., 2017; Woynaroski et al., 2013; See Feldman et al., 2018 for review) and dyslexia (Harrar et al., 2014; Hayes et al., 2003; Pulliam et al., 2023; Ramirez & Mann, 2005; van Laarhoven et al., 2018). For example, the temporal binding window (TBW), which is how close together two stimuli need to occur to be perceived together, has been shown to be larger in ASD, which may result in the incorrect binding of sensory information (Stevenson, Segers, Ferber, et al., 2014). These temporal processing discrepancies have been shown to have cascading impacts, whereby temporal processing impacts multisensory processing of social information (e.g., speech and face processing), which, in turn, contributes to deficits in speech perception (Stevenson, Segers, Ferber, et al., 2014; Stevenson, Segers, et al., 2018). One NDC that has been garnering more attention recently in relation to sensory and multisensory processing is attention-deficit/hyperactivity disorder (ADHD).

ADHD is highly prevalent and is characterized by developmentally inappropriate levels of inattention, hyperactivity, and impulsivity (5th ed.; DSM–5; American Psychiatric Association, 2013). Hyper- and hypo-sensitivities to sensory information across different modalities have been found in ADHD (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018). ADHD has also been related to difficulties in avoiding distracting stimuli (Ghanizadeh, 2011). Only within the past ten years has multisensory integration in ADHD been examined, with studies showing contradicting results.

In this introductory chapter, I will (1) discuss the principles of multisensory integration and different methodologies to study multisensory integration (2) discuss how multisensory integration changes across development and how this looks different in NDCs (3) discuss the role of attention in multisensory integration and higher-order cognitive functions (4) present the current study.

1.1 Principles and Behavioural Measures of Multisensory Integration

In the next section, the three key principles of multisensory integration namely inverse effectiveness, temporal congruence, and spatial congruence will be discussed in the context of behavioural paradigms.

Multisensory gain refers to the fact that successful multisensory integration can result in optimized behavioural performance, such as improved detection, improved localization, shorter response times, greater response accuracy, and greater processing efficiency (Bremner et al., 2012). These benefits in perceptual and behavioural processing of multisensory stimuli are relative to what would be predicted based on unisensory processing streams that do not interact (Stevenson, Ghose, Fister, et al., 2014). A larger or enhanced multisensory gain would be interpreted as stronger multisensory integration abilities. One key principle that is involved in multisensory gain is the idea of *inverse effectiveness*. The principle of inverse effectiveness states that as the responsiveness to unisensory stimuli decreases the strength of multisensory integration increases (Meredith & Stein, 1986). This suggests that less effective unisensory combinations produce the largest multisensory enhancements or gain, and strongly effective unisensory combinations produce weak, to no gain. Inverse effectiveness is often observed when unisensory stimuli are weak or presented in a poor signal-to-noise ratio (Stevenson, Bushmakin, et al., 2012; van de Rijt et al., 2019).

Temporal processing plays an important role in multisensory integration, as the relative timing of information across sensory modalities is a strong predictor of whether auditory and visual information came from the same source or multiple sources. Thus, temporal coincidence is a strong cue to bind, and auditory and visual information streams that are temporally synchronous are more likely to be integrated (Dixon & Spitz, 1980; Miller & D'Esposito, 2005; Powers et al., 2009; Stevenson et al., 2016; Wallace & Stevenson, 2014). Sensory inputs need not be exactly synchronous to be integrated however, but generally speaking, the closer in time the two inputs are, the higher the probability that they will be integrated, a probabilistic construct referred to as the *temporal binding window* (TBW; Colonius & Diederich, 2004). The TBW is not static, however, but changes according to a number of factors. For example, individuals adaptively recalibrate their TBW based on the statistical regularities of previous inputs (Fujisaki et al., 2004; Stevenson, Toulmin, et al., 2017; Vroomen et al., 2004), the TBW differs based on the type of stimuli being integrated (Stevenson & Wallace, 2013; van Eijk et al., 2008). More long term, the TBW exhibits changes across the lifespan (Chen et al., 2016; Han et al., 2022; Hillock et al., 2011; Stevenson, Baum, et al., 2018). Since temporal proximity is an important cue for determining whether integration will occur, accurate temporal processing is required for accurate multisensory integration (Dixon & Spitz, 1980; Miller & D'Esposito, 2005; Powers et al., 2009; Stevenson et al., 2016; Wallace & Stevenson, 2014).

Similar to temporally congruent stimulus being more likely to be integrated than inputs that are disparate, spatial congruency also plays a key role in multisensory integration. Sensory inputs that are presented close together in space are more likely to be integrated than signals that are spatially disparate (Delong & Noppeney, 2021; Meredith & Stein, 1996; Stevenson, Fister, et al., 2012; Teder-Sälejärvi et al., 2005; Wallace et al., 1992). In humans, participants have been shown to identify the presentation of simultaneous audiovisual stimuli faster when auditory and visual stimuli are presented close in space (Stevenson, Fister, et al., 2012).

The integration of sensory information across modalities can also be measured through perceptual biases or illusions (Stevenson, Ghose, Fister, et al., 2014) such as the McGurk effect (McGurk & MacDonald, 1976), the Ventriloquist illusion (Howard & Templeton, 1966), the rubber-hand illusion (Botvinick & Cohen, 1998), and the sound-induced flash illusion (SIFI; Shams et al., 2000). Illusions are key to studying multisensory integration because they demonstrate the brain’s effort to properly match cross-modal cues with each other to have a unified perception. They also demonstrate how sensory information in one modality can change what we perceive in another, such as a visual bias in localization tasks (Hairston et al., 2003). These studies can often allow us to investigate temporal and spatial biases. The SIFI can be used to investigate temporal biases. In the SIFI, a participant is presented with a single visual flash paired with multiple auditory beeps and is instructed to count the number of flashes while ignoring the beeps. The multiple beeps induce the perception of multiple flashes even when only a single flash is presented, but to get the illusion the pair stimuli must be presented close in time. The effect of spatial cues is seen with the Ventriloquist Illusion (Howard & Templeton, 1966). In this illusion, participants are presented with a synchronous but spatially discrepant audiovisual stimulus and when they are asked to localize the sound source, the perceived location of the sound source is biased toward the location of the visual stimulus (Bertelson & Radeau, 1981; Bruns, 2019). As these illusions often require accurate temporal or spatial processing to occur, higher illusion susceptibility is interpreted as stronger multisensory integration.

1.2 Neural Measures of Multisensory Integration

The earliest studies examining the neural basis of multisensory investigation described single neurons in cat superior colliculus which responded to multiple stimuli from multiple sensory modalities, including visual, auditory and somatosensory (Meredith et al., 1987; Meredith & Stein, 1983, 1986, 1996; Wickelgren, 1971). The SC served as a strong candidate region as it has a well-characterized spatiotopic organization, it exists across taxa and is well placed to receive a confluence of visual signals directly from retina and auditory signals from inferior colliculus and contains many multisensory neurons. Over time, multisensory neurons have been identified in several brain areas (Meredith & Stein, 1996; Wallace et al., 1992) and across many species (Barth et al., 1995; Bell et al., 2005). Multisensory integration has been studied using several different methodologies from single unit recordings, electroencephalography (EEG), functional Magnetic Resonance Imaging (fMRI), and behavioural paradigms (accuracy, detection and response time) (Stevenson, Ghose, Fister, et al., 2014).

Neural investigations of multisensory integration in humans have primarily employed EEG and fMRI (For review see, Stevenson, Ghose, Fister, et al., 2014). In multisensory research using EEG methods, there are two main criteria used for determining whether multisensory integration occurred: *additivity criterion* and *additive factors criterion*.

The *additivity criterion* is based on how ERP recordings directly measure the electrical fields generated by neuronal activity, and these electrical fields sum linearly. Due to this, if there are two populations of synchronously firing unisensory neurons, the predicted ERP response would be the linear sum of the responses recorded with the presentation of the two respective unisensory stimulus components (Besle et al., 2004, 2009; Giard & Besle, 2010). Multisensory research using ERPs has generally used the additive criterion, and not the maximum criterion (Barth et al., 1995; Berman, 1961; Besle et al., 2004). The reason for this is that the electrical activities that start from the brain region of interest travel equally in all directions and thus impact the electrical recording across the entire scalp topography. Due to this diffuse activity, the ability to account for independent pools of firing unisensory neurons, not involved in integration, cannot be indexed through the application of the maximum criterion. The additivity criterion is as follows:

$$ERP_{AV} \neq ERP_A + ERP_V$$

One limiting factor of the additivity criterion is called common activation (CA) which suggests that neural activity that is not directly related to sensory processing, such as motor activity, is also summed across unisensory conditions but it is only represented once in the multisensory response (Stevenson, Ghose, Fister, et al., 2014). Due to this, the typical multisensory responses as seen using EEG are subadditive and may be limited to use in early responses (< 200ms). Another approach would be to include null trials where the participant has the same task, and then subtract the null trials from each condition.

To control for the common activation a new approach called *additive factors* was developed. The additive factors consist of parametrically modulating some component of the auditory, visual, and AV stimuli and measuring a change in the relative responses to unisensory and multisensory presentations across levels of that modulation. The change in responses across these variations in unisensory stimuli is different from the respective change with multisensory stimuli, then effectiveness is not having a selective influence (i.e. changing the effectiveness of the stimulus in one modality impacts the processing of the second modality), and thus there is evidence for multisensory interaction. The equation is as follows:

$$AV_H - AV_L \neq (A_H - A_L) + (V_H - V_L)$$

Through the calculation of these differences, the CA is also subtracted out. While there may be differences in CA across the added factor, this method will reliably reduce the impact of CA (Stevenson, Bushmakin, et al., 2012). Therefore, use of the additive factors criterion provides a more conservative metric for identifying active integration across sensory modalities. The challenge with this approach is it increases the number of trials needed, decreases the experimental effect sizes, and may limit some experimental designs.

Multisensory integration involves a network of neural regions, some cortical and others subcortical, including the superior colliculus, superior temporal sulcus, intraparietal sulcus, posterior parietal cortex, thalamus, anterior cingulate cortex, insular cortex, and primary motor and sensory cortices (Brandwein et al., 2011; Calvert, 2001; Foxe & Molholm, 2009; Stevenson & Wallace, 2013). These areas collaborate to combine sensory information from different modalities, enabling coherent perception and effective responses to complex stimuli. Although EEG studies may not be able to directly measure the signal from specific brain areas, like fMRI, it can provide a lot of useful neural information allowing us to look at key factors in multisensory integration. For example, ERP studies show that there are overlapping but distinct patterns of multisensory integration for spatially congruent and incongruent audiovisual stimuli (Teder-Sälejärvi et al., 2005).

1.3 Multisensory Integration across Development

Temporal aspects of multisensory integration are present in infancy, with infants as young as four months of age being able to discriminate between synchronous and asynchronous multisensory stimuli albeit at large temporal offsets (Lewkowicz, 1996). Following infancy, there is a developmental narrowing of the TBW in childhood (e.g., Hillock-Dunn & Wallace, 2012, Kéïta et al., 2011). This narrowing coincides with an increased strength in multisensory integration. For the McGurk effect, the more precise the ability to discriminate between synchronous and asynchronous events, the stronger their perception of the McGurk effect (Stevenson, Zemtsov, et al., 2012). Conversely, children appear to be more susceptible to the SIFI illusion compared to adults (Innes-Brown et al., 2011) and susceptibility decreases with age (6 and 12; Nava & Pavani, 2013, or 4 to 11; Adams, 2016). A developmental decrease in SIFI susceptibility is consistent with the prolonged development of multisensory integration (Ernst, 2008; Gori et al., 2008; Murray et al., 2016) and a developmental shift in sensory dominance from audition towards vision as the audition influences vision in the SIFI (Hirst et al., 2018; Nava & Pavani, 2013). Further, children younger than 8 have been shown to use a modality switching strategy (Adams, 2016). In adults, the SIFI illusion arises from modulation of the visual cortex by auditory and multisensory areas (For review, see Hirst et al., 2020). Due to these differences in younger children's sensory systems, SIFI susceptibility in this group may not arise from the same optimal integration processes shown in adults (Hirst et al., 2020; Odegaard & Shams, 2016).

Compared to adults, children have been shown to benefit significantly less from observing visual articulations and show less audiovisual enhancement. The benefit associated with seeing a speaker's face and hearing their voice simultaneously increases across development and this benefit develops preferentially under noisy conditions (Ross et al., 2011).

One key aspect of the development of multisensory integration is a shift from early reliance on low-level (i.e., spatial proximity and temporal coincidence) factors to a much heavier weighting of higher-order experiential factors (Murray et al., 2016). When looking at multisensory temporal acuity, the TBW differs for different stimuli and tasks in infants (Lewkowicz, 1996, 2010), children (Hillock-Dunn et al., 2016), and adults

(Stevenson & Wallace, 2013), suggesting a dependence not only on physical stimulus characteristics but also on learned associations. For example, you can see these experiential factors play a role when adults display a wider TBW for semantically congruent pairings relative to incongruent pairings. The system binds semantically congruent information even when the physical stimulus characteristics are quite asynchronous (Ten Oever et al., 2013).

1.4 Multisensory Integration and Higher-Order Cognition

Multisensory integration is a key process which allows for higher-order cognitive and communicative functions to develop. As mentioned, using visual cues in processing speech is crucial in developing language and communication abilities. Additionally, multisensory processing maturation is linked to various cognitive abilities including tempo and numerical discrimination, associative learning, abstract rule learning, sequence detection, and face and affect discrimination (Bahrick et al., 2018; Bahrick & Lickliter, 2003; Flom & Bahrick, 2007, 2010; Frank et al., 2009; Gogate & Bahrick, 1998; Jordan et al., 2008; Lewkowicz, 2004). Further, it has been linked to more generalized cognitive development which has been supported by studies showing lower intellectual functioning in children with multisensory integration deficits (Barutchu et al., 2011; Rose et al., 1992, 1998). Some studies demonstrated that information transfer across different modalities predict verbal performance in school age children, providing further evidence multisensory skills can impact the acquisition of verbal abilities (Rose et al., 1992, 1998). Time discrimination abilities have been shown to improve in infants when information is presented redundantly from different sensory modalities (Bahrick et al., 2002; Bahrick & Lickliter, 2000). From infancy to adulthood, multisensory stimulation promotes heightened attention, perceptual processing, and memory in infants and adults (Bahrick & Lickliter, 2000).

Since multisensory integration has been related to higher-order cognitive skills, it follows that atypical multisensory processing may have downstream effects on cognition (Wallace et al., 2020). Altered sensory and multisensory processing have been found in different NDCs, such as ASD (Collignon et al., 2013; Foxe et al., 2015; Ostrolenk et al., 2019; Segers et al., 2020; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014; Stevenson, Baum, et al., 2017; Woynaroski et al., 2013; See Feldman et al., 2018 for review) and dyslexia (Harrar et al., 2014; Hayes et al., 2003; Pulliam et al., 2023; Ramirez & Mann, 2005; van Laarhoven et al., 2018). One example of this relationship is in ASD sensory abilities have been shown to have cascading impacts, whereby temporal processing impacts multisensory processing of social information (e.g., speech and face processing), which, in turn, contributes to deficits in speech perception (Stevenson, Segers, et al., 2018; Stevenson, Segers, Ferber, et al., 2014).

1.5 Multisensory Integration in Neurodevelopmental Conditions

1.5.1 Autism Spectrum Disorder (ASD)

Sensory issues have been associated with ASD since the original description of autism (Kanner, 1943). More recently, atypical sensory processing has more recently been added to the diagnostic guidelines for ASD (APA, 2013), and these sensory issues have been found across a wide array of sensory modalities. Specifically, autistic individuals are very sensitive to sensory information and take more information in than NT individuals (Feldman et al., 2020). Autistic individuals have been shown to have reduced multisensory integration and less precise multisensory temporal processing (Foss-Feig et al., 2010; Stevenson et al., 2016), and these differences may be enhanced in childhood and possibly to linguistic or social stimuli (Collignon et al., 2013; Ostrolenk et al., 2019; Stevenson, Baum, et al., 2017; Stevenson, Segers, Ferber, et al., 2014; Woynaroski et al., 2013).

When looking at multisensory illusions, autistic individuals have been shown to perceive the McGurk effect at a reduced rate. On the other hand, group differences have been found less reliably with the Sound-Induced Flash Illusion (Shams et al., 2000) with some studies showing reduced multisensory integration for autistic individuals (Foss-Feig et al., 2010; Kawakami et al., 2020; Stevenson, Siemann, Woynaroski, et al., 2014) and others finding no between-group differences (Keane et al., 2010; van der Smagt et al., 2007). One possible explanation for the discrepancies between these paradigms are that the differences in multisensory integration may be more pronounced when using social or linguistic stimuli, such as in the McGurk, compared to non-social and non-linguistic stimuli in the SIFI. However, a recent meta-analysis suggested that the overall effect sizes for between-group differences observed with social versus non-social stimuli were not significantly different (Feldman et al., 2018), but linguistic stimuli and/or to a lesser extent, other social properties were most highly associated with ASD symptomology.

The temporal binding window has been found to be longer in autistic individuals, suggesting they may bind sensory information that is unrelated (Foss-Feig et al., 2010; Stevenson et al., 2016). Autistic individuals have also shown reduced multisensory gain compared to neurotypical individuals in studies involving speech and non-speech stimuli (Collignon et al., 2013; Ostrolenk et al., 2019; Stevenson, Baum, et al., 2017; Stevenson, Segers, Ferber, et al., 2014; Woynaroski et al., 2013). Differences in multisensory integration have been found using pupillometry (Segers et al., 2020), EEG (Brandwein et al., 2015; Chmielewski et al., 2016; Magnée et al., 2011), and fMRI studies (Doyle-Thomas et al., 2013). There is some evidence that developmentally, multisensory integration differences are larger in studies with children, but these differences are smaller in adolescents and adults, which suggests some normalization by adulthood in ASD (Foxe et al., 2015). These findings are corroborated by a recent meta-analysis (Feldman et al., 2018).

1.5.2 Dyslexia or Reading Impairments

Reading is a multisensory process where cross-modal correspondence between visual orthographic tokens (e.g., letters, graphemes, words) and phonological forms (i.e., sounds) are required. Difficulties in cross-modal matching and audiovisual temporal processing have been found in individuals with dyslexia or individuals with reading impairments. Regarding reading, poor readers have shown reduced recognition of mismatched orthographic and phonological forms of words and pseudowords (Fox, 1994). EEG and fMRI evidence has also shown atypical neural responses to congruent versus incongruent letter-sound combination in individuals with reading impairments (Blau et al., 2009, 2010; Froyen et al., 2011; Mittag et al., 2013).

Deficits in multisensory integration in individuals with dyslexia/reading impairments may be partially explained by difficulty shifting their attention between sensory modalities (Harrar et al., 2014). Specifically, this may come from “sluggish attention shifting”, which impairs rapid processing in all modalities (Hari & Renvall, 2001). Shifting attention from visual to auditory modalities seem to be related to this “sluggish attention shifting” and suggests that dyslexics contribute their cross-modal attentional resources differently compared to neurotypicals (NTs). Dyslexic participants integrated auditory and visual information over a longer time intervals compared to neurotypicals, which suggested an extended TBW (Hairston et al., 2005). Further, individuals with dyslexia have shown reduced visual influence on speech perception, as they have been found to not benefit from visual cues as effectively as NTs (Ramirez & Mann, 2005; van Laarhoven et al., 2018). In a McGurk task, children with dyslexia reported only the visual component of the “McGurk” percept, despite being less accurate at identifying unisensory visual stimuli (Hayes et al., 2003). Less research has been conducted in adults with dyslexia or reading impairments, so the developmental trajectory is less understood (Pulliam et al., 2023), but recent work suggests group differences in multisensory integration persist into adulthood (Francisco et al., 2017; Laasonen et al., 2002; Norrix et al., 2006; Rüsseler et al., 2018). Adult dyslexic readers have been shown to have a reduced BOLD response in for the multisensory integration of letters and speech sounds (Blau et al., 2009). This reduced audiovisual integration is directly related to a more fundamental deficit in auditory processing of speech sounds, which in turn predicts performance on phonological tasks. Overall, differences in multisensory integration may in part explain some of the difficulties in reading these individuals’ experience.

In sum, surveying the literature on multisensory integration in these two NDCs highlights two things. First, both populations show differences in multisensory processing compared to their neurotypical counterparts, and these differences have subsequent effects on cognitive processing. Specifically, it may impact social processing, reading, and linguistic abilities. Second, there may be a delay in the development of multisensory integration in some NDCs as there is some normalization by adulthood. Taken together, it is important to understand whether multisensory integration may be affected in other

NDCs, such ADHD. This should especially be studied since there is a heterogeneity in findings between other NDCs, it is likely that multisensory integration follows different patterns in ADHD. ADHD itself is a heterogeneous disorder, so there may even be different multisensory integration patterns between presentations of ADHD. Further, these differences may be more pronounced in childhood compared to adulthood, as neurodevelopment is generally delayed in ADHD (Vaidya, 2012). This highlights the need to conduct neurophysiological investigations of multisensory processing using a common framework in both children and adults, with and without ADHD, to examine the effects of this disorder and its developmental trajectory. Next, I will review the existing literature on multisensory integration in ADHD.

1.6 Multisensory Integration in ADHD

As mentioned, multisensory integration has been extensively studied in some NDCs, such as ASD and dyslexia, but is less researched in ADHD. ADHD is a NDC characterized by developmentally inappropriate levels of inattention, hyperactivity, and impulsivity (5th ed.; DSM–5; American Psychiatric Association, 2013). ADHD has three presentations: predominately inattentive (ADHD-IA), predominately hyperactive-impulsive (ADHD-HI), and combined (ADHD-C). ADHD is highly prevalent with roughly 8.6% to 11.4% of youth receiving diagnoses (ages 3-17 years; Danielson et al., 2024; Espinet et al., 2022) and persists into adulthood roughly 60% of the time (Sibley et al., 2017). ADHD is often considered in terms of poor executive functioning (Roberts et al., 2017) and the impacts on educational and occupational functioning (Caye et al., 2016). As abnormalities in multisensory integration can have downstream effects on cognition, it is possible that altered sensory and multisensory processing may in part explain cognitive functioning differences in ADHD.

Individuals with ADHD have been shown to have atypical sensory processing across domains using questionnaire and behavioural measures (Bartgis et al., 2009; Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Lucker et al., 1996; Mangeot et al., 2007; Panagiotidi et al., 2018; Söderlund & Jobs, 2016). Beyond this, several structural and functional brain differences exist in the ADHD brain compared to the NT brain, many of which are involved in sensory processing. Specifically, grey matter reductions in parietal, temporal, frontal, and occipital areas have been found (Castellanos et al., 2002; Duerden et al., 2012; Makris et al., 2007; Proal et al., 2011; Valera et al., 2007). Differences in superior colliculus (Overton, 2008) and insula (Duerden et al., 2012) have been found in ADHD, both of which have been related to sensory and specifically multisensory processing. Functionally, neural pathways involving the superior colliculus, fronto-parietal, and temporo-parietal networks are affected in ADHD and have been implicated in attention and multisensory integration (Dionne-Dostie et al., 2015). Despite the importance of understanding multisensory integration, most research to date on sensory processing in ADHD has concentrated on individual sensory modalities. In the past ten years, multisensory integration has started to gain attention in ADHD research, and next I will review the literature to date.

1.6.1 Multisensory Gain

Multisensory gain has been the most common way to examine multisensory integration in ADHD, and the results have been conflicting. There is some evidence for larger multisensory gain in individuals with ADHD compared to NTs (Bisch et al., 2016; McCracken et al., 2020). On the other hand, youth with ADHD were found to benefit less from visual information during noise than youth without ADHD, especially at harder SNRs. In a visual search task with varying perceptual load of unisensory and multisensory distractors, adults with ADHD showed similar levels of multisensory integration as NT adults (Schulze et al., 2022). In low load conditions adults with ADHD showed enhanced multisensory integration, as evidence by the race model, but in high load conditions only the NT adults showed evidence of violating the race model.

In a study looking at ADHD traits in non-clinical university students, there was no difference in multisensory gain in a speech-in noise task (Hare, Muller, et al., in prep). On the other hand, Hyperactive-Impulsive traits in university students have been related to increased accuracy gain in a detection task (Hare, Luszawski, et al., in prep).

1.6.2 Illusion susceptibility

Adults with ADHD have no difference in illusion susceptibility in a SIFI task, but have shown reduced susceptibility to the McGurk illusion, and a preference for auditory stimuli, compared to NT adults (Schulze et al., 2021). In a study looking at ADHD traits in university students, there was no difference in illusion susceptibility between high ADHD trait and low ADHD trait individuals (Hare et al., in prep).

1.6.3 Multisensory temporal processing

There have been no known studies to date that look at multisensory temporal processing in clinically diagnosed individuals with ADHD. High ADHD traits have been related to shorter TBW using a simultaneity judgement task but not a temporal order judgement task (Panagiotidi et al., 2017). Another study using three different measures of temporal processing only found evidence for a shorter temporal binding window using an emotional SJ3 task in specifically anger and happy condition, but not the neutral task (Hare, Dalal, et al., in prep). Differences were not found in the TOJ and SJ3 task measures, which did not have emotional content.

1.6.4 Neural studies

In a simple response time task, differences in Event-Related Potentials (ERPs) amplitudes to multisensory stimuli have been found in frontal, parietal, and occipital regions between adults with and without ADHD (McCracken et al., 2019). Further source localization analysis suggested that the NT group was found to have greater neural activity responding to audiovisual stimuli compared to the ADHD group. The source of the increased activity was found to be in right-hemispheric parietal brain regions (McCracken et al., 2022). A reduced BOLD response has been found in the superior temporal gyrus in adults with ADHD compared to NT adults for multisensory and unisensory stimuli (Zuberer et al., 2020). In the aforementioned McGurk study, structural connectivity on a resting state scan was correlated with performance on the McGurk task. In ADHD adults, multisensory integration was related with higher connectivity between Heschl’s gyrus and auditory parabelt regions along with altered fronto-temporal network integrity (Schulze et al., 2023). These neural studies are finding differences in key multisensory areas and networks.

1.7 Multisensory Integration and Attention

Attention refers to our ability to process specific information in the environment while tuning out other details, which allows us faster processing of attended compared to unattended stimuli (Alais et al., 2010; Talsma et al., 2010). Initially, multisensory integration was characterized as an automatic process, but today it is understood that multisensory integration can occur across various stages of sensory processing that are linked to and can be modulated by attention (Choi et al., 2018; Talsma, 2015; Talsma et al., 2010). Bottom-up stimulus driven mechanisms induced by cross-modal interactions can automatically capture attention towards multisensory stimuli, especially when competition to focus elsewhere is relatively low and when the stimuli are salient. On the contrary, top-down attention can facilitate the integration of multisensory inputs leading to a spread of attention across sensory modalities. Top-down attention is goal-directed and influenced by higher order cognitive processes. As attentional processes are affected in some populations, such as in ADHD, we may see an interesting relationship between attention and multisensory integration.

1.8 ADHD, attention, and multisensory integration

The term ADHD suggests a deficit in attention; however, ADHD is better described as a dysregulation of attention (Banich et al., 2009; Ginapp et al., 2023). Individuals with ADHD have difficulties sustaining attention (Banich et al., 2009; Barkley, 1997; Tucha et al., 2017) and suppressing responses to irrelevant distractors (Cassuto et al., 2013; Ghanizadeh, 2011), although in some cases background noise may improve cognitive performance in ADHD (Batho et al., 2020; Söderlund et al., 2007). In other instances, individuals with ADHD can hyperfocus, which is intense concentration associated with reduced perception of irrelevant stimuli and improved task performance (Ashinoff & Abu-Akel, 2021; Hupfeld et al., 2019). Research argues whether hyperfocus and flow are the same phenomenon viewed through different lenses (Ashinoff & Abu-Akel, 2021) or distinct, inversely related constructs (Grotewiel et al., 2023). Hyperfocus occurs more often when a task or stimulus is novel or particularly interesting to the individual (Mourik et al., 2007; Tegelbeckers et al., 2016). As mentioned earlier, multisensory stimuli inherently capture our attention compared to unisensory stimuli, and it is possible that multisensory stimuli are more salient to individuals with ADHD. Specifically, bottom-up attention capture may be biased towards multisensory stimuli disproportionally in ADHD leading to larger multisensory gain. This may be why we see similar levels of multisensory accuracy in individuals with ADHD but reduced unisensory accuracy, compared to individuals without ADHD (Bisch et al., 2016). Beyond this, when cognitive or perceptual demands are too high (Schulze et al., 2022) or there is too much background noise (Michalek et al., 2014), the enhanced multisensory gain in ADHD disappears.

When looking at studies with multisensory illusions, individuals with ADHD may have a perceptual bias towards one modality similar to dyslexia (Hayes et al., 2003; Ramirez & Mann, 2005; van Laarhoven et al., 2018). Adults with ADHD more often identified the auditory component of the McGurk stimuli when the McGurk illusion was not perceived (Schulze et al., 2021). Individuals with ADHD have been found to be hypersensitive and have a higher distractibility to auditory information (Cheung & Siu, 2009; Ghanizedeh, 2011). In dyslexia, the bias may come from “sluggish attention shifting” where these individuals are slow to shift attention from visual to auditory modalities resulting in integrating auditory and visual information over a longer time interval (i.e., a larger TBW). Opposite to dyslexia and limited to non-clinical samples, research suggests a shorter temporal binding window may be related to higher ADHD traits, which has been suggested to reflect hyperactivity (Panagiotidi et al., 2017) and is more strongly related to the hyperactive-impulsive presentation of ADHD (Hare et al., in prep). Similar to the sluggish attention shifting found in dyslexia, the inattentive presentation of ADHD but not the hyperactive-impulsive presentation has been linked to “sluggish cognitive tempo”, which includes daydreaming, difficulty initiating and sustaining effort, lethargy and physical (Carlson & Mann, 2002; Jacobson et al., 2018; Skirbekk et al., 2011). Collectively, multisensory integration may be impacted by modality processing differences (e.g., auditory processing) and presentation differences in ADHD.

Clinical ADHD presentation differences have been found in several domains, such as cognition (Solanto et al., 2007), gender ratio (Gaub & Carlson, 1997; Ramtekkar et al., 2010; Willcutt, 2012), age of diagnosis (Hare et al., 2024), and comorbidity

(Eiraldi et al., 1997). Further, sensory sensitivity and trait anxiety had a differential impact on inhibitory control when hyperactive-impulsive traits and inattentive traits were added to the model (Hare, 2020). Taken together, given the heterogeneity in ADHD and in multisensory integration results, it may be important to look at the relationship between ADHD presentation and multisensory integration. Often studies do not report which presentation participants have, or they do not look at the relationship between specific ADHD presentation traits and multisensory integration measures.

Overall, the dysregulated attentional system in ADHD may be related differences in multisensory integration. This interaction between sensory and attentional systems, a possible auditory bias and presentation differences could be possible explanations for the discrepancy in results.

1.9 Objectives

The overall goal of this dissertation is to examine multisensory integration in ADHD. To begin (1) we conducted a meta-analysis to appraise the current state of the literature, elucidate observed inconsistent results, and identify gaps in the literature. Based on the gaps identified we conducted (2) behavioural and (3) EEG investigations in youth with and without ADHD to examine the effects of the disorder at this developmental stage. Finally, we conducted (4) an EEG investigation in adults with and without ADHD.

1.9.1 Multisensory Integration in Individuals with ADHD: A meta-analysis.

The first objective was to conduct a meta-analysis of the literature on multisensory integration in individuals with ADHD. First, we wanted to understand whether there was evidence for a difference between individuals with ADHD and NTs in multisensory processing, as the literature has been quite mixed. As this review included studies on multisensory integration and multisensory temporal processing, multisensory processing will be used to describe the studies. Second, we wanted to explore whether age, type of task (e.g., multisensory illusion, multisensory gain), and type of measure (e.g., behavioural, EEG, fMRI) moderated the relationship between ADHD diagnosis and multisensory processing. Third, from this analysis, we hoped to uncover the gaps in the literature and address these for my following three projects. Overall, we did not find evidence for a difference in multisensory processing between ADHD and NT individuals. Some statistical analyses were limited as there were 15 studies which fit the criteria, six of which are in preparation by me (and three of those are included in this dissertation). More research should be conducted in this area, to understand whether multisensory integration is not affected in ADHD or if the inconsistencies in methods and overall lack of research may be leading to this result.

The identified gaps were the lack of studies in children and youth, and a lack of neural studies. In the next three studies, our goal is to address this gap by conducting two studies in children, one employing behavioural methods with a battery of standard multisensory tasks and the other using EEG techniques, and one study in adults, using EEG techniques, while controlling unisensory differences in perception.

1.9.2 Behavioural Investigation of Multisensory Integration in Youth with ADHD

The second objective was to use common multisensory integration paradigms to examine multisensory integration in youth with and without ADHD. Further, we wished to examine whether stimulus complexity or measure (illusion susceptibility or multisensory gain) were related to differences in multisensory integration between groups. Additionally, we wanted to examine whether ADHD presentation (i.e., ADHD-IA or ADHD-HI) or age affected this relationship. In this study, youth (6-17) completed a Sound-Induced Flash Illusion (SIFI), McGurk task, and a speech-in-noise task. First, we examined whether illusions susceptibility differed between groups using the SIFI and McGurk task. We expected no group differences for the SIFI, but we expected reduced illusion susceptibility in the McGurk, in-line with previous findings in adults (Schulze et al., 2021). We examined whether ADHD youth may have a bias towards responding to the visual or auditory component of the McGurk stimuli, when the illusion is not perceived. Next, we examined whether multisensory gain was affected in the speech-in-noise task. Multisensory gain has been shown to be affected in high noise conditions and with high perceptual load in ADHD, therefore, we expect there to be reduced multisensory gain in ADHD youth compared to NT youth, as the high level of background noise may reduce gain. In sum, we have constructed a battery of well-established multisensory paradigms in an understudied diagnostic and age group.

1.9.3 Audiovisual Multisensory Integration in Youth with ADHD: An EEG Investigation.

The third objective was to examine multisensory integration and sensory sensitivity in youth with and without ADHD (ages 8-17) using behavioural and EEG measures. Participants completed a detection task with an adaptive staircasing procedure to find their which stimuli they can perceive 50% of the time. Then they completed a speeded response task set at their perceptual level (perception-matched) while simultaneous EEG was recorded. Participants were presented with auditory pure tones, visual Gabor patches, or a combination thereof, all embedded in audiovisual white noise. Participants responded as quickly as possible when they detected any stimulus. Multisensory gain will be measured by response time and accuracy. Then we examined their unisensory processing using behavioural, determined by the detection task, and caregiver-report measures. We expected larger multisensory gain in ADHD youth compared to NT youth, particularly using the response time measure. Previous research has shown increased multisensory gain using Miller's Race model, a response time measure, in ADHD adults compared to NT adults (McCracken et al., 2019). We expect there to be differences in the difference wave, calculated by subtracting the summed unisensory and audiovisual ERPS, in frontal, parietal, and occipital areas. Differences in these areas have been found in ADHD adults compared to NT adults previously (McCracken et al., 2019). We hypothesized that ADHD youth would be more sensitive and responsive to auditory and visual stimuli than NT youth using both behavioural and parent-report measures.

1.9.4 Multisensory Integration and Sensory Sensitivity in Adults with ADHD: An EEG Investigation

The fourth objective was to examine multisensory integration and sensory sensitivity in adults with and without ADHD using behavioural and EEG measures. Participants completed the same detection task above. Then participants completed a perception-matched and a stimulus-matched response time task. Multisensory gain will be measured by accuracy and response time. We expect larger multisensory gain in ADHD adults compared to NT adults. We then examined their unisensory processing using behavioural, determined by the detection task, and self-report measures. We expect differences in multisensory gain in the perception-matched compared to the stimulus-matched task, as the stimuli in the perception-matched task are controlled for differences in unisensory perception and the stimulus-matched stimuli are easier to detect for most participants. We expect there to be differences in the difference wave, calculated by subtracting the summed unisensory and audiovisual ERPS, in frontal, parietal, and occipital areas. We expect these differences to be more pronounced in the perception-matched condition. We hypothesized that ADHD adults would be more sensitive and reactive to auditory and visual stimuli than NT adults using both behavioural and self-report measures. The perception-matched condition allows us to control for individual differences in perceptual sensitivity, whereas the stimulus-matched paradigm is more similar to typical multisensory paradigms. For this study we wanted to use the same methods as the youth to provide a better understanding of whether developmental stage affects the relationship between multisensory integration and ADHD.

1.10 References

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Chapter 2

2 Multisensory Integration in Individuals with ADHD: A meta-analysis.

2.1 Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a common neurodevelopmental condition characterized by hyperactivity, impulsivity, and inattention (5th ed.; DSM–5; American Psychiatric Association, 2013). Incidence rates are very high, with roughly 8.6% to 11.4% of youth receiving diagnoses (ages 3-17 years; Danielson et al., 2024; Espinet et al., 2022). ADHD is often related to challenges in social, academic, and occupational functioning (Caye et al., 2016). There is also emergent evidence that sensory issues are present in ADHD, for example sensory sensitivities (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018) and a higher distractibility to external stimuli demonstrated by a failure to inhibit irrelevant stimuli, especially in the auditory domain (Ghanizadeh, 2011). While most research on sensory processing in ADHD has focused on single sensory modalities, most real-world sensory experiences are multisensory in nature, requiring our sensory systems to bind information across multiple sensory modalities through a process referred to as multisensory integration.

Multisensory integration is a foundational building block upon which many of our cognitive processes rely (Stein & Meredith, 1993). More specifically, multisensory integration differences have been observed in other neurological conditions including autism spectrum disorder (Collignon et al., 2013; Foxe et al., 2015; Ostrolenk et al., 2019; Segers et al., 2020; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014; Stevenson, Baum, et al., 2017; Woynaroski et al., 2013; See Feldman et al., 2018 for review) dyslexia (Harrar et al., 2014; Pulliam et al., 2023; van Laarhoven et al., 2018), and schizophrenia (de Gelder et al., 2003; Pearl et al., 2009; Stevenson, Park, et al., 2017; Vogel et al., 2016; See Dalal et al., 2024 for review), and have been linked to issues in higher-order cognition (Baum et al., 2015; Stevenson, Segers, Ferber, et al., 2014; Stevenson et al., 2018; See Wallace et al., 2020 for review). In the past decade, researchers have begun investigating whether this same pattern of differences in multisensory integration holds in ADHD, though with conflicting results (McCracken et al., 2019; Panagiotidi et al., 2017; Schulze et al., 2021, 2021, 2022; Zuberer et al., 2020). To look at these contradictory results, the present study aims to systematically review and quantitively synthesize the literature on whether multisensory processing differs in individuals with ADHD relative to neurotypicals (NTs). Additionally, whether levels of ADHD traits in non-clinical populations are related to multisensory processing. Further, we will examine whether age, measure of multisensory integration, or data collection method influence the results.

Multisensory integration in ADHD has been studied through several different approaches. The most common methods take advantage of the fact that successful multisensory integration can result in optimized behavioural performance, such as improved detection, improved localization, shorter response times, greater response accuracy, and greater processing efficiency (Bremner et al., 2012). Such benefits in perceptual and behavioural processing of multisensory stimuli relative to what would be predicted based on unisensory processing streams that do not interact is commonly referred to as *multisensory gain* (Stevenson, Ghose, et al., 2014). There is some evidence for larger multisensory gain in individuals with ADHD compared to neurotypicals (NT; Bisch et al., 2016; McCracken et al., 2020). Other studies have reported reduced multisensory gain is reduced in ADHD compared to NTs, particularly when task demands or difficulty are high (Michalek et al., 2014; Schulze et al., 2021). For example, in an audiovisual speech-in-noise task, adults with ADHD had reduced multisensory gain compared to NTs, especially in the conditions with the highest noise levels (Michalek et al., 2014). Multisensory gain differed in a visual search task with unisensory and multisensory distractors when varying perceptual load (Schulze et al., 2022). Specifically, adults with ADHD showed enhanced multisensory integration in low load conditions, but in high load conditions they showed reduced multisensory integration.

