Behavioral and Physiologic Relationships Between Sensory Processing, Attention, and Prediction in Autistic Children: An Eye Tracking Study

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Behavioral and Physiologic Relationships Between Sensory Processing, Attention, and Prediction in Autistic Children: An Eye Tracking Study

Courtney Hunter

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Behavioral and Physiologic Relationships Between Sensory Processing, Attention, and Prediction in Autistic Children: An Eye Tracking Study

Courtney Hunter
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Master of Science

Autism spectrum disorder (ASD) prevalence has risen to one out of every 36 children born in the United States being diagnosed. Many individuals diagnosed experience sensory processing difficulties that make life challenging for them and their caregivers. However, there is no clear consensus on why sensory processing issues occur. Previous research has linked attention function to atypical sensory processing. Our study aimed to understand potential underlying mechanisms and correlates of this relationship. We theorized that prediction is a key contributing factor to how attention and sensory processing interact. The purpose of this study was to examine the relationship between sensory processing, attention, and prediction in school age children. To accomplish this, we asked parents of 70 children aged 8-11 years old to complete a series of behavioral questionnaires addressing sensory processing, attention, prediction, and autistic traits. A subset of this sample (n = 40) participated in an eye tracking task which addressed the physiologic relationship between sensory processing, attention, and prediction. Partial correlations of the behavioral measures revealed that sensory processing, prediction, some measures of attention, and autistic traits correlated across the combined sample. Mediation analysis showed that prediction played a mediating role on how attention impacts sensory processing. Results from the eye tracking data revealed that prediction, attention, sensory processing, and autistic traits were significantly related to each other. Particularly, between group comparisons showed that the autistic children demonstrated significant difficulty with attention management as trials became more unpredictable, suggesting that autistic individuals struggle to manage their attention and sensory processing abilities as situations become more unpredictable. These novel results indicate the complex relationship that is present between prediction, attention, and sensory processing across the combined sample. These findings could provide insight to the origin of sensory processing difficulties found in ASD, improve diagnostic procedures, yield targets for services, and improve their quality of life for individuals affected by atypical sensory processing, regardless of a diagnosis.

Keywords: autism, sensory processing, attention, prediction, eye tracking
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DESCRIPTION OF THESIS STRUCTURE AND CONTENT

This thesis, *Behavioral and Physiologic Relationships Between Sensory Processing, Attention, and Prediction in Autistic Children: An Eye Tracking Study*, is written in a hybrid format. The preliminary pages of this thesis reflect requirements for submission at the university level. However, the thesis report is presented as a journal article and conforms to the style requirements for submitting research reports to scientific journals. Identity-first language (e.g., “autistic children”) is used throughout the report due to this terminology’s growing favor over person-first language in autism communities and published research data supporting its use (Kenny et al., 2016). However, we also recognize and respect many people’s preference for person-first language. The annotated bibliography is included in Appendix A. Appendix B contains the consent forms/Institutional Review Board Approval letter.
Introduction

Autism spectrum disorder (ASD) is characterized by difficulties in social communication and interaction and restricted, repetitive patterns of behavior, interests, or activities, with these traits presenting in the early developmental period and often causing clinically significant differences in social, occupational, or other important areas of current functioning (American Psychiatric Association [APA], 2022). According to the Centers for Disease Control and Prevention (CDC), this developmental disability affects one in 36 individuals, and currently, males to females are diagnosed 3.8:1 (Centers for Disease Control and Prevention, 2022; Maenner et al., 2023).

In recent years, sensory processing has been added as a core diagnostic criterion of ASD (American Psychiatric Association [APA], 2022). Sensory processing difficulties can be highly challenging for many individuals. Unfortunately, complete understanding of the behavioral and neurologic correlates of sensory processing remains elusive. However, previous literature has shown that attention and prediction are key components of cognition implicated in autism that affect an individual’s ability to process sensory information (Clark, 2013; Corbetta et al., 2008; Green et al., 2016; Kim, 2014). However, these factors have not, to our knowledge, been studied together from both behavioral and physiological perspectives. Thus, the current study proposes to investigate the behavioral correlates of sensory processing, attention, prediction, and components of their underlying neural mechanisms.

Sensory Processing in Autism

The term sensory processing encompasses a host of functions and difficulties with sensory processing in autism are highly varied. For example, autistic children can have difficulties processing input from tactile, auditory, visual, and/or proprioceptive/vestibular
systems (Ayres, 1981; Marco et al., 2011; Robertson & Baron-Cohen, 2017). These children are often considered to have challenges with sensory integration (SI), which is the ability of the nervous system to process and organize sensory stimuli for predictive and adaptive functioning (Ayres, 1981; Crasta et al., 2020). Additionally, difficulties with sensory processing can occur in any modality (e.g., visual, tactile, auditory) and can manifest as hypersensitivity and/or hyposensitivity to external stimuli, as well as sensory seeking behaviors. Such sensitivities and behaviors can negatively impact an individual’s participation in daily living, communication, and social environments (Foss-Feig et al., 2017; Hannant et al., 2016; Hilton et al., 2007; Lincoln et al., 1995; Matsushima & Kato, 2013; Philpott-Robinson et al., 2016; Reynolds et al., 2011; Thye et al., 2018; Tomchek & Dunn, 2007; Watson et al., 2011). Thus, one difficulty in gaining a comprehensive understanding of autism and sensory processing is the heterogeneity observed across the autism spectrum (Marco et al., 2011). However, because of the prevalence of sensory difficulties in autism (i.e., upwards of 90%; Ben-Sasson et al., 2009; Crane et al., 2009; Jassim et al., 2021), focusing on this aspect of autism may lead to identification of commonalities among autistic persons. Also, due to the difficulties atypical sensory processing can cause, working to increase our knowledge of its mechanisms and implications is a worthy endeavor.

Sensory processing difficulties are commonly associated with negative outcomes of various types. For instance, one study found that sensory symptoms not only preceded but also were predictive of social-communication deficits and repetitive behaviors in childhood (Robertson & Baron-Cohen, 2017; Thye et al., 2018)—e.g., an individual with hypersensitivity to auditory stimuli may feel overwhelmed by excess noise and engage in behaviors such as elopement or tantrums. On the other hand, an individual who is hyporesponsive to auditory stimuli may not respond or engage when their name is called. Additionally, an inability to
accurately respond to environmental sensory stimuli has been shown to correlate with higher levels of anxiety and intolerance of uncertainty in autistic children (Boulter et al., 2014; Wigham et al., 2015). These factors can lead to difficulty in participating in common aspects of life, such as being in public places, thriving in educational settings, benefitting from therapies, and connecting with loved ones.

Attempts at understanding sensory processing in autism have led to many theories. Unfortunately, to date, there is limited consensus on the origins, causes, and underlying processes that contribute to sensory processing differences across the autistic spectrum. However, pertinent to the current study are two potentially important aspects of sensory function: bottom-up and top-down neural processing. Bottom-up processing describes intake of environmental stimuli through the receptors of all sensory modalities and afferent conduction of the signals from these structures from the periphery to more central divisions of the nervous system. Numerous studies have attempted to explain sensory processing in ASD from this frame of thinking by analyzing function of the sensory receptors, peripheral afferent nerves, and connectivity of primary sensory regions (e.g., visual, auditory, somatosensory networks) within the cerebral cortex (Lincoln et al., 1995; Liss et al., 2006; Robertson & Baron-Cohen, 2017; Tomchek et al., 2014; Uddin et al., 2013). One meta-analysis of functional magnetic resonance imagining (fMRI) data studies investigating sensory region connectivity found that autistic individuals had increased activity within the visual processing cortices and a higher order visual processing areas compared to the neurotypical (NT) group, suggesting that there may be some level of bottom-up connectivity that is different in autistic individuals (Jassim et al., 2021). While the notion of bottom-up processing is highly complex and includes many important
aspects of sensory processing, it does not explain other factors, such as how the brain determines to which environmental stimuli it will attend or filter out.

The concept of top-down processing outlines that cognition dictates behavior (Menon, 2011). In other words, higher-order brain networks, such as attention, working memory, and sequential chaining dictate to which external stimuli one will attend and determine the extent of attentional resources that are devoted to processing sensory stimuli. If there is limited control or function of these processes, there is potential for maladaptive behaviors due to poor regulation (Liss et al., 2006; Murray et al., 2005). Furthermore, in their review, Allen and Courchesne (2001) suggest that irregular heightened reactivity to seemingly meaningless stimuli (e.g., intense tantrums in response to the hum of a blender) may be related to neurobehavioral driven distractibility. Distractibility has an impact on sensory processing because if someone is unable to determine that to which they should attend, everything has the potential to become a distractor—i.e., every input is given equal weight. In turn, if attentional resources are expended in the processing of unimportant sensory information, attentional and cognitive resources would not be available for processing the most important stimuli and could also lead to sensory overload. Thus, the selective and other aspects of the attention system are foundational for sensory processing.