Integration of sensory information across modalities can also be measured through perceptual biases or illusions (Stevenson, Ghose, et al., 2014) such as the McGurk effect (Mcgurk & Macdonald, 1976) or the sound-induced flash illusion (Shams et al., 2000). Illusions are key to studying multisensory integration because they demonstrate the brain’s ability to integrate sensory cues across modalities to form a unified perception. They also demonstrate how sensory information in one modality can change what we perceive in another, such as a visual bias in localization tasks (Hairston et al., 2003). Such illusions have been used to study multisensory integration in ADHD and have also provided conflicting results. For example, ADHD adults have been shown to have a lower susceptibility to a McGurk effect but exhibited no differences in the SIFI compared to controls (Shulze et al., 2021).

Complimenting the perceptual and behavioural multisensory effects described above, functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) studies have shown activation differences to multisensory stimuli between individuals with ADHD and NT individuals (McCracken et al., 2019; Zuberer et al., 2020).

In addition to these measures of multisensory integration, one can also measure sensory processes that underlie multisensory integration, such as the temporal processing of events. The temporal (and spatial) relationship between stimuli is used as a cue when trying to determine whether signals originate from the same external event or different external events, and thus whether these events should be bound into a single percept (Dixon & Spitz, 1980; Stein & Meredith, 1993; Stevenson et al., 2016). The window of time within which these inputs must fall to be integrated is referred to as the temporal binding window (TBW; Colonius & Diederich, 2004). Higher ADHD traits have been related to shorter temporal binding windows (Panagiotidi et al., 2017; Hare, Dalal, et al., in press). It is also hypothesized that the perceived temporal misalignment of two or more modalities can lead to distractibility (Panagiotidi et al., 2017). Further, studies have shown that temporal processing itself may be abnormal in children and adults with ADHD (see Toplak et al., 2006 for review). In this review, multisensory processing will be used to refer to studies on multisensory integration and multisensory temporal processing.

Overall, the literature is conflicting on whether multisensory integration is affected in ADHD, and if it is, whether multisensory integration is enhanced or diminished. There are a few theoretical reasons why we would expect multisensory integration to be affected in ADHD, beyond evidence from other NDCs. First, as mentioned, sensory processing differences have long been reported in ADHD, but these are often either parent-reported or self-reported (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018). These largely questionnaire-based findings have been corroborated by brain imaging studies as there is evidence of altered brain structures related to sensory processing in ADHD. A diffuse pattern of cortical thinning has been found in parietal, temporal, frontal, and occipital cortices in children and adults with ADHD (Castellanos et al., 2002; Valera et al., 2007; Proal et al., 2011; Duerden et al., 2012). Further, differences in the superior colliculus (Overton, 2008) and insula (Duerden et al., 2012) have been found in ADHD. These brain areas and structures have been related to sensory and specifically multisensory processing. Functionally, neural pathways involving the superior colliculus, fronto-parietal, and temporo-parietal networks are affected in ADHD and have been implicated in attention and multisensory integration (Dionne-Dostie et al., 2015). Second, multisensory integration can be modulated by attention (Choi et al., 2018; Talsma, 2015; Talsma et al., 2010), and ADHD has been linked to difficulties in different attentional aspects such as, sustained attention (Banich et al., 2009; Barkley, 1997; Tucha et al., 2017), task-switching (Cepeda et al., 2000), and blocking our irrelevant distractors (Cassuto et al., 2013; Ghanizadeh, 2011). When looking at multisensory stimuli, bottom-up stimulus driven mechanisms induced by cross-modal interactions can automatically capture attention towards multisensory stimuli, especially when competition to focus elsewhere is relatively low and when the stimuli are salient (Talsma et al., 2010). This attentional capture may help individuals with ADHD to attend better to multisensory stimuli compared to unisensory stimuli. On the contrary, top-down attention can facilitate the integration of multisensory inputs, leading to a spread of attention across sensory modalities. It is possible that this interplay between attention and multisensory integration is of particular interest when looking at ADHD populations.

Taken together, it is suggested that individuals with ADHD may show differences in multisensory processing relative to their peers. There are, however, a number of inconsistencies in the literature between methodologies and between individual studies. Here, we conducted a systemic review and meta-analysis of the literature on multisensory integration in ADHD to summarize the effects of this literature and to estimate the size of overall effects of interest and the variability around effects within a population. The variability around effects can be analyzed to determine (a) whether it is true variability or spurious variability, (b) whether any study-level factors moderate the effect, and (c) whether publication bias is evident in the literature.

2.1.1 Research Questions

The goal of this study was to conduct a systematic review and meta-analysis of the literature on multisensory integration in individuals with ADHD. The research questions are as follows:

1. Is there evidence for a difference between individuals with ADHD and Neurotypical (NT) individuals in multisensory processing? In nonclinical samples, is there evidence for a multisensory processing difference between high ADHD trait and low ADHD trait individuals? We hypothesize that individuals with ADHD or high ADHD traits would exhibit enhanced audiovisual multisensory integration compared to NTs on average across studies.

2. Are the differences between individuals with ADHD and NTs moderated by (a), mean age of participants, (b) the measure of multisensory processing (e.g., multisensory integration, multisensory temporal processing) (c) data collection method (e.g., behavioural, EEG, fMRI)?

2.2 Methods

This review was carried out in accordance with recommended procedures for conducting systematic reviews and meta-analyses (i.e., the Preferred Reporting Items for Systematic Reviews and Meta-Analyses [PRISMA] guidelines; Moher et al., 2009).

2.2.1 Eligibility criteria

There were two inclusion criteria for eligible studies. First, studies either needed to include an ADHD group and a NT group, or a measure of ADHD traits (e.g., ASRS; Kessler et al., 2005) in the general population. Second, studies were required to have either a behavioural or a neural measure of multisensory integration. Studies using parent or self-report measures of sensory behaviour were not considered. Multisensory integration could include any combination of visual, auditory, or tactile processing.

Studies that included posture or vestibular/proprioceptive integration were not included in the final analysis and were flagged in the full-text review stage. Papers not in English were excluded. There were no exclusion criteria based on country of origin or publication status.

2.2.2 Search Strategy

To identify all eligible studies, a comprehensive search strategy was completed using PsycINFO (ProQuest), Nursing and Allied Health (ProQuest), Scopus, Medline (Ovid), Embase (Ovid) and CINHAL databases and search engines. Three blocks of search terms were used. The first block focussed on the sensory modalities that could be included. The second block focussed on capturing the multisensory studies. The third block focussed on including papers with an ADHD group or ADHD measure. Subject headings of interest were selected for each search engine (except Scopus). The initial search was completed on October 26, 2020, and an updated search was conducted December 22, 2021, and re-run on July 18, 2023. No additional articles were included by email alerts. We contacted first authors and/or corresponding authors of the included studies and asked whether they had any preliminary analyses of ongoing research, unpublished data, or in preparation manuscripts that could be included.

Table 2.1. **Search Terms for Meta-analysis**

Term Block	**Terms Used**
Sensory	(“audio” OR “visuo” OR “visual” OR “olfactory” OR “haptic” OR “tactile” OR “Audiovisual” OR “visuo-auditory” OR “Audio-visual” OR “visual-tactile” OR “visuo-tactile” OR “visual-haptic” OR “visuo-haptic”)
Multisensory	AND (“visuo-auditory” OR “Audiovisual” OR “Audio-visual” OR “visual-tactile” OR “visuo-tactile” OR “visual-haptic” OR “visuo-haptic” OR “cross” OR “bi” OR “multi” OR “sensory” OR “modal”)
Participant	AND (“ADHD” OR “Attention Deficit Hyperactivity Disorder” OR “AD/HD” “Attention-Deficit/Hyperactivity Disorder” OR “Attention Deficit Disorder” OR “ADD” OR “attention-def*” OR “hyperact*”)

2.2.3 Study Selection

Results of the searches were imported into Covidence (Covidence systematic review software), and duplicate records were automatically removed. Titles and abstracts were screened to determine whether the studies met inclusion criteria. During full text review, exclusion criteria were considered using the following criteria:

1. Duplicate record not previously removed
2. Not in English
3. Not primary literature (i.e., review article)
4. For clinical studies, no ADHD or Control group for clinical studies or for trait studies, no measure of ADHD traits
5. No valid measure of multisensory integration
6. Balance and Posture

All studies that met the inclusion and exclusion criteria were included in the qualitative analysis, regardless of whether an effect size of interest could be extracted. For the title/abstract and full-text screening, there were two reviewers for each article. The inter-rater reliability (CH, EC) for the full-text review screening had a proportion agreement of .84 (Cohen’s kappa: .30). The inter-rater (CH, EC, RS) for the title/abstract screening had a proportion agreement of .96-89 (Cohen's kappa: .34–.45).

2.2.4 Data extraction

Articles that reported a group difference on a behavioural or a neural metric of multisensory processing and/or correlation between multisensory processing and ADHD traits were included in the quantitative analysis. The extracted effect sizes had to measure an aspect of multisensory processing which could include multisensory gain, cross-modal matching, temporal binding window size, or perception of a multisensory illusion.

Measures missing an unisensory comparison were not included, as measures of multisensory integration are not possible without an appropriate baseline (Stevenson, Ghose, et al., 2014).

Some studies reported multiple effect sizes of interest for a single sample. To account for statistically dependent effect sizes, robust variance estimation procedures were used (see Analyses). All nonoverlapping, eligible effect sizes were extracted from each study.

Group differences were extracted/calculated as Cohen's *d* or *r* and then converted to Hedge's *g*. Data was extracted from all eligible reports as first and/or corresponding authors were contacted to obtain sufficient information to calculate Cohen's *d* or *r*.

2.2.5 Analyses

All analyses were conducted in R (R Core Team, 2017). A meta-analytic model including all studies (i.e., individuals with ADHD and high ADHD traits) was conducted, followed by one model with only ADHD patients and another model with ADHD traits. As many of the group differences and correlations were extracted from non-independent samples, robust variance estimation procedures with small sample adjustments were used for each model (Hedges et al., 2010; Tanner-Smith et al., 2016; Tipton, 2015). These procedures analyze effect sizes within clusters, which in this case were groups of studies that reported on overlapping samples or one study that reported multiple effect sizes in one sample. These models were run using the Robumeta package in R (Fisher et al., 2017) and were evaluated for potential bias with a funnel plot and Egger test for funnel plot asymmetry (Egger et al., 1997) using the Metafor package in R.

Meta-regression analyses were used to answer the second research question regarding possible moderators of effect sizes across studies. The demographic information extracted from each study were the number of participants in each group, and the mean age of the group. In accordance with current recommendations (Tanner-Smith and Tipton, 2014), mean age of participants, a continuously quantified moderator which could vary both between and within clusters, was transformed into a cluster mean variable to model between-cluster effects and a cluster mean-centered variable to model within-cluster effects, using the Robumeta package in R (Fisher et al., 2017). Age was intended to be a moderator in the model to examine the effects across development, but most studies included adult participants, so this was not possible. Categorical variables (e.g., the type of task used to measure multisensory integration) were not transformed. The studies were coded for task design and stimuli. The coding variables included the data collection method used (i.e., eye tracking, EEG/ERP, fMRI, psychophysics, other behavioural observation) and how multisensory processing was assessed (i.e., temporal, multisensory integration).

2.3 Results

2.3.1 Study selection

The electronic search produced 4,856 (3,808 unique) studies, and a detailed breakdown of the screening and included articles are in Figure 2.1. Additionally, 1 dissertation was excluded at the full text stage because the relevant content was later published and thus available via the peer-reviewed literature. 9 full-text papers were included in the quantitative review, and all these studies were peer-reviewed articles published between 2014-2023. 6 additional papers were included in the quantitative review that were in preparation. All included studies measured audiovisual integration, except for one unpublished study contained visual-tactile integration but the unisensory condition results were not presented for the comparison therefore it was not included. Some effect sizes were not included because no responses were received by authors, or the researchers were unable to provide the information. Two additional studies that were secondary analyses of previously analyzed research will be discussed in terms of their results but not included in the analytical model (McCracken et al., 2022; Schulze et al., 2023). All included studies and their study characteristics are in Table 2.1.

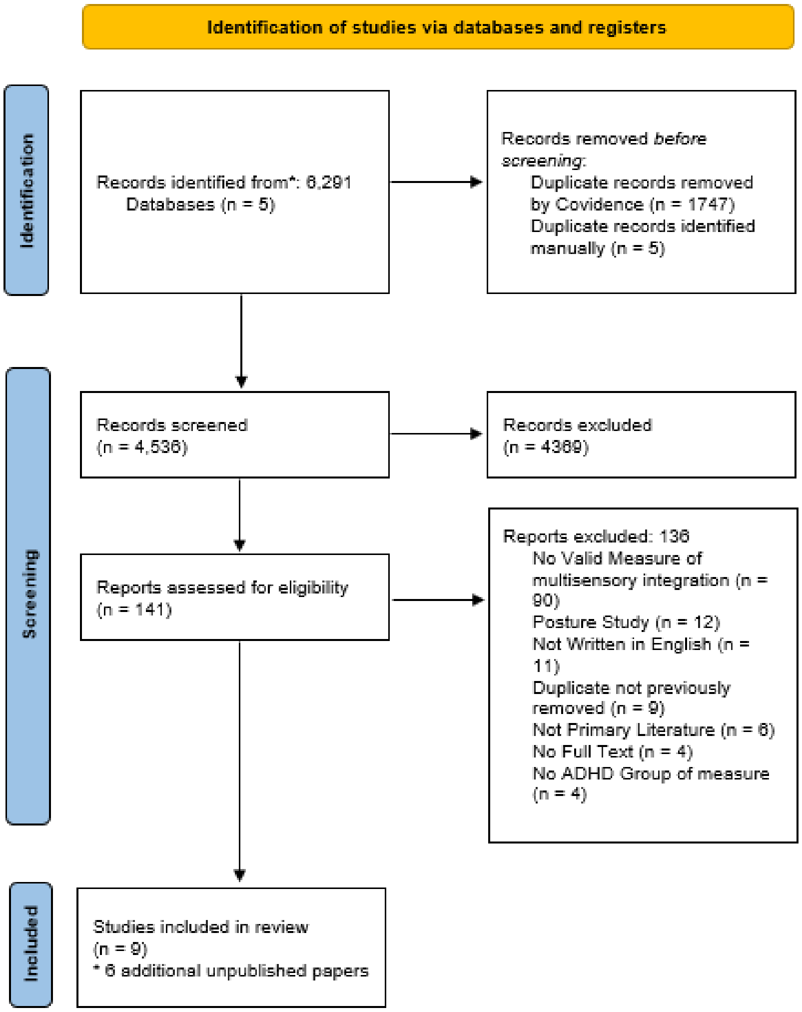

Figure 2.1. Prisma Flowchart. Flow chart of the selection process (Adapted from Page et al., 2021).

Table 2.2. Characteristics of Studies Included in Quantitative Analysis by Cluster

Cluster/Study	# ES	N	Task(s)	Type of Measure
Bisch et al. (2016)	10	ADHD= 23 NT= 31	Emotion Recognition	Behavioural
Chmielewski et al (2018) [α]	2	ADHD=21 NT= 21	Multisensory Go/NoGo Task	Behavioural, EEG [α]
D'Agostino et al. (2019)	3	ADHD= 22 NT= 22	Multisensory Go/NoGo Task	Behavioural
McCracken et al. (2019)	5	ADHD=10 NT= 11	Simple Response Time Task	Behavioural, EEG
Michalek et al. (2014)	6	ADHD= 24 NT= 38	SiN	Behavioural
Panagiotidi et al. (2017)	2	37	SJ, TOJ	Behavioural
Schulze et al. (2021)	2	ADHD= 25 NT= 24	McGurk, SIFI	Behavioural
Schulze et al. (2022) [α]	2	ADHD= 18 NT= 18	Load-Dependent Visual Search Paradigm	Behavioural
Stevenson Cluster				
Hare, Muller, et al. (in press)	1	104	McGurk	Behavioural
	1	97	McGurk*	Behavioural
	2	115	SiN	Behavioural
	1	96	SIFI	Behavioural
Hare, Dalal, et al. (in prep)	3	83	SJ3- Emotional	Behavioural
	1	85	TOJ	Behavioural
	1	97	SJ3*	Behavioural
Hare, Luszawski, Schulz, et al. (in prep)	2	123	Simple Response Time Task	Behavioural
Hare, Luszawski, Atta, et al (in prep)	5	ADHD= 32 NT= 32	Simple Response Time Task	Behavioural, EEG
Hare, Luszawski, Li, et al. (in prep)	2	ADHD= 30 NT= 23	Simple Response Time Task	Behavioural, EEG
Hare, Leung, et al. (in prep)	4	ADHD= 45 NT= 53	SIFI	Bebavioural
		ADHD=41 NT= 54	McGurk	
		ADHD= 37 NT= 26	SiN	
Zuberer et al. (2022) [α]	2	ADHD= 44 HC= 43	Emotion Recognition	Behavioural [α], fMRI

Note. The individual effect size metrics are reported in the forest plots. *In the Stevenson Cluster, the SJ3 task and McGurk share a sample but are in two different papers. [α] was used to denote any papers with missing effect sizes after contacting authors, and only ES relevant to analyses are included in the Table. All studies included were articles. SJ3= Ternary Simultaneity Judgment, TOJ= temporal order judgement, SiN= Speech in Noise, SIFI= Sound Induced Flash Illusion.

2.3.2 Meta-analysis

Multisensory perception in the ADHD/high ADHD traits group was used as the baseline; therefore, negative values indicate that multisensory perception was lower (e.g., less multisensory gain, lower illusion susceptibility, larger TBW) in the NT group than the ADHD group. Lower multisensory perception was defined as less multisensory gain, lower illusion susceptibility, larger TBW, and reduced amplitudes for EEG and fMRI. Fifteen studies (19 clusters) contributed 57 effect sizes converted to Hedges' g. Studies refers to the experiments which effect sizes are included in one manuscript, and clusters are based on experiments that share samples. The mean effect size was 0.022 indicating that there was no significant difference between individuals relative to NT peers with ADHD multisensory integration across studies (p = 0.766, 95% CI [-0.133, 0.178], T^2 = 0; see Figure 2.2).

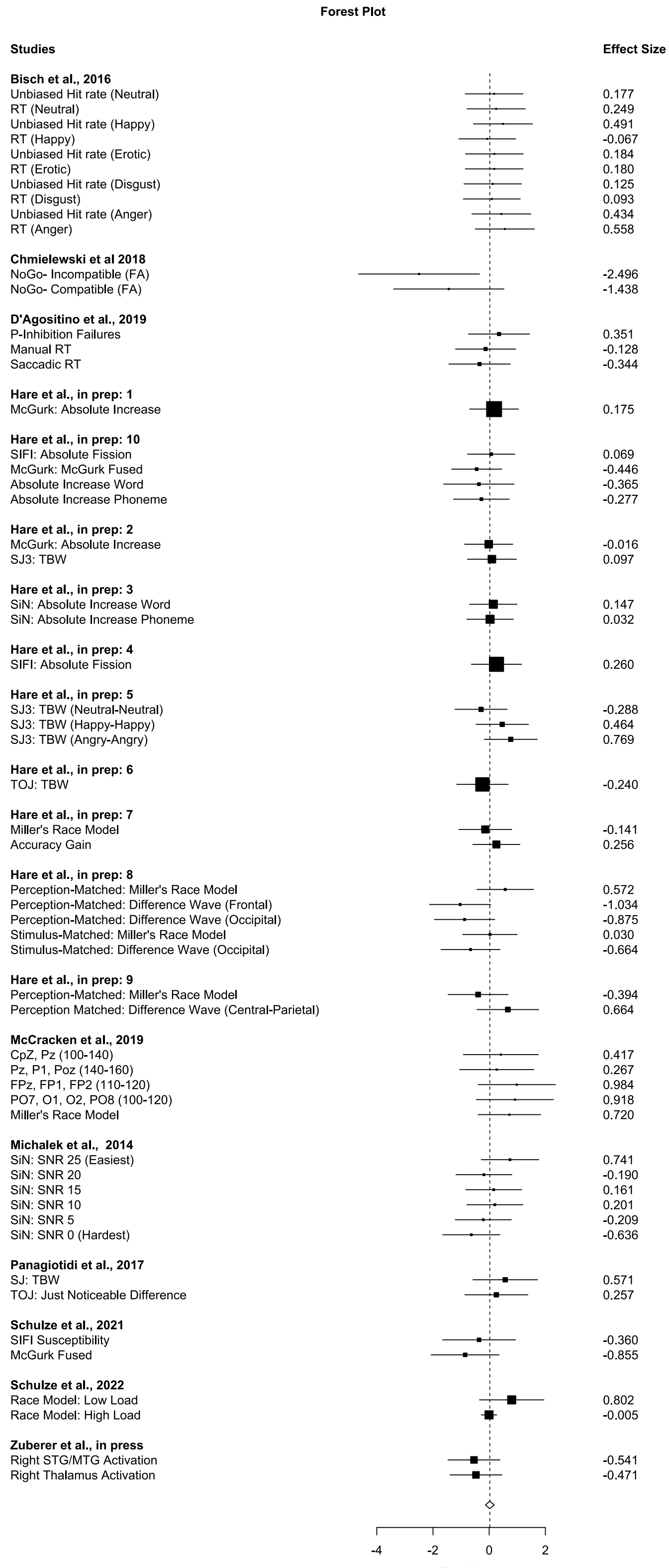
Forest Plot
Studies
Effect Size
Bisch et al., 2016
Unbiased Hit rate (Neutral) 0.177
RT (Neutral) 0.249
Unbiased Hit rate (Happy) 0.491
RT (Happy) -0.067
Unbiased Hit rate (Erotic) 0.184
RT (Erotic) 0.180
Unbiased Hit rate (Disgust) 0.125
RT (Disgust) 0.093
Unbiased Hit rate (Anger) 0.434
RT (Anger) 0.558
Chmielewski et al 2018
NoGo- Incompatible (FA) -2.496
NoGo- Compatible (FA) -1.438
D'Agositino et al., 2019
P-Inhibition Failures 0.351
Manual RT -0.128
Saccadic RT -0.344
Hare et al., in prep: 1
McGurk: Absolute Increase 0.175
Hare et al., in prep: 10
SIFI: Absolute Fission 0.069
McGurk: McGurk Fused -0.446
Absolute Increase Word -0.365
Absolute Increase Phoneme -0.277
Hare et al., in prep: 2
McGurk: Absolute Increase -0.016
SJ3: TBW 0.097
Hare et al., in prep: 3
SiN: Absolute Increase Word 0.147
SiN: Absolute Increase Phoneme 0.032
Hare et al., in prep: 4
SIFI: Absolute Fission 0.260
Hare et al., in prep: 5
SJ3: TBW (Neutral-Neutral) -0.288
SJ3: TBW (Happy-Happy) 0.464
SJ3: TBW (Angry-Angry) 0.769
Hare et al., in prep: 6
TOJ: TBW -0.240
Hare et al., in prep: 7
Miller's Race Model -0.141
Accuracy Gain 0.256
Hare et al., in prep: 8
Perception-Matched: Miller's Race Model 0.572
Perception-Matched: Difference Wave (Frontal) -1.034
Perception-Matched: Difference Wave (Occipital) -0.875
Stimulus-Matched: Miller's Race Model 0.030
Stimulus-Matched: Difference Wave (Occipital) -0.664
Hare et al., in prep: 9
Perception-Matched: Miller's Race Model -0.394
Perception Matched: Difference Wave (Central-Parietal) 0.664
McCracken et al., 2019
CpZ, Pz (100-140) 0.417
Pz, P1, Poz (140-160) 0.267
FPz, FP1, FP2 (110-120) 0.984
PO7, O1, O2, PO8 (100-120) 0.918
Miller's Race Model 0.720
Michalek et al., 2014
SiN: SNR 25 (Easiest) 0.741
SiN: SNR 20 -0.190
SiN: SNR 15 0.161
SiN: SNR 10 0.201
SiN: SNR 5 -0.209
SiN: SNR 0 (Hardest) -0.636
Panagiotidi et al., 2017
SJ: TBW 0.571
TOJ: Just Noticeable Difference 0.257
Schulze et al., 2021
SIFI Susceptibility -0.360
McGurk Fused -0.855
Schulze et al., 2022
Race Model: Low Load 0.802
Race Model: High Load -0.005
Zuberer et al., in press
Right STG/MTG Activation -0.541
Right Thalamus Activation -0.471
-4
-2
0
2
Effect Size

Figure 2.2. Full Meta-analytic Model. The dot indicates the effect size, the size of the dot represents the weight, and the line that emerges from both sides of the dot represents the confidence interval. The longer the line, the larger the confidence interval. Lines that do not reach the zero value indicate significant effect sizes.

3.2.1. Clinical Group Analysis

11 studies (11 clusters) contributed 43 effect sizes converted to Hedges' g. A meta-analysis model was run the integration studies, and the mean effect size was -0.095 indicating that there was no significant difference between individuals relative to NT peers with ADHD multisensory integration across studies (p = 0.497, 95% CI [-0.399, 0.209], T^2 = 0.092; see Figure 2.3).

Meta-analytic Model of Clinical ADHD Studies

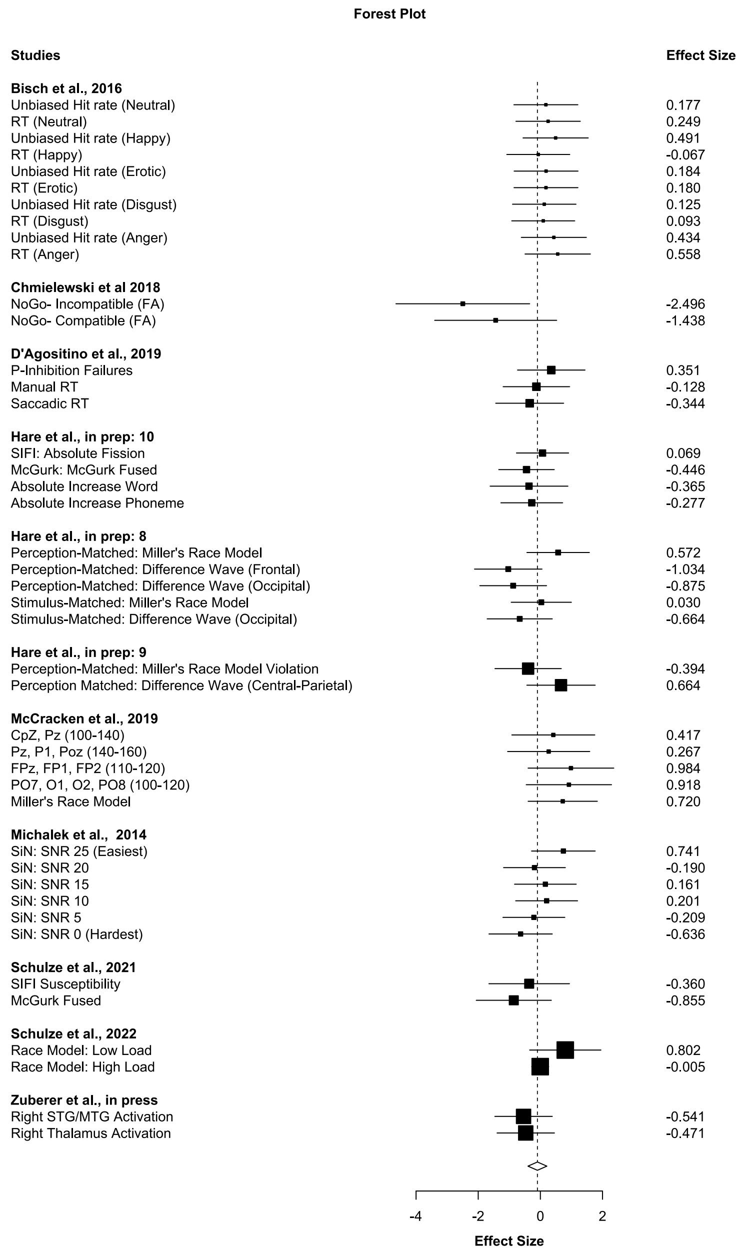

Figure 2.3. Meta-analytic Model of Clinical ADHD Studies. The interpretation of the forest plot can be found on Figure 2.2.

2.3.3 ADHD-traits Analysis

Five studies (8 clusters) looking at multisensory integration in relation to ADHD traits contributed 14 correlational effect sizes converted from r to Hedges' g. The mean effect size was 0.125 indicating that individuals with higher ADHD traits have a trending benefit in multisensory integration relative to individuals with lower ADHD traits across studies (p = .094, CI 95% [-0.027, 0.277], T^2= 0; see Figure 2.4).

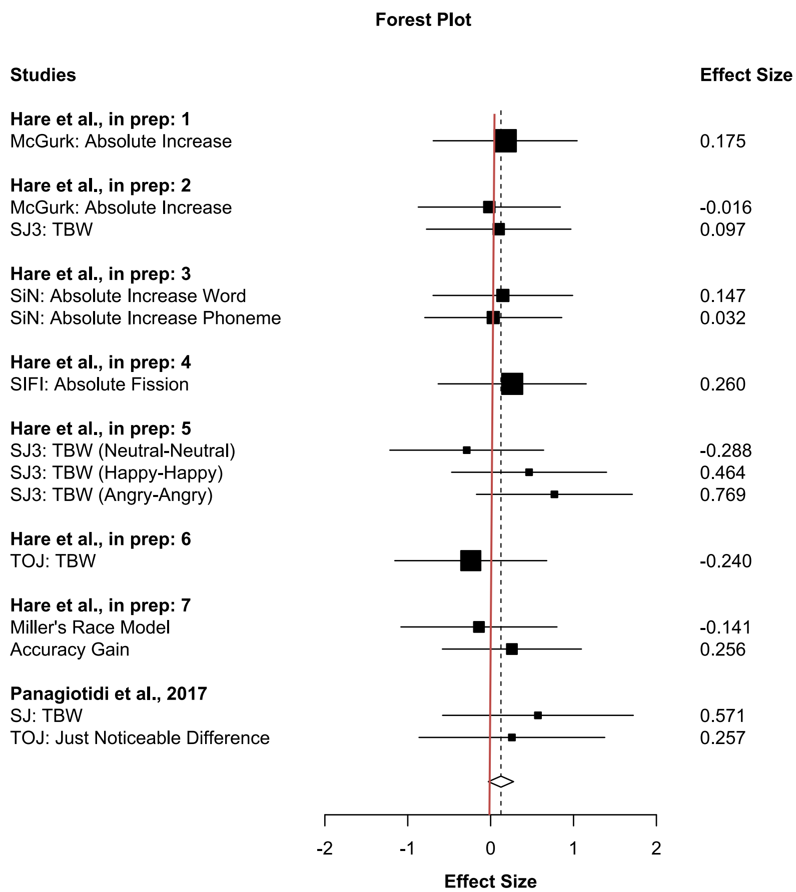

Figure 2.4. Meta-analytic model of ADHD-traits

2.3.4 Factors affecting multisensory integration

A meta-regression with the moderator of age could not be performed because all studies included adult samples. Meta-regressions for measures of multisensory integration and data collection method were reported as one of two categories of categorical moderators did not have enough studies, in these cases we ran a meta-analytic model.

2.3.4.1 Measure of Multisensory Integration

A meta-regression with the categorical moderator of how multisensory integration (Integration (k = 12, number of ES = 50), Temporal (k = 2, number of ES = 7)) was performed but is not interpretable because the *df* is below 4 for the temporal predictor. Alternatively, a meta-analysis model was run for the integration studies, and the mean effect size was -0.018 indicating that there was no significant difference between NT with ADHD individuals in multisensory integration (p = 0.82, 95% CI [-.186, 0.150], T^2 = 0; see Figure 2.5).

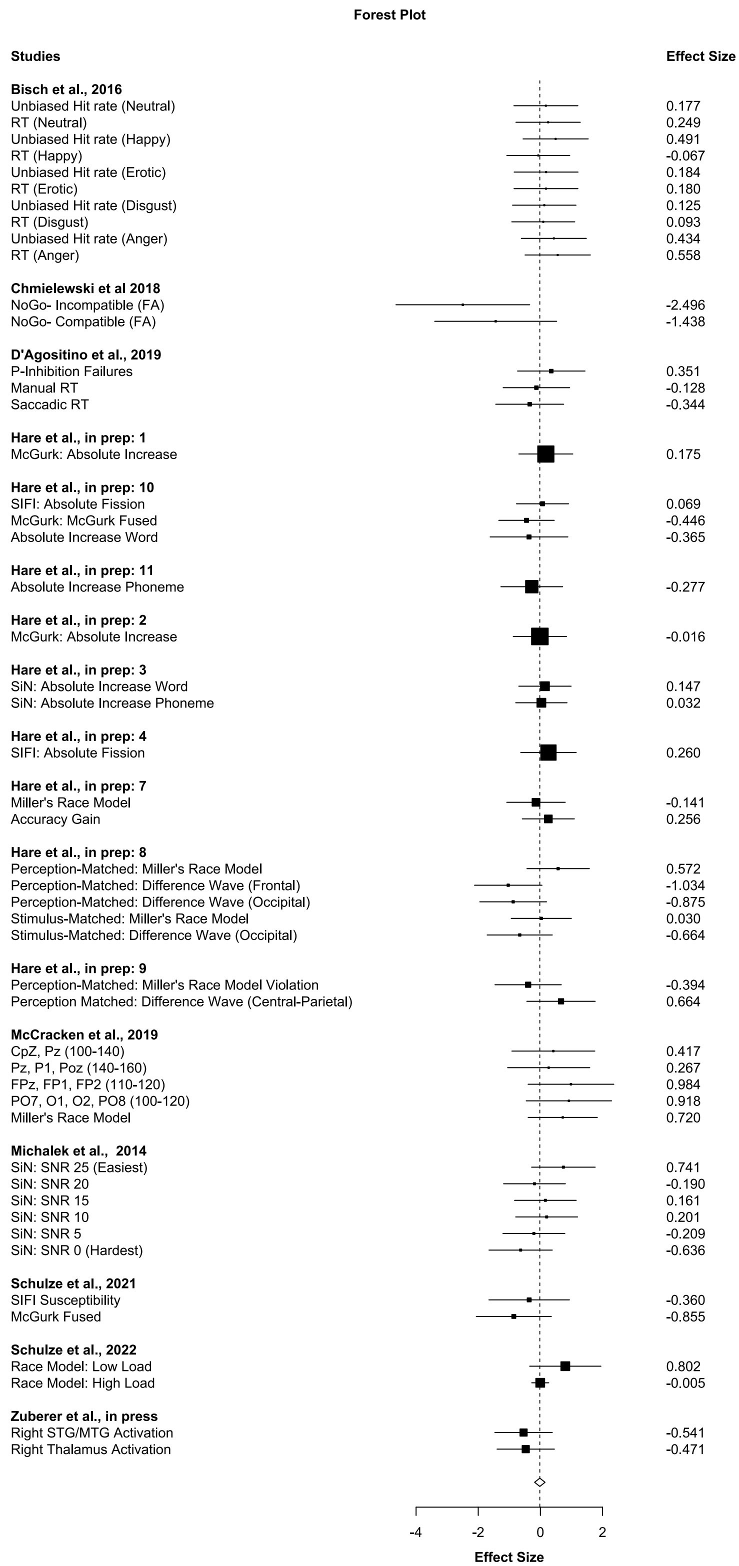

Figure 2.5. Meta-analytic model of Multisensory Integration Studies

2.3.4.2 Data Collection Method

A meta-regression with the categorical moderator of data collection method (Behavioural (*k* = 14, number of ES = 47), Neural (*k* = 4, number of ES = 10) was performed but is not interpretable because the *df* is below 4 for the neural predictor. A meta-analysis model was run on the behavioural studies, and the mean effect size was 0.048 indicating there was no significant difference between NT with ADHD individuals in multisensory integration across studies ($p = 0.53$, 95% CI [-0.114, 0.211], $T^2 = 0$; see Figure 2.6).

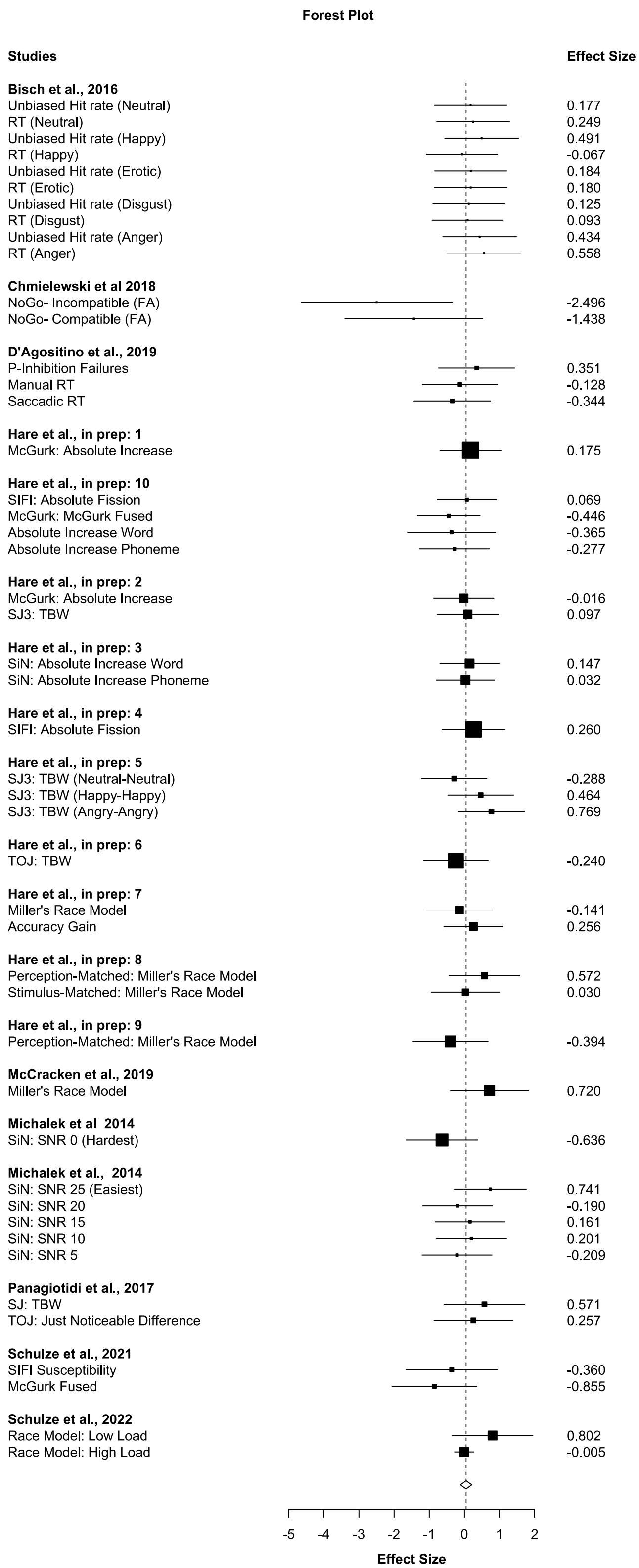

Figure 2.6. Meta-analytic Model of Behavioural Studies

2.3.5 Publication bias

Analyses to explore possible publication bias. Figure 2.7 shows the funnel plots for the overall meta-analytic model and the linear regression test of funnel plot asymmetry was not significant ($t = 0.60$, $p = 0.551$).

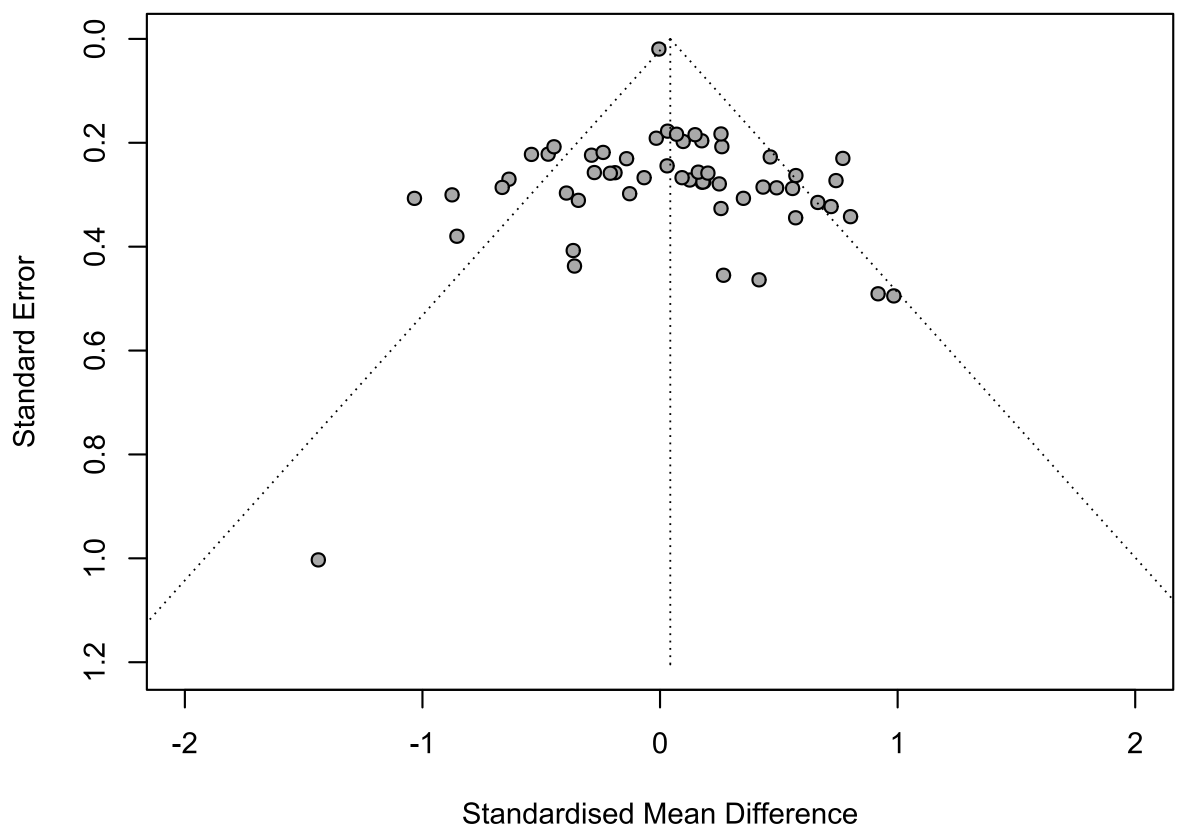

Figure 2.7. Funnel plot for meta-analysis. Results indicate no evidence of publication bias.

2.4 Discussion

This systematic review and meta-analysis investigated the literature on multisensory processing in individuals with ADHD. First, we hypothesized that multisensory processing differences would exist between individuals with ADHD or high ADHD-traits and NTs. Specifically, individuals with ADHD or high ADHD traits would exhibit enhanced audiovisual multisensory processing compared to NTs. To test if there was a difference between clinically diagnosed individuals with ADHD and non-clinical population studies with high ADHD traits, we ran three meta-analytic models: all studies, ADHD trait studies, and clinical ADHD studies. Our results did not provide evidence for that individuals with ADHD display differences in their ability to integrate multisensory information. This is inconsistent with our predictions that there would be differences between ADHD and NT individuals. Overall, there was not a consistent pattern with studies finding multisensory processing was enhanced or diminished in ADHD.

There are two possible explanations for finding no group differences between ADHD and NT individuals. First, no group differences exist, and multisensory integration is not affected in ADHD. This would be unexpected due to the sensory processing differences that exist in unisensory modalities revealed by behavioural paradigms, and questionnaire measures. If there are no differences in multisensory integration and especially if there are differences in unisensory perception, multisensory integration should be studied further as it is inconsistent with other NDCs. As multisensory integration influences the development of higher-order cognitive functions and language abilities. Second, there are group differences, and we were unable to detect them. Our inability to find an effect could be because research is still early in this area with only nine published papers, and we had too few papers to run some of our analyses. Our samples primarily included adults, and we see in other populations, such as in ASD, that multisensory integration is more affected before adulthood (Beker et al., 2018; Feldman et al., 2018; Foxe et al., 2015). On the other hand, one study in children found less group differences in multisensory integration than the adult study using the same paradigm (See Chapter 4 & 5). More studies found group differences than no group differences, but it was conflicting whether ADHD had enhanced or diminished multisensory integration. The studies suggest a trend for shorter TBWs and increased multisensory gain which were indexed as enhanced multisensory processing. Conversely, the studies showed a trend for reduced multisensory neural activity and reduced illusion susceptibility which were indexed as diminished multisensory processing. Possibly when combining studies with positive and negative effect sizes lead the model to be null. Even with both explanations, it is important to continue to research this area as this may shed light on whether multisensory integration differences exist in ADHD.

For the ADHD trait model, there were trending differences in audiovisual multisensory processing, with those with higher ADHD traits having better multisensory processing. This model included four clusters looking at TBWs and one response time based multisensory gain measure, out of the 8 clusters included. These temporal based measures largely follow the trend of faster response time or shorter TBW in those with high ADHD traits. The studies looking at accuracy gain, or multisensory illusions found ADHD traits were unrelated, which could suggest that ADHD traits need to reach a clinical level before finding a difference in these measures.

Overall, studying multisensory integration in ADHD seems to be a growing field with the majority of studies published in the past five years. Some studies do show compelling evidence that multisensory integration is affected, however, there is a lack of studies using similar methods to measure multisensory integration and temporal processing. The most common method was measuring multisensory gain using response time, but Miller’s Race Model violations calculated in different ways by the three different research groups.

2.4.1 Age

We aimed to examine whether the relationship between multisensory processing and ADHD would be moderated by age, measure of multisensory processing, or data collection method. There was a lack of studies conducted in children, which did not allow us to look at the trajectory of multisensory integration through development. Multisensory integration is slower to develop than other sensory processes (Ernst, 2008; Gori et al., 2008; Murray et al., 2016; Stevenson, Baum, et al., 2018), and reaches maturity later in development with estimates ranging from fourteen to adulthood (Brandwein et al., 2011; Stevenson, Baum, et al., 2018). It is possible that multisensory integration differences may be more pronounced in childhood, as multisensory integration differences have been shown in autism spectrum disorder to be less later in development (Beker et al., 2018; Feldman et al., 2018; Foxe et al., 2015).

2.4.2 Measure of Multisensory Integration

For the studies looking at multisensory integration there was not a significant difference in multisensory integration between groups. These studies used measures of multisensory gain through accuracy and response time, illusion susceptibility, and neuroimaging measures. For the multisensory integration measures, the complexity or content of the stimuli may influence results. In the both studies using the SIFI and the McGurk task, illusion susceptibility was reduced to the McGurk stimuli but no group differences were found for the SIFI (Schulze et al., 2021; Hare, Leung, et al., in prep). One explanation is that we may see more differences for linguistic stimuli compared to simple flashes and beeps. There were too few temporal studies to run the model, but there was a trend of a shortened temporal binding window in ADHD, although this seems to tend to depend on whether a SJ3 or a TOJ task is used. The SJ3 is less biased than the TOJ because it provides participants with a simultaneous option which minimizes bias in cases when they perceive synchrony and incorrectly choose audio-first or visual-first responses (Alcala-Quintana & García-Perez, 2013), whereas the TOJ only allows for audio-first or visual first responses. The emotional content of stimuli may affect results as larger differences in the TBW were found in trials with emotional content compared to neutral trials (Hare, Dalal, et al., in prep).

2.4.3 Methodology

The behavioural studies did not show any significant group differences between ADHD and NT individuals. Interestingly, some studies show conflicting results between behavioural and neural measures. For example, one study found enhancements in multisensory gain but a reduced EEG response in adults with ADHD compared to NT adults (McCracken et al., 2019). Further, source localization analysis suggested differences in right-hemispheric parietal brain regions to multisensory stimuli in ADHD adults (McCracken et al., 2022). Similarly, two papers from the same research group may show this discrepancy in behavioural versus imaging findings (Bisch et al., 2016; Zuberer et al., 2020). In the initial behavioural paper, the ADHD group had a greater accuracy gain in unbiased hit rates for all conditions in the NT group. In the follow-up, a reduced BOLD response to multisensory stimuli was found in the superior temporal gyrus, a key multisensory area. Neuroimaging has revealed differences to multisensory paradigms in other cases as well. Illusion susceptibility on the McGurk, which was reduced in ADHD, was related to higher connectivity in ADHD between Heschl's gyrus and auditory parabelt regions along with altered fronto-temporal network integrity during a resting-state scan (Schulze et al., 2023).

2.4.4 Limitations and future directions

There are several limitations in the extant literature that must be acknowledged in interpreting out findings. First, most studies included adult participants and not children. This does not allow us to examine how multisensory integration may change over the course of development. As mentioned, there may be an interplay between attention and multisensory integration in ADHD. Future studies should look at this by manipulating attentional demands when looking at multisensory integration, as only one known study has done this to date (Schulze et al., 2022). No known studies have looked at the impacts of multisensory integration differences in ADHD and related them to higher-order cognition measures, such as speech abilities. Overall, the multisensory integration differences in ADHD have not been well-classified and should be further examined to understand the impacts of these differences on higher-order cognition.

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Chapter 3

3 Behavioural Investigation of Multisensory Integration in Youth with ADHD

3.1 Introduction

Our perceptions of most external events are shaped by sensory inputs from multiple senses. Our sensory/perceptual systems typically combine these inputs from different sensory modalities into a unified perception, a process known as multisensory integration (Stein & Meredith, 1993). Multisensory integration is a building block in which higher-cognitive processing relies on and challenges can lead to issues in social domains (Wallace et al., 2020). Multisensory integration has been shown to mature across development and this process may be affected in different neurodevelopmental conditions, such as autism spectrum disorder (Foxe et al., 2015; Segers et al., 2020; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014; Stevenson, Baum, et al., 2017; Woynaroski et al., 2013; see Feldman et al., 2018 for review) and dyslexia (Harrar et al., 2014; Pulliam et al., 2023; van Laarhoven et al., 2018). Specifically, there is some evidence which suggests that atypical multisensory integration is more evident and adolescence, and some of these differences normalize by adulthood. Recently, within the past decade, multisensory integration has been shown to be affected in ADHD, though with mixed results (McCracken et al., 2019; Michalek et al., 2014; Schulze et al., 2021, 2022, 2023; Zuberer et al., 2020).

Attention-deficit/hyperactivity disorder (ADHD) is a highly prevalent neurodevelopmental condition with roughly 8.6% to 11.4% of youth receiving diagnoses (ages 3-17 years; Danielson et al., 2024; Espinet et al., 2022) and is characterized by inattention, hyperactivity, and impulsivity (5th ed.; DSM–5; American Psychiatric Association, 2013). Children with ADHD are more likely to have academic problems, difficulties with emotional regulation, and behavioural issues in the classroom (Coutinho et al., 2018). The cognitive aspects of ADHD, such as poor executive functioning, are often examined but evidence suggests that differences in ADHD exist as early as sensory processing. Specifically, individuals with ADHD have been shown to have atypical sensory processing across domains (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018). Although sensory processing issues are not as severe in ADHD as ASD; since sensory processing issues are part of the diagnostic criteria of ASD (5th ed.; DSM–5; American Psychiatric Association, 2013), studying sensory processing has garnered more attention in other neurodevelopmental conditions, such as ADHD. Most research on sensory processing in ADHD has concentrated on individual sensory modalities; however, real-world sensory experiences are inherently multisensory. Due to the multisensory nature of our experiences, more research should look at multisensory integration in ADHD and which factors, such as measure of multisensory integration, stimulus complexity, developmental stage, and symptom presentation may be leading to the discrepancy in findings.

3.1.1 Measurement and complexity

When using behavioural methods, multisensory integration can be quantified in multiple ways, including multisensory gain and illusion susceptibility. Multisensory gain is the improved behavioural performance in response to multisensory stimuli compared to unisensory stimuli, such as improved detection, improved localization, shorter response times, greater response accuracy and greater processing efficiency (Bremner et al., 2012). Creating conflicting information across different sensory modalities can lead to perceptual biases or illusions. The ability to perceive them is referred to as illusion susceptibility, with higher susceptibility suggesting greater integration (Stevenson, Ghose, et al., 2014). Some common examples of multisensory illusions are the McGurk effect (McGurk & MacDonald, 1976), the Ventriloquist illusion (Howard & Templeton, 1966), the rubber-hand illusion (Botvinick & Cohen, 1998), and the Sound-Induced Flash Illusion (Shams et al., 2000).

Previous behavioural research on multisensory integration in individuals with ADHD has been extremely mixed, with multiple studies suggesting that there is better multisensory integration in ADHD (Bisch et al., 2016; McCracken et al., 2019), one finding no difference (Shulze et al., 2021), and multiple finding reduced multisensory integration in ADHD (Michalek et al., 2014; Shulze et al., 2021). When looking at multisensory illusions, adults with ADHD showed a lower susceptibility to a McGurk illusion, but no differences in the Sound-Induced Flash Illusion compared to controls (Shulze et al., 2021). The authors suggested that these findings may be due to differences in stimulus complexity, with the SIFI using basic flashes and beeps, and the McGurk task using speech stimuli. This would be similar to ASD, where stimulus complexity may play a role with more linguistic stimuli showing larger multisensory integration differences compared to non-linguistic stimuli (Stevenson, Segers, et al., 2014; Stevenson et al., 2017; Zhang et al., 2019). Using multisensory gain measures, adults with ADHD benefitted less from visual information at high noise levels than healthy controls but benefitted more at lower noise levels suggesting task difficulty may also influence integration in ADHD (Michalek et al., 2014). Given these inconsistencies multisensory integration should be examined further and using different multisensory paradigms and examining ADHD presentation differences. Additionally, it should be examined whether multisensory integration differences are more prevalent in youth with ADHD compared to adults akin to other neurodevelopmental conditions.

3.1.2 Developmental Stage

Multisensory integration is slower to develop than other sensory processes (Ernst, 2008; Gori et al., 2008; Murray et al., 2016; Stevenson et al., 2018), and reaches maturity later in development with estimates ranging from fourteen to adulthood (Brandwein et al., 2011; Stevenson et al., 2018). Early on in infancy, the temporal aspects of multisensory integration are present with infants as young as four months old able to discriminate between synchronous and asynchronous multisensory stimuli but only at large temporal offsets (Lewkowicz, 1996). The window in which two stimuli need to occur to be perceived as synchronous is referred to as the TBW. As the child develops there is a developmental narrowing of the TBW which is aligned with an increased strength in multisensory integration (Noel et al., 2016). A narrower TBW window may reduce SIFI susceptibility (Stevenson et al., 2012; Setti et al., 2014), and because of the wider TBW in children they appear more susceptible to the SIFI compared to adults (Innes-Brown et al., 2011). This susceptibility decreases with age as TBW windows narrow (6 and 12; Nava & Pavani, 2013, or 4 to 11; Adams, 2016). A developmental decrease in SIFI susceptibility is consistent with the prolonged development of multisensory integration

(Ernst, 2008; Gori et al., 2008; Murray et al., 2016; Stevenson et al., 2018) and a developmental shift in sensory dominance from audition towards vision with development (Hirst et al., 2018; Nava & Pavani, 2013). This also suggests that young children would be susceptible to illusions in which audition influences vision (e.g., SIFI), but not illusions in which vision influences audition (e.g., McGurk) (Hirst et al., 2020). Corroborating this line of thinking, illusion susceptibility for the McGurk illusion has been shown to increase from childhood into adolescence (McGurk & MacDonald, 1976; Tremblay et al., 2007). Using both illusions may allow us to understand sensory dominance developmentally in ADHD.

3.1.3 ADHD Subtypes

Clinically, the DSM-5 defines three presentations of ADHD: Inattentive (IA), Hyperactive-Impulsive (HI) and combined (C) (DSM-5; American Psychiatric Association, 2013). ADHD is a heterogenous disorder, and sensory differences have been found when looking at the different subtypes/presentations (Shimizu et al., 2014). Further, clinical ADHD subtype differences have been found in several domains, such as cognition (Solanto et al., 2007), age of diagnosis (Hare et al., 2024), gender ratio (Gaub & Carlson, 1997; Ramtekkar et al., 2010; Willcutt, 2012) and comorbidity (Eiraldi et al., 1997). Due to the heterogeneity of ADHD and these subtype differences, the impact of subtype on multisensory integration in ADHD should be examined.

The current study used three experiments to assess whether multisensory integration differences exist in youth with ADHD compared to NT youth, and whether this differs by subtype presentation. The methods and analysis are pre-registered on OSF (https://osf.io/bewsm/). Multisensory integration was investigated using two measures of illusion susceptibility, specifically the McGurk effect (McGurk & MacDonald, 1976) and the SIFI (Shams et al., 2000), and one measure of multisensory gain, a speech-in-noise task (Muller et al., 2020; Sheffert et al., 1996; Stevenson et al., 2015, 2017). One key feature of this study is we increased the stimulus complexity, from low-level stimuli to speech stimuli, in each experiment to see whether this impacts multisensory integration in ADHD youth.

3.1.4 Present Study/Rationale

In Experiment 1, we used multisensory illusion comprised of simple auditory pure tones and visual beeps, the sound-induced flash illusion (Shams et al., 2000), to measure multisensory integration. In Experiment 2, we used a more complex, speech-based multisensory illusion at the level of a single syllable, the McGurk task, to measure integration. Lastly, in Experiment 3, a speech-in-noise task was used to measure perceptual benefit associated with multisensory integration for whole words in auditory noise.

We predicted that there would be no difference between ADHD and NT participants in the SIFI performance as previous studies have found no difference in adults (Hare, et al., in prep; Schulze et al., 2021). We predicted that there will be higher rates of the McGurk effect being perceived in NT participants compared to ADHD participants. A previous study in ADHD adults found lower McGurk perception and a bias towards responding to the auditory modality of the McGurk stimuli (Schulze et al., 2021). We predicted that for the speech-in-noise task there will be reduced multisensory gain in ADHD participants compared to NT participants. Previous research has found that multisensory gain was reduced during a speech-in-noise task in individuals with ADHD; at more difficult SNR levels (0 dB SPL SNR) compared to easier SNR levels (25 dB SPL SNR) (Michalek et al., 2014). Our SNR level is more difficult than previous research at -12 dB SLP, therefore, we would expect their to reduced multisensory gain in the ADHD group. In university students, ADHD traits were unrelated to multisensory gain in a speech-in-noise task show (Hare et al., in prep). Overall, as in other neurodevelopmental conditions such as autism spectrum disorder, some studies show see larger multisensory integration differences for more complex stimuli (e.g., speech and social stimuli) compared to more simple stimuli (Collignon et al., 2013; Ostrolenk et al., 2019; Stevenson, Baum, et al., 2017; Stevenson, Segers, Ferber, et al., 2014; Woynaroski et al., 2013). One possible explanation is that, more complex stimuli may rely more on top-down attentional control, as the incoming stimuli need to be compared to existing background knowledge via feedback loops to the sensory cortices (Schulze et al., 2021; Talsma et al., 2015). Due to the impairments in brain areas related with multisensory integration and attentional control, we would expect there to be a larger group difference for more complex stimuli. For each study we looked at the correlation between multisensory integration and ADHD presentation traits of inattention and hyperactive-impulsive. Additionally, whether age is related to multisensory integration was examined for each study as multisensory integration abilities develop into adolescence and adulthood (Brandwein et al., 2011; Stevenson et al., 2018).

3.2 General Materials and Methods

3.2.1 Participants

A total of 113 participants completed this study, 53 children with ADHD (21 girls, M_{age} = 10.02, age range = 4-17) and 60 NT children (23 girls, M_{age} = 9.85, age range = 4-16). Demographic information can be found in Table 3.1. Parents were asked to report when their child received a diagnosis and whether their child was taking any medications. 31 children were taking medication for their ADHD. In the NT group, 12 participants scored in the ADHD range on the SWAN and 11 were missing questionnaires. In the ADHD group, 7 participants did not score in the ADHD range on the SWAN and 6 were missing questionnaires. The ADHD group scored significantly higher on all SWAN scales compared to the NT group (all $p < .001$). IQ scores between the NT (M = 108.19, SD = 14.94, range = 79-142) and the ADHD (M = 102.38, SD = 16.43, range = 74-135) did not statistically differ $t(91) = 1.78$, $p = .08$, $d = .37$.

Parents were asked to report if their child takes stimulant medication for ADHD at time of testing or online. Participants in both groups were recruited using Western's OurBrainsCAN database (https://ourbrainscan.uwo.ca/) and community sampling. All participants were fluent in English, had parent-reported normal or corrected-to-normal hearing and vision. Ethics approval for all study procedures and materials was obtained by the University of Western Health Sciences Research Ethics Board (HSREB). Roughly half of participants completed all three experiments (N = 58), including the Sound-Induced Flash-Illusion, both unisensory and multisensory versions of the McGurk task, and the auditory, visual, and audiovisual speech-in noise task.

Table 3.1. Demographic and Survey Information for ADHD and NT Youth

	ADHD Youth (*N*=52)		NT Youth (*N*=61)	
	M	*SD*	*M*	*SD*
Age (years)	10.00	2.97	9.72	1.43
IQ	102.38	16.43	108.19	14.94
SWAN	.85	.36	.04	.20
SWAN-IA	6.87	2.11	2.62	2.53
SWAN- HI	6.02	2.96	1.76	.04

Note. For the SWAN-IA and HI, a score of 6 or above is probable for an ADHD diagnosis, and overall, for the SWAN a score of 1 suggests ADHD. There were 17 participants missing complete questionnaires, and 20 participants missing IQ scores.

3.2.2 ADHD Measure

The Strengths and Weaknesses of ADHD Symptoms and Normal Behaviour Scale (SWAN; Swanson et al., 2012) scales two subscales, inattention and hyperactive-impulsive, will be completed by parents/guardians. For each question a "not at all" or "just a little" response is coded 0 and a response of "quite a bit" or "very much" is coded as 1. A score of 6 or above, out of a possible 9 for each subscale, indicates that the child is likely to have ADHD-inattentive type or ADHD-Hyperactive/Impulsive Type. Inattention refers to trouble paying attention to details, getting easily distracted, having trouble organizing or finishing tasks. Hyperactivity-impulsivity refers to inability to sit still, fidgeting, difficulty waiting your turn and acting without thinking. This measure has demonstrated strong internal consistency of α = .95 in previous studies (Lakes et al., 2012). A score for the ADHD-combined presentation will be calculated by taking if they scored above the cut-off on both

3.2.3 IQ measure

Each child was administered the Weschler Abbreviated Scales of Intelligence II (WASI-II) Second Edition (Wechsler, 2011). The WASI-II is a quick measure of verbal, non-verbal and general cognitive ability. A Full-Scale IQ (FSIQ-2) estimate was calculated using the vocabulary subtest, which measures verbal comprehension, and the matrix reasoning, which measures perceptual reasoning. This test was given to IQ-match the samples, but participants were not excluded on the basis of IQ.

3.2.4 Demographics Information

Participants/guardians completed a demographic questionnaire about the participant which included questions about the child's sex, gender, handedness, vision, hearing, ethnicity, family income, caregiver education, child's education, child's language, child's medical history and immediate family's medical history.

3.2.5 Multisensory Analysis across Experiments

Pearson r correlations will also be conducted between all three behavioural measures to investigate whether their performance is interrelated. A power analysis was completed using effect sizes derived from Schulze et al., 2021 in which their McGurk Task in ADHD and HC adults had a large effect size (d = 0.87). An a priori power analysis for an independent samples t-test based on a power of .8, large effect size (d = 0.80), α = .05 estimated a sample of 26 ADHD and 26 NT participants was needed.

3.3 Experiment 1: Sound-Induced Flash Illusion

3.3.1 Rationale and Hypotheses

In experiment 1, we started by examining multisensory integration using simple stimuli without any semantic meaning. Beginning with low-level stimuli allows use to see if multisensory integration is affected in ADHD and to rule out finding an effect that may be contingent upon higher-level processing, such as speech. One previous study using the SIFI found individuals with ADHD did not differ from controls on illusion susceptibility, but they did differ in the McGurk task (Schulze et al., 2021). This highlights the importance of looking at different levels of processing. Experiment 1 includes a SIFI task where participants are presented with brief and simple auditory and visual stimulus pairs, typically auditory pure tones, and visual flashes. We predict that there will be no difference between ADHD and NT participants in illusion susceptibility on the SIFI performance as previous studies have found no difference in adults (Hare et al., in prep; Schulze et al., 2021). In both samples, we expect a positive relationship between illusion susceptibility and age.

3.3.2 Materials and Methods

3.3.2.1 Participants

A total of 98 participants completed this study, 45 children with ADHD (19 girls, M_{age} = 10.11, age range = 4-16) and 53 NT children (21 girls, M_{age}= 9.70, age range = 4-16).

3.3.2.2 Stimuli

The stimuli consist of visual flashes and auditory beeps presented concurrently. There are 4 multisensory conditions: 1 Flash and 1 Beep (A1V1), 1 Flash and 2 Beep (A2V1, Fusion Condition), 2 Flash and 2 Beep (A2V2), and 1 Beep and 2 Flash (A1V2, Fission Condition). The visual component of the sound-induced flash illusion (SIFI) task consisted of a white ring circumscribing the visual fixation cross on a black background. Visual stimulus duration was 10ms. Auditory stimuli consisted of 3500 Hz pure tone with a duration of 7 ms. The auditory and visual onsets were simultaneous. When multiple flashes were presented in the SIFI task, they were separated by 43 ms intervals. The task was initially introduced by Shams et al., 2000.

3.3.2.3 Procedures

Participants were instructed to count the number of flashes and ignore any beeps for all trials. After each trial, participants were asked to report whether they saw 1 or 2 flashes.

3.3.2.4 Analysis

For each of the four trial types, individuals' mean response was calculated. In the Fission illusory percept, which is more commonly studied, there is a single flash along with two beeps and the illusory percept would be anytime an individual reports two flashes. The fission illusion occurs because the brief auditory stimuli influence the number of perceived visual stimuli. The Fusion illusory percept is the opposite where there are two flashes and one beep, and the illusory percept is anytime an individual perceives one beep. For each of the trial types, each participant's mean response will be calculated, and a group average response will be calculated as a mean of individuals' means. Four indexes will be used to describe each individual's susceptibility to the illusion: absolute fission, proportion fission, absolute fusion, and proportion fusion. The following equations will be used:

$$Absolute\ Fission = A2V1 - A1V1$$

$$Proportion\ Fission = \frac{A2V1}{1 - A1V1}$$

$$Absolute\ Fusion = A2V2 - A1V2$$

$$Proportion\ Fusion = \frac{A2V2 - A1V2}{A2V2 - 1}$$

Higher Absolute Fission Scores indicate higher illusion susceptibility, as score of 0 represents the same number of flashes being perceived in Fission (A2V1) and Control (A1V1) conditions and a score of 1 represents the illusion occurred. Higher Absolute Fusion Scores

3.3.3 Results

3.3.3.1 Group Differences

Independent samples t-tests were conducted to test for differences in Absolute and Proportion Fission and Absolute and Proportion Fusion. Absolute Fission and Proportion Fission is the condition with 2 Beeps and 1 Flash, and individuals that perceive the illusion report 2 flashes; therefore, higher Absolute Fission values suggest more illusion susceptibility. Absolute Fission and Absolute Fusion are in Figure 3.1. The was not a significant difference in the Absolute Fission between the NT (*M* = .33, *SD* = .33) and the ADHD (*M* = .35, *SD* = .35) groups ($t(96) = -.35$, $p = .72$, $d = -.07$). The was not a significant difference in the Proportion Fission between the NT (*M* = .36, *SD* = .37) and the ADHD (*M* = .39, *SD* = .42) groups ($t(96) = -.36$, $p = .72$, $d = -.07$). The was not a significant difference in the Absolute Fusion between the NT (*M* = .33, *SD* = .35) and the

ADHD (*M* = .35, *SD* = .37) groups (*t*(96) = -.39, *p* =.70, *d* = -.08). There was not a significant difference in the Proportion Fusion between the NT (*M* = .55, *SD* = .44) and the ADHD (*M* = .49, *SD* = .60) groups (*t*(84) = -.61, *p* =.55, *d* = .13).

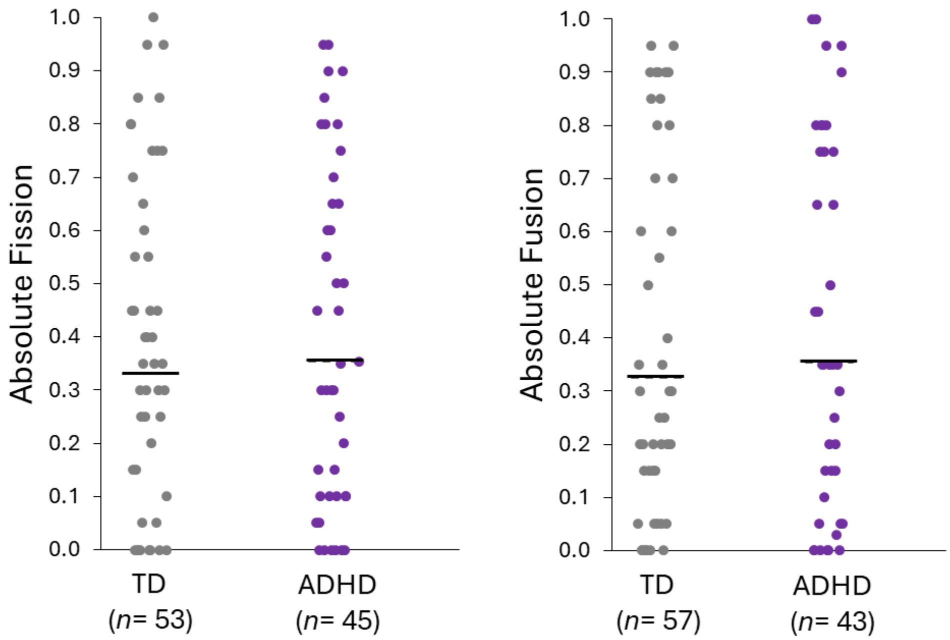

Figure 3.1. Absolute Fission and Fusion illusion susceptibility for NT and ADHD youth. Means are represented with black bars.

Correlational Analyses

Pearson r correlations were conducted to test for relationship between age and presentation traits with illusion susceptibility measures (See Table 3.2 & Figure 3.2). In the full sample, age was significantly positively correlated with higher illusion susceptibility in three measures.

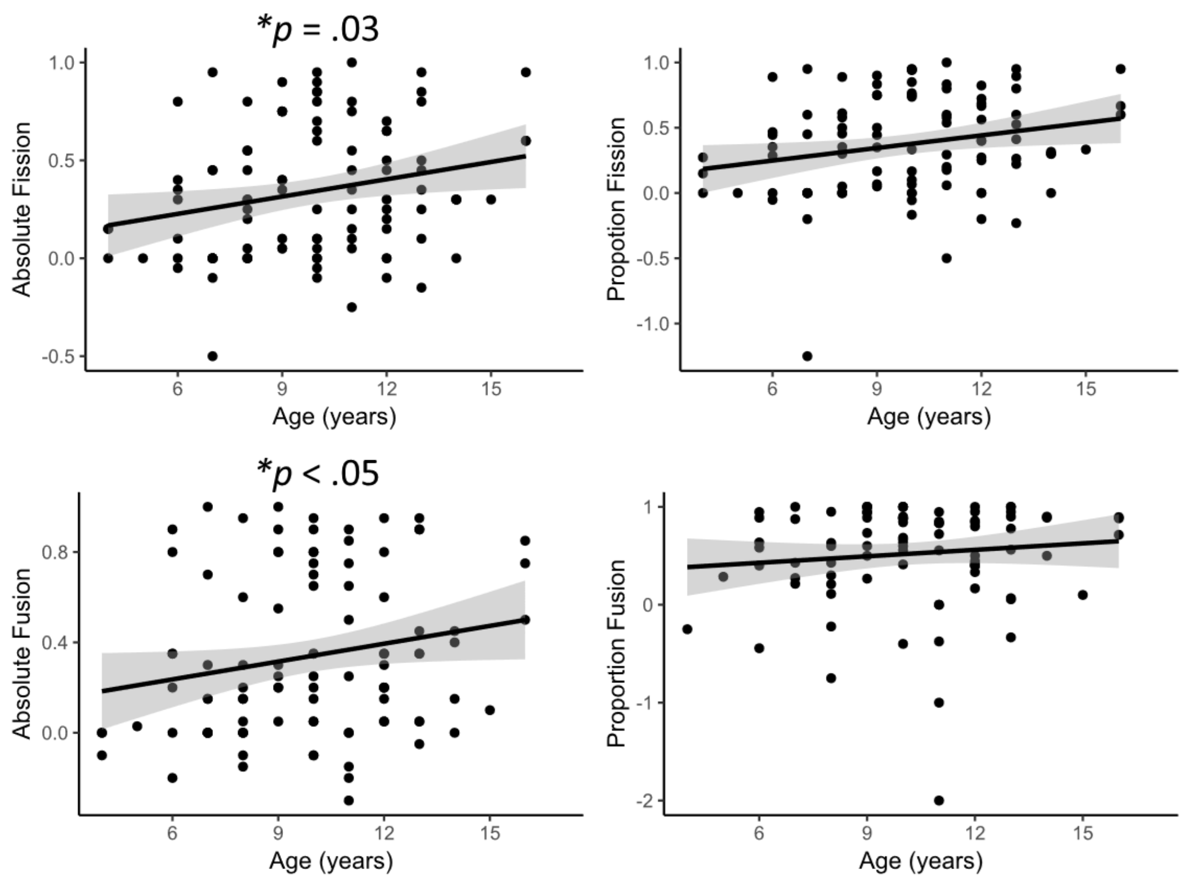

Figure 3.2. Scatterplots of Age versus Various Measures of SIFI Illusion susceptibility. Each plot displays a scatterplot of individual data points, with a linear trendline and 95% confidence intervals.

In NT youth, age was significantly correlated with Absolute Fission ($r(53) = .30$, $p = .03$) but the other measures of illusion susceptibility were not related to age Proportion Fission ($r(53) = 25$, $p = .07$), Absolute Fusion ($r(53) = .22$, $p = .11$), Proportion Fusion ($r(45) = .16$, $p = .31$). In ADHD youth, age was not significantly correlated with Absolute Fission ($r(45) = .17$, $p = .27$), Proportion Fission ($r(45) = .20$, $p = .19$), Absolute Fusion ($r(45) = .17$, $p = .26$), and Proportion Fusion ($r(41)= .08$, $p= .63$). A Fisher Z-test suggests there is no significant difference between the ADHD and NT groups correlations with age (range: $p = .25$ to $p =.46$).

Table 3.2. Correlations between age and ADHD subtypes with illusion susceptibility measures

	Absolute Fission		Proportion Fission		Absolute Fusion		Proportion Fusion	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Age	.24	.02	.23	.03	.20	<.05	.11	.32
SWAN-IA	-.11	.33	-.11	.33	-.07	.55	-.12	.31
SWAN-HI	-.08	.47	-.10	.39	-.04	.70	-.11	.38
SWAN-C	-.003	.98	-.01	.93	.03	.77	-.04	.75

Note. *N* = 98 for age. *N* = 82 for SWAN correlations.

3.3.4 Discussion

There was not a significant difference between NT and ADHD groups on all measures of illusion susceptibility. Further, there was no difference between ADHD presentation traits and measures of illusion susceptibility. These findings are in line with our hypotheses that we would not find differences and agree with previous research in adults (Hare et al., in prep; Schulze et al., 2021). Higher age was related to increased illusion susceptibility for three of the four measures of illusion susceptibility. This is inconsistent with prior literature which suggest that children appear more susceptible to the SIFI compared to adults (Innes-Brown et al., 2011) and susceptibility decreases with which suggests that SIFI susceptibility decreases with age (6 and 12; Nava & Pavani, 2013, or 4 to 11; Adams, 2016). A developmental decrease in SIFI susceptibility is consistent with the prolonged development of multisensory integration (Ernst, 2008; Gori et al., 2008; Murray et al., 2016; Stevenson et al., 2018) and a developmental shift in sensory dominance from audition towards vision with development (Hirst et al., 2018; Nava & Pavani, 2013). Further, children younger than 8 have been shown to use a modality switching strategy (Adams, 2016). The SIFI arises from modulation of the visual cortex by auditory and multisensory areas (For review, see Hirst et al., 2020). Due to these differences in younger children's sensory systems, SIFI susceptibility in this group may not arise from the same optimal integration processes shown in adults (Odegaard & Shams, 2016; Shams et al., 2005; Wozny et al., 2008). A narrower TBW windows may be related to lower SIFI illusion susceptibility (Setti et al., 2014) and individuals with high ADHD traits have been related to narrower TBWs in some contexts (Hare et al., in press; Panagiotidi et al., 2017).

3.4 Experiment 2: McGurk

3.4.1 Rationale and Hypotheses

In experiment 2, we increased stimulus complexity from low-level flashbeep stimuli to single-syllable speech stimuli. Stimuli with higher complexity, such as speech, has previously been shown to be associated with more multisensory integration differences in individuals with neurodevelopmental conditions, compared to stimulus with lower stimulus complexity, such as flashes and beeps. For example, a weaker McGurk effect due to reduced perceptual binding of audiovisual speech signals has been found in ASD (Stevenson et al., 2017; Stevenson, Segers, et al., 2014; Zhang et al., 2019), whereas some SIFI studies find no group differences (Keane et al., 2010, van der Smagt et al., 2007) and some with reduced susceptibility in ASD (Foss-Feig et al., 2010, Stevenson, Siemann, Woynaroski, et al., 2014). Previous research in ADHD adults has found a lower susceptibility to a McGurk illusion, but no differences in the Sound-Induced Flash Illusion (SIFI) compared to controls (Schulze et al., 2021). Further, ADHD adults responded favouring the auditory presentation (Schulze et al., 2021) and ADHD individuals have shown auditory hypersensitivity (Micoulaud-Franchi et al., 2015) and possibly increased auditory cross modal activity in the visual cortex (Schramm et al., 2023). In Experiment 2, participants were presented with a speaker uttering the auditory syllable “ba” in combination with the speaker visually articulating the syllable “ga”. Participants commonly report perceiving the speaker saying “da” or “tha”, a syllable that is not present in either of the unisensory stimuli, and this percept (the McGurk Effect) is strong evidence of multisensory integration. If we find no differences in illusion susceptibility for the SIFI in Experiment 1, but we do find group differences in McGurk illusion then this would suggest that stimulus complexity or type of stimuli differentially impacts multisensory integration in individuals with ADHD. We predict that there will be higher rates of the McGurk effect being perceived in NT participants compared to ADHD participants. In our study we will be asking what syllable the speaker said in modality-neutral wording ("What did she say?"), whereas the previous research had a bias towards the auditory modality.

3.4.2 Materials and Methods

3.4.2.1 Participants

A total of 95 participants completed this study, 41 children with ADHD (17 girls, M_{age} = 10.42, age range = 5-16) and 54 NT children (22 girls, M_{age} = 9.74, age range= 4-16). Participants were only included in the analysis if they completed both the unisensory and multisensory McGurk tasks.

3.4.2.2 Stimuli

The videos presented in the McGurk task have been previously used in studies of the McGurk effect (Quinto et al., 2010; Stevenson, Siemann, et al., 2014; Muller et al., 2020). Stimuli include visual-only, auditory-only, and congruent audiovisual presentations of the phoneme "ba" or "ga," and the incongruent McGurk stimuli, a visual "ga" presented with an auditory "ba". All presentations are temporally synchronous.

3.4.2.3 Procedures

The task was divided into a multisensory run followed by a unisensory run. The audiovisual run included congruent "ba" and "ga" presentations, as well as the McGurk stimulus, an auditory "ba" paired with a visual "ga". The run began with a screen instructing participants to identify what syllable the speaker said in modality-neutral wording "What did she say?" to not bias the participant towards the auditory or visual modality. Each trial began with a fixation screen, randomly jittered from 0.5 to 1.5s. Eight-speaker multitalker babble then ramped up linearly for 500 ms, at which point the stimulus was presented, with babble continuing during the stimulus presentation. After the stimulus presentation, the multi-speaker babble persisted for another 500 ms with a linear ramp down. Each trial was finished with an additional 250 ms fixation screen.

After each presentation, participants were shown a response screen and asked to identify what the speaker said, "ba," "ga," "da," and "tha,", by pressing one of four keys, "b," "g," "d," or "t," respectively. Immediately after responding, the jittered fixation screen for the subsequent trial was presented. In the multisensory run, participants were presented with a total of 60 trials, with each audiovisual condition presented 20 times in random order.