Attention in Autism

Attention is a limited resource that is required by the cortex to facilitate behavioral decisions and reactions (Craig et al., 2016; Petersen & Posner, 2012; Sabatos-DeVito et al., 2016). All individuals learn to divide and allocate this resource to maintain equilibrium with the environment to one degree or another. Because it is a limited resource, higher-order networks must determine the relevance of stimuli in terms of alerting, orienting, and maintaining attention.
Alerting

Attention networks need to be alerted to know when, to what, and how long to engage with stimuli in the environment. Autistic individuals often struggle with discerning what stimuli require attention and filtering out unwanted inputs which impedes the alerting of their attention networks (Corbetta et al., 2008; Green et al., 2016; Kim, 2014). Current theories suggest that this lessened ability to determine which stimuli are salient may be grounded in literal versus non-literal thinking (Van Boxtel & Lu, 2013; Van de Cruys et al., 2014). Literal thinking involves processing all incoming stimuli with equal weight, requiring equal amounts of attention to process and synthesize the information. However, when the brain ascribes salience to stimuli by distinguishing significance versus non-significance, resources of attention can be conserved for the more salient stimuli and irrelevant/predictable stimuli can be disregarded or processed to a lesser extent. Based on this logic, ascribing salience to stimuli is considered non-literal thinking. For example, in a conversation with a teacher, a student using nonliteral thinking, would be able to disregard environmental stimuli such as the noise from the hallway, flickering lights, or the uncomfortable chair they are sitting in, and allocate their attentional resources to listening to what the teacher was saying. However, a student who primarily uses literal thinking would process the environmental stimuli the same as the teacher’s words, leading to heavy loads on their attentional and other cognitive systems. Additionally, it has been said throughout the literature that autistic individuals are known to “see the trees but not the forest” and favor processing local stimuli more readily than global stimuli (Happé et al., 2001; Robertson & Baron-Cohen, 2017). This notion may be another example of literal thinking, in which autistic people are sometimes less able to integrate, see relationships between, and combine elements of the environment for a cohesive overview, but rather process each element as its own entity. Such
a processing style might lead to allocating/splitting attentional resources to process each stimulus, which could be quickly overwhelming. Overall, autistic individuals who engage in literal thinking may have differences in salience detection which more frequently leads to greater attentional loads (Van de Cruys et al., 2014).

In conjunction with literal styles of thinking, narrowed interest and repetitive behaviors may contribute to differences in attentional shifting/alerting in autism (Marco et al., 2011). To further support the idea that autistic individuals may have attentional differences in terms of alerting, one study found that while neurotypical (NT) individuals showed a heightened attention preference for objects of interest to them during a distraction task (e.g., personal hobbies or fields of study), autistic individuals did not. In contrast, those on the spectrum had heightened attention to their interests only when attention demands were low (Parsons et al., 2017). Despite some autistic people’s preference for their restricted interests generally, when their attention system is heavily engaged by other environmental elements, they did not demonstrate a heightened attention preference for their specific interests. The results from this study suggest that for the NT participants’ interests, expertise, and previous experience appear to increase the salience of items related to their interests. In contrast, for the autistic participants, interest items and non-interest items were treated the same when attention demands were high, regardless of previous experience or preference (i.e., their ability to detect salience was interrupted by other items that heavily demanded their attention). These findings provide evidence for the theory that autistic individuals process stimuli the same way regardless of previous experience (Van Boxtel & Lu, 2013; Van de Cruys et al., 2014). Thus, predictions, arising from previous experiences, seem to play an essential role in alerting the brain to salient information and delegating attentional
resources toward that information (Bar, 2009; Parsons et al., 2017; Van de Cruys et al., 2014; Wills et al., 2007).

**Orienting**

Once the attention system has been alerted to attend to a stimulus, there is an attentional reaction and orientation to the cue (Sabatos-DeVito et al., 2016; Vohs & Baumeister, 2013). One study defined orienting as a facilitated reaction to a target after a predictive cue (Fan et al., 2002). These attentional reactions are coordinated by the orientation network, which selects the stimuli to which one attends (Corbetta et al., 2008). Current eye tracking studies measure the orientation of visual attention through gaze fixations, which are classified as engagement with a stimulus (Falck-Ytter et al., 2013; Sabatos-DeVito et al., 2016). Previous research has aimed to analyze visual attention in autistic children, largely due to the impacts poor visual engagement can have on social interaction (Chita-Tegmark, 2016; Guillon et al., 2014). Some results have shown that autistic individuals spend less time engaging with social stimuli than typically developing control groups (e.g., Chita-Tegmark, 2016; Frost-Karlsson et al., 2019).

Other researchers have preferred to use non-social stimuli for eye tracking studies arguing that salience detection lies beyond just social stimuli and environments (Bacon et al., 2020; Gale et al., 2019; Król & Król, 2020; Watson et al., 2015). Regardless of type of stimuli presented, evidence supports that there are differences in attention engagement within the autistic spectrum compared to their neurotypical peers (Hames et al., 2016; Harris et al., 1999; Landry & Parker, 2013; Mutreja et al., 2016).

Most of the work done in the field of attention in autism has revolved around social and nonsocial communication. However, attention difficulties may be more fundamental. Other research has aimed to discover whether engagement/orientation difficulties lie with the type of
stimuli or could be rooted in differences of the visual and attention systems. Studies have used methods such as fMRI to investigate the functional connectivity between cortical networks related to attention to gain a deeper understanding of neurophysiologic difference in autism. Across these studies, there is a mixed pattern of both stronger and weaker functional connectivity between regions and networks such as the visual cortex, medial prefrontal cortex, the default mode network, anterior insula, and other sensory processing regions across the autistic spectrum (Gadgil et al., 2013; Hames et al., 2016; Harikumar et al., 2021; Lukito et al., 2020).

While fMRI data has been successful in identifying brain regions associated with attention generally, measuring attentional orientation specifically is usually accomplished using a biological marker like gaze fixation (Falck-Ytter et al., 2013). Other researchers have used methods, like pupillometry, to measure the effects of top-down cognitive influences, like attention, on biological reflexes, such as pupil dilation (Geva et al., 2013; Naber et al., 2013; Sara & Bouret, 2012). It is theorized that the previously understood as solely reflexive constriction and dilation of the pupil is actually modulated by covert visual attention engagement (Mathôt et al., 2013), suggesting that eye tracking and pupillometry may be a more useful measures for assessing orientation directly.

**Maintaining**

Some postulate that autistic individuals experience difficulties with disengagement or reorienting their attention, once they have engaged with a stimulus (Elsabbagh et al., 2013; Johnson et al., 1991). This difference could underlie difficulties relating to rigid behaviors and insistence of routines. For instance, one study showed that autistic individuals experience delayed disengagement and reengagement time compared to their typically developing peers (Sabatos-DeVito et al., 2016). When information is determined to be salient, the ventral
frontoparietal attention network facilitates the disengagement from a central stimulus and reallocates attentional resources to the peripheral, unexpected and explorable stimuli (Corbetta et al., 2008; Kim, 2014). Because stimuli seldom occur independently and sequentially, there is a requirement for coordinating the engagement and disengagement of attention to upcoming stimuli. Maintaining alertness to upcoming stimuli requiring attention is regulated by the subcortical locus coeruleus-norepinephrine (LC-NE) system (Aston-Jones & Cohen, 2005; Mückschel et al., 2017; Petersen & Posner, 2012). Furthermore, through norepinephrine (NE) maintenance and recruitment of the ventral attention network (VAN), the LC-NE maintains arousal towards sensory and cognitive processing of salient information (Vazey et al., 2018), and thus is a critical component of regulating attention during task performance (Sara & Bouret, 2012). In other words, through a series of engagement and disengagements, the cortex can maintain attention balance and avoid becoming overwhelmed (Mückschel et al., 2017; Petersen & Posner, 2012).

Previous studies suggest that autistic individuals often find it difficult to disengage and reengage their attention networks such as the dorsal attention network (DAN) and the ventral attention network (VAN; Markram & Markram, 2010; Menon, 2011). An inability to efficiently disengage and reengage networks disrupts and individual’s capacity to distinguish between their internal world and external environment, which can lead to inflexibility and excessive awareness of internal processes (Bolton et al., 2020). Additionally, reports show that when considering multisensory integration autistic individuals struggle to reengage and disengage, furthering the strain on their attention system (Magnée et al., 2011), especially if all sensory inputs are processed with equal weight (Van de Cruys et al., 2014).
Because attention disengagement can be difficult for autistic individuals, it can lead to aversions to activities that are attentionally demanding, such as language, for instance (Murray et al., 2005; Poole et al., 2021). A common feature of ASD is monotropism, in which an individual develops intense restricted or repetitive interests that may influence their attention by limiting their capacity to process multi-faceted stimuli at once (e.g., language, social communication, and shifting attention; Murray et al., 2005). Something as important as language could become unappealing to a child who is deeply monotropic because it might disrupt their attentional focus and force disengagement with interests that are more attractive. For example, a child’s attention could be engaged with a ball, but a parent could call their attention to a cat by saying, “Look, a cat!” Language thus disrupts their attentional engagement and could lead to discomfort as their attention system tries to disengage from the ball and reengage with a new stimulus without adequate priming. However, some suggest that the difficulty does not necessarily lie with the difficulties with disengagement, rather the difficulty lies with alerting the system to new engagements (Bast et al., 2018).

The LC-NE’s ability to alert the system to upcoming stimuli requires that there is previous experience to dictate salience or not (Bast et al., 2018). Without previous experience, the LC-NE would not know how to determine salience and, instead, weight everything as equally salient, which likely leads to a sense of overwhelm. An overwhelming of the attention system could manifest as sensory over-responsivity (SOR). SOR is considered as responding to too much, for too long (Green et al., 2016). This is exhibited by sensitivity to and/or avoidance of sensations such as loud or unpredictable noises (Green & Wood, 2019). Some individuals with clinically significant SOR experience what may seem to be irrelevant stimuli as a harmful, painful, or distracting sensation which leads to an inability to habituate to the stimuli and cannot
function effectively in their presence, which often leads to meltdowns and other behaviors (Stagnitti et al., 1999). Predictions are made based on past experience and, therefore, play a critical role in alerting, orienting, and maintaining attention. Previous reports suggest that an individual’s sensitivity to reoccurring regularities in the environment aid in facilitating predictions (Van de Cruys et al., 2014). Such sensitivity may be related to salience detection, though this remains an open question.

**Predictability in Autism**

Interacting with an environment requires extensive cognitive resources. The brain is required to process all multi-sensory inputs, choosing to what it will attend, and preparing for the most adaptive responses (Gomot & Wicker, 2012). When engaging in an unfamiliar environment with new objects, sounds, smells, lights, etc. the brain engages in a series of linking and connecting the information with previously experienced information (Bar, 2009). For example, when a child is introduced to cauliflower for the first time, their mind may associate the shape with broccoli, a vegetable they have eaten before, which can lead to motivation to try the new food. Upon further investigation, the color, texture, and taste would all be novel to the brain. The initial unfamiliarity causes uncertainty, but by linking the new food with previously experienced food, an element of predictability is introduced which leads to less uncertainty. These predictive relationships aid individuals as they experience new and familiar environments and facilitate feelings about the safety of a given scenario and smooth environmental interactions.

It could be argued that all environments are new/novel because nothing occurs exactly the same way twice. Consider a daily classroom routine. It will have familiar structure, but there will also be new words, colors, smells, among other novel experiences. Predictive coding theory explains that we routinely attempt to minimize prediction errors by comparing input from
sensory stimuli with predictions that stem from previous experience with the environment (Clark, 2013). Also, the DAN may aid in amplifying relevant stimuli and suppressing unwanted distractors based on previous experience with the environment (Lanssens et al., 2020; Van de Cruys et al., 2014). This higher-order network helps the brain prioritize what stimuli are important for goal-directed behavior and habit learning during novel circumstances (Corbetta et al., 2008; Kim, 2014).

Habitual learning aids in predictability by helping one to learn to what he/she should attend. For instance, when investigating habit-formation in rats, researchers found that when events were predictable, rats paid less attention to unimportant stimuli (Thrailkill et al., 2018). The power of prediction allows individuals to anticipate some context-specific elements that do not require attention. By doing this, they can maintain selective attention resources for exploration of new environments from which they can learn what novelties are important and those that are to be avoided (Bar, 2009; Wills et al., 2007). In this way, prediction and attention are tightly linked.

When mismatches occur between what is predicted and what actually takes place, it typically causes one to pause (i.e., use attention), and can often be unpleasant or surprising. Frequent prediction mismatches, and their associated unpleasantness, over time, could lead to dislike of unpredictable situations, or intolerance of uncertainty (IU; Boulter et al., 2014; South & Rodgers, 2017; Wigham et al., 2015). Such aversion to unpredictability might lead one to build in as much predictability as possible into their life—e.g., through routine and rigidity and avoidance of unpredictable situations. Thus, behaviors such as rigidity and insistence of sameness could be associated with difficulties in prediction (Tam et al., 2017).
The DAN controls selective attention and helps in the suppression of cortical representations of undesirable input (Lanssens et al., 2020). Our predictive mechanism is likely linked to how the DAN chooses that to which we attend and filter via the LC-NE. That is, when the brain can accurately predict an event (i.e., the prediction matches the stimuli closely enough), attentional resources can be focused on salient information and are not required to attempt to process everything in a given scenario (Corbetta et al., 2008; Kim, 2014). Additionally, the VAN may also be involved by working with the sensory systems to capture salient, but previously not considered, sensory inputs (Kim, 2014).

The above processes may be of high importance in understanding autism. For instance, it is well known that autistic individuals most often function more successfully with a routine (Lidstone et al., 2014). When a routine is established, an individual can familiarize themself with sensory input associated with the routine, and thus, might more easily predict what would be important, non-threatening, etc. For example, a child with ASD at school may become overwhelmed in the classroom during a new lesson because they are taking in all information around them, unfamiliar with what is happening next. Given that prediction of upcoming events would be inherently more difficult in this scenario, the child might experience an overwhelming of her attentional and sensory systems—i.e., because of mismatches between sensory inputs and predictions. In contrast, a more routine-based lesson might facilitate predictability and lead to less aversive reactivity, because predictions would likely match sensory stimuli more accurately. In turn, this latter scenario would hypothetically require fewer attentional resources, because the child’s attention system(s) (especially the DAN) would be able to suppress unimportant or highly predictable stimuli and allocate attention to the relevant information.
Prediction difficulties may manifest themselves in common behaviors associated with an ASD diagnosis. For example, self-stimulating behaviors (e.g., clapping, eloping, shouting) are common in autistic individuals (Lipsky, 2011). Research suggests that self-stimulating behaviors may be a coping mechanism for lack of ease of prediction when a situation becomes uncertain (Sinha et al., 2014). Such responses could be an attempt to drown out the influx of stimuli from an unpredictable environment by providing a familiar, predictable sensory input. It has been theorized that autistic individuals exhibit predicative differences that sometimes prevent them from navigating common environments (Gomot & Wicker, 2012). A reduction in the ability to predict relationships between events in a stimulus sequence would reduce a person’s ability to predict the onset of the next event. Such a lack of predictability might compromise habituation, promote uncertainty, and could lead to hypersensitivity of stimuli (Herry et al., 2007)—all of which are characteristics commonly associated with autism. Additionally, the LC-NE is theorized to be involved in determining salience based on previous experiences (Bast et al., 2018). As such, this system may be at the center of the overlap between prediction and attention. Overall, if predictive capabilities are compromised, then it is likely that regulation of the attention network would be compromised as well.

When considering sensory processing and prediction, it is logical to infer that as predictive capabilities increase, sensory processing difficulties might decrease. Several studies have exhibited evidence of this effect (Bubic et al., 2010; Clark, 2013; Gomot & Wicker, 2012). This notion implicates top-down processing (i.e., prediction) in sensory processing and regulation (Green et al., 2016). Additionally, poor regulation of sensory processing can lead to difficulties with selective attention (Parsons et al., 2017; Van de Cruys et al., 2014). Furthermore, when considering attentional engagement and disengagement, the role that
prediction can play in facilitating attention allocation seems clear—i.e., a child who has difficulty with salience detection and weights stimuli equally, may feel aversion towards disengagement, because of the attentional demand required of their system to reengage with alternative stimuli. Thus, attention and prediction are intertwined and critical components of top-down sensory processing.

We propose that the type of predictions discussed above, while needing to be accurate to some degree, have an element of flexibility, encompassing a range of acceptable possibilities. This quality allows room for error with respect to the original prediction without causing an aversive response (i.e., change of the type of food, but it is still lunch time). However, when a stimulus is outside of this range of expectation—a more significant mismatch to the original prediction—the brain must use more attentional resources to process and understand the apparently novel situation/stimuli, which might be associated with less adaptive responsivity (see Figure 1).

Given findings in the literature about salience detection, attentional alerting and orienting, and prediction differences, we propose that autistic individuals may experience a smaller range of acceptable prediction deviations which could lead to higher instances of sensory-prediction mismatches. Significant incongruencies between predictions and actual events/stimuli, in turn, might result in more strain on the attentional and sensory systems, as well as associated distress (Bubic et al., 2010). It has been found that autistic individuals experience higher levels of these predictive mismatches when more demand was placed on their attention network (e.g., divided attention through auditory and visual stimuli; Burack, 1994; Van de Cruys et al., 2014), creating a loop of high attention and less accurate prediction (novel, distressing stimuli), and leading to sensory processing breakdowns. In other words, the predictions of
autistic people may be more specific, literal, and/or rigid, reducing the degree of comfortable/allowable deviations. Unfortunately, the world presents a seemingly infinite array of possible deviations from one’s predictions. Together, a limited range of acceptable possibilities in predictions and an environment full of unpredictability could lead to maladaptive reactivity more often to stimuli that are considered non-threatening by others—a trait that is commonly observed in autistic people, especially in the context of sensory processing (Dellapiazza et al., 2018; Nieto et al., 2017).