The unisensory run followed the same structure as the multisensory run, except the stimuli were either visual-only or auditory-only presentations of "ba" or "ga". Each unisensory condition was presented 10 times, for a total of 40 trials. Unisensory runs were always presented second to avoid participants realizing that there were no unisensory "da" or "tha" presentations.

3.4.2.4 Analysis

For each of the six non-McGurk conditions, an accuracy score was calculated for each participant. This was calculated as the proportion of trials the participant accurately identified as the syllable that was presented. Average visual accuracy was calculated as the average proportion of visual-alone trials perceived correctly as "ba" or "ga". Average auditory accuracy was calculated as the average proportion of auditory-alone trials perceived correctly as "ba" or "ga". For the McGurk trials, we calculated the proportion of trials the participant reported having perceived "da" or "tha". To account for some individuals' increased reporting of "da" or "tha" in the absence of the illusion, the absolute change from unisensory to multisensory reports of "da" or "tha" was calculated ("da" alone will be used in the following equation for simplicity):

$$p(da|AV\ McGurk) - \left[p(da|A_{ba}) + p\left(da\middle|V_{ga}\right) - \left(p(da|A_{ba}) * p\left(da\middle|V_{ga}\right)\right)\right],$$

where p(AV McGurk) represents the individual's proportion of McGurk percepts with audiovisual McGurk stimuli, and $\left[p(da|A_{ba}) + p\left(da\middle|V_{ga}\right) - \left(p(da|A_{ba}) * p\left(da\middle|V_{ga}\right)\right)\right]$ represents the probability summation that a participant would report perceiving a "da" or "tha" in response to the presentations of the McGurk stimulus' unisensory components. A t-test was be used to compare illusion susceptibility of the ADHD and NT groups, using the perception of the McGurk effect.

3.4.3 Results

The proportion of phonemes perceived are shown for each individual in Figure 3.3.

3.4.3.1 Group Differences

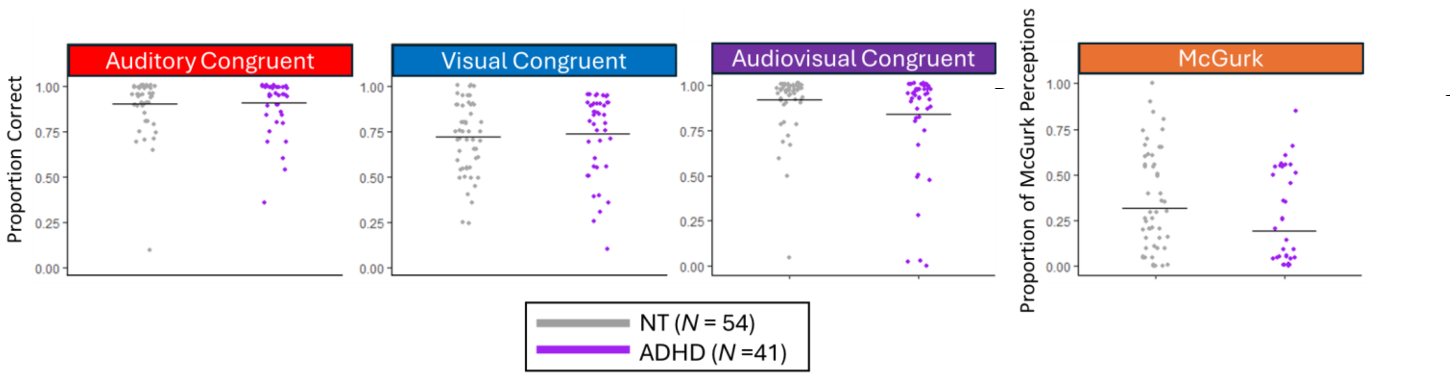

Figure 3.3. Proportion of phonemes perceived for audiovisual, auditory, and visual trials

Independent samples t-tests were conducted to test for differences in the perceived McGurk effect for the ADHD and NT groups. There was a significant difference in the perceived McGurk effect (t(93) = 2.18, p =.03, d = .45), with significantly more McGurk phonemes perceived in the NT group (M = .33, SD= .29) compared to the ADHD group (M =.20, SD =.25). There were no significant differences between groups in the phonemes perceived for the auditory, visual, and congruent audiovisual stimuli.

3.4.3.2 Correlational Analyses

Correlational analyses are presented in Figure 3.4. Inattentive symptoms from the SWAN were trending significantly with McGurk perception (r(91) = -.20, p = .06). Hyperactive-Impulsive symptoms were trending significantly correlated with McGurk perception (r(90) = -.21, p = .05). The overall combined SWAN score was significantly correlated with McGurk Perception (r(90) = -.32, p = .002). Age was significantly positively correlated with McGurk perception in both samples (r(106) = -.27, p = .005). In NT youth, age was significantly correlated with McGurk perception (r(59) = .38, p =

.003). In ADHD youth, age was not significantly correlated with McGurk perception ($r(47) = .19$, $p = .22$). A Fisher Z-test suggests there is no significant difference between the ADHD and NT groups correlations with age ($p = .17$.

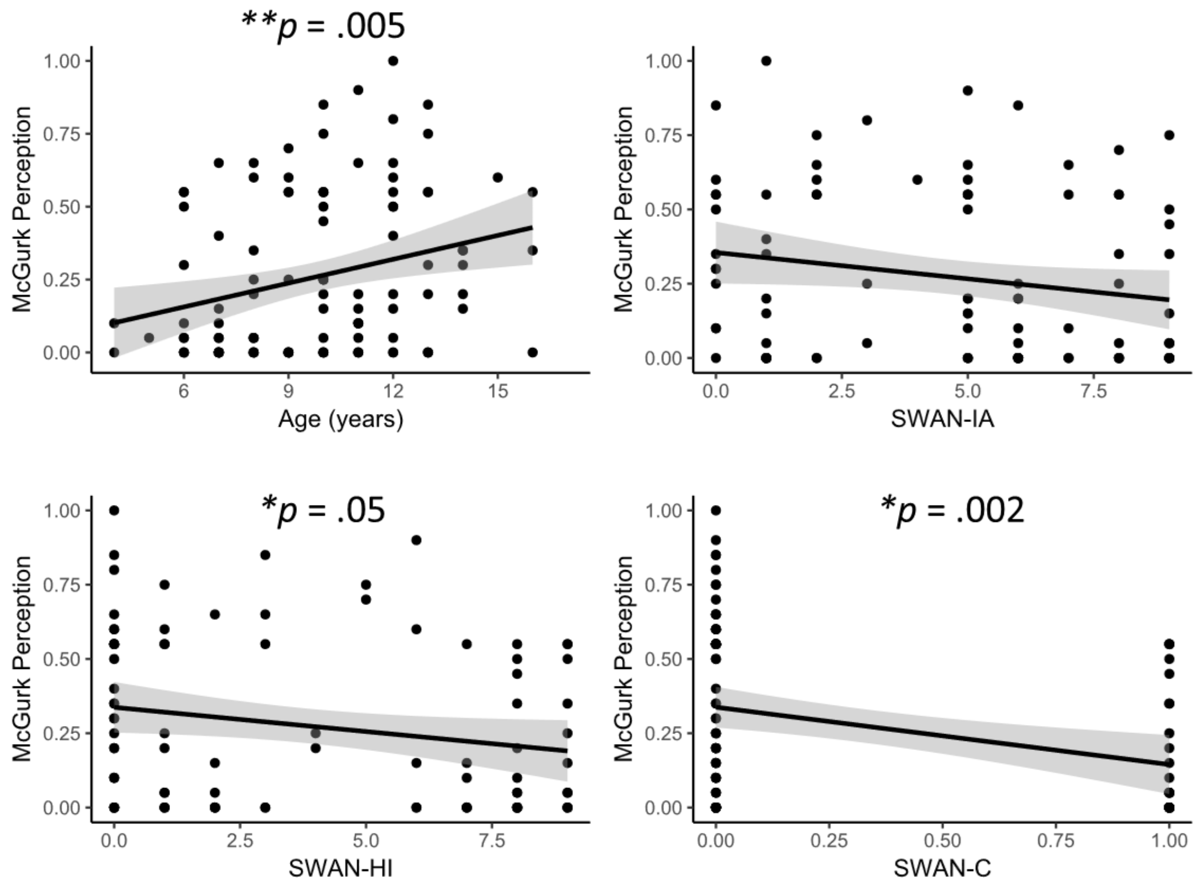

Figure 3.4. Scatterplots of Age and ADHD measures versus McGurk Illusion Susceptibility. Each plot displays a scatterplot of individual data points, with a linear trendline and 95% confidence intervals.

3.4.4 Discussion

NT children had a higher susceptibility of the McGurk illusion compared to the ADHD children. This is in line with our predictions and previous literature (Schulze et al., 2021). On the other hand, we did not find the same preference for the auditory modality to the McGurk stimuli as the previous literature showed. There was not a significant difference in ADHD presentation, with both hyperactive-impulsive traits being significantly negatively associated with McGurk perception and inattentive traits being trend negatively associated with McGurk perception. Previous research looking at ADHD-traits in a university population found that ADHD traits were not related to McGurk susceptibility, but this may suggest we only see deficits when the ADHD traits are in the clinical range.

McGurk perception was related to older age in the full sample, with no difference in this relationship between NT and ADHD. This is consistent with prior research which suggests McGurk susceptibility increases with age (Tremblay et al., 2007). As mentioned, children demonstrate a preference for auditory information when processing multisensory events, and this shifts to vision having a larger influence in adulthood (Hirst et al., 2018; Nava & Pavani, 2013). Given studies in adult find lower McGurk susceptibility in ADHD individuals, and that the correlation was not stronger for age in the ADHD group compared to the NT group, this may suggest that the multisensory integration deficit may not normalize by adulthood. As there were no differences in illusion susceptibility for the SIFI, but there were differences for McGurk this suggests that stimulus complexity may play a role in whether multisensory integration is affected in ADHD. Similar to research in other NDCs, such as ASD, differences in multisensory integration are sometimes found to be more pronounced using more complex or social stimuli, such as speech (Baum et al., 2015; Stevenson et al., 2016).

3.5 Experiment 3: Speech in Noise

3.5.1 Rationale and Hypotheses

In experiment 3, we are examined if multisensory integration is different in ADHD youth compared to NT youth using a speech-in-noise task. This speech-in-noise task (Muller et al., 2020, Stevenson et al., 2015; Stevenson, Segers, et al., 2017), requires participants to identify words in the presence of noisy background speech to measure audiovisual speech perception. The speech-in-noise task measured multisensory integration by comparing speech in unisensory and multisensory conditions. Previously, during an audiovisual speech-in-noise task young adults with ADHD benefitted less from visual information in high noise levels (0 SNR) than NT young adults but benefitted more at lower noise levels (25 SNR) (Michalek et al., 2014). Previous results for speech-in-noise task in non-clinical adults showed that ADHD traits did not impact performance (Hare et al., in prep). Task difficulty may be related to multisensory integration in ADHD (Michalek et al., 2014). In a visual search task with varying perceptual load, adults with ADHD showed similar levels of multisensory integration as NT adults (Schulze et al., 2022). In low load conditions adults with ADHD showed enhanced multisensory integration, but in high load conditions only the neurotypical adults showed evidence of multisensory integration. Multisensory gain has been shown to be affected in high noise conditions and with high perceptual load, therefore, we expect there to be reduced multisensory gain in ADHD youth compared to NT youth, as the high level of background noise may reduce gain. In experiment 3, we are using more complex speech stimuli than the McGurk task and measuring multisensory gain instead of multisensory illusion susceptibility. Further, some evidence suggests that multisensory integration may be affected by perceptual load more in adults with ADHD compared to NT adults, with multisensory integration being stronger in the low load adults with ADHD compared to NT adults but no group differences in high load (Schulze et al., 2022). We also expect multisensory gain to increase with age.

3.5.2 Materials and Methods

3.5.2.1 Participants

A total of 63 participants completed this study, 37 children with ADHD (15 girls, M_{age} = 10.76, age range = 6-17) and 26 NT children (9 girls, M_{age} = 10.12, age range = 6-16), with an additional 6 participants who were removed for not completing all tasks.

3.5.2.2 Stimuli

Stimuli for the speech-in-noise task included audiovisual recordings of a female speaker saying 72 triphonemic words. Stimuli were selected from a previously published stimulus set, The Hoosier Audiovisual Multi-Talker Database (Sheffert et al., 1996). All stimuli were spoken by speaker F1. The stimuli selected were monosyllabic English words that were matched across sets for accuracy on both visual-only and audio-only recognition (Lachs & Hernandez, 1998), and were also matched across sets in lexical neighborhood density (Luce & Pisoni, 1998; Sheffert et al., 1996). Audio signal levels were measured as root mean square (RMS) contrast and equated across all words. All stimuli lasted 2 s and included all pre-articulatory gestures. Visual stimuli were grayscale and square, spanning 9.9 cm per side or 9.43◦ of visual angle. This set of single words has been used successfully in previous studies of multisensory integration and with NDDs samples (e.g., Stevenson et al., 2015). All presentations included 8-channel multitalker babble at 66 dB SPL. The presentation of auditory babble presentation began 500 ms prior to the beginning of the word and ended 500 ms following the end of the word. The RMS of the auditory babble was linearly ramped up and down, respectively, during the pre- and post-stimulus 500 ms periods, and was presented with the first and last frames of the visual word, respectively. Auditory stimuli were presented at a signal-to-noise ratios (SNR) of 54 dB (− 12 dB SPL). Auditory decibel levels and SNRs were chosen in accordance with previous studies using this stimulus set and analysis (Stevenson et al., 2015; Stevenson, Segers, et al., 2017, Stevenson, Baum, et al., 2017).

3.5.2.3 Procedures

Each participant is presented with three separate runs of 24 single-word presentations, for a total of 72 words at -12 dB SNR. The presentations include a visual-only presentation, an auditory-only presentation, and a multisensory (audiovisual) presentation, which all include auditory multitalker babble. The stimuli are from The Hoosier Audiovisual Multitalker Database (Sheffert, Lachs, & Hernandez, 1996), which have previously been used successfully in studies of multisensory integration (Stevenson et al., 2010; Stevenson et al., 2010, 2017; Stevenson, James, et al., 2009; Stevenson, Kim, et al., 2009; Muller et al., 2020).

3.5.2.4 Analysis

As done previously (Muller et al., 2020, Stevenson et al., 2015 Stevenson, Segers, et al., 2017), responses were scored at both the whole-word level and at the phoneme level. Whole words were scored as correct only if the entire word reported was correct. Each tri-phonemic word was also scored on the proportion of phonemes that were perceived correctly. Word and phoneme accuracies were calculated as the average score across all trials for each condition. Multisensory gain was calculated by comparing accuracy scores in audiovisual trials relative to the predicted audiovisual accuracy based on the unisensory component accuracies assuming independence, using the following equation (Stevenson et al., 2015):

$$\widehat{pAV} = p(A) + p(V) - [p(A) * p(V)]$$

where $\widehat{pAV}$ represents a null hypothesis of the response to audiovisual presentations if the auditory and visual information are processed independently, and where p(A) and p(V) represent response accuracy to auditory- and visual-only presentations, respectively. For word accuracy, phoneme accuracy and phoneme detection, absolute increase and proportion increase was calculated. Absolute increase was calculated as:

$$oberserved\ AV\ accuracy - \widehat{pAV}\ accuracy$$

Proportion increase was calculated as:

$$\frac{observed\ AV\ accuracy - \widehat{pAV}\ accuracy}{1 - \widehat{pAV}\ accuracy}$$

A t-test will be used to compare multisensory gain (absolute increase) of the ADHD and NT groups. Further, a correlation between multisensory gain and ADHD traits will be conducted.

3.5.3 Results

The proportion of word and phoneme accuracy for all three conditions (visual, auditory, and audiovisual) and the absolute and proportion increase the speech-in-noise task are shown in Figure 3.5. A positive value indicates multisensory gain. One outlier (± 3 SD) from the ADHD group was removed.

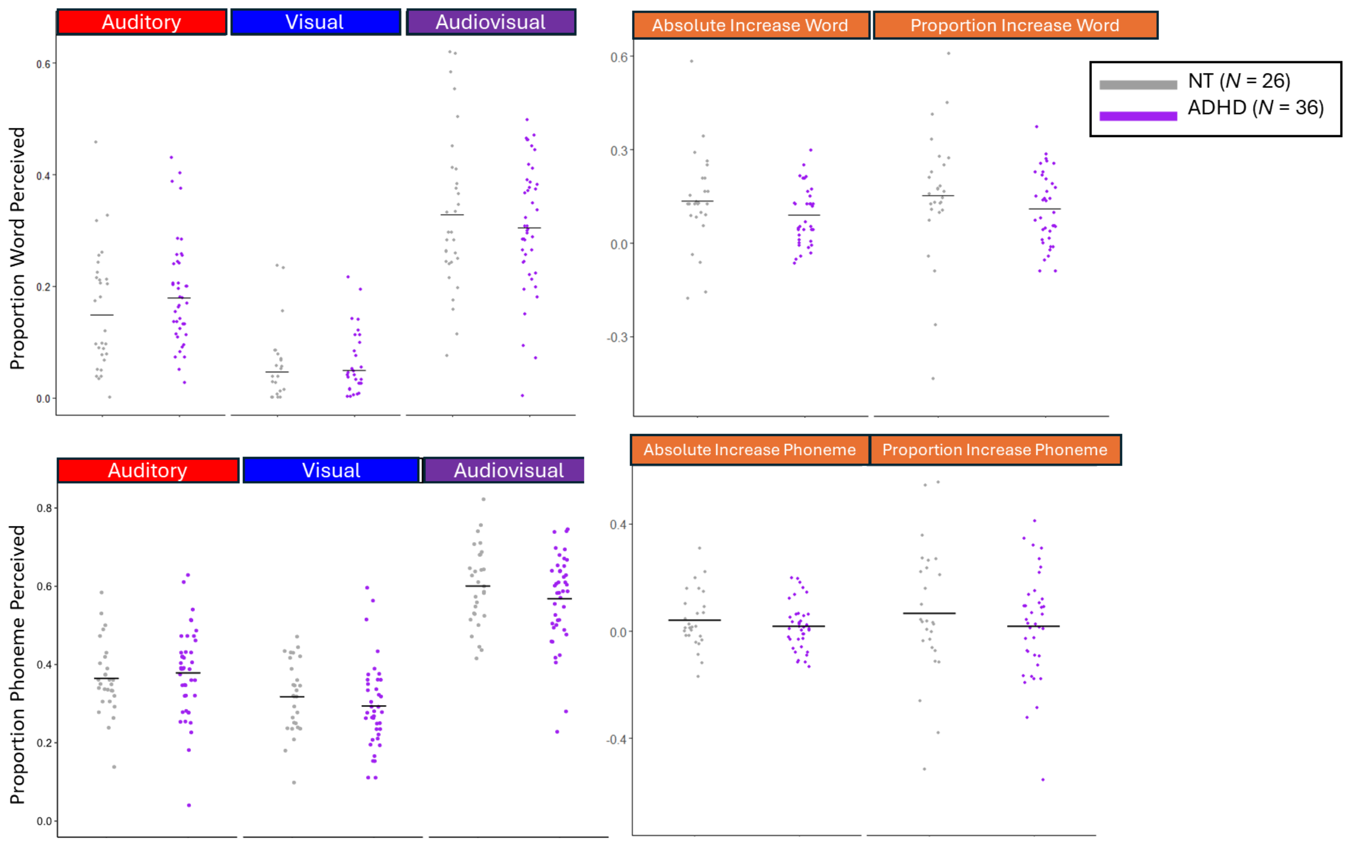

Figure 3.5. Proportion of word and phoneme accuracy for visual, auditory, and audiovisual conditions of the speech-in-noise task, as well as audiovisual gain. Black lines indicate group means.

3.5.3.1 Group Differences

There was not a significant difference in the Absolute Increase Word between the NT (*M* = .14, *SD* = .15) and the ADHD (*M* = .09, *SD* = .10) groups ($t(60) = 1.33$, $p = .19$, $d = .34$). There was not a significant difference in the Proportion Increase Word between the NT (*M* = .15, *SD* = .21) and the ADHD (*M* =.11, *SD* = .12) groups ($t(60) = .96$, $p = .34$, $d = .25$). There was not a significant difference between the Absolute Increase Phoneme in the NT (*M* = .04, *SD* = .11) and the ADHD (*M* = .01, *SD* = .10) groups ($t(60) = .83$, $p = .41$, $d = .21$). There was not a significant difference in the Absolute Increase Word between the NT (*M* = .06, *SD* = .24) and the ADHD (*M* = .02, *SD* = .20) groups

($t(60) = .75$, $p = .46$, $d = .19$). There were no significant group differences in word and phoneme accuracy for all three conditions.

3.5.3.2 Correlational Analyses

Pearson r correlations were conducted to test for relationship between age and presentation traits with illusion susceptibility measures (See Table 3.3 & Figure 3.6). Age was not related to multisensory gain in the full sample, in NT youth, or in ADHD youth. Hyperactive-Impulsive presentation traits were trending negatively correlated with measures of multisensory gain for phonemes.

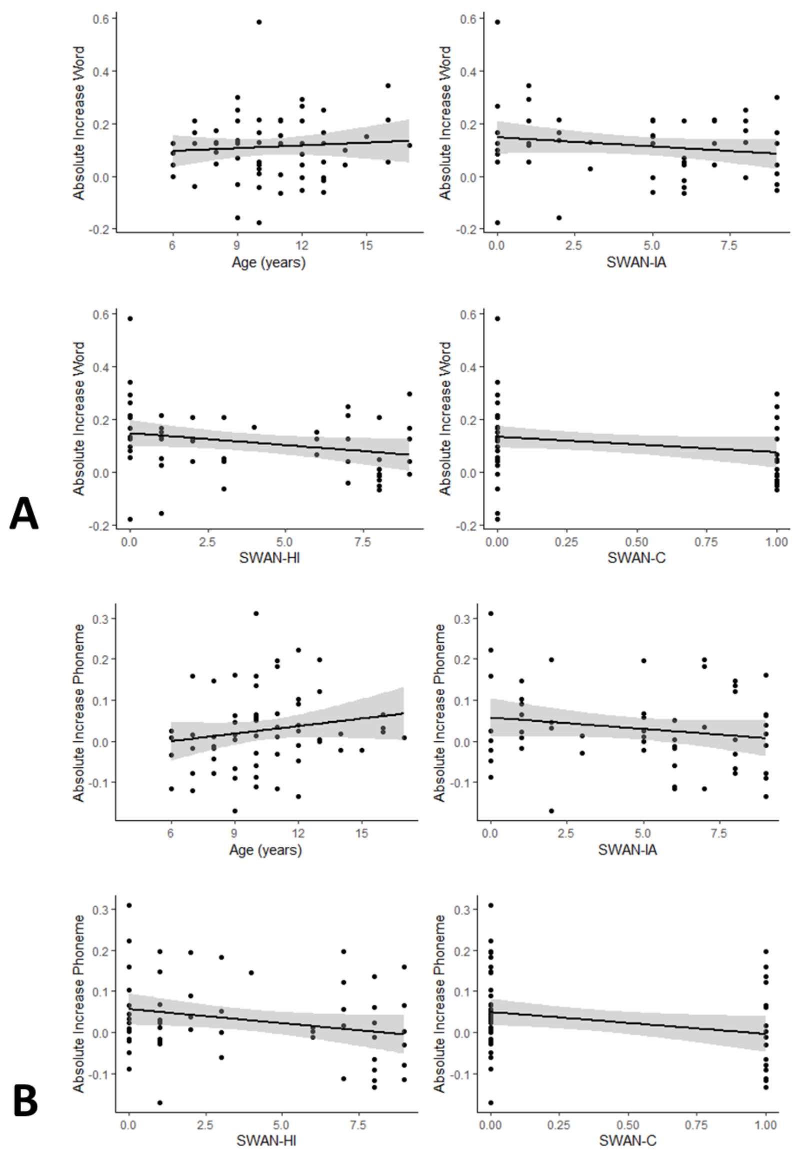

Figure 3.6. (A) Scatterplots of Age and ADHD measures versus Multisensory Gain for Words. (B) Scatterplots of Age and ADHD measures versus Multisensory Gain for Phonemes.

Table 3.3. Correlations between age and ADHD subtypes with measures of multisensory gain in the speech-in-noise task

	Word				Phoneme			
	Absolute		Proportion		Absolute		Proportion	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Age	.06	.67	.12	.39	.16	.27	.17	.24
SWAN-IA	-.17	.23	-.13	.37	-.13	.37	-.18	.21
SWAN-HI	-.23	.09	-.20	.16	-.25	.07	-.24	.09
SWAN-C	-.22	.10	.21	.13	-.32	.02	-.32	.02

Note. $N = 53$.

3.5.4 Discussion

There was not a significant difference in multisensory gain in phoneme accuracy or word accuracy between the NT and ADHD group. We found that higher Hyperactive-Impulsive symptoms were trend related to lower multisensory gain in phoneme accuracy. We hypothesized less multisensory gain in the ADHD group, and our results are partially in line with this. As mentioned, reduced multisensory gain has been found at high noise levels and when perceptual load is increased (Schulze et al., 2022). Previous research has found that multisensory gain was reduced during a speech-in-noise task in individuals with ADHD; at more difficult SNR levels (0 SNR) compared to easier SNR levels (25 SNR) (Michalek et al., 2014). Previous lab results for speech-in-noise task show that ADHD traits in university students did not impact performance (Hare et al., in prep). Our task was set at a more difficult SNR level than the initial study, and we see some evidence for reduced multisensory gain in participants with high Hyperactive-Impulsive traits. Auditory only studies have found that noise levels may impact sensory discrimination in ADHD, as noise levels increased both ADHD and NT groups showed decreased sensory discrimination (Tien et al., 2019). The ADHD showed lower discrimination ability than the NT group, even though both groups successfully detected signal against noise levels from 35 to 55 dB. Further, in this study they found no differences related to ADHD presentation.

Due to inverse effectiveness, at different SNR levels we see varying levels of multisensory gain. However, our results may not show a group difference because the SNR is so low. There appears to be an ideal noise range where individuals with ADHD perform better than individuals without ADHD, but if that noise is beyond this level, then the benefits disappear (Michalek et al., 2014). Previous research has found an optimal multisensory integration at specific levels of noise, in NT adults and other populations (Foxe et al., 2015; Stevenson, et al., 2015, 2017). Background white noise has been shown to be helpful to cognitive performance in ADHD, but babble has been shown to increase task difficulty ratings (Batho et al., 2020; Söderlund et al., 2007). Age was not significantly correlated with multisensory gain, which is not consistent with our predictions or previous literature (Brandwein et al., 2011; Foxe et al., 2015; Ross et al., 2011), nor with results in experiments 1 and 2, though again, this may be due to the low SNR.

3.6 Relating measures of Multisensory Integration across Experiments

Pearson r correlations were run for multisensory integration measures of participants who completed all three tasks. The correlations between each experiment's measures of multisensory integration for the participants that completed all three experiments (*N*=60) are shown in Table 3.4. McGurk Perception and the Absolute Increase Word from the speech-in-noise were trending related. No other study measures were correlated.

Table 3.4. Correlations between each experiment's multisensory integration measures.

	1.		2.		3.		4.	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
1. Absolute Fission	-	-						
2. Absolute Fusion	.83	<.001	-	-				
3. McGurk Perception	.19	.14	.09	.51	-	-		
4. Absolute Increase Word	.07	.62	.01	.93	.22	.09	-	-
5. Absolute Increase Phoneme	-.004	.97	.05	.71	.11	.39	.65	<.001

Note. *N* = 60. For simplicity we only included the absolute measures and not the proportion, as results were similar.

3.7 General Discussion

The current study examined multisensory integration in youth with ADHD, using three common multisensory tasks. We hypothesized that in the SIFI there would be no group differences in multisensory integration, but for both the McGurk and speech-in-noise task, that multisensory integration would be reduced in the ADHD group. Our findings for illusion susceptibility on the SIFI and McGurk tasks are in line with our hypotheses and previous literature. We found no group differences for the speech-in-noise task. Further, we hypothesized that multisensory integration differences would be more strongly related to the hyperactive-impulsive symptom presentation. We only found support for this in the speech-in-noise task. Lastly, we expected multisensory integration to be affected by age for each task, and we only found partial support for this.

Our findings for illusion susceptibility were in agreement with the previous research in ADHD adults (Schulze et al., 2021). Since there were group differences in the McGurk and not the SIFI, it is possible that stimulus complexity or speech processing may influence multisensory integration in ADHD. In auditory only studies, differences in detection abilities between pure tones and speech sounds may provide an additional explanation for differences in illusion susceptibility between the tasks. The ability to detect pure tones in children with ADHD is largely comparable to that of NT individuals (Fuermaier et al., 2018), with notable differences emerging in the auditory perception of speech sounds (Lucker et al., 1996; Söderlund & Jobs, 2016). Specifically, children with ADHD exhibit significantly lower recognition thresholds for speech sounds compared to NT children (Lucker et al., 1996; Söderlund & Jobs, 2016). The previous multisensory illusion study suggested that the McGurk task includes more complex stimuli which rely on top-down influences, whereas the SIFI task includes more simple stimuli relying on bottom-up mechanisms (Schulze et al., 2021). Similarly, we predicted that due to alterations in brain areas and networks related to multisensory integration and attentional control in ADHD, we expected there to be larger group differences and reduced multisensory integration for more complex stimuli compared to simple stimuli in youth with ADHD. In both studies, there was evidence of this relationship. They also found that the ADHD group preferred to respond with the phoneme in the auditory modality, which may have been due to how the question was phrased as they were asked to report what they heard. In our results, we did not find a difference as to whether participants responded with the visual or auditory modality. The previous study was done in adults which often rely more on the visual modality, and in our study, we examined youth which may rely more on the auditory modality or have a mixed strategy. It is possible that ADHD adults may continue to rely more on the auditory modality than NT adults. The inattentive and hyperactive-impulsive traits were not differentially related to task performance. One study looking at ADHD traits in university students found no relationship between illusion susceptibility on the SIFI and McGurk (Hare et al., in prep), which may suggest that symptoms may need to be at clinical levels to find differences in multisensory integration.

Higher age was related to increased illusion susceptibility for illusion susceptibility in the SIFI and McGurk. For the SIFI, this is inconsistent with previous research which suggest that children appear more susceptible to the SIFI compared to adults (Innes-Brown et al., 2011) and susceptibility decreases with which suggests that SIFI susceptibility decreases with age (6 and 12; Nava & Pavani, 2013, or 4 to 11; Adams, 2016). For the McGurk, this is consistent with previous research which suggests McGurk susceptibility increases with age (Tremblay et al., 2007). Further, children demonstrate a preference for auditory information when processing multisensory events and in the SIFI illusion auditory events affect vision (Hirst et al., 2018; Nava & Pavani, 2013). Later, there is a shift to vision having a larger influence on multisensory events, and in the McGurk illusion vision affects auditory events (Hirst et al., 2018; Nava & Pavani, 2013).

For the speech-in-noise task, there was not a significant difference in multisensory gain in phoneme accuracy or word accuracy between the NT and ADHD group. There was a trend-level relationship between higher Hyperactive-Impulsive symptoms were related to lower multisensory gain in phoneme accuracy. We hypothesized less multisensory gain in the ADHD group, and our results are partially in line with this. As mentioned, reduced multisensory gain has been found at high noise levels and when perceptual load is increased (Schulze et al., 2022). Previous research has found that multisensory gain was reduced during a speech-in-noise task in individuals with ADHD; at more difficult SNR levels (0 SNR) compared to easier SNR levels (25 SNR) (Michalek et al., 2014). There appears to be an ideal noise range where individuals with ADHD perform better than individuals without ADHD, but if that noise is beyond this level, then the benefits disappear (Michalek et al., 2014). Previous lab results for speech-in-noise task show that ADHD traits in university students did not impact performance (Hare et al., in prep). Our task was set at a more difficult SNR level than the initial study; however, we only included one SNR level for the speech-in-noise task where group differences may depend on SNR level. At our difficult SNR we see some evidence for reduced multisensory gain in participants with high Hyperactive-Impulsive traits. Of note, our sample size was smaller for this experiment compared to the two prior which may have attributed to non-significant effects. Age was not significantly correlated with multisensory gain, which is not consistent with our predictions or previous literature (Brandwein et al., 2011; Foxe et al., 2015; Ross et al., 2011), nor with results in experiments 1 and 2. Further, McGurk illusion susceptibility and the multisensory gain for words from the speech-in-noise were trending related.

3.7.1 Limitations and Future Directions

This is the first known study to look at multisensory integration across several tasks in youth with ADHD. There are some limitations for these studies. First, we kept participants on their usual medication regiment, so some participants were on medication where others were not. Some previous studies have opted to have participants not take their medication (Schulze et al., 2021), but research is inconclusive as to whether it affects sensory processing (Kim et al., 2015; Pfeiffer et al., 2015). We had less participants complete the speech-in-noise task compared to the other tasks and the largest effect size for the task was (d = .37). We would have required a larger effect size (d = .72) with our sample size to get a significant group difference if power was .80.

Future studies should use different SNR levels for the speech-in-noise task to see if multisensory gain is affected in ADHD youth by SNR level. Whether medication use affects multisensory integration in ADHD should be examined. Using a larger sample size in the future, would allow for more age-based analysis to look at the developmental trajectory of multisensory integration in ADHD and whether ADHD participants responding preferentially to a single modality is affected by age.

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Chapter 4

4 Audiovisual Multisensory Integration in Youth with ADHD: An EEG Investigation.

4.1 Introduction

Our sensory experiences are inherently multisensory in nature as we are constantly taking in sensory information across different modalities from the environment. Our ability to combine these experiences into one perceptual experience is referred to as multisensory integration. Multisensory integration develops slower than the other sensory abilities (Ernst, 2008), with the estimates ranging from 14 to adulthood for when it reaches maturation (Brandwein et al., 2011; Stevenson et al., 2018). In childhood, there is a developmental shift in sensory dominance from audition towards vision with development (Hirst et al., 2018; Nava & Pavani, 2013). Further, children younger than 8 have been shown to use a modality switching strategy (Adams, 2016).

Previous research has shown a gradual fine-tuning of multisensory gain of performance and a relationship between age and brain processes underlying multisensory integration. Further, a significant positive correlation between behavioural and neurophysiological measures of multisensory integration suggest that the underlying brain processes contributed to the fine-tuning of multisensory gain of behaviour (Brandwein et al., 2011, Lauzon et al., 2022). Some research suggests that using simple response time tasks, that in fronto-central regions an immature multisensory integration can first be found (7-9; Brandwein et al., 2011, or 8-10; Vannasing et al., 2024) followed by a pattern closer to adults later in development (13-16; Brandwein et al., 2011, or 15-17; Vannasing et al., 2024). The trajectory of multisensory integration maturation may be affected in some populations.

Atypical multisensory integration and delays in multisensory integration have been found in dyslexia and ASD. Specifically, the development of multisensory integration has been shown to be delayed in ASD, with studies showing larger group differences in studies with children compared to studies with adults (Feldman et al., 2018; Foxe et al., 2015). One neurodevelopmental condition that has more recently received attention for its differences in sensory processing and multisensory integration is ADHD.

Attention-deficit/hyperactivity disorder (ADHD) is a neurodevelopmental condition characterized by developmentally inappropriate levels of inattention, hyperactivity, and impulsivity (5th ed.; DSM–5; American Psychiatric Association, 2013). ADHD has three presentations: predominately inattentive (ADHD-IA), predominately hyperactive-impulsive (ADHD-HI), and combined (ADHD-C). ADHD is highly prevalent with roughly 8.6% to 11.4% of youth receiving diagnoses (ages 3-17 years; Danielson et al., 2024; Espinet et al., 2022). ADHD has been related to challenges with executive functions (e.g., planning, set shifting, organization, inhibition and behavioural regulation), sustained attention, emotional dysregulation, processing speed and working memory. Neurodevelopment in ADHD has been found to be generally delayed compared to neurotypical peers (Vaidya, 2012). Specifically, individuals with ADHD have been shown to have atypical sensory processing across domains (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Lane & Reynolds, 2019; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018; Reynolds & Lane, 2009; Sanz-Cervera et al., 2017; Yochman et al., 2004).

The research on multisensory integration in ADHD is mixed, with some behavioural studies showing enhanced multisensory integration in ADHD (McCracken et al., 2019), while others have shown either no difference (Schulze et al., 2021) or reduced multisensory integration in ADHD (Bisch et al., 2016; Michalek et al., 2014; Schulze et al., 2021). Enhanced multisensory integration has been shown in adults with ADHD through greater benefits in response times compared to NT adults (McCracken et al., 2019). Turning to neural studies, previous research indicates that during multisensory trials, group differences in event-related potentials (ERPs) in frontal and parietal regions were found (McCracken et al., 2019). Further, source localization analysis suggested that NT controls were found to have greater neural activity responding to audiovisual stimuli compared the ADHD group. The source of the increased activity was found to be in the right postcentral gyrus (McCracken et al., 2022). It would be expected that there are multisensory integration differences in ADHD as there are many structural and/or functional differences in ADHD from cortical areas, basal ganglia, and cerebellar brain regions, which are related to sensory processing (Castellanos et al., 2002; Duerden et al., 2012; Makris et al., 2007; Proal et al., 2011; Valera et al., 2007). Further, attentional and multisensory integration share subcortical networks, such as the superior colliculus (Overton, 2008), and operate with cortical regions, including the fronto-parietal and temporo-parietal networks, which have been shown to be affected in ADHD (Dionne-Dostie et al., 2015). Evidence suggests there is a bidirectional relationship between multisensory integration and attention (Choi et al., 2018; Talsma, 2015; Talsma et al., 2010). With the alterations found in these networks, it is likely that the interplay between attention and multisensory integration is important to understand in ADHD. As there is research done on the attentional networks in ADHD, more work needs to be done strictly looking at multisensory integration, then we can investigate the play between these networks.

4.1.1 Current Study

The influence of ADHD on multisensory integration is debated, possibly due to varying measures and methods. Behavioural studies using different metrics like multisensory gain, illusion susceptibility, or accuracy versus response time may yield different results. Our study will focus on multisensory gain, examining accuracy gain and Miller's race model. Previous studies have shown more pronounced differences in multisensory integration for ADHD individuals compared to NT when looking at neuroimaging results compared to behavioural results. This could occur due to differences in methodology, compensatory mechanisms or due to stages in processing. First, EEG or fMRI data is more sensitive to neural processes and even when behavioural responses do not show significant differences, techniques such as EEG can detect subtle differences. The behavioural tasks may not be sensitive enough to capture subtle differences in multisensory integration, especially if the tasks are too simple or if individual variability is high. In such situations, EEG can reveal differences. Second, individuals with ADHD may compensate for multisensory integration difficulties behaviourally, masking potential differences in performance. To achieve similar behavioural outcomes, the brain may engage different cognitive resources. Third, multisensory integration occurs at various stages of sensory processing, from early (sensory-driven) to late (cognitive-driven) stages. EEG may be able to detect early-stage integration differences that may not translate into behavioural differences or show differences between lower-level sensory areas and higher-level cognitive areas.

ADHD individuals exhibit hypo- and hyper-sensitivities to sensory information (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018), which may influence multisensory integration. Our study will control for these individual differences in sensory sensitivities as our study is perception-matched, whereas most other studies are stimulus-matched. Further, we will be able to examine whether we find the same trend of enhanced multisensory gain as other studies, and whether group differences were enhanced by controlling for sensory sensitivities. If differences in multisensory integration are found for the perception-matched task only, then it suggests that differences in sensory sensitivity or differences in task difficulty may explain the group differences in multisensory integration and could be related to the discrepancies in multisensory integration findings. Following looking at the behavioural differences, even if there are not group differences, we may still expect to see differences in the EEG data because multisensory integration differences can be more pronounced in neuroimaging data compared to behavioural in previous samples.

This study aims to determine if audiovisual multisensory integration differs between youth with ADHD and neurotypical (NT) youth. First, participants completed a detection task with a staircasing procedure 50% detectability to measure and to control for sensory sensitivity in both visual and auditory domains. Second, participants completed a speeded-response time task with the individualized, perception-matched stimuli determined by the first task. There is some suggestion that the interplay between multisensory integration and attention may be important in ADHD (Dionne-Dostie et al., 2015; Schulze et al., 2022), which may be why there is poorer unisensory perception in ADHD, but no difference in multisensory perception because multisensory stimuli are more attention capturing.

First, we expect the ADHD group to have a larger violation of Miller's Race Model, as previous studies have found an earlier violation (McCracken et al., 2019). Second, we expect no group differences in accuracy gain. Further, the accuracy data will be used to ensure that the stimuli are successfully matched across the groups. Third, we expect there to be differences in frontal, parietal, and occipital regions of the difference wave of the EEG response, with the ADHD youth having a less integration in the ERPs compared NT youth. Occipital areas are related to basic visual processing, parietal areas are often discussed as a being a sensory integration site (Brandwein et al., 2011), and frontal areas are related to attentional and cognitive control (Corbetta & Shulman, 2002). Differences in these areas are consistent with previous research (McCracken et al., 2019), and parietal and occipital areas of the brain have been shown to be thinner in ADHD individuals (Valera et al., 2007; Proal et al., 2011; Duerden et al., 2012). Fourth, as multisensory integration abilities are later to develop, we will examine if there is a relationship between age and multisensory integration expecting both behavioural measures of multisensory integration to improve with age. Further, we will be looking at the relationship between ADHD subtype traits and behavioural measures of multisensory integration. Fifth, we expect there to be differences in sensory processing ability in both the auditory and visual domains between ADHD and NT youth, as sensory sensitivity differences to sensory information have been found in ADHD (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018). Most of these studies looked more at questionnaire measures of sensory processing and did not look at psychophysiological paradigms. Previous work has suggested that these measures may be looking at distinct concepts (Schulz & Stevenson, 2020).

4.2 Methods

4.2.1 Participants

A total of 54 participants completed this study, 30 youth with ADHD (13 females, M_{age} = 11.27, age range = 7-17) and 23 NT youth (9 females, M_{age} = 11.75, age range = 7-16), after 3 ADHD participants were excluded for failure to finish the task and 1 NT participant did not respond to any visual stimuli. One additional participant was missing a WASI score, and 2 additional participants were missing questionnaires, but were included in the analysis. Parents were asked to report when their child received a diagnosis, which presentation their child had (e.g., ADHD-C) and whether their child takes medication. Of the 19 participants with ADHD who their parents responded, 15 reported being on medication for their ADHD.

Participants were recruited using Western's OurBrainsCAN database (https://ourbrainscan.uwo.ca/) and community sampling. All participants were fluent in English, had self-reported normal or corrected-to-normal hearing and vision. Ethics approval for all study procedures and materials was obtained by the University of Western Ontario's Medical Research Ethics Board. Participants were be paid $10 for each hour of the study. Demographic information can be found in Table 4.1. There was no significant group difference for age and IQ, but the ADHD youth scored significantly higher than the NT youth on the ADHD questionnaire.

Table 4.1. Demographic and Survey Information for ADHD and NT Youth

	ADHD Youth (*N*=30)		NT Youth (*N*=23)				
	M	*SD*	*M*	*SD*	*t* (51)	*p*	*d*
Age	11.27	2.68	11.74	2.03	.75	.48	.20
IQ	104.14	16.60	106.78	26.06	.45	.66	.12
SWAN	0.77	0.43	0.13	0.34	-.58	<.001*	.40
SWAN-IA	6.79	2.38	1.77	2.56	-7.15	<.001*	2.46
SWAN- HI	5.89	2.95	1.41	2.77	-5.48	<.001*	2.87

Note. For the SWAN-IA and HI, a score of 6 or above is probable for an ADHD diagnosis, and overall, for the SWAN a score of 1 suggests ADHD. 3 NT youth scored in the ADHD range, and 7 ADHD youth did not score in the ADHD range, but analysis did not change whether they were included or not. 3 ADHD participants were missing SWAN and SP-2 scores, and 1 of those was missing a WASI score.

4.2.2 Caregiver-Report Measures

4.2.2.1 ADHD Measure

The Strengths and Weaknesses of ADHD Symptoms and Normal Behaviour Scale (SWAN; Swanson et al., 2012) scales two subscales, inattention and hyperactive-impulsive, was completed by a caregiver. For each question a "not at all" or "just a little" response is coded 0 and a response of "quite a bit" or "very much" is coded as 1. A score of 6 or above, out of a possible 9 for each subscale, indicates that the child is likely to have ADHD-inattentive type or ADHD-Hyperactive/Impulsive Type. Inattention refers to trouble paying attention to details, getting easily distracted, having trouble organizing or finishing tasks. Hyperactivity-impulsivity refers to inability to sit still, fidgeting, difficulty waiting your turn and acting without thinking. This measure has demonstrated strong internal consistency of α=.95 in previous studies (Lakes et al., 2012).

4.2.2.2 IQ measure

Each child was administered the Weschler Abbreviated Scales of Intelligence II (WASI-II) Second Edition (Wechsler, 2011). The WASI-II is a quick measure of verbal, non-verbal and general cognitive ability. A Full-Scale IQ (FSIQ-2) estimate was calculated using the vocabulary subtest, which measures verbal comprehension, and the matrix reasoning, which measures perceptual reasoning. This test was given to IQ-match the samples, but participants were not excluded based on IQ.

4.2.2.3 Sensory Processing Measure

Caregivers completed the Child Sensory Profile-2 (Dunn, 2014), which has 9 subscales (Auditory Processing, Visual Processing, Touch Processing, Movement Processing, Body Position Processing, Oral Sensory Processing, Conduct Associated with Sensory Processing, Social Emotional Responses Associated with Sensory Processing, Attentional Responses Associated with Sensory Processing) and 86-items. For each question the score ranged from “does not apply” coded as 0 to “almost always” coded as 5. Most questions are assigned a sensory processing quadrant: seeking, avoiding, sensitivity, or registration. The measure is for ages 3 to 14 years and 11 months, and there were four participants above this age range but were given this measure for consistency. This study will focus on the Auditory and Visual Processing subscales as our caregiver-reported sensory processing.

4.2.2.4 Demographics Information

Participants/guardians completed a demographic questionnaire about the participant which included questions about the child’s sex, gender, handedness, vision, hearing, ethnicity, family income, caregiver education, child's education, child's language, child's medical history and immediate family's medical history.

4.2.3 Stimuli

All stimuli were presented using E-Prime 3 (Psychology Software Tools, 2016) software with NetStation Extensions version 2.0. on a monitor with a refresh rate of 16.67 ms (60 Hz). Further, the task was gaze contingent and we used a Tobii Pro Spectrum eye tracker. Auditory tones ranged from 37.5 dB SPL, and at 67.5 dB SPL in half decibel steps. Visual stimuli were 100 sinusoidal luminance gratings (Gabor patches) evenly positioned according to Michelson contrast between 0.01 to 0.1 and placed in visual noise. Gabor patches were randomly oriented for each contrast, excluding exactly vertical and horizontal orientations. To create multisensory stimuli, the auditory and visual stimuli were presented simultaneously. Null trials consisted of auditory and visual noise without the luminance gratings or auditory tones (Schulz & Stevenson, 2020). All trials were embedded in dynamic audiovisual noise, which continued without break during inter-trial intervals. As such, participants were not aware of when an individual trial began and ended. The auditory, visual, and audiovisual stimuli were presented 100 times each and null trials were presented 300 times, which is equal to the combined number of trials with stimuli presented. All stimuli were presented for 100 ms. Responses were collected for the 1500 ms following stimulus presentation. Regardless of if a response was given or note, the task continued to the next trial. An example of trial procedure can be found in Figure 4.1.

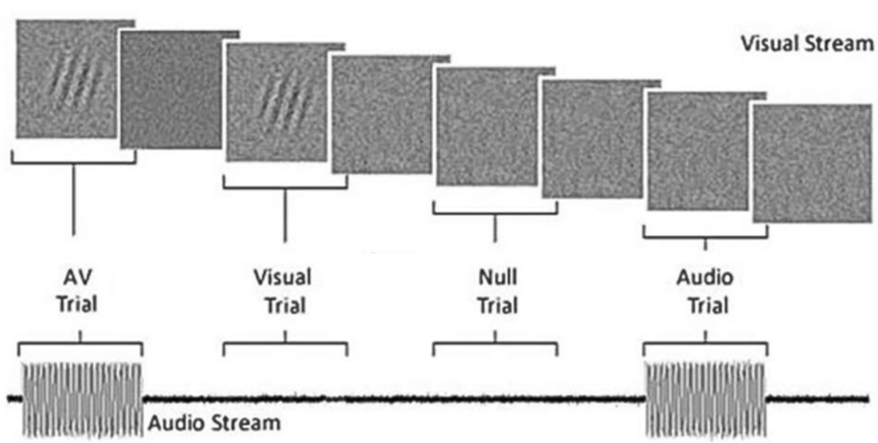

Figure 4.1. Trial procedure for audiovisual detection task. Trial procedure with example of unisensory and multisensory stimuli. Adapted from (Schulz & Stevenson, 2020).

4.2.4 Procedures

Before completing the behavioural portion of the study, participants caregivers completed a series of surveys. These included basic demographics and health questions, the SP-2 (Dunn, 2014) and the SWAN (Swanson et al., 2012). After participants completed the Full Scale-2 version of the WASI with a researcher. For the threshold determination and speeded-response time tasks, participants were seated in a dark room approximately 75 cm away from the monitor (HP LCD Monitor). Visual stimuli were presented with a refresh rate of 16.67 ms (60 Hz) for both tasks. All auditory stimuli were presented via a speaker on either side of the participant, approximately 90 cm from their head. Responses were collected using a Chronos Serial Response Box (Model 200 A; Psychology Software Tools, Inc., 2003).

Participants were instructed to press the leftmost button if they were left-handed and the rightmost button if they were right-handed on a Chronos Serial Response Box. A Tobii Pro X3 – 120 eye-tracker was attached to the monitor for gaze-contingent trial control, the following trial would not begin until the participant fixated on the screen for 100 ms. Participants rested their chin on a chin rest to minimize head motion and control the distance to the monitor. The chin rest was aligned with the centre of the monitor and with each participant's eye level. While completing the tasks, continuous EEG signal will be recorded using a 256-channel EGI Hydrocel net.

4.2.4.1 Threshold Determination

We used an interleaved, adaptive one-up-one-down staircase procedure to determine each participant's 50% threshold. The starting point for the two auditory staircases ranged in difficulty from 40 dB SPL (hardest) to 65 dB SPL (easiest) in noise. The starting point for the two visual staircases similarly ranged in difficulty by using Michaelson contrasts of 0.001 (hardest) to 0.50 (easiest) in noise. For instance, if a stimulus was accurately detected by the participant, the subsequent trial within the same staircase would present a stimulus at a lower intensity that is harder to detect. If the stimulus was not accurately detected, then the next stimulus would be presented at a higher intensity that is easier to detect. The staircase changed in difficulty by eight levels until the first reversal. After the first reversal occurred, the step size decreased to four levels until the second subsequent reversal. In other words, the intensity of the stimulus altered between high and low until a barely detectable stimulus was presented after an undetectable stimulus for that participant. To calculate each participants' threshold level, the mean position of the two respective auditory and visual staircases following six reversals within each staircase was calculated.

4.2.4.2 Speeded Response Time Task

Directly following threshold determination, the speeded response-time task began. The unisensory trials were presented at each participant's 50% response threshold, and multisensory trials included both auditory and visual stimuli presented at their unisensory 50% threshold. Stimulus intensities continued to slightly adapt (1 step) based on performance on unisensory trials throughout this portion of the task to account for fatigue. In total, there were 600 trials after the staircase: 100 auditory, 100 visual, 100 audiovisual, and 300 null trials. Participants were instructed to press the leftmost button if they were left-handed and the rightmost button if they were right-handed on a Chronos response pad.

4.2.5 Behavioural Data Acquisition and Analysis

4.2.5.1 Race Model Violation

Response times were recursively trimmed, removing any times that were three standard deviations (SD) above or below the mean. The MATLAB RSE-box (Otto, 2019) was used to calculate the race model and response-time based multisensory gain. The race model utilizes cumulative distribution functions (CDF) to represent the cumulative probability that a response has been made at a given time (Miller, 1982; Raab, 1962). Miller's bound was used as a baseline for identifying multisensory gain, accounting for statistical facilitation due to redundant target effects and assumes a maximum negative correlation between auditory and visual response times, making it a conservative baseline (Miller, 1982).

Race model violations are identified when the observed audiovisual CDF crosses to the left of Miller's bound. Violations of Miller's bound indicate that a multisensory interaction has occurred, and the difference between the observed audiovisual CDF and Miller's bound is indicative of how much multisensory gain is experienced. If the values are positive, the values are taken as evidence of multisensory integration. Positive values are interpreted as evidence of multisensory integration. Conversely, the absence of violations, or values of zero, cannot be conclusively interpreted as evidence for or against multisensory integration. This lack may suggest sub-optimal integration, independent processing, or interference instead (Stevenson et al., 2014). The RSE-box reports the Violation of Miller's bond as a singular number, which we will report. Other methods of calculating race model provide different information, such as time bins. For an example see Figure 4.2.

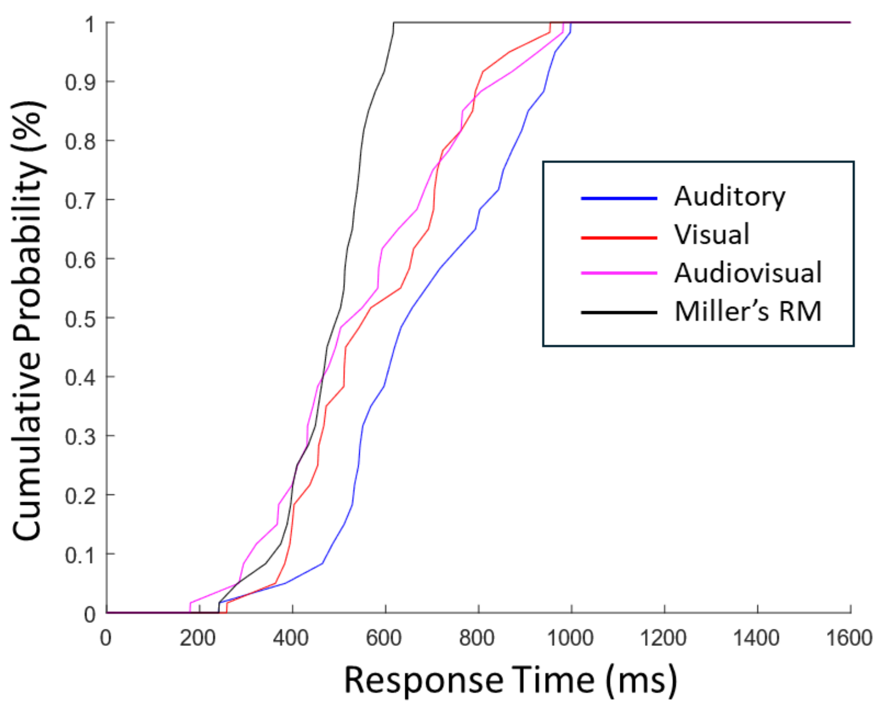

Figure 4.2. Example Violation of Race Model for ADHD Participant X. *Note.* Probability quantile distribution response times in the three stimulus conditions

(Auditory, Visual, Audiovisual) in comparison to Miller's Race Model (Miller's RM) distribution.

Violations above 0 on Miller's Race Model provides evidence that multisensory integration has occurred. First, a Chi-Square will be completed between groups with scores of 0 (no violation) and scores above 0 (violation and evidence of multisensory integration) to see if the number of participants with violations differs. Second, an independent samples t-test will be used to compare the magnitude of the violations of ADHD adults and NT adults. If there is no significant difference on the Chi-Square, then all participants will be added into the t-test analysis. If there is a significant difference, then the t-test analyses will be run with the full sample and without participants who had a violation of 0.

4.2.5.2 Accuracy

Accuracy gain was measured two ways: max unisensory and probability summation criteria. Maximum unisensory compares the accuracy in audiovisual trials to the accuracy in the best unisensory condition: $\widehat{p(AV)} = \max\,[p(A), p(V)]$. Multisensory gain was then derived using the following equation: $observed\ AV\ accuracy - \widehat{pAV}\ accuracy$. Positive values indicated that information is being used from both modalities. Trials with response times under 100ms were removed, as they were not considered to be real responses, and the final accuracy was calculated from the remaining trials after the removal. The probability summation is more conservative, which conveys some advantages compared to maximum unisensory as it can identify active integration across sensory modalities, and accounts for statistical facilitation.

For probably summation, predicted audiovisual accuracy was calculated from the unisensory component accuracy, assuming independence using the following equation:

$$\widehat{p(AV)} = p(A) + p(V) - [p(A) * p(V)]$$

Where pAV represents the null hypothesis of the response to audiovisual presentations if the auditory and visual information are processed independently, and where *p*(A) and *p*(V) represent response accuracy to auditory- and visual-only presentations. Same as with the maximum unisensory, multisensory gain was then derived using the following equation: $observed\ AV\ accuracy - \widehat{pAV}\ accuracy$.

Positive values indicated that multisensory integration had occurred, while negative values failed to conclude that multisensory integration had occurred. Trials with reaction times under 100 ms were removed, as a response this fast cannot occur physiologically following the perception of the target stimuli,

4.2.5.3 Sensory Processing

Previous research has suggested that questionnaire measures and behavioural paradigms measure distinct aspects of sensory processing (Schulz & Stevenson, 2020). Sensory responsivity or sensory reactivity refer to questionnaires, particularly third-party reports, as they rely on observable behavioural response to sensory stimuli. Sensory sensitivity refers to the individual's ability to detect and perceive sensory inputs, which can be measured using behavioural paradigms, such as a detection task. This current study will use this framework, sensory responsivity was measured using caregiver-report measures and sensory sensitivity was measured using a staircasing detection task.

The caregiver-reported measure of sensory responsivity was calculated using the scores of the Auditory Processing and Visual Processing subscales on the SP-2. The behavioural sensory sensitivity was calculated in the auditory and visual domains by taking the first auditory stimuli's decibel value and the first visual stimuli's Michelson contrast after threshold determination in the staircasing procedure.

For both caregiver-report and behavioural measures, independent samples t tests were used to compare auditory and visual sensory processing in ADHD and NT youth. Then Pearson r correlations were used to determine the relationship between sensory responsivity and sensory sensitivity.

4.2.5.4 Subtype and Age Analyses

There is some evidence that ADHD presentation (e.g., inattentive versus hyperactive-impulsive) may affect unisensory and multisensory processing (Hare et al., in prep; Shimizu et al., 2014), whereas other studies suggest there are not subtype differences in sensory processing (Ghanizadeh, 2011). Pearson correlation between ADHD presentation symptoms (Inattentive, Hyperactive-Impulsive Symptoms) from the SWAN, sensory sensitivity measures, and multisensory integration measures will be conducted. We hypothesize that the Hyperactive-Impulsive symptoms will be more positively correlated with sensory sensitivity and multisensory integration. A Benjamini-Hochberg correction for multiple comparisons will be used.

4.2.6 EEG Data Acquisition and Analysis

Electrophysiological data was collected using a 256-channel EGI Hydrocel GSN net (Electrical Geodescis Inc., Eugene, OR, USA) recording through EGI NetStation with an online reference to Cz. The sampling rate was 1000 samples/second. Analysis was done using MATLAB. Data was initially band-pass filtered at 0.3–50 Hz. Additionally, a 60 Hz notch filter was applied to filter out powerline interference. Only correct trials (correctly identifying the target, and correctly withholding a response for all other trials) will be included in the analyses. Epochs of 1200 ms will be extracted from the data, with the first 200 ms used for baseline correction, and the last 1000 ms post-stimulus presentation. An average reference was computed, and data was re-referenced to the average. Data was cleaned in two ways: (1) Independent Components Analysis; (2) Epochs in which there was an artifact across 10 channels (>300 μV, window size = 640 ms; moving average = 80 ms) were excluded. Bad channels were removed based on visual inspection and replaced by spherical spline interpolating the signal from the surrounding electrodes. Participants with more than 40% of epochs removed, were removed from the analysis.

The amplitudes from the unisensory and multisensory signals were compared to quantify multisensory interactions. As electrical fields detected by EEG sum linearly, interactions between auditory and visual processing are identified by summing the two unisensory signals and comparing this sum to the audiovisual signal, known as the additive criterion (Besle et al., 2004; Stevenson et al., 2014). Interactions are thus defined by significant differences: $A+V \neq AV$.

For multisensory integration, independent samples t-tests will be calculated between ADHD and NT adults along the time course of the difference wave. If there are significant differences between the groups at $\alpha = .05$ for 5 consecutive ms then this will be considered a significant difference. These analyses will be run for our four clusters or regions of interest, which were defined a priori clusters using prior literature (Lauzon et al., 2022). Typically, multisensory responses occur before 250ms, but we see a delayed ERP response due to the stimuli being at such a low perceptual level it may take longer to come into awareness for participants. For sensory sensitivity, independent samples t-tests will be calculated between ADHD and NT adults along the time course of auditory and visual trials.

4.3 Results

4.3.1 Behavioural Results

4.3.1.1 Response Time Analysis

Violation of Miller's Race Model (*M* = 1.79, *SD* = 3.57) ranged from 0 to 16.02, with non-zero values suggesting a violation of Miller's Race Model and evidence for multisensory integration. Chi-square analysis was conducted to compare the number of violations between groups and indicated no significant relationship between the number of violations in the ADHD and NT group, X^2 (1, *N* = 53) = .03, *p* = .10, φ = -.02. In some instances, Levene's Test for Equality of Variances was significant, and to correct for this the statistics for equal variances not assumed were reported, which leads to a reduction in the *df*s from expected. Violations for the ADHD group (*M* = 1.16, *SD* = 4.41) did not differ significantly from those in the NT group (*M* = 2.58, *SD* = 4.58), *t*(31.51) = 1.35, *p* = .19, BF_{10} = .53, with a small to medium effect size (*d* = .40) (Figure 4.3). When excluding violations of 0, there was not a significant difference between the ADHD and NT group, *t*(16.73) = 1.45, *p* = .17. One outlier (± 3 SD) from the ADHD group was removed.

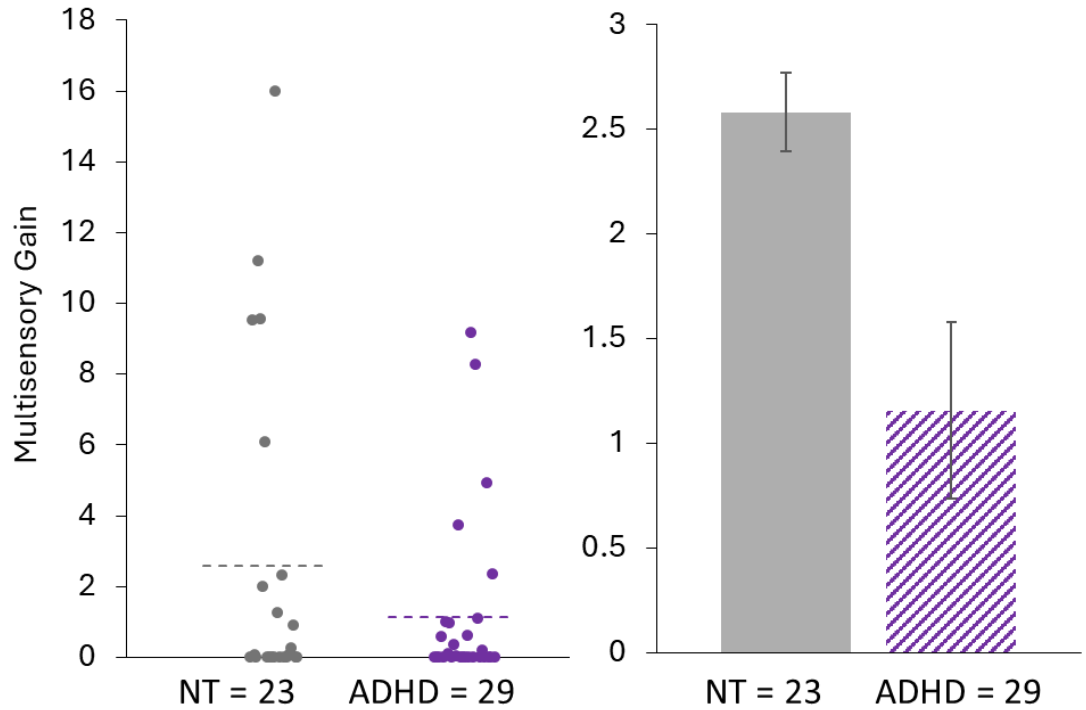

Figure 4.3. Individual and mean multisensory gain data using Miller's Race Model Violations. Left panel indicates individual multisensory gain values. Right panel indicates mean differences in multisensory gain. Horizontal lines indicate means, and error bars indicate standard error of the mean.

4.3.1.2 Accuracy

Two participants with auditory accuracy above 80% with decibel levels approaching or at task maximum were removed. Two participants with visual accuracy below 20% with contrast levels at minimum level were removed. One participant was removed for being an outlier (± 3 SD) for audiovisual accuracy. The rest of the analyses were conducted listwise with 27 ADHD youth and 21 NT youth.

Auditory accuracy ($t(46) = -.86$, $p = .40$, $d = -.25$, $BF_{10} = .30$), visual accuracy ($t(46) = -.09$, $p = .93$, $d = -.03$, $BF_{10} = .22$) and audiovisual accuracy ($t(46) = .31$ $p = .38$, $d = .09$, $BF_{10} = .23$) did not significantly differ between groups. For graphs of the accuracy in each modality and predicted accuracy are in Figure 4.4. According to the maximum unisensory, both the ADHD ($t(29)= 4.69$, $p < .001$, $d = .88$) group and TD group ($t(20) = 8.60$, $p <.001$, $d = 1.88$), showed significant accuracy gain ADHD.

According to the probability summation, neither the ADHD (*t*(29)= .30, *p* = .78, *d* = .05) group and TD group (*t*(20) = .64, *p* = .53, *d* = .14), showed significant accuracy gain ADHD. Accuracy Gain using the max unisensory (*t*(46) = 1.29, *p* = .20, *d* = .38, BF_{10} = .45) and the probability summation (*t*(46) = 1.05, *p* = .30, *d* = .31, BF_{10} = .35).

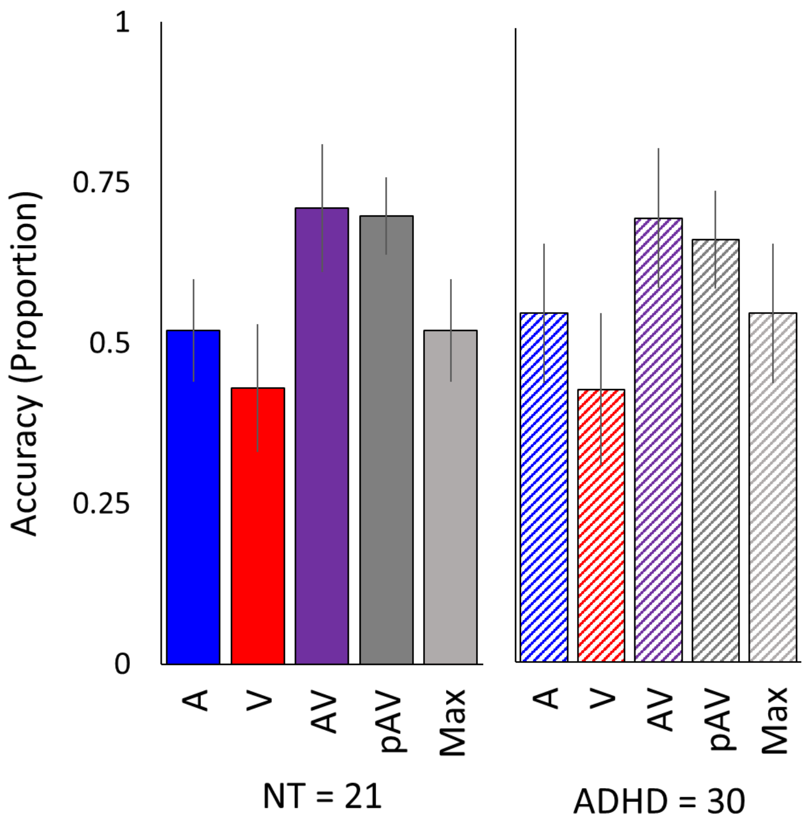

Figure 4.4. Auditory, Visual, Audiovisual Accuracy and Multisensory Gain. pAV denotes the probability summation and Max the max unisensory

4.3.2 Sensory Processing

4.3.2.1 Behavioural Sensory Sensitivity

Sensory sensitivity was measured behaviourally by taking the first auditory, measured in dB, and visual stimulus, measured in Michelson Contrast, after the staircasing procedure (See Figure 4.5). 30 ADHD and 23 NT participants completed the staircasing procedure, and the Auditory Sensitivity in dB ranged from 40.25 (hardest stimuli presented) to 65 and the Visual Sensitivity in Michelson Contrast ranged from .031 to .50 (easiest stimuli presented). There was a trending significant difference in

Auditory Sensitivity between ADHD (*M* = 45.99, *SD* = 4.96) and NT (*M* = 44.27, *SD* = 3.93) groups, $t(51) = -1.75$, $p = .09$, $d = -.48$, $BF_{10} = .79$. There was a significant difference in Visual Sensitivity between ADHD (*M* = .22, *SD* = .16) and NT (*M* = .13, *SD* = .11) groups $t(50.39) = -2.40$, $p = .02$, $d = -.63$, $BF_{10} = 1.97$.

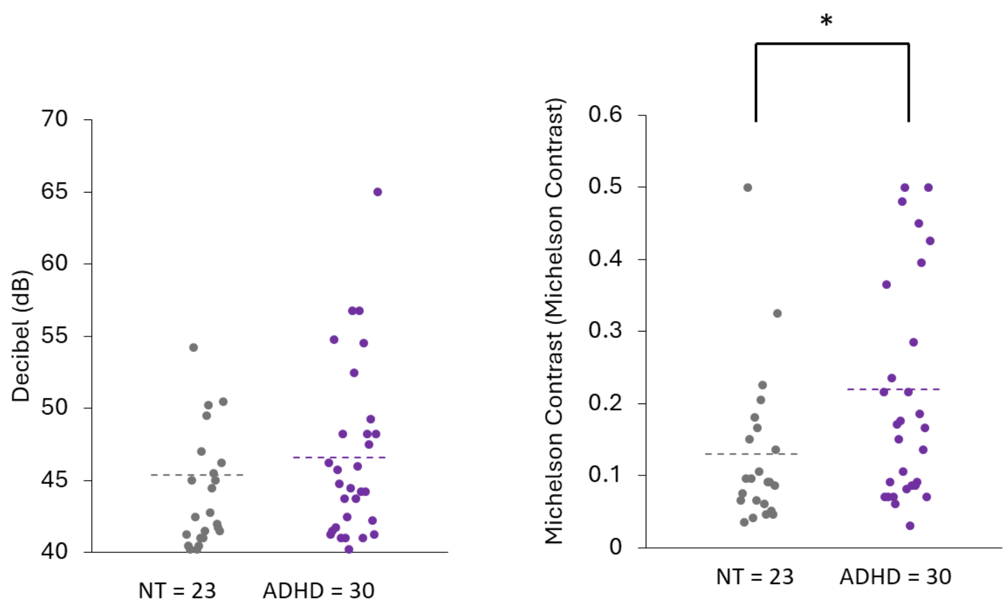

Figure 4.5. Behavioural Sensory Sensitivity from Threshold Determination. *$p < .05$.

4.3.2.2 Caregiver-Report Sensory Responsivity

Sensory sensitivity was measured using caregiver-reports from the SP-2 Auditory and Visual Processing subscales (See Figure 4.6). 28 ADHD and 23 NT participants completed the questionnaires, and the Auditory scores ranged from 2 to 39 and the Visual Scores ranged from 5 to 23. There was a significant difference in Auditory Sensitivity between ADHD (*M* = 24.43, *SD* = 6.69) and NT (*M* = 13.48, *SD* = 6.69) groups, $t(49) = -5.28$, $p < .001$, $d = -1.48$. There was a significant difference in Visual Sensitivity between ADHD (*M* = 14.29, *SD* = 4.50) and NT (*M* = 9.52, *SD* = 4.37) groups, $t(49) = -3.81$, $p < .001$, $d = -1.10$.

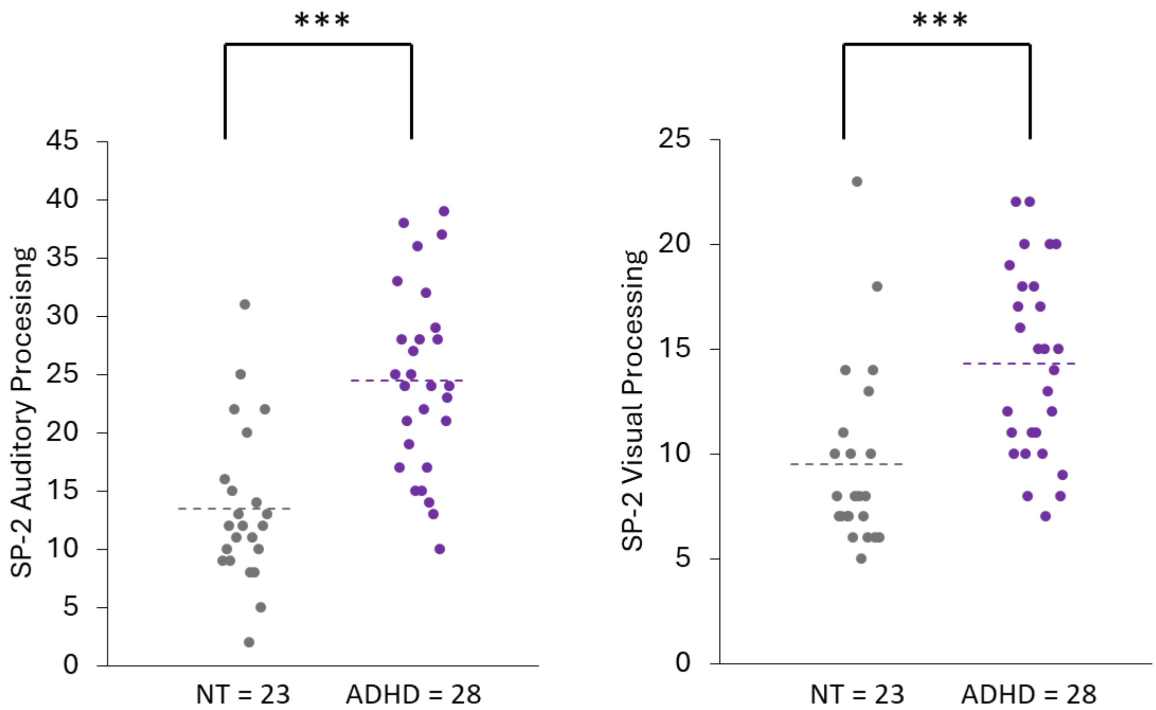

Figure 4.6. Caregiver-reports of sensory responsivity. ***$p < .001$.

For the full sample, behavioural sensory sensitivity was significantly positively related between auditory and visual modalities (See Table 4.2). Caregiver reports of sensory responsivity was significantly positively related between auditory and visual modalities. In the auditory modality, sensory sensitivity and responsivity were trend level related, but in the visual modality, sensory sensitivity and responsivity were not related.

Table 4.2. Correlations between sensory sensitivity and sensory responsivity in auditory and visual domains

	1.		2.		3.	
	r(47)	*p*	*r*(47)	p	*r*(47)	*p*
1. Decibel	-	-				
2. Michelson Contrast	.32	.03	-	-		
3. SP2 Auditory	.25	.08	.18	.21	-	-
4. SP2 Visual	.18	.22	-.02	.88	.64	.001

Note. N = 49. Reported are uncorrected p-values, any significant correlations that did not survive correction are indicated with $^{\alpha}$.

4.3.3 Subtype and Age Analyses

Pearson r correlations between age, ADHD scores, and measures of multisensory integration and sensory processing for the full sample are in Table 4.3.

Table 4.3. Correlations between age, ADHD scores, and measures of multisensory integration and sensory processing

	Age		SWAN-IA		SWAN-HI	
	r(48)	*p*	*r*(48)	*p*	*r*(48)	*p*
Miller's Violation	-.10	.47	.06	.67	.10	.49
AV Acc	.13	.35	-.39*	.005	-.37*	.008
Max Uni	.31	.03 $^{\alpha}$	-.28	.05 $^{\alpha}$	-.37*	.009
Proportion Increase	.24	.08	-.35*	.01	-.40*	.004
Decibel	-.39*	.004	.18	.22	.11	.46
Michelson Contrast	-.28	.05 $^{\alpha}$	.36*	.009	.39*	.006
SP2 Auditory	-.25	.08	.60*	<.001	.64*	<.001
SP2 Visual	-.11	.45	.30	.03 $^{\alpha}$	.44	.002

Note. $N = 50$. Reported are uncorrected p-values, any significant correlations that did not survive correction are indicated with $^{\alpha}$.

4.3.4 EEG Results

Only correct trials were included for visual, auditory, and audiovisual trials. 11 participants were excluded because more than 40% of their data was rejected, and the final analysis included 22 ADHD and 20 NT participants. There were four regions of interest (ROI): frontal, central, central-parietal, and occipital.

4.3.4.1 Unisensory

There were no significant group differences between the Auditory and Null conditions in all areas of interest (See Figure 4.7). There was a significant difference in the Visual ERP from 65 to 69 ms between NT and ADHD participants in the Occipital region. A mean difference ($M = -2.06$ μV) was found to be significant ($t(40) = 2.31$, $p = .03$, $d = .71$) at 65 ms.

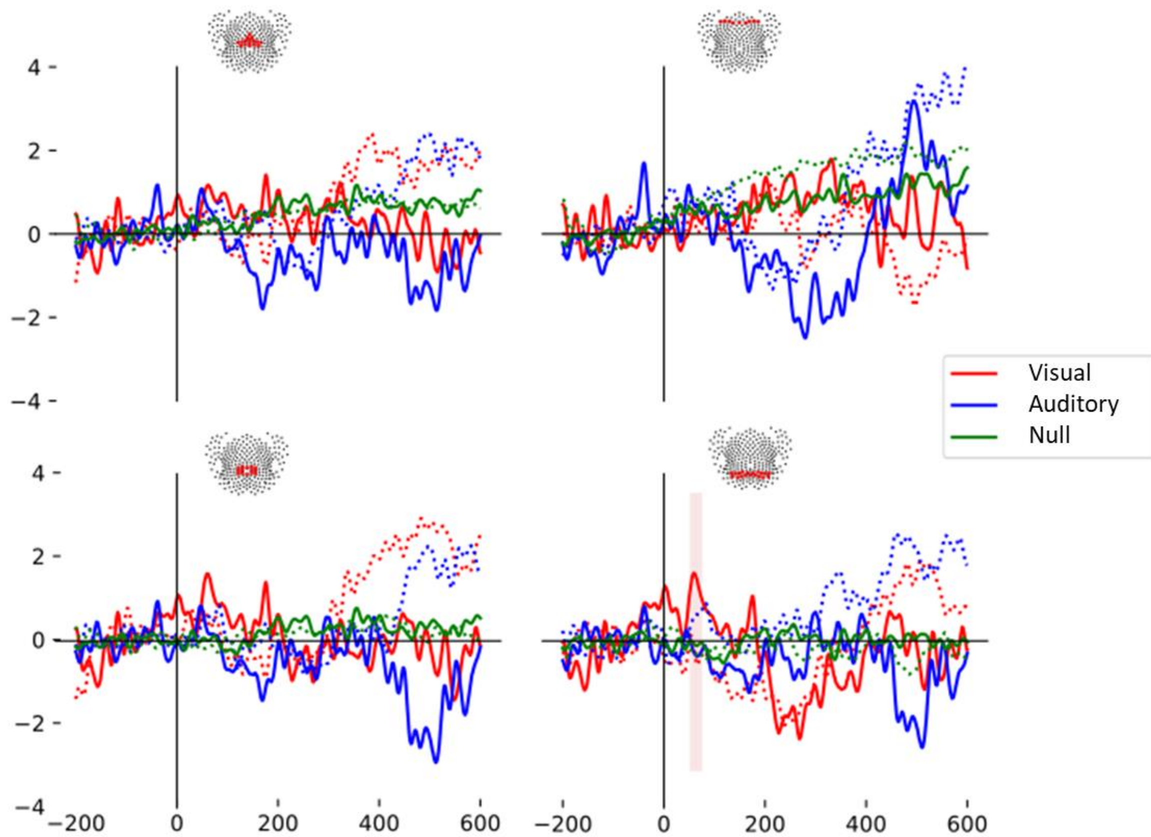

Figure 4.7. Waveforms for Visual, Auditory, and Null Trials at Central, Frontal, Central-Parietal and Occipital Regions. Solid lines are NT youth, and hashed lines are ADHD youth. Visual is red, auditory is blue, and the null is green. Red box denotes significant group difference ($p < .05$) for visual trials.