**Aims and Hypothesis**

Thus, we proposed to carry out a study aimed at investigating the role of attention, prediction, and sensory processing using both behavioral and physiologic data. We hypothesized that more adaptive predictive abilities would be associated with fewer predictive mismatches, improved attentional function, and fewer sensory difficulties.

This study aimed to explore the relationship between attention, prediction, and sensory processing in autistic and neurotypical school age children using eye tracking, behavioral tasks, and parent-report questionnaires. To our knowledge, no study has examined the relationships between these factors in the above populations. These findings have the potential to provide insight into the foundational origins of autism, improve diagnostic measures, and yield better supports for autistic people.

**Method**

The current study was comprised of two phases. In Phase 1, participant caregivers were asked to fill out a set of questionnaires regarding the participant, designed to examine several aspects of the aforementioned behaviors (e.g., sensory processing, attention, intolerance of uncertainty, and autistic traits). Participants (ages 8-11) who were recruited for Phase 2 were
invited to undergo an attention task and eye tracking experiment. Methods specific to these two phases of the study are discussed below.

**Phase 1: Behavioral Relationships Between Sensory Processing, Attention, Prediction, and Autistic Traits**

**Participants**

We recruited 70 children, 57 neurotypical (NT) children and 13 with ASD aged 8-11 (see Table 1 for demographic information). The age range of 8-11 years old was utilized due to our pilot procedures revealing that children ages 6 and 7 struggled to optimally tolerate the eye tracking task. We limited the age range to control for age effects. Subjects were recruited via word of mouth, virtual (e.g., social media) and physical advertisements, and from a pool of previous research subjects who gave permission to be contacted for future research studies. Everything in our power was done to recruit equal numbers of males and females, though, given current diagnostic ratios, more males were recruited. All subjects underwent the appropriate consenting procedures prior to participation. All methods were approved by the Institutional Review Board (IRB) of Brigham Young University and were in agreement with the declaration of Helsinki.

**Materials and Data Collection**

Caregivers of participants were asked to complete a battery of surveys via an online platform (Qualtrics XM, 2021). After obtaining consent and a brief summary of participant demographics, the caregiver completed the Short Sensory Profile-2 (SSP-2), Intolerance of Uncertainty Scale-Short From (IUS-12), the Social Responsiveness Scale, Second Edition-School Age (SRS-2), the Attention Checklist, and the Social Communication Questionnaire-Lifetime (SCQ-Lifetime).
The Short Sensory Profile (SSP) is a shortened version of the Sensory Profile (Dunn, 2014). The survey consists of 38 questions aiming to classify a child’s sensory processing behaviors according to parent report. Categories assessed include Tactile Sensitivity, Taste/Smell, Movement Sensitivity, Under-Responsive/ Seeks Sensation, Auditory Filtering, Low Energy/ Weak, and Visual/Auditory Sensitivity. The total score from these categories indicates the level of abnormality in the child’s overall sensory processing, with lower scores indicating greater sensory processing difficulties (Dunn, 2014).

The IUS-12 evaluated participants’ reaction to unpredictable life events such as the future and ambiguity (Carleton et al., 2007). It is a short-form that is taken from the 27-item original Intolerance of Uncertainty Scale. Participants will respond using a 5-point Likert scale and are measured on two factors of IU—prospective and inhibitory IU. The IUS-12 was selected for our study as an indirect measure of behavioral prediction difficulties.

The SRS-2 provided an indirect assessment of autistic characteristics as perceived by parents via a 65-item rating scale (Bölte et al., 2008; Bruni, 2014; Constantino et al., 2004; Kamio et al., 2013). It contains a school-age portion which characterizes individuals ages 4.0-18.0 years. Results from a 2014 test review psychometric study determined adequate psychometric properties in terms of internal consistency and interrater reliability (Bruni, 2014).

The SCQ-Lifetime provided a measure of autistic traits for all participants regardless of a formal autism diagnosis. It assesses three core areas of functioning characteristics of ASD: social interaction, language and communication, and repetitive patterns of behavior (Rutter et al., 2003; Ung et al., 2016). It was chosen for this study as a way to assess autistic traits across our combined sample.
The Attention Checklist uses a 4-point Likert Scale, 12-question parent survey to assess current attention function in children. Results from a 2008 study determined that the survey was effective in measuring attention functioning in school age children (Boersma & Das, 2008).

Caregivers spent between 30-45 minutes completing the online survey. Lastly, caregivers were asked to share, if willing, the diagnostic status related to ASD and ADHD for their child. Permission to contact caregivers was asked if they were interested in their child participating in a second phase of the study which involved eye tracking measures and administration of subtests from the TEA-Ch-2 (Manly et al., 2016; see Phase 2). Subjects were offered compensation in the form of a drawing for one of several gift cards for the survey portion of the study.

**Phase 2: Attentional Task and Eye Tracking Experiment**

**Participants**

We recruited 40 children from Phase 1 of the study to participate in Phase 2 (7 autistic and 33 neurotypical; see Table 2 for demographic information), which involved an eye tracking task testing and assessment with the Test of Everyday Attention-Children (TEA-Ch2).

**Instrument One: TEA-Ch2**

Participants participated in the Test of Everyday Attention-Children 2nd Edition (TEA-Ch2; Manly et al., 2016). This instrument was used to assess the selective attention capabilities of the participants. At the subtest level, there are scaled scores, composite scores, and percentile ranks. The test has strong criterion, concurrent, and construct validity. It is computerized assessment that uses three subtests for selective attention for ages 5-7 years (Junior), and 4 subtests for selective attention for ages 8-15 years (Adolescent). Our study used the adolescent subtest. Below are descriptions of the selective attention tasks:
• **Hector Cancellation:** Examines how many targets a participant can find and identify within a series of 10-second trials in which the level and frequency of distractors is varied.

• **Hector B Cancellation:** This task requires the participant to complete an additional page of the Hector Cancellation task without an imposed time limit. The examiner will need to use a stopwatch to record completion time.

• **Troy Dual Task:** Participants cancel out targets once a cymbal crash is heard. During the cancellation, a drum sequence plays. Another cymbal crash denotes the end of the task and the participants must report how many sounds were presented. This task required them to utilize selective attention to count while crossing out the symbols and targeted selective attention function.

• **Hecuba Visual Search:** This task requires the participant to orally report whether a target is present or absent amongst distractors while inspecting a series of panels within a limited time.

This test has been used in previous studies to assess children’s different attention capabilities, including children with difficulties with attention, learning, and memory (Holmes et al., 2018; McKay et al., 2019). Additionally, it has been used as a measure of attention in recent autism studies (Crasta et al., 2020; LaGasse et al., 2019).

The administration of the test took place in a quiet room with assistance from a previously trained assistant. It took approximately 20 minutes. Once completed they were given a short break.
**Instrument Two: Eye Tracking Task**

**Apparatus.** Stimuli was presented on a computer monitor with a screen resolution of 640 x 250 pixels. Eye movements were recorded with a EyeLink 1000 Plus sampled at 1000 Hz (SR research, 2005-2010).

**Stimuli.** Using a modified version of the Posner task (Petersen & Posner, 2012), participants were asked to focus on a stimulus in the center of the screen represented by a white cross against a grey background. On either side of the cross were white outlined rectangles. During trials, a white star appeared in either rectangle, requiring the child to look away from the cross to the star (peripheral stimulus). Before the star appeared, a yellow arrow was presented, denoting which rectangle the star would appear in. The yellow arrow served as a predictive cue to the star. Stimuli trials were presented in three conditions aimed to simulate different portions of our prediction model: Expected, Positive (EP), Novel, Acceptable (NA), and Novel, Distressing (ND). In an attempt to violate predictions, in certain trials, the arrow incorrectly pointed to where the star would appear, thus violating the participants’ prediction (see Figure 2).

1. **Expected, Positive (EP):** In this condition, the yellow arrow correctly denoted which box the star would appear. These trials conditioned the participants to expect the arrow’s direction and star location to match. This trial simulated the expected, positive condition in the prediction model.

2. **Novel, Acceptable (NA):** These trials violated the participant’s predictive/conditioning by placing the star around the white rectangle region that was slightly deviant from the congruent position. The arrow still indicated the correct side. During violation presentations, the star appeared in varied positions horizontally (classified as close, medium, far). In this phase of the experiment, participants’
predictions were violated slightly by altering the horizontal position of the star. To further increase the level of prediction violations, the star was also positioned vertically but still on the congruent side. The trials in this condition are classified as either medium up and medium down. These random violations of horizontal and vertical position were interspersed between regular congruent stimuli in 20% of all presentations.