4.3.4.2 Multisensory

Difference Wave below refers to amplitude differences between the sum of the unisensory conditions (Audio + Visual) and the Audiovisual (AV condition) (See Figure 4.8). Typically, multisensory responses would be expected before 250ms, but the entire time course will be examined as we may see a delayed ERP response due to the stimuli being at such a low perceptual level.

The Sum A+V, Audiovisual and the Difference wave (AV- Sum) are in Figure X. There was a significant difference in the Difference Wave from 509 ms to 519 ms between NT and ADHD participants in the Central-Parietal region. There were no other significant difference between groups in the other three ROIs. A mean difference (M= 9.26 µV) was found to be significant ($t(40) = -2.19$, $p = .03$, $d = 0.68$).

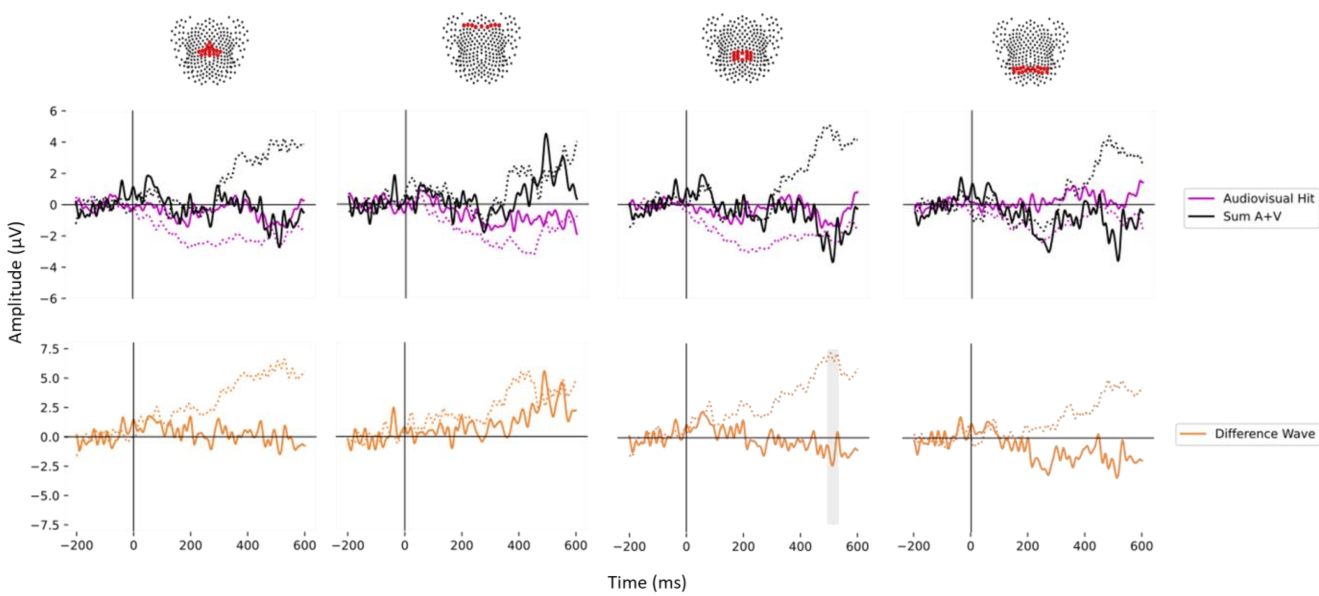

Figure 4.8. Waveforms for Audiovisual, Summed Unisensory, and Difference Wave at Central, Frontal, Central-Parietal and Occipital Regions. NT is the solid line, and the ADHD group is the dashed line. Audiovisual is purple, Sum A + V is black, and the Difference Wave is orange. Shaded grey areas are significant, $p < .05$.

4.4 Discussion

Previous research has shown conflicting results as to whether multisensory integration is affected in individuals with ADHD (Bisch et al., 2016; McCracken et al., 2019; Schulze et al., 2021, 2022; Zuberer et al., 2020). Although there has been a lack of studies looking at multisensory integration in youth with ADHD, especially using neural measures. The goal of this study was to examine using behavioural and EEG methods whether multisensory integration differed in youth with ADHD compared to NT youth. Using behavioural methods, we found no differences between youth with ADHD and NT youth in multisensory integration. Using EEG methods, we did not see a group difference in multisensory integration in the expected timeframe (< 250ms) but did see group differences later in processing. We expected ADHD youth to have higher sensory sensitivity and sensory reactivity in both auditory and visual domains compared to NT youth. We found NT youth showed higher sensory sensitivity to visual stimuli compared to ADHD youth, and trend level higher sensory sensitivity to auditory stimuli. ADHD youth rated higher on auditory and visual sensory reactivity measures than TD youth.

Turning to behavioural findings, we found no group differences in multisensory integration using the response-time based measure or the accuracy-based measure. We expected there to be differences in multisensory integration as a prior study found an earlier violation of Miller's Race Model in adults with ADHD, compared to NT adults (McCracken et al., 2019). One key difference between the studies was that our task was matched for perception and was set at each individual's perceptual level, whereas stimuli were presented at the same intensity for all participants in the other study. Multisensory integration differences may be diminished in youth when individual differences in perception are taken into account. Further, we expected differences in multisensory integration to be more pronounced in youth compared to adults, similar to research in other neurodevelopmental conditions, such as autism spectrum disorder (Feldman et al., 2018; Foxe et al., 2015). In ADHD, multisensory integration differences may follow a different trajectory, with differences being more apparent in adulthood but this requires further investigation as there is a paucity of studies in youth. In the full sample, older age was related to improved multisensory integration for accuracy measures but not response time measures, where we would expect to see improvements in both measures (Brandwein et al., 2011). As there can be larger multisensory gain in ADHD, which may be partially attributable to poorer unisensory performance, this benefit may increase over time. In our study, we did not find differences in unisensory performance, but the perception-matched task should account for these differences. Previous research has shown differences in EEG and fMRI findings, even when there were smaller to no group differences in the behavioural results (McCracken et al., 2019; Zuberer et al., 2020).

Turning to EEG findings, we did not see a group difference in multisensory integration in the expected timeframe (< 250ms) but did see group differences later in processing. Specifically, there was a group difference in the Central-Parietal difference wave at 509 ms to 519 ms, where the ADHD group showed a larger difference between the summed unisensory and audiovisual response. These later differences suggest could be related to post-perceptual processing, such as combing the integration to sensory information with cognitive processes like memory, attention, and decision-making. For unisensory responses, in the occipital region there was a significantly reduced response to visual stimuli also around 65 to 69 ms in ADHD youth, suggesting a smaller response to visual stimuli in ADHD. The lack of differences in frontal regions suggest there may not of been differences in the cognitive and attentional control of the multisensory signals. When analyzing EEG results in a mixed-age group of youth, interpretation becomes challenging due to the maturation of EEG responses over development. For instance, in fronto-central regions an immature multisensory integration, where the multisensory response was smaller in amplitude than the summed unisensory, is found earlier in development (7-9; Brandwein et al., 2011, or 8-10; Vannasing et al., 2024) and then followed by a pattern closer to adults with the multisensory response having a larger amplitude than the summed unisensory later in development (13-16; Brandwein et al., 2011, or 15-17; Vannasing et al., 2024). In a study with ADHD adults, group differences have been demonstrated in frontal, parietal, and occipital multisensory ERPs in adults with and without ADHD, with the ADHD adults showing reduced amplitude to summed unisensory and multisensory stimuli (McCracken et al., 2019). The previous study included the summed unisensory and multisensory waves but did not do a comparison directly between the two using a difference wave making interpretation less clear. Further, the multisensory time windows of interest for this study ranged from 100-160 ms. When looking developmentally, there is some suggestion that sensory processing components may have a later latency, as latency decreased in unisensory components (P1, N2) as a function of age, as it peaked at 80 ms in the 7-9 year olds, 74 ms in the 10-12 year olds, 68 ms in the 13-16 year olds, and 40 ms in adults (Brandwein et al., 2011). In the current study, we used really dim stimuli which will make the ERPs significantly later as it takes longer to perceive. Altogether, 500 ms is late in processing for multisensory integration but may reflect differences in post-perceptual processing related to the integration of sensory information, suggesting that youth with ADHD may not have differences in multisensory integration but with how it is updated into memory or with attentional aspects.

One study used multisensory stimuli in adolescents with ADHD to look at response inhibition and found differences in later response selection stages but not earlier sensory or attentional stages (Chmielewski et al., 2018). In multisensory go/no go task, response inhibition processes were impaired under conflicting conditions (incongruent auditory and visual information) in ADHD adolescents but were similar to NT adolescents when no or redundant auditory information was presented. These impairments were evident in the medial frontal gyrus during the response selection stage (P3 ERP), but not during the attentional selection (P1, N1 ERPs) or resource allocation stage (P2 ERP). Overall, they found differences in later processing of response selection mechanisms, but not during earlier attentional and sensory mechanisms. Our group differences were even later in processing than the P3 component, but we may see a delayed ERP response due to the stimuli being at such a low perceptual level it may take longer to come into awareness for participants.

We expected group differences between ADHD and NT youth and for ADHD youth to have higher sensory sensitivity and sensory reactivity in both auditory and visual domains. NT youth showed higher sensory sensitivity to visual stimuli compared to ADHD youth, and trend level higher sensory sensitivity to auditory stimuli. On the other hand, caregiver-reports suggested higher sensory reactivity in ADHD youth across both modalities compared to NT youth. When looking at visual sensory sensitivity using behavioural methods, previous research looking at contrast sensitivity has been inconsistent, with some research suggesting reduced contrast sensitivity in ADHD children (Bartgis et al., 2009), while other studies finding no differences in ADHD (Kim et al., 2015; Stevens et al., 2012). One review found that the detection or pure tones in ADHD is largely intact compared to NT individuals (Fuermaier et al., 2018), and that differences in auditory perception are more noticeable for speech sounds (Lucker et al., 1996; Söderlund & Jobs, 2016). Auditory hypersensitivity is often found in ADHD, but auditory processing deficits may increase with age in children with ADHD whereas processing in other modalities seems to improve slightly with ADHD (Cheung & Siu, 2009). Further, individuals with ADHD often have difficulty with sensory gating and have a higher distractibility to external stimuli, especially in the auditory domain (Ghanizadeh, 2011). The measure of sensory responsivity was consistent with previous research using questionnaire methods (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Lane & Reynolds, 2019; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018; Reynolds & Lane, 2009; Sanz-Cervera et al., 2017; Yochman et al., 2004). Previous work has suggested that these measures may be looking at distinct concepts (Schulz & Stevenson, 2020). As we did not find a relationship between behavioural and questionnaire measures of sensory processing, our results support that they may be measuring distinct concepts.

Overall, we did not find differences in multisensory integration between youth with ADHD compared to NT youth. NT youth showed higher sensory sensitivity abilities in both modalities compared to ADHD youth. On the other hand, caregiver-reports suggested higher sensory challenges in ADHD youth across both modalities compared to NT youth.

4.4.1 Limitations and Future Directions

Our study is one of the first to examine multisensory integration in youth with ADHD, especially using neural measures, but it has limitations. First, we kept participants on their medication regiment that they take every day, so some participants were on medication where others were not. Some previous studies have opted to have participants not take their medication (Schulze et al., 2021), but research is inconclusive as to whether it affects sensory processing (Pfeiffer et al., 2015). One study looking at visual detection thresholds found that medicated patients with ADHD who stopped stimulant medication for at least 24 hours prior to the assessment had a lower, although not significantly lower, detection threshold compared to non-medicated patients (Kim et al., 2015). Future studies should examine sensory processing and multisensory integration in ADHD participants with and without medication.

Second, participants completed a perception-matched task but not the traditional stimulus-matched task where everyone is presented stimuli at the same intensity. In a separate study in adults by our group, both tasks were presented but the tasks together were to maintain the attention of children. Future research should examine whether multisensory integration is affected when the task is stimulus-matched task using neural measures. Third, we did not have a large enough sample size to run our analyses by age groups, which would have let us investigate the developmental trajectory of multisensory integration in ADHD. Our results may be less clear as the multisensory response develops to be more similar to the adult response in our studies age range. Lastly, we had more ADHD participants than TD participants, but more ADHD participants data needed to be removed for the EEG analysis. Future studies should include a larger sample to have more statistical power for analyses and to look at the developmental trajectory.

There are several exciting avenues for future research looking at multisensory integration in ADHD. First, more studies should use EEG and fMRI techniques as there is an interesting relationship between reduced neural responses to multisensory stimuli but enhanced multisensory integration in behavioural measures (McCracken et al., 2019). Second, more research should look at youth or follow the developmental trajectory as age related differences in multisensory integration have been found in other NDCs. Currently there are no studies looking at multisensory temporal processing in youth with ADHD, which should be examined due to its strong link to multisensory integration but also because there is some evidence that TBWs are narrower in individuals with high ADHD traits (Panagiotidi et al., 2017; Hare, Dalal et al., in prep).

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Chapter 5

5 Multisensory Integration and Sensory Sensitivity in Adults with ADHD: An EEG Investigation

5.1 Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a highly prevalent neurodevelopmental condition with roughly 8.6% to 11.4% of youth receiving diagnoses (ages 3-17 years; Danielson et al., 2024; Espinet et al., 2022), but it persists into adulthood around 60% of the time (Sibley et al., 2017). The core symptoms include inattention, hyperactivity, and impulsivity. ADHD is often related to executive functioning challenges and challenges with occupational, social, and academic functioning in adulthood (Caye et al., 2016). An area that is starting to gain more attention is sensory processing in ADHD. Children with ADHD have been shown to have hyper and hypo-sensitivities to sensory information in different domains (Dunn & Bennett, 2002; Ghanizadeh, 2011; Little et al., 2018; Mangeot et al., 2007; Shimizu et al., 2014). Further, the presentation of ADHD may be related to sensory thresholds, which refer to the weakest stimuli an organism or individual can sense. Having a low threshold is associated with distractibility, especially in the auditory domain, whereas, a high threshold could be attributed to inattentive behaviour, since certain stimuli will be missed (Shimizu et al., 2014). Sensory differences persist into adulthood with adults with ADHD showing deficient sensory inhibition and auditory hypersensitivity (Kamath et al., 2020; Panagiotidi et al., 2018; Schulze et al., 2020). Further, adults with ADHD often report being overwhelmed by sensory input (Faraone et al., 2000). Given how sensory processing is affected in single modalities, it is likely that the sensory phenomenon of multisensory integration is altered in ADHD.

Multisensory integration refers to the ability to combine multiple sensory inputs from different modalities into one unified percept (Stein & Meredith, 1993). This is an extremely important process, as the majority of our sensory experiences are multisensory in nature, and this process is a building block in which higher-cognitive processing relies on (Wallace et al., 2020). Multisensory integration has been shown to be affected in different neurodevelopmental conditions, such as autism spectrum disorder (Collignon et al., 2013; Foxe et al., 2015; Ostrolenk et al., 2019; Segers et al., 2020; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014; Stevenson, Baum, et al., 2017; Woynaroski et al., 2013; See Feldman et al., 2018 for review) and dyslexia (Harrar et al., 2014; Pulliam et al., 2023; van Laarhoven et al., 2018). These challenges in multisensory integration can impact higher-order cognitive and communicative processes in these populations. There is some evidence which suggests that multisensory in ADHD may be affected but the results are conflicting (McCracken et al., 2019; Schulze et al., 2021a, 2021b; Zuberer et al., 2020).

Previous research into multisensory integration in ADHD using behavioural paradigms is quite mixed, with some studies suggesting greater multisensory integration in ADHD (Bisch et al., 2016; McCracken et al., 2020), while others report no difference (Shulze et al., 2021) or reduced multisensory integration (Michalek et al., 2014; Shulze et al., 2021). A limited number of studies have used EEG or fMRI methods to examine multisensory integration in ADHD. In a simple response time task, multisensory gain was found to be increased in ADHD adults while event-related potentials (ERPs) amplitudes were reduced to multisensory stimuli in frontal, parietal regions were found (McCracken et al., 2019). Further source localization analysis suggested greater neural activity to audiovisual stimuli in the NT group were compared the ADHD group. The source of the increased activity was found to be right postcentral gyrus (McCracken et al., 2022).

In a study examining emotion recognition using fMRI, lower BOLD activation was found across modalities (visual, auditory, and audiovisual) in participants with ADHD versus healthy control subjects in the cortex adjacent to the right superior temporal gyrus/middle temporal gyrus and the right posterior thalamus, which represent important areas for processing socially relevant signals and multisensory integration (Zuberer et al., 2020). A measure comparing the activation between unisensory and multisensory was not provided. A similar paradigm was conducted by the same research group, and they found increased multisensory gain (Bisch et al., 2016). In ADHD adults, better multisensory integration measured using a McGurk task was related with higher connectivity between Heschl's gyrus and auditory parabelt regions along with altered fronto-temporal network integrity from a resting-state scan (Schulze et al., 2023). Taken together, these studies show strong evidence that areas and pathways involved in multisensory integration are affected in ADHD.

Several structural and functional brain differences have been found in the ADHD brain including several sensory areas, then it would follow that we would see differences in multisensory integration. For structural differences, more broadly there are grey matter reductions across the cortex, including parietal, temporal, frontal, and occipital brain regions (Castellanos et al., 2002; Duerden et al., 2012; Makris et al., 2007; Proal et al., 2011; Valera et al., 2007) and more targeted brain areas such as the insula (Duerden et al., 2012) and superior colliculus (Overton, 2008). For functional differences, neural pathways involving the superior colliculus, fronto-parietal, and temporo-parietal networks are affected in ADHD and have been implicated in attention and multisensory integration (Dionne-Dostie et al., 2015).

5.1.1 Current Study

As mentioned, findings are mixed as to whether multisensory integration is affected by ADHD and these differences may exist for a few reasons. First, the method in which we are studying multisensory integration, such as using behavioural versus neuroimaging, may influence results. For example, neural studies have shown a reduced response in ADHD participants to multisensory and unisensory stimuli, even while behavioural measures show enhanced multisensory integration in ADHD participants compared to NT (McCracken et al., 2019; Zuberer et al., 2020). Differences in EEG or fMRI data can occur even when behavioral responses do not show significant differences, as these neuroimaging techniques are more sensitive to subtle neural processes. Behavioral tasks might not capture subtle multisensory integration differences, especially if they are too simple or if there is high individual variability, but EEG can reveal these differences. Additionally, individuals with ADHD may use compensatory strategies that mask behavioral differences, engaging different cognitive resources to achieve similar outcomes. Finally, multisensory integration occurs at different stages of processing, from early sensory-driven to late cognitive-driven stages. EEG can detect differences in these stages, even when they don’t manifest behaviorally. Reduced ERP amplitudes or BOLD response have been shown across many different cognitive and sensory domains and across multiple different brain areas in ADHD, even when behavioural findings may not be as clear (Dimoska et al., 2003; Johnstone et al., 2009; Liotti et al., 2010; Papp et al., 2020; Plichta et al., 2009). We expect there to be differences in multisensory integration in lower-level sensory regions, such as frontal electrodes, and in higher-level sensory regions, such as frontal electrodes. Differences in fronto-temporal network connectivity has been found in ADHD and related to differences in multisensory illusion susceptibility (Schulze et al., 2023). Second, individuals with ADHD have been shown to have hypo- and hyper-sensitivities to sensory information so it may be that these individual differences in unisensory processing are affecting multisensory integration. Using the perception-matched task, we will be able to control for these individual differences in unisensory processing.

Here, we attempt to address these methodological issues through two experiments. In Experiment 1, participants will be presented auditory and visual stimuli at the same intensity, which we will refer to as stimulus-matched. In Experiment 2, we will control for individual differences in sensory sensitivity by presenting the stimulus at each individual’s perceptual level, which we will refer to as perception-matched. The perception-matched detection task will be matched to which each individual is able to perceive 50% of the time and will give us a measure of sensory sensitivity in both the visual and auditory domains. In this way, we will be able to account for individual differences in sensory sensitivities associated with ADHD.

The purpose of this study was to understand whether audiovisual multisensory integration in adults with ADHD is different than in neurotypical adults. Multisensory integration has been found to be affected in many other neurodevelopmental disorders, but multisensory integration in individuals with ADHD does not necessarily fit these patterns. In ADHD, there is often poorer unisensory perception, but multisensory perception is similar to controls, which suggests that their multisensory performance “catches up” through a larger multisensory gain (Bisch et al., 2016; Zuberer et al., 2020). One reason for this may be due to the interaction between attention and multisensory integration. Since an object that is simultaneously detected by several sensory systems has a greater potential for capturing one’s attention, it is possible that multisensory stimuli are more attention-capturing to individuals with ADHD compared to unisensory stimuli which leads to this improvement in behaviour (Talsma, 2015; Talsma et al., 2010). For this to be true, we would expect to see differences in unisensory accuracy using behavioural measures in the stimulus-matched task and differences in unisensory ERPs in both tasks. We can also directly test whether this relationship plays a role by controlling for unisensory accuracy in the perception-matched paradigm.

First, we expect there to be differences in frontal, parietal, and occipital regions of the difference wave of the EEG response, with the ADHD adults having less integration than NT adults. Further, we expect all these results to be more pronounced in the perception-matched task compared to the stimulus-matched task. Second, we also expect the ADHD group to have increased multisensory benefit in response times, as previous studies have found (McCracken et al., 2019). Third, we expect the ADHD group to have significantly more multisensory gain in accuracy compared to the NT group, especially in the stimulus-matched condition. Previous studies have shown lower accuracy in unisensory conditions in ADHD compared to controls but around the same audiovisual accuracy, suggesting they would likely have higher multisensory gain (Zuberer et al., 2020). Fourth, we expect there to be differences in sensory discrimination ability in both the auditory and visual domains between ADHD and NT adults, as both hyper and hypo-sensitivities to sensory information have been found in ADHD. Most of these studies looked more at questionnaire measures of sensory processing and did not look at psychophysiological paradigms. Previous work has suggested that these measures may be looking at distinct concepts (Schulz & Stevenson, 2020).

5.2 Experiment 1: Stimulus-Matched

5.2.1 Methods

5.2.1.1 Participants

A total of 64 participants completed this study, 32 adults with ADHD (26 females, M_{age}= 24.47, age range= 18-52) and 32 NT adults (22 females, M_{age}= 20.75, age range= 17-59), after 1 participant was excluded for failure to do questionnaires. Adults were asked to report when they received a diagnosis. At time of testing, participants were asked if they took stimulants or consumed caffeine that day. Participants in both groups were recruited through Western University's Psychology Research Participant Pool, using Western's OurBrainsCAN database (https://ourbrainscan.uwo.ca/) and community sampling. All participants were fluent in English, had self-reported normal or corrected-to-normal hearing and vision. Ethics approval for all study procedures and materials was obtained by the University of Western Ontario's Non-Medical Research Ethics Board. Participants were paid $10 for each hour of the study. Demographic information can be found in Table 5.1. There was a significant difference between ADHD scores for the ADHD and NT adults, and a trending difference in age between the ADHD and NT adults.

Table 5.1. Demographic and Survey Information for ADHD and NT adults

	ADHD Adults (*N*=32)		NT Adults (*N*=32)				
	M	SD	M	SD	t	p	d
Age	24.47	8.39	20.75	4.45	-1.86	.07	-.46
Total ASRS	47.91	7.88	32.00	12.18	-6.20	<.001	-1.56
ASRS-IA	25.94	5.03	17.59	6.93	-5.51	<.001	-1.38
ASRS-HI	21.97	4.915	14.41	6.12	-5.45	<.001	-1.90

5.2.1.2 Self-Report Measures

5.2.1.2.1 ADHD Measure

The adult ADHD Self-Report Scale (ASRS-v1.1) (Kessler et al., 2005) was used to assess each participant's symptoms associated with ADHD. The ASRS is a self-report scale intended to reflect symptom presentation in ADHD adults, based on the DSM-IV diagnostic criteria. The 18-item questionnaire is rated on a 5-point Likert scale ranging from "Never" to "Very Often" (Kessler et al., 2005). Answers indicated for each of the questions in the questionnaire were computed as 0, 1, 2, 3, or 4 and reported responses were added up, scored, and used to ensure participants were in the correct group for analysis. This exclusion process was included to confirm that participants in the ADHD group had persistent symptoms that had not fully resolved, and similarly, that participants in the control group did not potentially have ADHD. Subjects in the ADHD group were noted if their total score was less than 34, as that indicates they are unlikely to have ADHD, and subjects in the neurotypical group were noted if their total score was above 46, as that indicates they were likely to have ADHD (Stark et al., 2011). Three participants in the NT group scored high enough for probable ADHD. The analyses were run with and without these individuals and as the results did not change, we opted to leave them in.

5.2.1.2.2 Sensory Processing Measure

To measure sensory processing patterns, participants completed the Adolescent/Adult Sensory Profile (Brown & Dunn, 2002). The AASP is a 60 –item self-report questionnaire that measures the frequency of behavioural responses to sensory events. Items are scored on a 5-point Likert scale ranging *almost never* to *almost always*. The questionnaire has 4 scales: low registration, sensation seeking, sensory sensitivity, and sensation avoiding. Each scale has 15 statements representing individual’s sensory experiences in different modalities (Taste/Smell Processing, Visual Processing, Auditory Processing, Touch Processing, Activity Level and Movement Processing) as well as behavioural/self-regulatory reactions to these experiences. In this study, we are using the Visual Processing and Auditory Processing subscales.

5.2.1.3 Stimuli

All stimuli were presented using E-Prime 3 (Psychology Software Tools, 2016) software with NetStation Extensions version 2.0. on a monitor with a refresh rate of 16.67 ms (60 Hz). Further, the task was gaze contingent and we used a Tobii Pro Spectrum eye tracker. The visual stimulus was a Gabor patch with a Michelson contrast of 0.36. The auditory stimulus was a tone of 59dB presented at a frequency of 800 Hz embedded in continuous 40 dB SPL auditory white noise. Audiovisual trials included both visual and auditory stimuli. Null trials used the same visual and auditory noise without an embedded Gabor patch or auditory tone. All trials were embedded in dynamic audiovisual noise, which continued without break during inter-trial intervals. The auditory, visual, and audiovisual stimuli were presented 75 times each, and null trials were presented 225 times (equal to the combined number of trials with stimuli presented). All stimuli were presented for 100 ms. Responses were collected for the 1500 ms following stimulus presentation. Regardless of if a response was given or note, the task continued to the next trial. An example of trial procedure can be found in Figure 5.1.

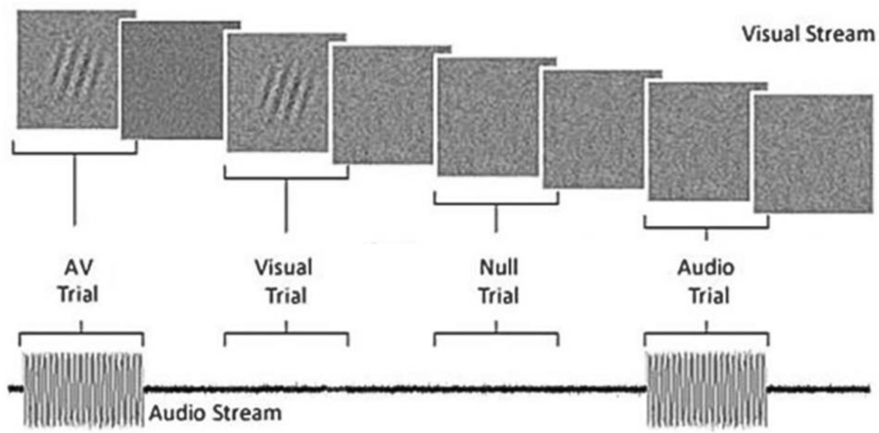

Figure 5.1. Trial procedure for stimulus-matched audiovisual detection task. Trial procedure with example of unisensory and multisensory stimuli. Adapted from (Schulz & Stevenson, 2020).

5.2.1.4 Procedures

Before completing the behavioural portion of the study, all participants completed a series of surveys. These included basic demographic and health questions, Adult/Adolescent Sensory Profile (AASP; Brown & Dunn, 2002) and the Adult ADHD Rating Scale (ASRS; Kessler, 2005).

For the speeded-response time task, participants were seated in a dark room approximately 75 cm away from the monitor (HP LCD Monitor). Visual stimuli were presented with a refresh rate of 16.67 ms (60 Hz) for both tasks. All auditory stimuli were presented via a speaker on either side of the participant, approximately 90 cm from their head. Responses were collected using a Serial Response Box (Model 200 A; Psychology

Software Tools, Inc., 2003). Experiments were conducted using E-Prime 3 (Psychology Software Tools, Inc., 2016) using NetStation Extensions version 2.0.

Participants were instructed to press the leftmost button if they were left-handed and the rightmost button if they were right-handed on a Chronos response pad. A Tobii Pro X3 – 120 eye-tracker was attached to the monitor for gaze-contingent trial control, the following trial would not begin until the participant fixated on the screen for 100 ms. Participants rested their chin on a chin rest to minimize head motion and control the distance to the monitor. The chin rest was aligned with the centre of the monitor and with each participant's eye level. While completing the tasks, continuous EEG signal will be recorded using a 256-channel EGI Hydrocel net.

5.2.1.5 Behavioural Data Acquisition and Analysis

5.2.1.5.1 Response Time

Response times were recursively trimmed, removing any times that were three standard deviations (SD) above and below the mean.

The MATLAB RSE-box (Otto, 2019) was used to calculate the race model, the response-time based multisensory gain. The race model utilizes cumulative distribution functions (CDF) to represent the cumulative probability that a response has been made at a given time (Miller, 1982; Raab, 1962). Miller's bound was used as a baseline for identifying multisensory gain, accounting for statistical facilitation due to redundant target effects and assumes a maximum negative correlation between auditory and visual response times, making it a conservative baseline (Miller, 1982).

Race model violations are identified when the observed audiovisual CDF crosses to the left of Miller's bound (Figure 5.2). Violations of Miller's bound indicate that a multisensory interaction has occurred, and the difference between the observed audiovisual CDF and Miller's bound is indicative of how much multisensory gain is experienced. If the values are positive, the values are taken as evidence of multisensory integration. Positive values are interpreted as evidence of multisensory integration. Conversely, the absence of violations, or values of zero, cannot be conclusively interpreted as evidence for or against multisensory integration. This lack may suggest sub-optimal integration, independent processing, or interference instead (Stevenson et al., 2014). The RSE-box reports the Violation of Miller's bond as a singular number, which we will report. Other methods of calculating race model provide different information, such as time bins.

Violations above 0 on Miller's Race Model provides evidence that multisensory integration has occurred. First, a Chi-Square will be completed between groups with scores of 0 (no violation) and scores above 0 (violation and evidence of multisensory integration) to see if the number of participants with violations differ. Second, an independent samples t-test will be used to compare the magnitude of the violations of ADHD adults and NT adults. If there is no significant difference on the Chi-Square, then all participants will be added into the t-test analysis. If there is a significant difference, then the t-test analyses will be run with the full sample and without participants who had a violation of 0.

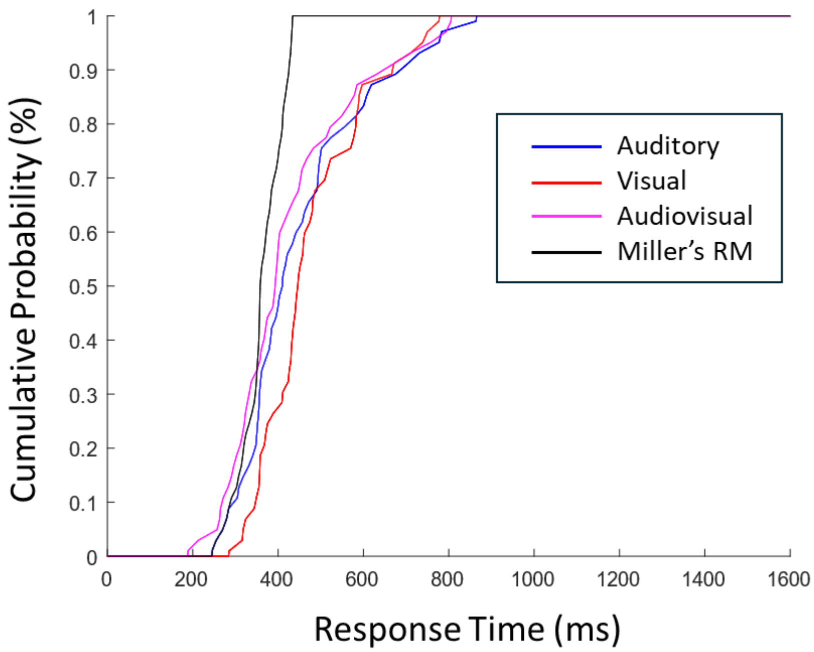

Figure 5.2. Example Violation of Race Model for ADHD Participant X. Probability quantile distribution response times in the three stimulus conditions (Auditory, Visual, Audiovisual) in comparison to Miller's Race Model (Miller's RM) distribution.

5.2.1.5.2 Accuracy

Accuracy gain or multisensory gain was calculated by comparing accuracy scores in the audiovisual trials relative to their predicted audiovisual accuracy using the probability summation criteria. Predicted audiovisual accuracy was calculated from the unisensory component accuracy, assuming independence using the following equation:

$$\widehat{pAV} = p(A) + p(V) - [p(A) * p(V)]$$

Where pAV represents the null hypothesis of the response to audiovisual presentations if the auditory and visual information are processed independently, and where *p*(A) and *p*(V) represent response accuracy to auditory- and visual-only presentations. Multisensory gain was then derived using the following equation: $observed\ AV\ accuracy - \widehat{pAV}\ accuracy$. Positive values indicated that multisensory integration had occurred, while negative values failed to conclude that multisensory integration had occurred. Trials with response times under 100 ms were removed, as a response this fast cannot occur physiologically following the perception of the target stimuli, and the final accuracy was calculated from the remaining trials after the removal.

5.2.1.5.3 Subtype Analyses

The Hyperactive-Impulsive presentation of ADHD has been related to multisensory processing differences (Hare et al., in prep, Shimizu et al., 2014) but other studies suggest there are not subtype differences in sensory processing (Ghanizadeh, 2011). Pearson correlations between ADHD presentation symptoms (Inattentive, Hyperactive-Impulsive Symptoms) from the ASRS, sensory sensitivity measures, and multisensory integration measures will be conducted. We hypothesize that the Hyperactive-Impulsive symptoms will be more positively correlated with sensory sensitivity and multisensory integration. A Benjamini-Hochberg correction for multiple comparisons will be used.

5.2.1.6 EEG Data Acquisition and Analysis

We collected electrophysiological data was using a 256-channel EGI Hydrocel GSN net (Electrical Geodescis Inc., Eugene, OR, USA) recording through EGI NetStation with an online reference to Cz. The sampling rate was 1000 samples/second. Analysis was done using MATLAB. Data was initially band-pass filtered at 0.3–50 Hz. Additionally, a 60 Hz notch filter was applied to filter out powerline interference. Only correct trials (correctly identifying the target, and correctly withholding a response for all other trials) will be included in the analyses. Epochs of 1200 ms will be extracted from the data, with the first 200 ms used for baseline correction, and the last 1000 ms post-stimulus presentation. An average reference was computed, and data was re-referenced to the average. Data was cleaned by excluding epochs in which there was an artifact across 10 channels (>300 μV, window size = 640 ms; moving average = 80 ms). Bad channels were removed based on visual inspection and replaced by spherical spline interpolating the signal from the surrounding electrodes. Participants with more than 40% of epochs removed, were removed from the analysis.

The amplitudes from the unisensory and multisensory signals were compared to quantify multisensory interactions. As electrical fields detected by EEG sum linearly, interactions between auditory and visual processing are identified by summing the two unisensory signals and comparing this sum to the audiovisual signal, known as the additive criterion (Besle et al., 2004; Stevenson et al., 2014). Interactions are thus defined by significant differences: $A+V \neq AV$

For multisensory integration, independent samples t-tests will be calculated between ADHD and NT adults along the time course of the difference wave. If there are significant differences between the groups at $\alpha = .05$ for 5 consecutive ms then this will be considered a significant difference. These analyses will be run for our four clusters or regions of interest, which were defined a priori clusters using prior literature (Lauzon et al., 2022) and we expect to see multisensory responses occur before 250 ms. The time point with the lowest p-value will be reported. For sensory sensitivity, independent samples t-tests will be calculated between ADHD and NT adults along the time course of auditory and visual trials.

For multisensory integration, independent samples t-tests will be calculated between ADHD and NT adults along the time course of the difference wave. If there are significant differences between the groups at $\alpha = .05$ for 5 consecutive ms then this will be

considered a significant difference. Typically, multisensory responses occur before 250ms, but we see a delayed ERP response due to the stimuli being at such a low perceptual level it may take longer to come into awareness for participants. For sensory sensitivity, independent samples t-tests will be calculated between ADHD and NT adults along the time course of auditory and visual trials.

5.2.2 Results

5.2.2.1 Behavioural Results

5.2.2.1.1 Response Time Analysis

Violation of Miller's Race Model (*M* = 1.16, *SD* = 1.75) ranged from 0 to 25.56, with non-zero values suggesting a violation of Miller's Race Model and evidence for multisensory integration. Chi-square analysis was conducted to compare the number of violations between groups and indicated no significant relationship between the number of violations in the ADHD and control group, X^2 (1, N = 64) = 1.02, *p* = .31, φ =.13. Violations for the ADHD group (*M* = 9.53, *SD* = 6.41) did not differ significantly from those in the control group (*M* = 9.32, *SD* = 6.42), *t*(62) = -.12, *p* = .91, BF_{10} = 0.19 with a very small effect size (*d* = -.03) (Figure 5.3).

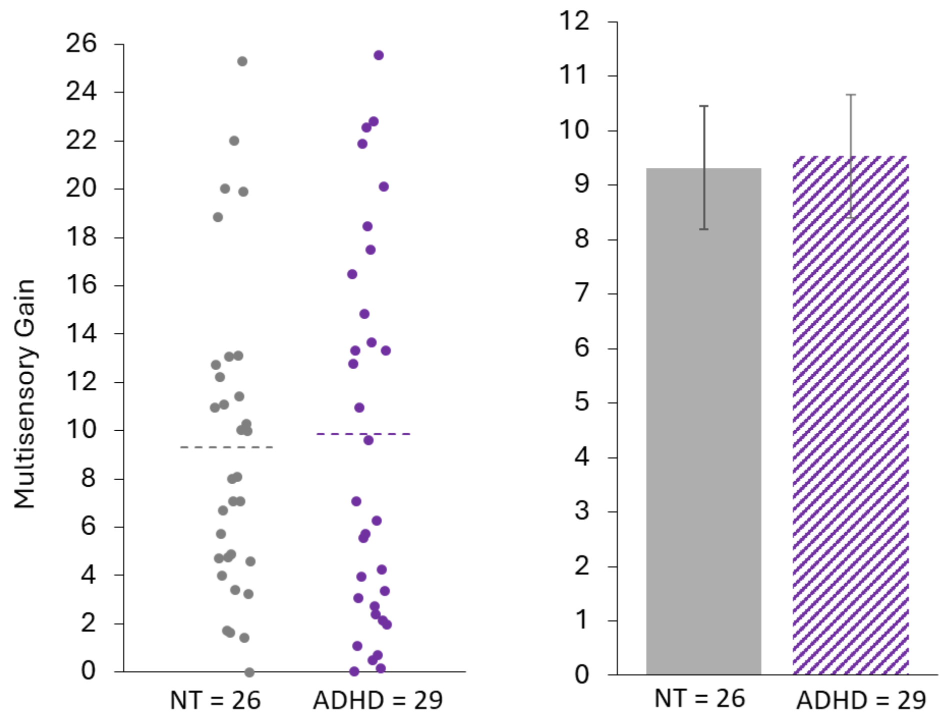

Figure 5.3. Individual and mean multisensory gain data using Miller's Race Model Violations for the Stimulus-Matched Task. Error bars indicate SEM.

5.2.2.1.2 Accuracy

Levene's Test for Equality of Variances was significant, and to correct for this the statistics for equal variances not assumed were reported, which leads to a reduction in the *df*s from expected. Visual accuracy for the ADHD group (*M* = .88, *SD* = .14) differed marginally significant from the control group (*M* = .78, *SD* = .26), *t*(46.47) = -1.91, *p* = .06, *d* = -.47, BF_{10} = 0.97. Auditory (*t*(49.70) = -.99, *p* = .33, *d* = -.25 BF_{10} = 0.29) and Audiovisual (*t*(62) = .80 *p* = .53, *d* = .20, BF_{10} = 0.25) accuracy did not significantly differ between groups. For graphs of the accuracy in each modality and predicted accuracy are in Figure 5.4. Accuracy Gain for the ADHD group (*M* = -.01, *SD* = .02), differed significantly from the control group (*M* = .00, *SD* = .01), *t*(43.0) = 2.99, *p* = .005, BF_{10} = *9.01* with a medium to large effect size (*d* = .75). Neither the ADHD group (t(31)

= -1.79, *p* = .08, *d* = -.32), nor the TD group (t(31) = .15, *p* = .88, *d* = .03) showed significant accuracy gain ADHD. The accuracy gain should be interpreted with caution because the baseline of unisensory accuracy was at ceiling.

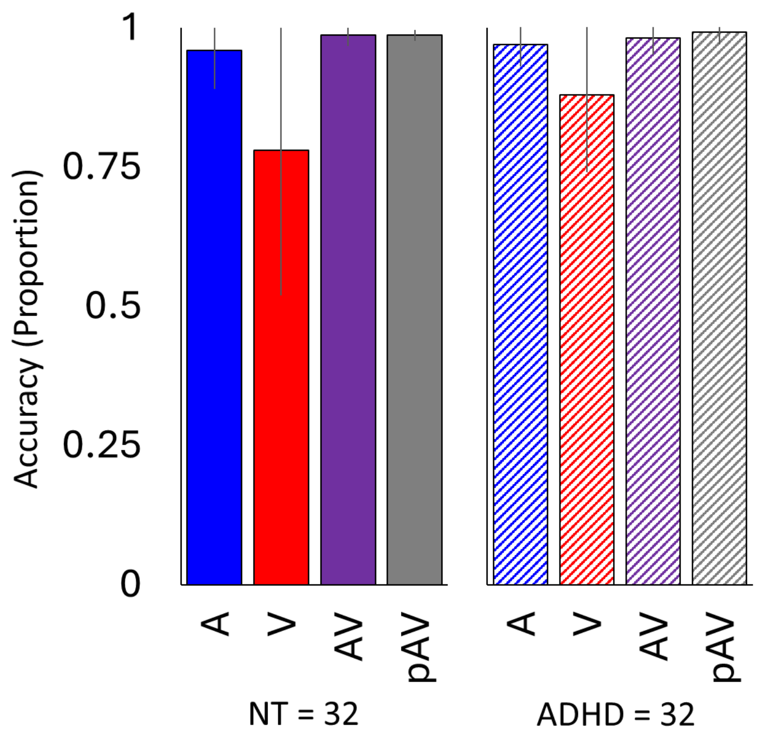

Figure 5.4. Accuracy in the auditory, visual, audiovisual domains and accuracy gain for the Stimulus-Matched Task.

5.2.2.1.3 Subtype Analyses

Correlation with the Inattentive and Hyperactive-Impulsive symptoms with the measures of multisensory gain are included in Figure 5.5. Accuracy gain was significantly negatively correlated with Inattentive and Hyperactive-Impulsive symptoms. Violations were not significantly correlated with Inattentive (*r*(64) = .05, *p* = .67) and Hyperactive-Impulsive symptoms (*r*(64) = .002, *p* = .99). Accuracy gain was significantly correlated with Inattentive (*r*(64)= -.27, *p* = .03) and trend level significantly correlated with Hyperactive-Impulsive symptoms (*r*(64) = -.01, *p* =. 05).

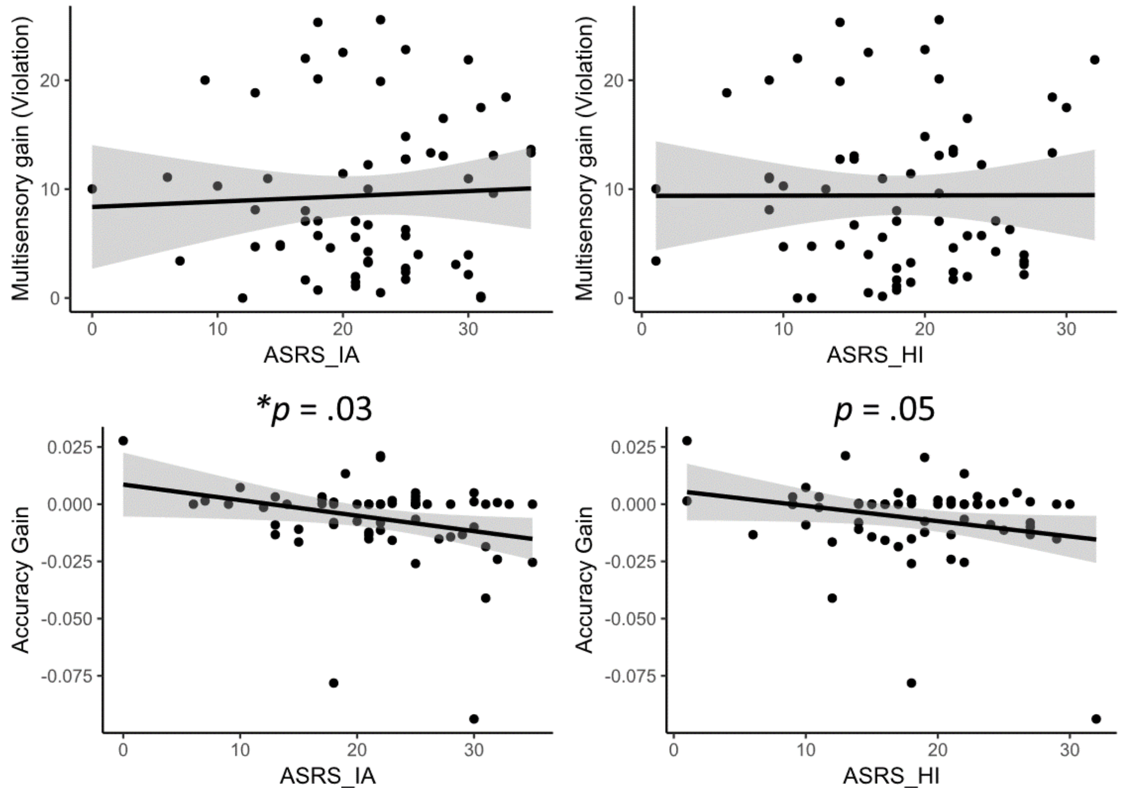

Figure 5.5. Scatterplots of multisensory gain and ADHD presentation traits in the Stimulus-Matched Task.

5.2.2.2 EEG Results

Only correct trials were included for visual, auditory, and audiovisual trials. The final analysis included 28 ADHD and 22 NT participants; 14 participants were excluded because more than 30% of trials rejected. There were four regions of interest (ROI): frontal, central, central-parietal, and occipital.

5.2.2.2.1 Unisensory

There were no significant group differences between the Visual and Auditory conditions in all areas of interest (Figure 5.6).

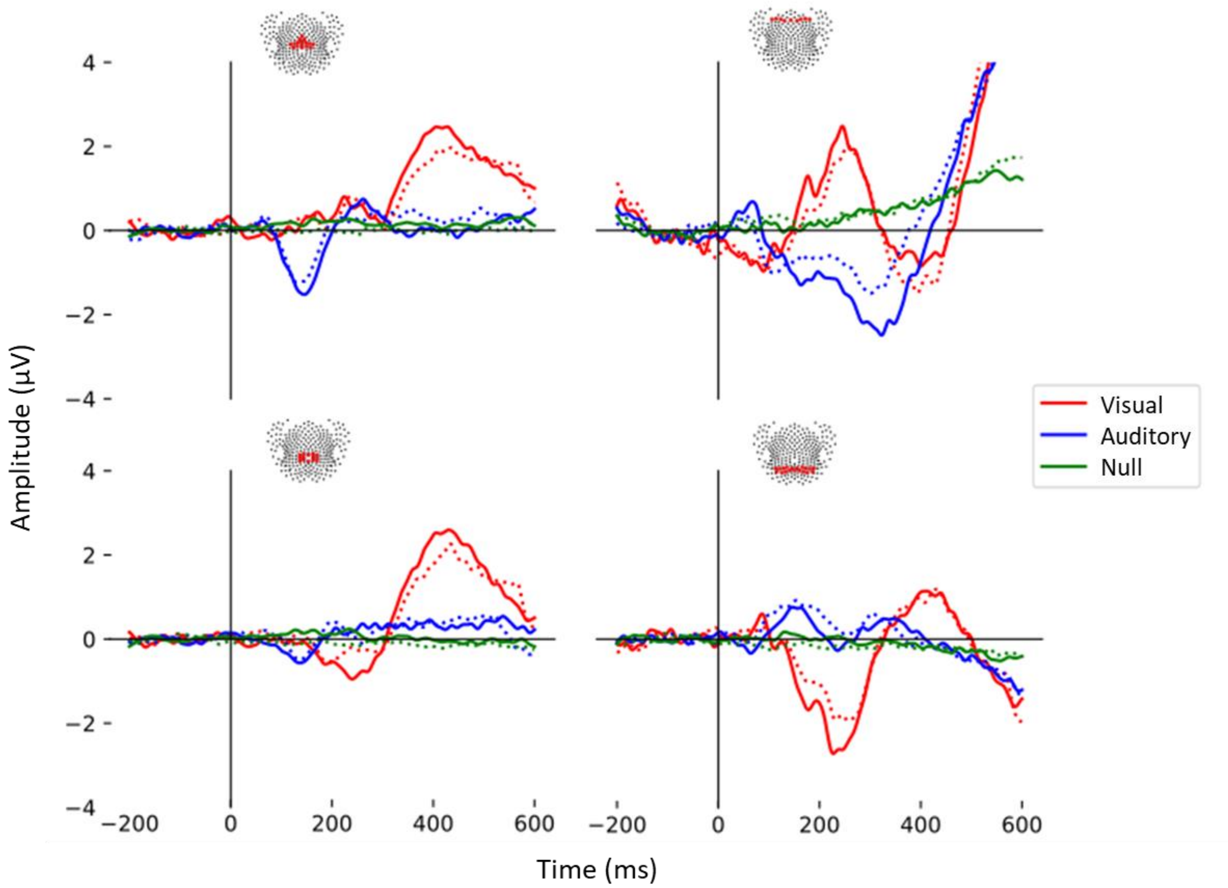

Figure 5.6. Waveforms for Visual, Auditory, and Null Trials at Central, Frontal, Central-Parietal and Occipital Regions in the Stimulus-Matched Task. Solid lines are NT adults, and hashed lines are ADHD adults. Visual is red, auditory is blue, and the null is green.

5.2.2.2.2 Multisensory

Difference Wave below refers to amplitude differences between the sum of the unisensory conditions (Audio + Visual) and the Audiovisual (AV condition). Multisensory responses would be expected before 250ms, but the entire time course will be examined.

There was a significant difference in the Difference Wave from 300ms to 321ms between NT and ADHD participants in the occipital region (Figure 5.7). At 309 ms, a mean difference of $M = 1.42$ was found to be significant $t(46) = -2.37$, $p = .02$, $d = .68$. There were no other significant differences between groups in the other three ROIs.

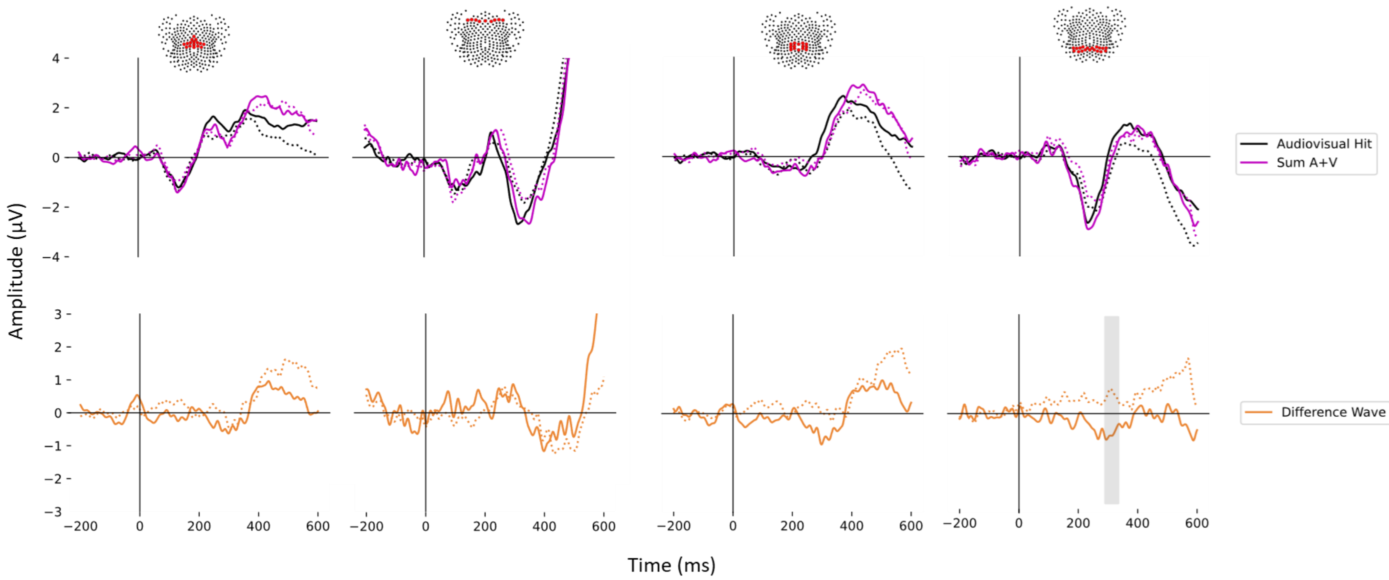

Figure 5.7. Waveforms for Audiovisual, Summed Unisensory, and Difference Wave at Central, Frontal, Central-Parietal and Occipital Regions in the Stimulus-Matched Task. NT is the solid line, and ADHD is the dashed line. Audiovisual is purple, Sum A + V is black, and the Difference Wave is orange.

5.2.3 Discussion

For response time gain we found no group differences, which is inconsistent with our predictions and prior research. A previous study found an earlier violation of Miller's Race Model using a stimulus-matched speeded response time task (McCracken et al., 2019). We could not assess accuracy gain because the baseline of unisensory accuracy was at ceiling. For the ERP results, the Difference Wave only showed a significant group difference in the occipital area after expected multisensory integration processes (< 250 ms). Previous research has found more pronounced differences between summed unisensory and audiovisual ERPs in ADHD and NT adults, although they did not calculate a difference wave (McCracken et al., 2019). For the unisensory conditions, we saw expected ERPs to visual and auditory information, such as the P1, N1, P2, and N2, but no group differences.

5.3 Experiment 2: Perception-Matched

5.3.1 Methods

5.3.1.1 Participants

A total of 64 participants completed this study, 31 adults with ADHD and 31 NT adults, after 1 participant was excluded for failure to do questionnaires and 2 were excluded for technical difficulties.

5.3.1.2 Stimuli

The stimuli and presentation software used in this task were identical to the previous experiment, except the intensity of stimulus presentation and number of presentations. Auditory tones ranged from 37.5 dB SPL, and at 67.5 dB SPL in half decibel steps. Visual stimuli were 70 sinusoidal luminance gratings (Gabor patches) evenly positioned according to Michelson contrast between 0.01 to 0.1 and placed in static visual noise. Gabor patches were randomly oriented for each contrast, excluding exactly vertical and horizontal orientations. To create multisensory stimuli, the auditory and visual stimuli were presented simultaneously. All stimuli were presented for 100 ms. Null trials consisted of auditory and visual noise without the luminance gratings or auditory tones (Schulz & Stevenson, 2020).

5.3.1.3 Procedure

5.3.1.3.1 Threshold Determination

There was an adaptive one-up-one-down staircase procedure to determine each participant's 50% threshold. The starting point for the two auditory staircases ranged in difficulty from 40 dB SPL (hardest) to 65 dB SPL (easiest) in noise. The starting point for the two visual staircases similarly ranged in difficulty by using Michaelson contrasts of 0.001 (hardest) to 0.50 (easiest) in noise. For instance, if a stimulus was accurately detected by the participant, the subsequent trial within the same staircase would present a stimulus at a lower intensity that is harder to detect. If the stimulus was not accurately detected, then the next stimulus would be presented at a higher intensity that is easier to detect. The staircase changed in difficulty by eight levels until the first reversal. After the first reversal occurred, the step size decreased to four levels until the second subsequent reversal. In other words, the intensity of the stimulus altered between high and low until a barely detectable stimulus was presented after an undetectable stimulus for that participant. To calculate each participants' threshold level, the mean position of the two respective auditory and visual staircases following six reversals within each staircase was calculated.

5.3.1.3.2 Speeded Response Time Task

Directly following threshold determination, the speeded response-time task began. The unisensory trials were presented at each participant's 50% response threshold, and multisensory trials included both auditory and visual stimuli presented at their unisensory 50% threshold. Stimulus intensities continued to slightly adapt (1 step) based on performance on unisensory trials throughout this portion of the task to account for fatigue. In total, there were 600 trials after the staircase: 100 auditory, 100 visual, 100 audiovisual, and 300 null trials. Participants were instructed to press the leftmost button if they were left-handed and the rightmost button if they were right-handed on a Chronos response pad.

5.3.1.4 Analysis

Consistent with the first experiment, multisensory gain values were calculated using the race model for each participant.

Accuracy gain for each participant was also calculated. Note that these analyses used only data following thresholding, excluding the data during the adaptive staircase used to determine the individual's threshold. Accuracy was expected to be around 50% for all participants, but it is possible that some participants would not be able to perceive the easiest stimuli, and some participants could perceive the most difficult stimuli.

Participants with accuracy or violations ±3SD will be excluded from accuracy gain, violation, and EEG analyses.

EEG analyses were consistent with the first experiment, only trials during the speeded response time task will be included in the averages. Compared to Experiment 1, we may see a delayed ERP response due to the stimuli being at such a low perceptual level it may take longer to come into awareness for participants.

Pearson r correlation with the Inattentive and Hyperactive-Impulsive symptoms will be conducted with the measures of multisensory gain.

5.3.1.4.1 Sensory Sensitivity

Previous research has suggested that questionnaire measures and behavioural paradigms measure distinct aspects of sensory processing (Schulz & Stevenson, 2020). Sensory responsivity or sensory reactivity refer to questionnaires, particularly third-party reports, as they rely on observable behavioural response to sensory stimuli. Self-report questionnaires of sensory processing primarily measure responsivity to stimuli and may be inaccurate when it comes to sensory thresholds. Sensory sensitivity refers to the individual's ability to detect and perceive sensory inputs, which can be measured using behavioural paradigms, such as a detection task. This current study will use this framework, sensory responsivity was measured using self-report measures and sensory sensitivity was measured using a staircasing detection task.

The self-reported measure of sensory responsivity was calculated using the scores of the Auditory Processing and Visual Processing subscales on the AASP. The behavioural sensory sensitivity was calculated in the auditory and visual domains by taking the first auditory stimuli's decibel value and the first visual stimuli's Michelson contrast after threshold determination in the staircasing procedure.

For both self-report and behavioural measures, independent samples t-tests were used to compare auditory and visual sensory processing in ADHD and NT adults. Pearson correlations between self-report sensory responsivity, behavioural sensory sensitivity and ADHD scores will be calculated. A Benjamini-Hochberg correction for multiple comparisons will be used.

5.3.2 Results

5.3.2.1 Behavioural Results

26 NT and 29 ADHD participants were included in the final analysis.

5.3.2.1.1 Response Time Analysis

Violation of Miller's Race Model ranged from 0 to 8.11, with non-zero values suggesting a violation of Miller's Race Model and evidence for multisensory integration. Chi-square analysis was conducted to compare the number of violations between groups and indicated no significant relationship between the number of violations in the ADHD and control group, X^2 (1, N = 64) = .61, p = .43, φ = .10. In some instances, Levene's Test for Equality of Variances was significant, and to correct for this the statistics for equal variances not assumed were reported, which leads to a reduction in the *df*s from expected. Violations for the ADHD group (M = 1.68, SD = 2.26) significantly differed from those in the control group (M = .66, SD = .90), t(37.44) = -2.25, p = .03, BF_{10} = 1.56 with a medium effect size (d = -.58) (Figure 5.8).

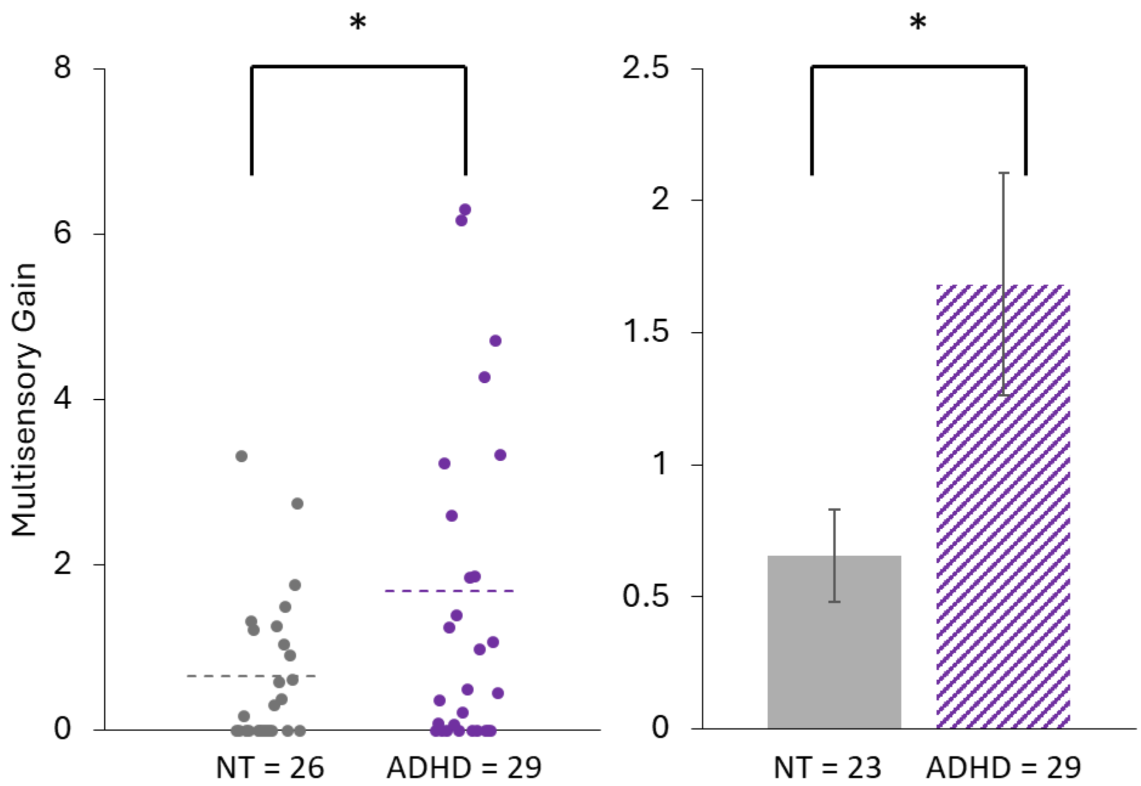

Figure 5.8. Individual and mean multisensory gain data using Miller's Race Model Violations for the Perception-Matched Task. Error bars indicate SEM. **p* < .05.

5.3.2.1.2 Accuracy

Positive scores for accuracy gain suggest multisensory integration occurred optimally. Auditory accuracy for the ADHD (*M* = .57, *SD* = .11) and the control (*M* = .51, *SD* = .05) group significantly differed with *t*(39.46) = -2.58, *p* = .01, *d*= -.70, BF_{10} = 3.54 with 7 ADHD participants and 2 NT having an accuracy above 60%. Visual accuracy for the ADHD group (*M* = .47, *SD* = .04) did not significantly differ from the control group (*M* = .48, *SD* = .05), *t*(53) = -1.09, *p* = .28, *d*= -.30, BF_{10} = .35. Audiovisual accuracy for the ADHD group (*M* = .79, *SD* = .08) marginally differed from the control group (*M* = .75, *SD* = .79), *t*(53) = -1.96, *p* = .06, *d*= -.53, BF_{10} =1.10. Neither the ADHD group (*t*(28) = .165, *p* = .87, *d* = .03) or TD group (*t*(25) = .339, *p* =.74, *d* = .07) showed significant accuracy gain. For graphs of the accuracy in each modality and predicted accuracy are in Figure 5.9. Accuracy Gain for the ADHD group (*M* = .01, *SD* = .06), differed significantly from the control group (*M* = .01, *SD* = .06), $t(53) = .181$, $p = .86$, $d = .05$, $BF_{10} = 0.21$.

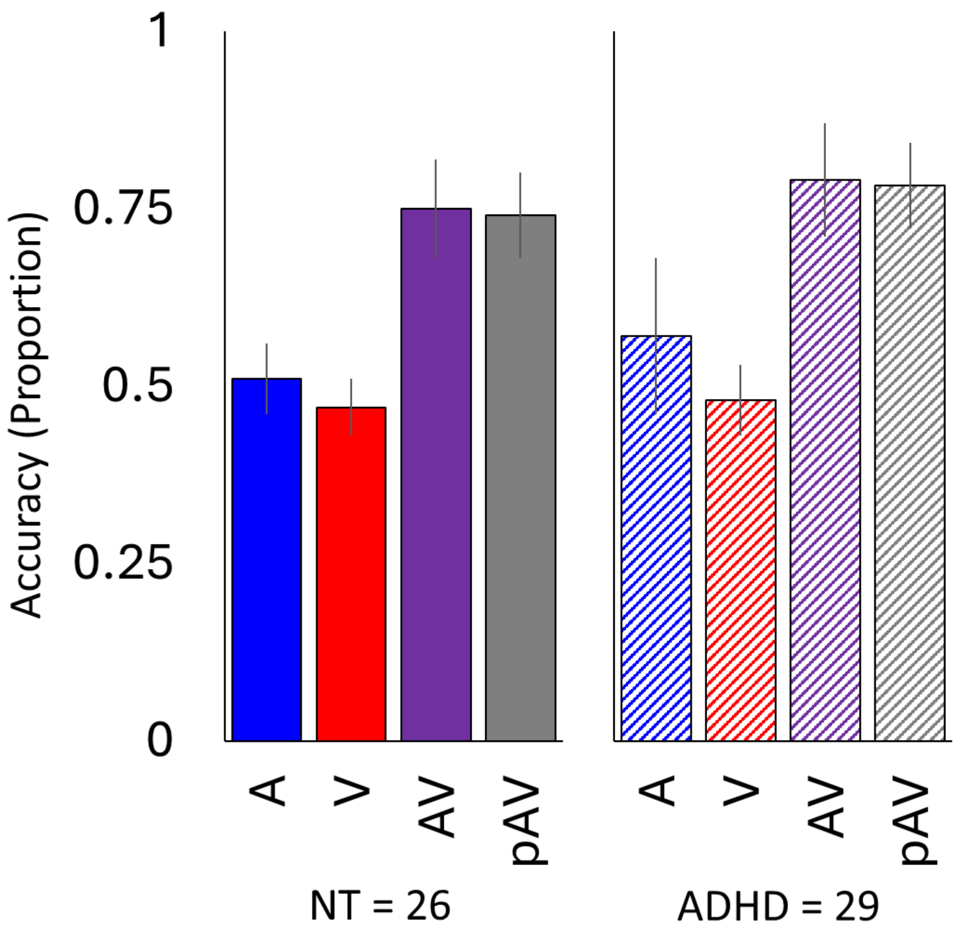

Figure 5.9. Accuracy in the auditory, visual, audiovisual domains and accuracy gain for the Perception-Matched Task.

5.3.2.2 Subtype Analysis

Correlation with the Inattentive and Hyperactive-Impulsive symptoms with the measures of multisensory gain are included in Figure 5.10. Violations were not significantly correlated with Inattentive ($r(60) = .13$, $p = .32$) and Hyperactive-Impulsive symptoms ($r(60) = .16$, $p = .22$). Accuracy gain were not significantly correlated with

Inattentive ($r(63) = -.10$, $p = .42$) and Hyperactive-Impulsive symptoms ($r(63) = -.01$, $p = .93$).

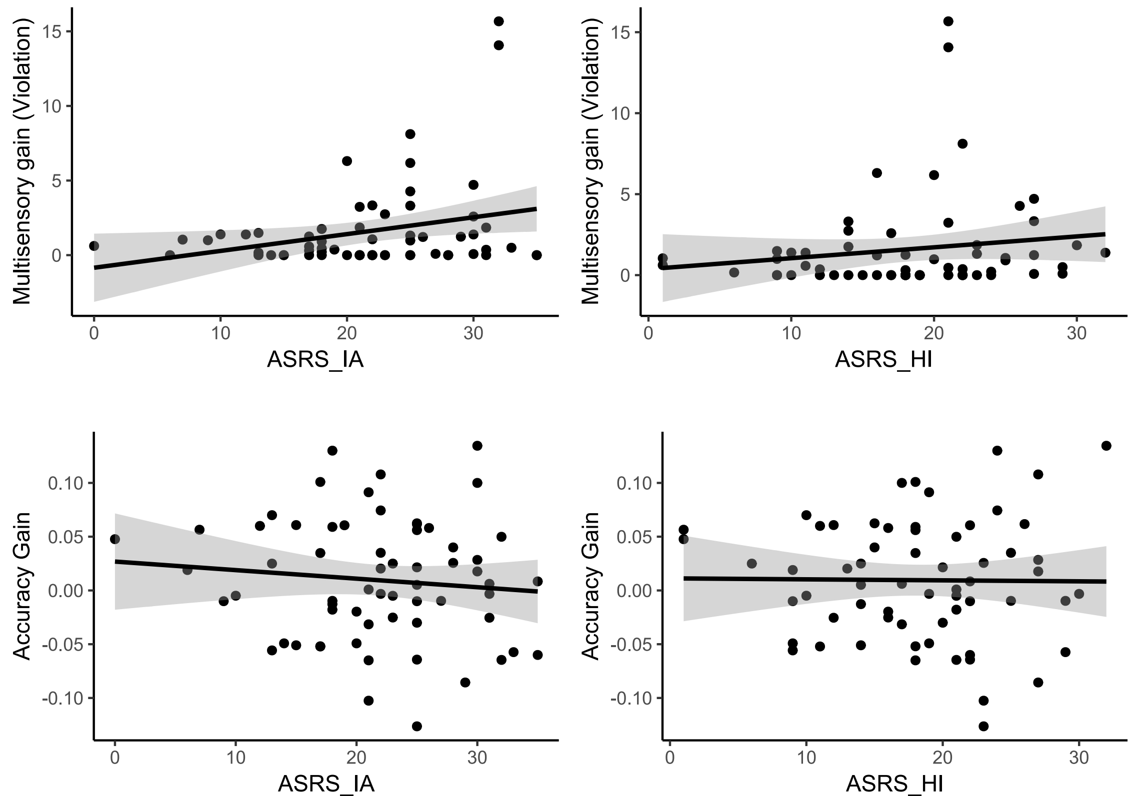

Figure 5.10. Scatterplots of multisensory gain by ADHD presentation symptoms in the Perception-Matched Task.

5.3.2.3 Sensory Processing

5.3.2.3.1 Behavioural Sensory Sensitivity

Sensory sensitivity was measured using behavioural methods by taking the first auditory, measured in dB, and visual stimulus, measured in Michelson Contrast, after the staircasing procedure (See Figure 5.11). 32 ADHD and 31 NT participants completed the staircasing procedure, and the Auditory Sensitivity in dB ranged from 40.25 (hardest stimuli presented) to 57.50 and the Visual Sensitivity in Michelson Contrast ranged from .026 to .50 (easiest stimuli presented). There was no significant difference in Auditory Sensitivity between ADHD (*M* = 46.60, *SD* = 4.31) and NT (*M* = 45.35, *SD* = .67) groups, *t*(61) = -1.23, *p* = .23, *d* = -.31. There was no significant difference in Visual Sensitivity between ADHD (*M* = .11, *SD* = .11) and NT (*M* = .11, *SD* = .11) groups, *t*(42.40) = 1.54, *p* =.13, *d* = -.39.

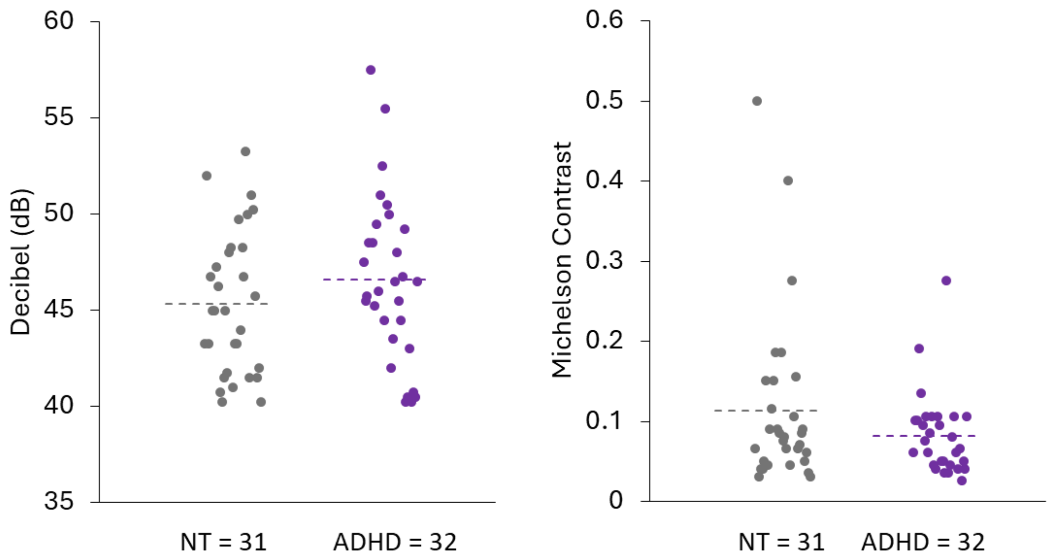

Figure 5.11. Behavioural Sensory Sensitivity from Threshold Determination

5.3.2.3.2 Self-Report Sensory Responsivity

Sensory responsivity was measured using self-reports from the AASP Visual and Auditory subscales (See Figure 5.12). 32 ADHD and 32 NT participants completed the questionnaires, and the Auditory scores ranged from 16 to 49 and the Visual Scores ranged from 14 to 39. There was a significant difference in Auditory Sensitivity between ADHD (*M* = 34.09, *SD* = 7.38) and NT (*M* = 28.16, *SD* = 5.31) groups, *t*(62) = -3.38, *p* < .001, *d* = -.84. There was a significant difference in Visual Sensitivity between ADHD (*M* = 26.88, *SD* = 5.31) and NT (*M* = 22.91, *SD* = .50) groups, *t*(62) = -3.07, *p* = .002, *d* = -.77.

Self-Report and behavioural measures of sensory sensitivity were significantly positively related for visual stimuli (*r*(63) = .26, *p* = .04), but were not related for auditory stimuli (*r*(63) = -.18, *p* = .16). The visual correlation did not survive multiple comparisons. Self-reported visual and auditory responsivity were to Inattentive Traits

($r(64) = .38$, $p = .002$; $r(64) = .52$, $p < .001$). Hyperactive-Impulsive Traits was significantly related to self-reported auditory responsivity $r(64) = .42$, $p < .001$), but not related to self-reported visual responsivity ($r(64) = .18$, $p = .15$). Behavioural visual and auditory sensitivity were not correlated with Inattentive ($r(63) = -.08$, $p = .52$; $r(63) = .16$, $p = .21$) or Hyperactive-Impulsive Traits ($r(63) = -.10$, $p = .43$; $r(63) = .13$, $p = .32$).

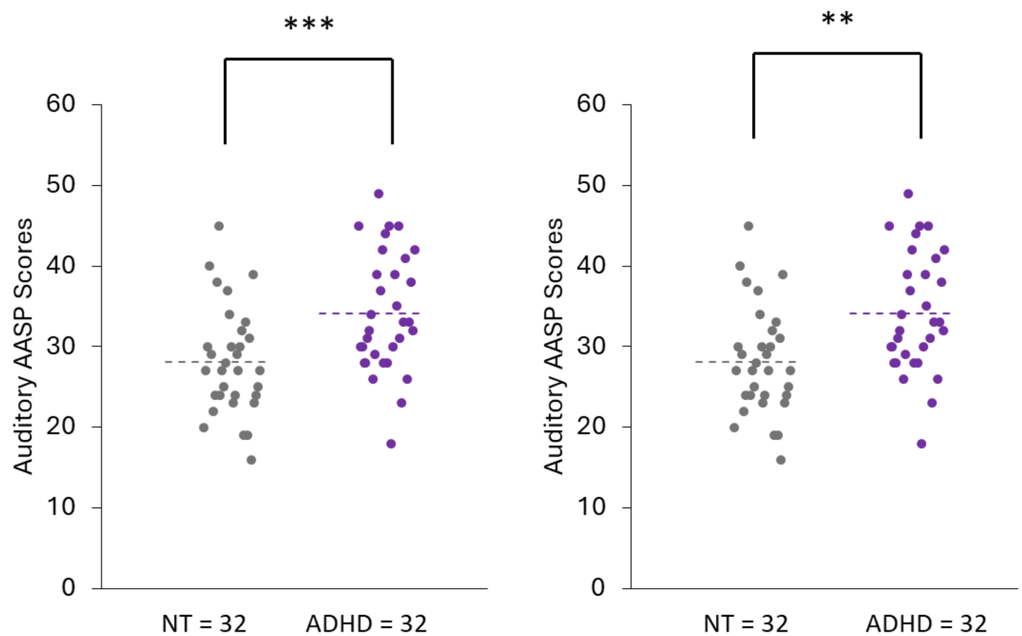

Figure 5.12. Self-Report Auditory and Visual Sensory Responsivity. $^{**}p$ <.01, $^{***}p$ <.001.

5.3.2.4 EEG Results

Only correct trials were included for visual, auditory, and audiovisual trials. The final analysis included 28 ADHD and 20 NT participants; 16 participants were excluded because more than 30% of their data was rejected. There were four regions of interest (ROI): frontal, central, central-parietal, and occipital.

5.3.2.4.1 Unisensory

There were no significant group differences between the Visual conditions in all areas of interest (Figure 5.13). There was a significant group differences in Auditory conditions for frontal (66 - 118 ms, 144 – 210 ms, and 227 – 277 ms) and central (339 - 344 ms) ROIs. At the most significant point (190 ms), a mean difference of *M*= -1.63 was found to be significant $t(46) = 2.98$, $p = .005$, $d = .87$ for the frontal ROI. At 339ms, a mean difference of $M = -1.02$ was found to be significant $t(46) = 2.11$, $p = .04$, $d = .62$ for the central ROI. There were no other significant difference between groups in the other two ROIs.