3. Novel, Distressing (ND): Finally, to create a maximum violation of predictions, the star appeared on the opposite side of the arrow’s direction and not within the box. These maximum violations occurred in 10% of trials. These trials were associated with the novel, distressing classification in the prediction model.

In this way, we reasoned that we would be able to test participants’ reactions to varied degrees of prediction mismatch. Additionally, two baseline periods of two minutes were conducted at the beginning and end of the eye tracking task.

While the participants were completing these tasks, their parents or caregivers were asked to complete the Child Sensory Profile-2. The Child Sensory Profile 2 (SP-2) assessed sensory processing characteristics through an 86-item parent-report. It measures sensory sensitivity, sensation seeking, low registration, and sensory avoidance. The SP-2 classifies six sensory systems including touch, movement, body position, auditory, oral, and visual using a 5-point Likert rating scale. Additionally, three behavioral sections are assessed: attention, conduct, and social/communication. This measure was selected for our study because it combines sensory processing and attention. It was normed on children aged 3 to 14 years and demonstrates strong psychometric properties (Dunn, 2014).
Procedures

Participants were oriented to the eye tracking apparatus and expectations associated with it. To engage with the system, participants were seated on a chair positioned 93 cm from the monitor in a quiet, well-lit room. The participant’s eyes were calibrated at the start of the eye tracking test. Manual calibration consisted of the participant focusing on a stimulus, when focus was steady, the examiner confirmed the position. After a series of 12 trials, calibration was complete. After calibration, the experimental stimuli were presented. Subjects were instructed using standardized verbal instructions: “Please look at the cross on the screen. Pay attention to the direction the arrow points and move your eyes as quickly as possible to the star when it appears. Once you have looked at the star, please move your eyes back to the cross for your next turn.” The eye tracking task lasted approximately 15 minutes. The stimulus task was presented in one sitting and the child received a reward (e.g., sticker or treat) for their efforts.

Data Analysis

Phase 1 Data

Data analysis first included non-parametric group comparisons using Mann-Whitney U tests of the total and sub-scores of the above measures. Additionally, the relationships between scores on the aforementioned questionnaires was assessed by carrying out planned partial Spearman rank order correlations, controlling for age and sex.

Phase 2 Data

Data analysis compared findings from the selective attention index from the TEA-Ch2, eye tracking data (e.g., pupil dilation (PD), disengagement time from central stimulus, reengagement time with peripheral stimulus, and saccade reaction time), and Phase 1 questionnaire data (especially sensory processing). Eye tracking data consisted of five variables.
1. Central engagement accuracy (ce): This variable measured the participant’s ability to fixate on the central stimulus (the white cross). A gaze fixation was considered accurate if the participant was able to successfully fixate on the central stimulus in 200x200 pixel region for 500ms. Each trial required fixation before beginning the trial.

2. Peripheral reengagement accuracy (pr): For this measure, the participant needed to accurately fixate on the peripheral stimulus (the white star). Trials that were incorrect, meaning the participant did not fixate on the peripheral stimulus, were discarded.

3. Central Saccade Reaction Time (cs): This variable measured how long it took the participant to visually disengage from the central stimulus once the peripheral stimulus appeared. In other words, once the star appeared on the screen how long did it take for the participant to stop looking at the cross?

4. Peripheral Saccade Reaction Time (ps): For this variable, the participant’s saccade duration was measured once they disengaged from the central stimulus and reengaged with the peripheral stimulus. In other words, what was the duration of the saccade once the participants stopped looking at the cross and moved to look at the star?

5. Pupil Dilation (PD): Research has shown that PD is an excellent biological marker of engagement and disengagement due to its close relationship with the LC-NE system (Anderson & Colombo, 2009; Falck-Ytter et al., 2013; Fan et al., 2009; Zhao et al., 2019). To measure PD in our experiment, for each trial we measured a baseline of 50ms before the peripheral stimulus appeared to gather a baseline period. PD was then measured during the trial period and subtracted from the baseline to give us a change in pupil size for each trial.
Each variable was then analyzed in the context of trial types. For instance, central saccade reaction time (cs) was analyzed in the context of expected, positive (EP); novel, acceptable (NA); and novel, distressing (ND) trials. Variables are shown as follows: csEP (central saccade reaction time-expected positive), csNA (central saccade reaction time-novel acceptable), csND (central saccade reaction time-novel distressing; see Table 3 and Table 4).

For each variable, means across all trial types within a given category of prediction were computed for each participant (e.g., the average cs was taken EP, NA, and ND in each participant).

Nonparametric Spearman’s correlations were then used to evaluate the relationships between total scores of our measures of interest across all participants. Additionally, nonparametric statistics, such as Friedman tests and Wilcoxon signed rank tests, were used to determine any main effect and bivariate repeated-measures differences in eye tracking measures across our participants.

Results
Phase 1 Results: Behavioral Data From Surveys
Mann-Whitney U tests revealed significant differences between autistic and NT participants on the SSP ($U = 151.5; p < .001$), the Attention Checklist ($U = 228.5; p = .03$), SCQ-lifetime ($U = 639.5; p < .001$), and the SRS-total score ($U = 623.00; p < .001$).

Spearman correlations revealed significant correlations with SSP and the IUS-12 ($r = -.56; p < .001$), SSP and the Sensory Profile Attention Score (SPAS) ($r = .51; p < .001$) (see Figure 3), the SSP and the SCQ-L ($r = -.66; p < .001$), the SSP and SRS-total ($r = -0.81; p < .001$). The Attention Checklist was also correlated with the SCQ-L ($r = -0.36; p = .002$) and the
SRS-total \( (r = -.54; \ p < .001) \). Furthermore, the IUS-12 was significantly correlated with the SCQ-L \( (r = -.45; \ p < .001) \) and the SRS total \( (r = .59; \ p < .001; \) see Table 1).

To further investigate the interrelationship between sensory processing, prediction, and attention, we carried out a mediation analysis between the SSP, IUS-12, and the SPAS. The analysis suggested that IUS mediated the relationship between attention (SPAS) and sensory processing (SSP; see Figure 4). Specifically, the association between SPAS and the IUS-12 scores was \( (\beta = 1.10; \ p < .001) \). Similarly, SPAS and the SSP were also significantly related \( (\beta = -.92; \ p < .001) \). The direct effect of the IUS on SSP was also significant \( (\beta = -1.17; \ p < .001) \).

Indirect effects in this model were tested using bootstrapping methods (5,000 samples). The model had a lower confidence interval of -2.29 and an upper confidence interval of -.54. Both lower and upper confidence intervals being negative suggests significance of the model.

Together, these results suggest that prediction contributed to the effect that attention had on sensory processing.

**Phase 2 Results: Behavioral and Eye Tracking Data**

After removing incorrect trial responses and cleaning data, 39 participants remained in the sample (NT \( n = 33 \), ASD \( n = 7 \)). Mann-Whitney U tests comparing behavioral data between NT and autistic children from the in-person sample revealed significant differences in the following: SSP total score \( (U = 50.00; \ p = .018) \), IUS-12 total score \( (U = 69.5; \ p = .05) \), SCQ-Lifetime score \( (U = 193.00; \ p = .004) \), SRS-2 total score \( (U = 192.00; \ p = .005) \), Seeking/Seeker raw score \( (U = 183.50; \ p = .013) \), Avoiding/Avoider raw score \( (U = 187.50; \ p = .008) \), Sensitivity/Sensor Raw score \( (U = 176.00; \ p = .03) \), Registration/ Bystander raw score \( (U = 173.00; \ p = .041) \), Attentional raw score \( (U = 175.5; \ p = .03) \).
Non-parametric repeated measures testing within groups revealed the following:

Friedman tests showed an overall difference across condition type (main effect) in both the NT and autistic participants in both central (central (NT: x2(2) = 10.17; \( p = .006 \); ASD: x2(2) = 6.00; \( p = .05 \)) and peripheral (NT: x2(2) = 20.08; \( p < .001 \); ASD: x2(2) = 6.00; \( p = .05 \)) trial types.

More detailed investigation of the differences between conditions, via Wilcoxon signed rank tests, revealed significant differences between both the csEP (\( Z = -2.52; \ p = .012 \)) and csNA (\( Z = -3.03; \ p = .002 \)), and the csND trials in the NT group. The ASD group showed trends towards significance in the cs condition for csEP and csNA (\( Z = -1.83; \ p = .068 \)) and the csNA/csND (\( Z = -1.83; \ p = .068 \)) pairings (see Figure 5).

Similarly, for the ps condition, in the NT group, there were significant difference between all pairings between psEP and psNA (\( Z = -3.48; \ p < .001 \)), psNA and psND (\( Z = -3.31; \ p < .001 \)). Trends toward significant differences between psNA and psND (\( Z = -1.83; \ p = .068 \)) and psEP and psND (\( Z = -1.83; \ p = .068 \)) pairings were evident in the pairings of the ASD group in the ps condition (see Figure 6).

Next, partial correlations (controlling for age) showed that csEP was significantly correlated with the Selective attention raw score (\( r = -.39; \ p = .05 \)), the Troy Dual Task Subtest (\( r = -.42; \ p = .02 \)), and the SSP-Visual/Auditory Sensitivity score (\( r = -.39; \ p = .05 \)). csNA was correlated with the Troy Dual Task Subtest (\( r = -.42; \ p = .04 \)), and the SSP-Visual/Auditory Sensitivity score (\( r = -.37; \ p = .07 \); see Figure 7). Additionally, psNA was correlated with the Troy Dual Task Subtest (\( r = -.41; \ p = .04 \)), and the SSP-Visual/Auditory Sensitivity score (\( r = -.38; \ p = .08 \); see Figure 7). Additionally, pupil dilation in the novel acceptable condition (pdNA) was found to be significantly associated with IUS-12 total score (\( r = -.55; \ p = .012 \)) in NT
participants. Finally, ANOVA Single factor tests revealed a significant difference between
groups in peripheral saccade accuracy (pr; $F = 4.05; p = .05$; see Figure 8).

**Discussion**

Atypical sensory processing is commonly associated with an autism diagnosis, which can lead to discomfort and difficulty in some environments encountered in daily living. Because autistic traits lie along a continuous spectrum, it is reasonable to assume that some NT individuals experience sensory processing difficulties as well. While there is no clear explanation of why atypical sensory processing occurs, previous research has linked attention function to atypical sensory processing (Crasta et al., 2020; Dellapiazza et al., 2018; Green & Wood, 2019). Our study aimed to investigate potential underlying mechanisms and correlates between attention and sensory processing. We theorized that prediction capabilities are major contributors to sensory processing and attention function. Although other studies have compared attention to sensory processing (Crasta et al., 2020; Dellapiazza et al., 2018; Green & Wood, 2019) and prediction to sensory processing (Aitken et al., 2020; Gomot & Wicker, 2012; Van de Cruys et al., 2014) few studies have examined all three factors together using both behavioral and physiologic methods. Overall, we found evidence that prediction plays a direct role on how attention impacts sensory processing, which was supported by a mediation analysis of the behavioral data and significant correlations between eye-tracking measures and behavioral data.

**Findings**

The model we initially proposed (see Figure 1) submitted that sensory processing, attention, and prediction all shared a complex interaction. As sensory environments became more unpredictable, we suggested that higher demands on attention would be required to process sensory information. Various results from our study support the above notions.
Behavioral Data

One of the principal findings of our study was that sensory processing was correlated with all of our behavioral measures across the combined sample. For instance, it was closely connected with autistic traits, echoing previous reports that sensory processing is a key contributor to the autism diagnosis (American Psychiatric Association [APA], 2022; Ayres, 1981; Crasta et al., 2020; Marco et al., 2011; Robertson & Baron-Cohen, 2017). Additionally, sensory processing was significantly connected to attention and prediction, which is consistent with our hypothesis and is supported by previous literature (Bar, 2009; Robertson & Baron-Cohen, 2017; Thye et al., 2018; Van de Cruys et al., 2014). Recognizing the multiple factors that impact sensory processing is important as sensory processing is a key part of the autism diagnosis, as well as an area where clinical supports are often needed.

Our hypothesized model also suggested that predictive abilities were contributing to atypical sensory processing and attention function. From the behavioral results, we found that the IUS-12 (one indirect measure of prediction) was significantly correlated with our measures of sensory processing and autistic traits. It was also correlated with the attention subsection of the sensory profile (see Figure 3). This finding was surprising as we expected to see more correlations between our prediction and attention measures in our behavioral data. Perhaps the IUS-12 as an indirect measure of prediction is too far removed from the type of prediction that interacts with attention in real-time. We also contemplated that perhaps the Attention Checklist was not assessing the type of attention we theorized was related to prediction (e.g., selective attention).

Despite the above findings, in our mediation model, we found that rather than prediction having a direct relationship with attention and sensory processing, it plays a mediating role in the
relationship between attention and sensory processing (see Figure 4). These findings support our model, indicating that an individual’s predictive abilities impact how attention is used to process sensory information. In other words, as situations became less predictable, participants would be more likely to experience the novel, distressing (ND) zone of Figure 1. Additionally, previous literature has shown that prediction and attention are in fact dependent on one another regarding sensory processing, which further corroborates our hypothesis of the direct relationship between attention and prediction (Hsu et al., 2014).

In addition to the mediating role prediction played in the association between attention and sensory processing, behaviorally, prediction and sensory processing were directly correlated with each other. Specifically, the IUS-12 was correlated with the SSP-Visual/Auditory processing scale. It is interesting to note anecdotally that during the experiment, participants in both groups demonstrated visceral reactions to stimuli when they were less predictable, evidenced by facial reactions, vocalizations of surprise, and even becoming upset by prediction violations. These observed reactions are in line with current literature suggesting that unpredictability can lead to discomfort, frustration, and difficulty processing continued sensory information (Bast et al., 2018; Van de Cruys et al., 2014).

**Physiologic Data**

We also observed several connections between behavioral and eye tracking data that were germane to our hypotheses. For instance, the Short Sensory Profile-Visual and Auditory Processing score was correlated with reaction times during the csEP, csNA, and psNA conditions. In other words, difficulty with visual and auditory processing was most often positively correlated with trials that were less predictable in our experiment. When considering specific brain regions that could contribute to this relationship, previous research showing
atypical functional connectivity between auditory and visual regions to higher-order brain networks (e.g., prediction and attention) in autistic children might offer insight (Menon, 2011; Oldehinkel et al., 2019). Additionally, the above finding is in keeping with current literature that indicates that auditory and vision issues are some of the most common sensory difficulties that autistic individuals experience (Baum et al., 2015; Demopoulos & Lewine, 2016; Jao Keehn, 2021; Kuiper et al., 2019). Specifically, autistic people commonly have auditory/vision sensitivities and difficulty with attention in the presence of noise and filtering out unwanted signals (Marco et al., 2011; Schauder & Bennetto, 2016; Thye et al., 2018). The data suggested that attention and visual and auditory processing are linked across our combined sample.

While results were limited in the behavioral data regarding the relationship between attention and prediction, the eye tracking measures revealed that there is a physiologic level of interaction between attention and prediction. That is, csND and psND all correlated with the Troy Dual Task in the TEA-ch2 (see Figure 7) pointing to the complex relationship between prediction and attention. The Troy Dual task was the most complex attention task the participants completed, requiring high levels of selective attention. It is interesting that the selective attention task correlated with the two most incongruent types of trials: csND and psND. This shows that more difficulty managing attention was related to how the participants performed during trials in which their predictions were violated the most, suggesting that prediction does play a role in attention management. The idea of prediction impacting attention function is supported by previous literature, which outlines prediction as a top-down processing effect (Corbetta et al., 2008; Kim, 2014). Past research has theorized that neurologic systems, particularly the LC-NE, coordinates the engagement and disengagement of attention on environmental stimuli based on previous experience or prediction (Aston-Jones & Cohen, 2005; Petersen & Posner, 2012). Thus,
our findings add to the current literature, supporting the idea that prediction influences how attention is monitored and executed by individuals, and that these functions may be subserved by the LC-NE system.

In addition to saccade function and its implications on prediction and attention, of particular interest was the overall performance of the autistic children on the eye tracking task as compared to the NT children. As seen in Figures 5 and 6, the autism group were more successful in managing their attention (e.g., disengagement and reengagement time) compared to their NT peers when trials were predictable (csEP, psEP), but unlike the NT group, which experienced a gradual increase in difficulty as trials became more unpredictable, the ASD group experienced a precipitous decrease in abilities to effectively manage their attention. This difficulty was evidenced by repeated measures testing that showed a clear difference in how autistic and NT children processed expected versus unexpected sensory information—i.e., the autistic children took longer to disengage their attention and make accurate saccades during conditions with less predictability when compared to their own performance on simpler tasks. These findings suggest that the trials in which prediction was violated the most was appreciably more difficult for autistic participants than the NT participants. This effect was also evident in the overall accuracy of the trials during the eye tracking task. Autistic children had significantly more errors in accuracy of fixations as trials became more unpredictable as seen in Figure 8. Difficulty with prediction and attention have been supported in previous literature (Chita-Tegmark, 2016). For example, some studies have suggested that attention allocation in autism is atypical, and allocation of attention resources becomes more difficult when there are too many stimuli in an environment that are unpredictable (Chawarska et al., 2013). Taken together, these findings
support our hypothesis that as predictive abilities become taxed, management of attention and sensory processing can be impacted.

In NT children, we also found a significant correlation between our direct physiologic measure of prediction, pupil dilation, and the IUS-12, which served as an indirect measure of prediction. Previous research has theorized that pupil size is modulated by covert visual attention engagement (Mathôt et al., 2013). This relationship suggests that there is a physiologic relationship between attention and prediction, and that eye tracking measures may be able to provide great insight into the predictive mechanisms of the brain, especially as the relate to attention and sensory processing. Future studies might yield highly informative data using such techniques to further study these effects in larger samples of autistic individuals.