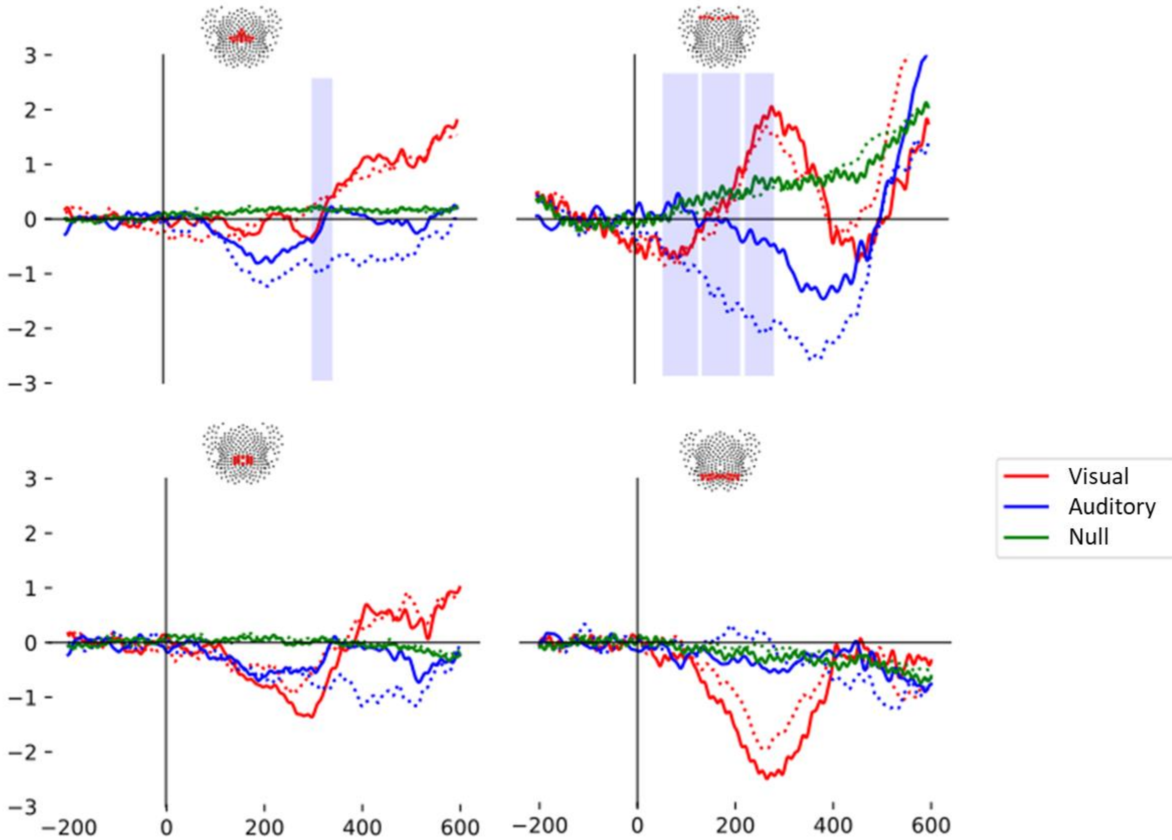

Figure 5.13. Waveforms for Visual, Auditory, and Null Trials at Central, Frontal, Central-Parietal and Occipital Regions in the Perception-Matched Task. Solid lines are NT adults, and hashed lines are ADHD adults. Blue box denotes significant group difference ($p < .05$) for auditory trials.

5.3.2.4.2 Multisensory

Difference Wave below refers to amplitude differences between the sum of the unisensory conditions (Audio + Visual) and the Audiovisual (AV condition).

Multisensory responses would be expected before 250ms, but the entire time course will be examined.

The Sum A+V, Audiovisual, and Difference wave (AV- Sum) are in Figure 5.14. There was a significant difference in the Difference Waves from 147 ms to 336 ms between NT and ADHD participants in the frontal region. At 233ms, a 2mean difference of $M = -2.42$ was found to be significant $t(46) = 3.59$, $p = .0008$, $d = 1.05$. There was a significant difference in the Difference Waves from 192ms to 281ms between NT and ADHD participants in the occipital region. At 248ms, a mean difference of $M = 1.33$ was found to be significant $t(46) = -3.07$, $p = .004$, $d = .90$. There were no other significant difference between groups in the other two ROIs.

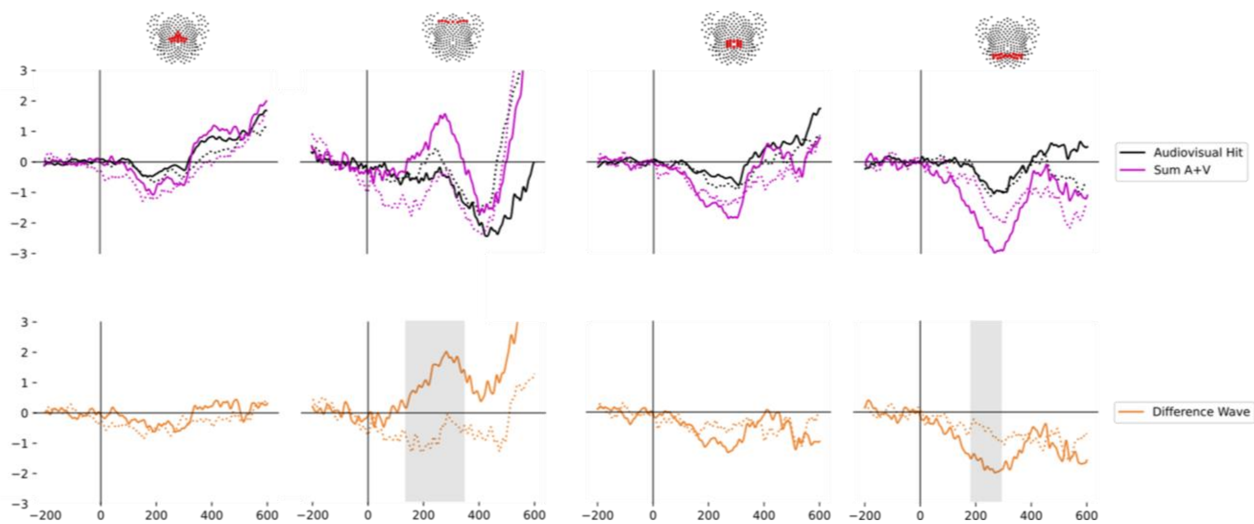

Figure 5.14. Waveforms for Audiovisual, Summed Unisensory, and Difference Wave in the Perception-Matched Task. NT is the solid line, and the ADHD group is the dashed line. Audiovisual is purple, Sum A + V is black, and the Difference Wave is orange. Shaded grey areas are significant, $p < .05$.

5.3.3 Discussion

We hypothesized that for multisensory gain, both accuracy gain and response time gain, would be higher in the ADHD group compared to the NT group. There was partial support for these hypotheses, with response time gain higher in the ADHD group. This is consistent with previous research which has found an earlier violation of Miller's Race Model (McCracken et al., 2019). Both groups did not show evidence of accuracy gain according to the probability summation criteria, which is a conservative criterion (Stevenson, Ghose, et al., 2014). Based on prior research, we expected differences in frontal, parietal and occipital areas to show differences in the difference wave between NT and ADHD adults (McCracken et a., 2019). There were group differences in both frontal and occipital difference waves, with the ADHD group showing a reduced response. We expected there to be differences in sensory sensitivity in both the auditory and visual domains between ADHD and NT adults. This was not supported as we found no group differences. Research examining contrast sensitivity in children with ADHD has yielded inconsistent findings. Some studies have found reduced contrast sensitivity in children with ADHD (Bartgis et al., 2009), while others have reported no discernible differences (Kim et al., 2015; Stevens et al., 2012). One review found the ability to detect pure tones in children with ADHD is largely comparable to that of NT individuals (Fuermaier et al., 2018). On the other hand, children with ADHD exhibit significantly lower recognition thresholds for speech sounds compared to NT children (Lucker et al., 1996; Söderlund & Jobs, 2016). We did find differences in self-reported auditory and visual sensory responsivity with ADHD adults scoring higher than NT adults, which is consistent with prior literature (Dellapiazza et al., 2021; Little et al., 2018; Panagiotidi et al., 2018).

5.4 General Discussion

The goal of this study was to examine whether multisensory integration differed in adults with ADHD compared to NT adults using behavioural and EEG methods. Experiment 1 was stimulus-matched where everyone was presented stimuli at the same intensity, and Experiment 2 was perception-matched where the unisensory stimuli were presented at what the participant could perceive 50% of the time. We hypothesized that there would be enhanced multisensory gain in ADHD, especially in the perception-matched task. We found partial support for this, as the response time measure of multisensory gain was significantly larger in the ADHD group. We expected there to be differences in frontal, parietal, and occipital regions of the difference wave of the EEG response, with the ADHD adults having a smaller ERP response compared to the NT adults. We found support for this, primarily in the perception matched task. We expected there to be differences in sensory sensitivity in both the auditory and visual domains between ADHD and NT adults, but we did not find any group differences.

Our behavioural findings of multisensory gain using a response time measure were in-line with previous research which has found an earlier violation of Miller's Race Model in ADHD (McCracken et al., 2019). One possible explanation for this larger gain is that in ADHD speeded tasks often find slow and variable response times, suggesting a slower information processing speed (Karalunas et al., 2012). When presented with two redundant signals, processing speed is increased due to the race model. Presenting redundant signals in ADHD may show a larger enhancement in processing speed as it helps to focus attention, which in leads to a larger violation in multisensory integration. More pronounced differences were found in the perception-matched than the stimulus-matched task, which may be due to the perception-matched task controlling for unisensory differences in perceptions as individuals with ADHD have been shown to have altered sensory sensitivity (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Ghanizedeh, 2011; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018). However, we did not find group differences for behavioural sensory sensitivity. The perception-matched task may have been more challenging for participants, as for almost all participants their perceptual level was more difficult to perceive than the stimuli in the stimulus-matched task, which could have shown more group differences as participants may show a larger benefit for harder to perceive stimuli.

Multisensory stimuli have been argued to capture attention more effectively than unisensory stimuli. According to many studies, this enhanced multisensory response is not merely due to the summed effects of concurrent information, as multisensory stimuli often elicit faster and more accurate responses than would be predicted by additive models of the two unisensory stimuli (Colonius and Diederich, 2004, Hughes et al., 1994, Laurienti et al., 2004, Molholm et al., 2002, Murray et al., 2004, Pannunzi et al., 2014, Senkowski et al., 2005, Talsma et al., 2007). This has led to the suggestion that multisensory stimuli may also be particularly effective in capturing attention (e.g. Santangelo & Spence, 2007). Whilst this may, under some conditions, be beneficial (i.e.

when a multisensory stimulus is of behavioural relevance), it may, on the contrary, be disruptive in other conditions (i.e. by pulling attention away from our current goals).

Additionally, this multisensory integration benefit in ADHD may disappear if the system is overly taxed. In a visual search paradigm with varying cognitive loads of unisensory and multisensory distractors, robust bottom-up multisensory integration was found independent of perceptual load in ADHD patients (Schulze et al., 2022). In the high-load condition, ADHD adults showed reduced gain compared to NT controls but showed more gain in the low-load condition.

We expected there to be differences in frontal, parietal, and occipital regions of the difference wave of the EEG response, with the ADHD adults having a smaller difference wave compared to the NT adults. We found support for this, especially in the perception-matched task. Previous research has found reduced ERPs in frontal, parietal, and occipital brain regions in ADHD compared to NTs (McCracken et al., 2019). Differences in lower order sensory cortices, such as the occipital region suggests that processing may be different in these areas. Specifically, a reduced response in the occipital areas suggests reduced visual processing in ADHD, although this was not related to behavioural visual sensory sensitivity differences. Reduced ERP amplitudes or BOLD response have been shown across many different cognitive and sensory domains and across multiple different brain areas in ADHD (Dimoska et al., 2003; Johnstone et al., 2009; Liotti et al., 2010; Papp et al., 2020; Plichta et al., 2009), which may suggest a general underactive neural response. Whereas differences in higher order cortices, such as the frontal areas, may reflect the interplay between multisensory integration and attention, as individuals with ADHD have shown altered temporal-frontal network integrity (Schulze et al., 2023). Further, reduced neural responses have also been found in fMRI studies in the superior temporal sulcus, an important multisensory integration area (Zuberer et al., 2020; Stevenson et al., 2007, 2010; Stevenson & James, 2009). We found more distinct ERPs for unisensory stimuli in the stimulus-matched task, such P1, N1, P2, and N2. Since the perception-matched task was set at the individuals’ perceptual level, the stimuli may have been harder to detect with longer times to detection which may have attenuated the ERPs.

We expected there to be differences in sensory detection ability in both the auditory and visual domains between ADHD and NT adults. Our findings did not support this hypothesis, as there were no group differences. Previous studies on contrast sensitivity suggest it may be affected in ADHD with some studies indicating reduced contrast sensitivity in children with ADHD (Bartgis et al., 2009), while others report no significant differences (Kim et al., 2015; Stevens et al., 2012). A review found that pure tone detection in ADHD is comparable to neurotypical individuals (Fuermaier et al., 2018), but auditory perception differences are more evident for speech sounds (Lucker et al., 1996; Söderlund & Jobs, 2016). ADHD is often associated with auditory hypersensitivity, with auditory processing deficits potentially worsening with age, unlike other sensory modalities which may show slight improvement (Cheung & Siu, 2009). ADHD individuals frequently struggle with sensory gating and are more easily distracted by external auditory stimuli (Ghanizadeh, 2011). Self-reported auditory and visual sensitivity was significantly higher in ADHD, which is consistent with previous findings (Dellapiazza et al., 2021; Little et al., 2018; Panagiotidi et al., 2018). Self-report sensory responsivity and behavioural sensory sensitivity were positively related for visual stimuli but were not related for auditory stimuli, which suggests that self-report and behavioural measures of sensory sensitivity may measure distinct constructs (Schulz & Stevenson, 2020) but they could be related.

In the perception-matched task, there was more evidence for multisensory integration differences between ADHD adults in neurotypical adults compared to the stimulus-matched task. There are some possible explanations for the results. First, task difficulty may be related to multisensory integration differences as the majority of participants' threshold stimuli were harder to perceive than the stimuli in the stimulus-matched condition. Second, more differences may exist when we have controlled for individual differences in unisensory perception, but we did not find group differences in detection ability.

Overall, we found evidence for differences in multisensory integration in ADHD. Specifically, the ADHD group showed enhance response time gain and reduced ERPs to multisensory stimuli.

5.4.1 Limitations and Future Directions

One limitation is participants stayed on their daily medication regiment, so some participants were on medication where others were not. Some previous studies have opted to have participants not take their medication (Schulze et al., 2021), but research is questionable as to whether it affects sensory processing (Pfeiffer et al., 2015). One study looking at visual detection thresholds found that medicated patients with ADHD who stopped stimulant medication for at least 24 hours prior to the assessment had a lower, although not significantly lower, detection threshold compared to non-medicated patients (Kim et al., 2015). Future studies should examine sensory processing and multisensory integration in ADHD participants with and without medication. Another limitation is that our stimulus-matched task accuracy was at ceiling which may have limited the multisensory gain participants may have shown, especially for accuracy gain.

Future research on multisensory integration in ADHD could explore several promising areas. First, studies using EEG and fMRI could investigate the paradox of reduced neural responses to multisensory stimuli but enhanced behavioral integration (McCracken et al., 2019). Second, more research is needed on the relationship between attention and multisensory integration, as only one study has examined attentional load in this context (Schulze et al., 2022). This is crucial given ADHD-related difficulties with sustained attention and filtering distractions (Cassuto et al., 2013; Ghanizadeh, 2011). Finally, the impact of multisensory integration on cognitive development should be investigated, as atypical integration may affect cognitive outcomes (Wallace et al., 2020).

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Chapter 6

6 General Discussion

6.1 Summary of Main Findings

Multisensory integration is an important sensory process, as many of our daily experiences are multisensory in nature. Further, multisensory integration is a foundational building block upon which many of our cognitive processes rely (Stein & Meredith, 1993), and abnormalities in multisensory integration may have downstream effects on higher-order cognitive functioning (Wallace et al., 2020). In the past decade, researchers have begun investigating whether multisensory integration is affected in ADHD and have found conflicting results (McCracken et al., 2019; Panagiotidi et al., 2017; Schulze et al., 2021, 2022, 2023; Zuberer et al., 2020).

The aim of this dissertation work is to examine multisensory integration in ADHD. We first conducted a meta-analysis to evaluate the current state of the literature, interpret observed inconsistencies in results, and identify gaps in the literature. From this, we focused the following three studies on the gaps identified in the meta-analysis, namely, developmental studies and neural studies (e.g., EEG and fMRI). Overall, we found evidence for atypical multisensory integration in ADHD; however, our results were also conflicting. Our most consistent finding was a reduced neural response to multisensory integration in ADHD, but this was more pronounced in adults using a task controlling for unisensory differences in sensory perception. Our behavioural findings were largely consistent with prior literature in adults with ADHD using similar tasks, such as the SIFI, McGurk, speech-in-noise, and speeded-response time (McCracken et al., 2019; Michalek et al., 2014; Schulze et al., 2021). In individuals with ADHD, there appears to be a larger multisensory gain for response time measures, reduced multisensory integration with higher stimulus complexity (e.g., speech), and a reduced neural response to multisensory stimuli and multisensory integration. This pattern of results suggests that multisensory integration is affected differently in ADHD compared to other NDCs, such as autism spectrum disorder (Collignon et al., 2013; Foxe et al., 2015; Ostrolenk et al., 2019; Segers et al., 2020; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014; Stevenson, et al., 2017; Woynaroski et al., 2013; See Feldman et al., 2018 for review) and dyslexia (Harrar et al., 2014; Pulliam et al., 2023; van Laarhoven et al., 2018). Future research in multisensory integration in ADHD should continue to use neural measures of multisensory integration, examine the developmental trajectory, examine the interplay of attention and multisensory integration, and investigate the relationship between multisensory integration and higher-order cognition. For all studies, a discussion of findings related to multisensory integration across development will be discussed together in Section 6.1.5.

6.1.1 Multisensory Integration in Individuals with ADHD: A meta-analysis.

We conducted a meta-analysis to explore the extant literature and examine whether multisensory processing is different in ADHD individuals compared to NT individuals. Next, we examined non-clinical studies which investigated the relationship between multisensory processing and ADHD traits. Lastly, we wanted to look at whether age, type of measure, and data collection method moderated the relationship between multisensory processing and ADHD. Multisensory processing is used as the studies include either multisensory integration or multisensory temporal processing. Fifteen papers with 57 effect sizes were included in the full meta-analytic model and run using robust variance estimation procedures with small sample adjustments. Overall, our results did not provide evidence that individuals with ADHD display differences in their multisensory processing abilities. This was not an expected result as many of the clinical studies show either enhanced or reduced multisensory processing in ADHD, but less studies show null results. There are two possibilities for these results, first, no group differences exist, and multisensory processing is not affected in ADHD, or second, group differences exist but we were unable to detect them. When some studies show a benefit in ADHD and others show a disadvantage, combining them in one model may lead to a null result. ADHD trait studies showed a trend towards enhanced multisensory processing in individuals with high ADHD traits, but many of these studies included temporal processing measures and higher ADHD traits being associated with shorter TBWs is one of the more consistent findings (Hare, Dalal, et al., in prep, Panagiotidi et al., 2017).

Only three studies did not use adult populations, so we were unable to examine whether age moderated the relationship between multisensory processing and ADHD. This is an important area for future study as multisensory integration differences are more pronounced in children with other NDCs, such as ASD, and normalize around adulthood (Feldman et al., 2018; Foxe et al., 2015). There were not enough temporal or neural studies to run the last two meta-regressions, therefore meta-analytic models were run for multisensory integration and behavioural studies, but no significant differences were found. The identified gaps in the literature included developmental studies, neural measures, and multisensory temporal processing. The next three projects sought to address the first two gaps.

6.1.2 Behavioural Investigation of Multisensory Integration in Youth with ADHD

As mentioned, the meta-analysis revealed a lack of research done in youth with ADHD. Our goal for this study was to examine whether multisensory integration differed in youth with ADHD compared to NT youth using three different behavioural tasks (i.e., SIFI, McGurk, and speech-in-noise). Overall, we found that multisensory integration was different in youth with ADHD compared to NT youth, but this differed by task. First, the SIFI showed no group differences for illusion susceptibility, which is consistent with prior literature (Schulze et al., 2021). Second, the McGurk task revealed differences with reduced illusions susceptibility in ADHD youth compared to NT youth, which is consistent with prior literature (Schulze et al., 2021). Further, both hyperactive-impulsive traits and inattentive traits were related to reduced illusion susceptibility. The hyperactive-impulsive traits have been more strongly related to temporal processing of multisensory stimuli (Hare, Dalal, et al., in prep) and subtype differences have been found in sensory processing (Shimizu et al., 2014). Lastly, the speech-in-noise task showed no differences in multisensory gain between the ADHD and NT youth. However, there was a trend-level relationship between hyperactive-impulsive traits and multisensory gain on phoneme accuracy. Less participants completed this speech-in-noise task compared to the other two studies; therefore, the lack of group differences may be partially attributable to less power from a reduced sample size. Previous research suggested that multisensory gain depended on SNR level, but specifically at more difficult SNR levels the ADHD group had reduced multisensory gain (Michalek et al., 2014). In our task participants were only presented stimuli at one SNR, so we were unable to examine whether SNR level affects multisensory gain in ADHD. In the McGurk task and the speech-in-noise task, some measures of multisensory integration were trend level related. Overall, the findings suggest that multisensory integration may differ in youth with ADHD and these differences may be more pronounced in experiments with higher stimulus complexity, such as speech.

6.1.3 Audiovisual Multisensory Integration in Youth with ADHD: An EEG Investigation.

The goal of this study was to examine whether multisensory integration differed in youth with ADHD compared to NT youth using behavioural and EEG methods, while controlling for unisensory differences in perception. Prior research has shown behavioural enhancements in multisensory integration even when the ERP amplitudes were reduced to multisensory stimuli (McCracken et al., 2019). Further, we wanted to examine sensory sensitivity in both the auditory and visual domains and compare these to caregiver-report measures of sensory responsivity. Looking at the behavioural findings, we found no differences in multisensory integration between youth with ADHD and NT youth. We expected there to be differences in multisensory integration as a prior study found an earlier violation of Miller's Race Model in adults with ADHD, compared to NT adults (McCracken et al., 2019).

Turning to EEG findings, we did not see a group difference in multisensory integration in the expected timeframe (< 250 ms) but did see group differences later in processing (after 500 ms). Previous research looking at multisensory integration across development using EEG found that latency decreased in unisensory components (P1, N2) as a function of age (Brandwein et al., 2011); but these results do not suggest that multisensory integration would be occurring after 500ms in youth. When grouping together youth of various ages it can make EEG results harder to interpret as over development responses mature to reflect adults. For example, in fronto-central regions an immature multisensory integration where the multisensory response was smaller in amplitude than the summed unisensory can first be found (7-9; Brandwein et al., 2011, or 8-10; Vannasing et al., 2024) followed by a pattern closer to adults with the multisensory response having a larger amplitude than the summed unisensory later in development (13-16; Brandwein et al., 2011, or 15-17; Vannasing et al., 2024).

We found NT youth showed higher sensory sensitivity to visual stimuli compared to ADHD youth, and trend level higher sensory sensitivity to auditory stimuli. Previous research looking at contrast sensitivity has been inconsistent, with some research suggesting reduced contrast sensitivity in ADHD children (Bartgis et al., 2009), while other studies finding no differences in ADHD (Kim et al., 2015; Stevens et al., 2012). One review found that the detection of pure tones in ADHD is largely intact compared to NT individuals (Fuermaier et al., 2018), and that differences in auditory perception are more noticeable for speech sounds (Lucker et al., 1996; Söderlund & Jobs, 2016). On the other hand, caregiver-reports suggested higher sensory responsivity in ADHD youth across both modalities compared to NT youth which is consistent with prior literature (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Fuermaier et al., 2018; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018). Interestingly, these unisensory group differences in perception did not lead to group differences in multisensory integration.

6.1.4 Multisensory Integration and Sensory Sensitivity in Adults with ADHD: An EEG Investigation

The goal of this study was to examine whether multisensory integration differed in adults with ADHD compared to NT adults using behavioural and EEG methods. Experiment 1 was stimulus-matched where everyone was presented stimuli at the same intensity, and Experiment 2 was perception-matched where the unisensory stimuli were presented at what the participant could perceive 50% of the time. Further, we wanted to examine group differences in sensory sensitivity in both the auditory and visual domains and then compare their sensitivity to self-report measures of sensory responsivity. Previous research suggests that behavioural (i.e. sensory sensitivity) and self-report measures (i.e. sensory responsivity or reactivity) of sensory processing may measure distinct concepts (Schulz & Stevenson, 2020).

In the stimulus-matched task, there were no significant differences in multisensory gain for the response time measure. We could not interpret the accuracy gain results as performance was at ceiling. Visual accuracy was trend level higher in ADHD, but there was no difference in auditory or audiovisual accuracy. There was a significant difference in the difference wave in the occipital region. Most multisensory paradigms are stimulus-matched, and one stimulus-matched study has found more pronounced differences in multisensory integration in ADHD adults than the current study (McCracken et al., 2019).

In the perception-matched task, which controls for unisensory differences in perception, ADHD adults showed larger multisensory gain in the response time measure compared to NT adults, which is in agreement with prior literature (McCracken et al., 2019). For accuracy gain, we did not see a significant difference between the groups. In the perception-matched task unisensory accuracy was kept constant (~50%). There were significant differences in the difference wave between groups in frontal and occipital regions, with ADHD adults having a smaller amplitude difference between audiovisual and summed unisensory trials. We found no differences in sensory sensitivity ability in the auditory and visual domains. As mentioned in the previous study, some research suggests reduced contrast sensitivity in ADHD children (Bartgis et al., 2009), while other studies find no differences in ADHD (Kim et al., 2015; Stevens et al., 2012). Further, one review found that the detection of pure tones in ADHD is largely intact compared to NT individuals (Fuermaier et al., 2018), and that differences in auditory perception are more noticeable for speech sounds (Lucker et al., 1996; Söderlund & Jobs, 2016). Self-report measures showed that ADHD adults had both a higher visual and auditory sensory responsivity, which is consistent with prior literature (Dellapiazza et al., 2021; Dunn & Bennett, 2002; Little et al., 2018; Mangeot et al., 2007; Panagiotidi et al., 2018).

Overall, in the perception-matched task there were more group differences present in multisensory integration, compared to the stimulus-matched task. There are two possible explanations. First, this task accounted for individual differences in perception; however, our sensory discrimination results do not suggest that there were group differences in the sensory thresholds. On the other hand, our self-report measures suggest that ADHD adults scored higher on self-reported auditory and visual sensory reactivity measures. Second, the perception-matched task was more difficult for participants compared to the stimulus-matched task. Accuracy performance in the stimulus-matched task was at ceiling, and the vast majority of participants had sensory discrimination thresholds at lower stimulus intensity than what was presented in this task. These differences in multisensory integration may be more pronounced in ADHD when the task requires you to sustain attention, but the task demands are not too high or low, as the multisensory stimuli may have an attention enhancing effect.

6.1.5 Multisensory Integration across Development and the Role of Attention

The participants included in Chapter 4 and Chapter 5 completed the same perception-matched speeded response time task, but one sample included youth (ages 8-17) and the other sample included adults (ages 18-59) allowing us to examine how multisensory integration differed between the samples. Multisensory integration matures more slowly compared to other sensory processes, with full development occurring later, with estimates ranging from adolescence into adulthood (Brandwein et al., 2011; Ernst, 2008; Gori et al., 2008; Murray et al., 2016; Stevenson et al., 2018). Previous research in other NDCs has also found more pronounced multisensory integration deficits in autistic children, with multisensory integration normalizing in autistic adults in some studies (Beker et al., 2018; Feldman et al., 2018; Foxe et al., 2015). In our youth sample, increasing age was positively correlated with accuracy gain measures. Age was not related to our multisensory integration measure of response time, which is inconsistent with prior literature (Brandwein et al., 2011). Interestingly, in adults we saw multisensory gain was increased for Miller's race model violations in ADHD compared to NT adults, but we found no group differences in children.

For the EEG results when looking at the perception-matched task, there were much more pronounced differences in multisensory integration adults with ADHD compared to youth with ADHD, especially during the expected timeframe. As mentioned, when analyzing EEG results in a mixed-age group of youth, interpretation becomes challenging due to the maturation of EEG responses over development, where you see a change in the multisensory response having a smaller in amplitude than the summed unisensory in children, to multisensory response having a larger amplitude than the summed unisensory in adolescents and adults (Brandwein et al., 2011; Vannasing et al., 2024). With this in mind, we found reduced difference wave amplitudes in ADHD adults compared to NT adults, but larger difference wave amplitudes in ADHD youth compared to NT youth. It is possible that the ADHD group sees an earlier maturation of the multisensory response leading to these amplitude differences, which is unexpected as neurodevelopment is generally delayed in ADHD (Vaidya, 2012). Further research should examine the developmental trajectory of multisensory integration in ADHD using both behavioural and neural measures, as we can see enhanced behavioural multisensory gain in ADHD adults and a reduced neural multisensory response.

For unisensory sensory processing, in adults, there were no group differences in sensory sensitivity; whereas, in ADHD youth there was significantly reduced visual and trend level reduced auditory sensory sensitivity. Further, we saw that in all youth sensory sensitivity increased with age, especially for auditory stimuli. This is largely inconsistent with prior literature which suggests that auditory hypersensitivity is often found in ADHD, but auditory processing deficits may increase with age in children with ADHD whereas processing in other modalities seems to improve slightly with ADHD (Cheung & Siu, 2009). Interestingly, as unisensory sensitivity improves by adulthood in ADHD to reach the same levels as NT adults, we also see enhancements in multisensory integration in ADHD adults but not in ADHD youth. This avenue should be examined more, as it is possible that enhanced multisensory integration develops as a compensatory mechanism to counteract poorer unisensory performance while unisensory performance improves.

In the behavioural study, all three experiments had previously been done in clinical adult samples (Michalek et al., 2014; Schulze et al., 2021) or using non-clinical samples with ADHD traits (Hare, Muller, et al., in prep). The studies using non-clinical samples with ADHD traits did not find any relationship between ADHD traits and multisensory integration, but this may be because multisensory integration differences may only become apparent when someone reaches clinical criteria. The results of our findings are largely in agreement with the previous findings in clinical adults. Specifically, there was no group differences in illusion susceptibility for the SIFI, decreased illusion susceptibility in ADHD youth compared to NT youth for the McGurk task, and there was partial evidence for reduced multisensory gain in ADHD youth in the speech-in-noise tasl. In the McGurk task, we did not find a bias towards responding to the auditory component of the McGurk stimuli, as previous research has (Schulze et al., 2021), but in our study, we asked what they perceived in a modality neutral fashion. For the SIFI, increased illusion susceptibility was related with increased age, which is inconsistent with prior literature which suggests that SIFI susceptibility decreases with age (Adams, 2016; Nava & Pavani, 2013). It typically decreases with age as the SIFI uses auditory information to modulate visual information and younger children rely more on auditory information (Hirst et al., 2018; Nava & Pavani, 2013). In the McGurk task, increased age was related to increased multisensory integration ability. The relationship between age and multisensory integration did not differ between the ADHD youth and the NT youth for the SIFI and McGurk task when a Fisher Z-test was conducted. Further, age was unrelated to measures of multisensory gain for the speech-in-noise task, this is inconsistent with previous literature (Ross et al., 2011).

For the speech-in-noise task, less participants completed this task than the previous experiments, which may have limited our ability to find group differences, but correlations suggested that phoneme accuracy was negatively related to ADHD traits. In our study we used one SNR level, but previous research suggests that there may be an effect of SNR level on multisensory gain in ADHD. Specifically, there appears to be an ideal noise range where individuals with ADHD perform better than individuals without ADHD, but if that noise is beyond this level, then the benefits disappear (Michalek et al., 2014). This optimal SNR level where the maximum multisensory gain is found in other populations as well (Foxe et al., 2015; Stevenson, et al., 2015, 2017). In ADHD, there may be an interaction between task demands or difficulty and multisensory integration.

Previous research has also found that when cognitive load demands are low, ADHD adults show enhanced multisensory integration compared to NT adults, but when cognitive demands are higher then ADHD adults show diminished multisensory integration (Schulze et al., 2022). As multisensory stimuli may be particularly effective in capturing attention (Santangelo & Spence, 2007), above and beyond the additive models of concurrent information (Colonius & Diederich, 2004; Hughes et al., 1994; Laurienti et al., 2004; Molholm et al., 2002; Murray et al., 2004; Pannunzi et al., 2014; Senkowski et al., 2005; Talsma et al., 2007), they may be particularly salient to individuals with ADHD. While the attentional enhancement can be beneficial when the stimuli are behaviorally relevant, it can also be disruptive by diverting attention from current goals. When stimuli are near a threshold or when multiple stimuli are competing for processing resources, top-down attention is required, which has been described as a late framework of multisensory integration (Calvert & Thesen, 2004; MacAluso et al., 2016). Top-down attention may be affected in ADHD, whereas, whether sensory filtering is affected is more inconclusive. One study found that ADHD children exhibited efficient attentional filtering when task demands were high, but showed deficient and atypical distractor filtering under low task demands which suggests that attention deficits in ADHD may stem from a failure to efficiently engage top-down control rather than an inability to implement filtering in sensory processing regions (Friedman-Hill et al., 2010). Further, previous studies on auditory filtering in individuals with ADHD have found no group differences compared to individuals without ADHD (Conzelmann et al., 2010; Hanlon et al., 2009; Holstein et al., 2013), however, other studies have shown relations between auditory filtering and attention problems (Conzelmann et al., 2015; Hutchison et al., 2017). Consequently, the connection between specific auditory filtering processes and attention remains inconclusive. Further research should examine the interplay between attention and multisensory integration in ADHD, as it may help to explain the inconsistent results.

6.2 Limitations and Future Directions

There were a few limitations to our studies. First, we kept participants on their medication regiment that they take every day, so some participants were on medication where others were not. Some previous studies have opted to have participants not take their medication (Schulze et al., 2021), but research is inconclusive as to whether it affects sensory processing (Pfeiffer et al., 2015). One study looking at visual detection thresholds found that medicated patients with ADHD who stopped stimulant medication for at least 24 hours prior to the assessment had a lower, although not significantly lower, detection threshold compared to non-medicated patients (Kim et al., 2015). Future studies should examine sensory processing and multisensory integration in ADHD participants with and without medication. Second, for our stimulus-matched task accuracy was at ceiling which may have limited the multisensory gain participants may have shown. Third, our speech-in-noise task was only presented at one SNR level. Previous research showed that group differences in multisensory gain were affected by SNR level. There seems to be a point at which having audiovisual stimuli is more beneficial in individuals with ADHD, but we may have made it too hard. Fourth, we did not have enough participants to make age groups when examine the developmental trajectory of multisensory integration in ADHD using EEG measures.

There are several exciting avenues for future research looking at multisensory integration in ADHD. First, more studies should use EEG and fMRI techniques as there is an interesting relationship between reduced neural responses to multisensory stimuli but enhanced multisensory integration in behavioural measures (McCracken et al., 2019). Second, more research should look at youth or follow the developmental trajectory as age related differences in multisensory integration have been found in other NDCs. This would be a particularly interesting avenue to pursue for EEG research to see whether maturation of the multisensory response occurs at the same rate or slower in ADHD. Currently there are no studies looking at multisensory temporal processing in youth with ADHD, which should be examined due to its strong link to multisensory integration but also because there is some evidence that TBWs are narrower in individuals with high ADHD traits (Panagiotidi et al., 2017; Hare, Dalal et al., in prep). Third, more research should examine the interplay between attention and multisensory integration. To date, there is only one known study that varies attentional load while looking at multisensory integration (Schulze et al., 2022). This relationship may be important because since individuals with ADHD have difficulties with sustained attention and blocking out irrelevant distractors (Cassuto et al., 2013; Ghanizadeh, 2011). Research should also look at the relationship between multisensory integration and cognitive development, as atypical multisensory integration can have downstream effects on cognition (Wallace et al., 2020).

6.3 Concluding remarks

The goal of this dissertation was to examine multisensory integration in ADHD. Overall, multisensory integration seems to be affected and there is evidence for worse, no difference, and better multisensory integration in ADHD. Neural measures suggest a reduced response to multisensory stimuli in ADHD. Response time-based measures of multisensory gain show enhanced multisensory gain, even when the neural response is reduced in ADHD. Illusion susceptibility is reduced for the McGurk task, but not the SIFI task which could reflect. Multisensory integration differences in ADHD do not seem to improve with age.

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2020	Ontario Graduate Scholarship, $15,000
2019	SSHRC CGS Master's Award, $17,500
2019	Ontario Graduate Scholarship (declined)
2019	Faculty of Social Science Student Research Award, 1,500$
2018 & 2019	Dual Diagnosis Scholarship, $949
2018	DGS Entrance Scholarship
2018	FGS Research Fellowship Match
2014-2017	Dean's List
2014-2017	Brock Entrance Scholarship & Scholars Renewal
2017	Match of Minds Grant (Developmental Neuroscience Lab)
2014, 2015 & 2017	Orange Scholars Recipient
2015 & 2016	CUPE Scholarship

Publications & Talks

Journal Articles

Hare, C., Leslie, A., Bodell, L., Kaufman, E.K., Morton, J.B., … & Stevenson, R.A. (2024). Sex and Intelligence Quotient Differences in Age of Diagnosis among Children with Attention-Deficit Hyperactivity Disorder. *British Journal of Clinical Psychology*. https://doi.org/10.1111/bjc.12485

Hare, C., Johnson, B., Vlahiotis, M., Panda, C., Tekok-Kilic, A., & Curtin, S. (2024). Children's Reading Comprehension in Digital and Print Mediums: A Systematic Review [Learning to Read in a Digital Age: Children's Contemporary Reading Experiences]. *Journal of Research in Reading*. https://doi.org/10.1111/1467-9817.12461

Hare, C., Panda, E., Segalowitz, S.J. & Tekok-Kilic, A., (Under Revisions). The Interaction of ADHD-Traits and Trait Anxiety on Inhibitory Control. Submitted to *Psychophysiology. 10.22541/au.169507088.85380351/v1*

Talks

Hare, C. (March 2024). Workshop: A Neurodiversity-Affirming Approach to Research and Grad School. Inspiring Diversity in STEM. London, Ontario, Canada.

Hare, C., Luszawski, M., *Atta, C., Zhai, G., Li, Y., & Stevenson, R.A. (November 2023). Neural Underpinnings of Audiovisual Multisensory Integration in Adults with ADHD: An EEG Investigation. Society for Neuroscience. Washington, DC, United States.

Hare, C. (April 2020). Effects of Sensory Processing Patterns on Cognitive Control as a Function of Anxiety and ADHD in Emerging Adults. Mapping the New Knowledges. St. Catharines, Ontario, Canada (Conference cancelled due to COVID-19).

Hare, C. (April 2019). Impact of inattention, anxiety and sensory processing patterns in cognitive control. Mapping the New Knowledges. St. Catharines, Ontario, Canada.

Guest Lectures

King's University College (Western University), October 12th, 2023, Psychology 2040: Child Development. Lecture on ADHD and Neurodiversity.

Selected Posters

*- Presenting Author

***Hare, C.,** Luszawski, M., Atta, C., Zhai, G., Li, Y., Shannon, J., McCombe, K., & Stevenson, R.A. (April 2024). Sensory Sensitivity and Multisensory Integration in adults with ADHD: An EEG Investigation. Cognitive Neuroscience Society. Toronto, ON, Canada.

*Li, Y., **Hare, C.,** Luszawski, M., Shannon, J., Leung, B., & Stevenson, R.A. (February 2024). Audiovisual Multisensory Integration in Youth with ADHD. LOVE Conference. Niagara Falls, ON, Canada. *Won Best Poster Award.*

***Hare, C.,** Luszawski, M., Atta, C., Zhai, G., Li, Y., & Stevenson, R.A. (November 2023). Neural Underpinnings of Audiovisual Multisensory Integration in adults with ADHD: An EEG Investigation. Society for Neuroscience: Trainee Professional Development Award Poster Session. Washington, DC, United States.

***Hare, C.,** Atta, C., Zhai, G., Luszawski, M., & Stevenson, R.A. (June 27-30, 2023) An EEG Investigation of Multisensory Integration in ADHD Adults. International Multisensory Research Forum. Brussels, Belgium.