Several researchers have suggested the predictive coding model may shed light on sensory processing in autism (Van Boxtel & Lu, 2013; Van de Cruys et al., 2014). The model suggests that autistic individuals struggle to make and incorporate predictions into current contexts based upon previous experiences. The mismatches between what was expected and the reality of the situation can often lead to very shocking or unpleasant reactions (e.g., jumping into a swimming pool that is colder than expected; Boulter et al., 2014; Tam et al., 2017; Wigham et al., 2015). These responses can be all-consuming of attention resources and could lead to atypical sensory processing. On the other hand, some suggest that atypical sensory processing is what causes these imperfect predictions (South & Rodgers, 2017; Wigham et al., 2015). Either theory could be key to understanding sensory difficulties observed in autistic individuals. Our results suggest that atypical predictive adaptability results in altered sensory processing. When considering attention in relation to prediction and sensory processing, we found that as predictions were violated, attention management was impacted, and ultimately sensory
processing was impaired. These findings are in agreement with the current literature that prediction impacts sensory processing and attention abilities (Boulter et al., 2014; Meng et al., 2023). Overall, our hypothesized theoretical model and novel adaptation of eye tracking methods are promising in being able to explain and further investigate the interplay between sensory processing, prediction, and attention.

**Limitations**

Despite significant findings obtained in the current study, there are limitations that are important to note. First, while the eye tracking paradigm we used was based on well-established paradigms (Doricchi et al., 2010; Petersen & Posner, 2012; Posner, 1994), our version of the task was the first time it was utilized in an experiment. As such, there may have been issues that may have impacted the data. For example, ND had the highest instance of errors for participants, leading to the discarding of these trials, therefore reducing our data set. In the future, we would want to modify the task and include more ND trials to make up for trials that are incorrect.

Additionally, we had limited participants in our ASD group because several autistic children we recruited were unable to tolerate the eye tracking task due to duration of the task and the requirement to remain still for the eye tracking portion. However, to address this limitation, most of our correlations used a dimensional view of autism rather than the categorical limitation to compensate for low numbers in our ASD groups. Additionally, we anticipate continuing to use (perhaps modified) methods to further investigate the above effects in larger samples of autistic individuals. As such, in addition to the significant findings were present herein, we submit this report as a proof of concept of novel methodology used in mostly neurotypical children that has promise for use in autistic persons.
The behavioral data that was collected was not randomized or counterbalanced. As a result, there may have been fatigue effects. Additionally, the behavioral measures were parent reported, which could have introduced issues such as personal bias or effects of outside influence when answering the questionnaires. Understanding these limitations is relevant as interpretation of each correlation, data point, and conclusions are made. However, the types of statistics used and following similar experiment formats lends support to the validity of our data.

Implications for Future Research

Results from this study suggest that there is a complex interrelationship between sensory processing, attention, and prediction. We found that prediction plays a mediating role on how attention impacts sensory processing. Further research should aim to investigate further underlying mechanisms of this relationship. Additionally, research should target the types of attention being impacted (e.g., selective, sustained, divided, etc.). Future research should investigate how to facilitate improved predictive abilities and how they can directly apply them to an individual’s life. Methods regarding how to manage sensory processing and attention in the framework of prediction should be explored. Another area of interest for future research would be whether or not atypical predictive abilities impact sensory processing or atypical sensory processing impacts one’s ability to make accurate predictions. There is a complex relationship between our three constructs and how they are related to autistic traits that provide countless questions for future research and how we can better improve the lives of individuals struggling with sensory processing.

Implications for Practitioners and Other Stakeholders

Individuals providing support to those on the autism spectrum would benefit from an understanding of how to facilitate improved sensory processing. For example, if a speech-
language pathologist expects a child with a dysregulated sensory system to participate optimally in therapy sessions without accounting for intolerance of uncertainty, it may be more difficult for the child to manage their attention function, leading to slower progress in speech/language abilities. Recognizing the difficulty this client may experience and tailoring therapy sessions to facilitate predictive sensory environments could lead to better attention on therapy and increase effectiveness in treatment. Additionally, collaborating with educators, physical and occupational therapists, and other common providers that serve this community could maximize improvement across all domains. In addition, caregivers and friends could benefit from strategies to reduce uncertainty, helping the child to have better attention and sensory processing, leading to increased positive engagement with their environment.

Results from this study suggest that sensory processing difficulties, and subsequently attention issues, are not limited to individuals with a formal autism diagnosis. Many researchers have suggested that autistic traits lie along a continuous spectrum, meaning that many NT individuals experience degrees of autistic traits (Baron-Cohen et al., 2001; Constantino & Todd, 2003; Landry & Chouinard, 2016; Robertson & Simmons, 2013). Research has coined this as the broader autism phenotype (BAP). With this in mind, stakeholders working with children in therapy, schools, at home, etc. should work to facilitate improved sensory processing for all individuals, regardless of a formal diagnosis. By doing so, they could positively impact sensory processing for all individuals, not just those with a formal autism diagnosis.

**Conclusion**

Most individuals with autism experience sensory processing difficulties that make life challenging. Our study aimed to investigate the relationships between sensory processing, attention, and prediction both behaviorally and physiologically. Our results revealed that sensory
processing, attention, prediction, and autistic traits were significantly correlated across our combined sample. We found that prediction plays a mediating role between attention and sensory processing function. Our hypothesized model of how our three constructs interact was also supported by physiologic eye tracking data, providing insight into the neural mechanisms underlying the complex relationship between the above constructs. We found that, as situations become more unpredictable, attentional demand was significantly increased. Additionally, autistic individuals experienced greater difficulty with attention management when situations were less predictable. These findings could increase awareness for the challenges autistic children face as they aim to process sensory stimuli in an unpredictable world. We found that these results were also evident in our NT sample, suggesting that sensory processing difficulties that are present in NT individuals follow similar patterns as those in autistic persons. By creating more predictable environments or helping affected individuals be more resilient to unpredictability, we could facilitate increased attention and sensory processing function, leading to more pleasant sensory experiences for all individuals, not just those diagnosed with autism. These findings could provide insight to the origin of sensory processing difficulties found in autism, improve diagnostic procedures, yield targets for services, and improve the quality of life for individuals affected by atypical sensory processing, regardless of diagnosis.
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Tables

Table 1

Demographics Table

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<th>Variable</th>
<th>NT</th>
<th>ASD</th>
<th>SD NT</th>
<th>SD ASD</th>
<th>U-Value</th>
<th>p-Value</th>
</tr>
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<td>n</td>
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<td>13.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
<td></td>
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<td>-</td>
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<td>Female</td>
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<td>-</td>
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<td>120.69</td>
<td>23.44</td>
<td>25.16</td>
<td>151.50</td>
<td>0.001</td>
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<tr>
<td>IUS-12</td>
<td>23.67</td>
<td>29.69</td>
<td>11.62</td>
<td>12.90</td>
<td>483.00</td>
<td>0.089</td>
</tr>
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<td>SRS-2</td>
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<td>4.08</td>
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<td>0.000</td>
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<td>Attention Checklist</td>
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<td>7.82</td>
<td>6.34</td>
<td>228.50</td>
<td>0.032</td>
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*p < .05 **p < .01 p < .001.
### Table 2

**Phase 2 Demographics Table With Means**

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<th>SD ASD</th>
<th>U-Value</th>
<th>p-Value</th>
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<td>7.00</td>
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<td>2.00</td>
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<td>-</td>
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<td>-</td>
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<td>9.95</td>
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<td>151.50</td>
<td>0.001</td>
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<td><strong>Attention Checklist</strong></td>
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<td>0.032</td>
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<td><strong>SP-2- Seeking/ Seeker</strong></td>
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<td>183.50</td>
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<tr>
<td><strong>SP-2- Avoiding/ Avoider</strong></td>
<td>39.09</td>
<td>61.86</td>
<td>12.98</td>
<td>22.10</td>
<td>187.50</td>
<td>0.008</td>
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<td><strong>SP-2- Sensitivity/ Sensor</strong></td>
<td>36.52</td>
<td>54.43</td>
<td>11.00</td>
<td>22.08</td>
<td>176.00</td>
<td>0.030</td>
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<tr>
<td><strong>SP-2- Registration/ Bystander</strong></td>
<td>38.64</td>
<td>56.71</td>
<td>13.73</td>
<td>21.73</td>
<td>173.00</td>
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<tr>
<td><strong>SP-2- Visual/ Auditory Sensitivity</strong></td>
<td>12.03</td>
<td>17.14</td>
<td>4.09</td>
<td>7.38</td>
<td>164.00</td>
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<td><strong>Attention Raw Score</strong></td>
<td>36.48</td>
<td>27.14</td>
<td>6.48</td>
<td>10.89</td>
<td>175.50</td>
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<tr>
<td><strong>Troy Dual Scaled Score</strong></td>
<td>10.21</td>
<td>8.86</td>
<td>3.45</td>
<td>3.67</td>
<td>91.00</td>
<td>0.400</td>
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<td><strong>csEP</strong></td>
<td>379.98</td>
<td>359.69</td>
<td>154.33</td>
<td>118.94</td>
<td>64.00</td>
<td>1.000</td>
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<tr>
<td><strong>csNA</strong></td>
<td>362.53</td>
<td>231.61</td>
<td>128.39</td>
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<td><strong>csND</strong></td>
<td>457.93</td>
<td>648.36</td>
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<td>147.52</td>
<td>79.00</td>
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<td><strong>psEP</strong></td>
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<td>76.01</td>
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<td><strong>psNA</strong></td>
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<td><strong>psND</strong></td>
<td>517.69</td>
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<td><strong>Accuracy Quotient</strong></td>
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<td>0.10</td>
<td>0.18</td>
<td>118.00</td>
<td>0.390</td>
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</table>

*p < .05  **p < .01  p < .001.*
Table 3

*Variable Abbreviations*

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<tr>
<th>Variable</th>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Central Engagement Accuracy</strong></td>
<td>ce</td>
<td>Did they fixate on the cross?</td>
</tr>
<tr>
<td><strong>Peripheral Reengagement</strong></td>
<td>pr</td>
<td>Did they fixate on the star?</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Central Saccade Reaction Time</strong></td>
<td>cs</td>
<td>How long did it take to stop looking at the cross?</td>
</tr>
<tr>
<td><strong>Peripheral Saccade Reaction Time</strong></td>
<td>ps</td>
<td>How long did the saccade take?</td>
</tr>
</tbody>
</table>

Table 4

*Trial Type Abbreviations*

<table>
<thead>
<tr>
<th>Trial Type</th>
<th>Abbreviations</th>
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<tr>
<td>Expected, Positive</td>
<td>EP</td>
</tr>
<tr>
<td>Novel, Acceptable</td>
<td>NA</td>
</tr>
<tr>
<td>Novel, Distressing</td>
<td>ND</td>
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</tbody>
</table>
Figures

Figure 1

*Prediction Model*

*Note.* Prediction Model illustrating the relationship between prediction, attention, and sensory processing. Blue lines indicate acceptable region for variance and red lines indicate outside acceptable region of variance. A sensory experience may occur anywhere on the model. If it occurs in the red region, more attention is required to process the novel sensory stimuli.
Figure 2

Eye Tracking Trial Types

*Note.* Stimuli trials in context of the prediction model.
Figure 3

*Scatter Plots of Behavioral Correlations Between Measures of Sensory Processing, Attention, and Prediction*

![Scatter Plots](image-url)

- Sensory Profile Attention Score vs. Sensory Profile Total Score: $r = 0.71$, $p < 0.001$
- Intolerance of Uncertainty Scale vs. Sensory Profile Attention Score: $r = -0.79$, $p < 0.001$
- Intolerance of Uncertainty Scale vs. Sensory Profile Total Score: $r = -0.55$, $p < 0.001$
Figure 4

Attention, Prediction, Sensory Processing Mediation Model

\[ \beta = 1.10^{**} \]

\[ \beta = -1.17^{**} \]

Model:
\[ r = 0.71 \]
\[ r^2 = 0.5 \]
\[ p < 0.001 \]
Lower CI = -2.23
Upper CI = -0.54

\[ \beta = -0.92^{**} \]

\( ** p < 0.001 \)
Figure 5

Central Saccade Reaction Time in Within and Between Groups

Note. Bar graph representing within group (thin line) and between group (bold line) comparisons of central saccade reaction time.

csEP- central saccade reaction time in the expected, positive condition

csNA- central saccade reaction time in the novel, acceptable condition

csND- central saccade reaction time in the novel, distressing condition
Figure 6

Peripheral Saccade Reaction Time in Within and Between Groups

Note. Bar graph representing within group (dotted line) and between group comparisons (solid line) of peripheral saccade reaction time.

psEP- peripheral saccade reaction time in the expected, positive condition

psNA- peripheral saccade reaction time in the novel, acceptable condition

psND- peripheral saccade reaction time in the novel, distressing condition
Figure 7

Scatter Plot of the Correlation Between Troy Dual Task and Central/Peripheral Saccade

$r = -0.38$
$p = 0.04$

$r = -0.38$
$p = 0.04$
Figure 8

Accuracy Quotient of Peripheral Accuracy Between Groups

*p < 0.05

Note. Bar graph representing between group comparison of peripheral accuracy.
APPENDIX A

Annotated Bibliography


**Objective:** This study aimed to compare and correlate Autistic traits and sensory patterns of hyper- and hyporesponsiveness in children with ASD and other comparison groups using the Sensory Experiences Questionnaire (SEQ).

**Methods:** Caregivers of 258 children (ages 5-80 months) in five diagnostic groups (ASD, PDD, DD/MR, Other DD, Typical) completed the questionnaire.

**Results and Analysis:** The ASD group had higher sensory symptoms than the typical or DD groups and presented with hyporesponsiveness in both social and nonsocial contexts. Additionally, Both ASD and DD clinical groups presented with hyperresponsiveness.

**Conclusions:** The SEQ was able to identify sensory factors in the ASD group and differentiate them from other comparison groups.

**Relevance to the current work:** As our study will be correlating behavioral data with neuroimaging data, the SEQ is a potential behavioral measure we could use to give us valid results of the sensory features among autistic children.

**Objective:** Researchers wanted to create an appropriate assessment of joint attention for school-age children ages 7-17 to properly assess how joint attention continues to impact development in children diagnosed with ASD. Joint attention in older children can affect how a child learns greetings, gestural imitation, and other social cues that are important for social communication.

**Methods:** Two participant groups were used all from ages 7-17 years. The samples had 18 participants diagnosed with ASD and 24 control, typical developing participants. Participants were excluded from the study if they had an IQ lower than 85 to limit the confounding factor of ID. Participants sat across from an examiner and were assessed on six naturalistic tasks (e.g., gaze following, respond time, social imitation, etc.). They were assessed and scored on levels of engagement. Results from the measure were then compared to participants’ test scores on several standardized exams (e.g., PPVT-III, CELF-4, FSIQ) which assessed expressive/receptive language, social readiness, etc.

**Results and Analysis:** For the individuals diagnosed with ASD, better performance on the experimental joint attention measure was positively related to better performance on measures of receptive language, parent report of joint attention, and the theory of mind.
Conclusions: School-age children diagnosed with ASD exhibit differences in joint attention than their same-age peers. Joint attention is still an important factor to consider as children get older because it can impact how they interact with their world.

Relevance to the current work: Joint attention is a specific type of attention that could be correlated to behaviors we are aiming to assess in the study. It is still relevant for the population that we are wanting to gather data from.


Objective: This longitudinal study aimed to investigate sensory over-responsivity (SOR) in school-aged children followed from infancy and how it impacts their ability to regulate.

Methods: 1,329 families with children without developmental disorders were contacted once or twice annually to complete surveys. Surveys included the Sensory Over-Responsivity Scales which describe sensations in all sensory domains that a child may have difficulty with.

Results and Analysis: Parents reported that tactile or auditory domains affected their children the most. Elevated SOR was prevalent in 16.5% of children aged 7-11 years old. Parents with children who have elevated SOR at school-age reported that their child exhibited more difficulty with social-emotional regulation problems and lower ability to adapt their social skills.
Conclusions: All children could potentially exhibit some level of SOR. It is important to be aware that a medical/developmental diagnosis is not needed for SOR to negatively impact a child’s development.

Relevance to the current work: Sensory over-responsitivity can negatively impact all children. If it is impacting typically developing children, it most certainly negatively impacts children diagnosed with ASD because they are more likely to struggle with regulating their sensory responsitivity.


Objective: Researchers aimed to pinpoint network-to-network interactions between the default mode (DMN), central executive (CEN), and salience networks (SAL) using fMRI.

Methods: To determine functional connectivity, the team examined co-activation patterns in the Anterior insula and the desired networks in 19 subjects diagnosed with subclinical disturbances. They compared these connections to fMRIs gathered from 29 healthy, matched control participants.

Results and Analysis: The data linked the anterior insula to governing how and when the CEN to DMN transitions occur. This governing appeared dysfunctional in the experimental group’s fMRI data.

Conclusions: Results suggest that abnormal network switching disrupts an individual’s capacity to distinguish from internal and external environments. This causes rigidity and excessive awareness of internal and external stimuli.
Relevance to the current work: The data suggests the anterior insula as responsible for switching between different attentional networks. I am interested to see if this region of the brain is also affected in individuals with ASD.


Objective: Researchers investigated relationships between deficits in executive functioning, language, social function, and emotion using quantitative EEG data findings from 20 children with ASD and 20 controls matched for gender, age, and IQ.

Methods: The EEG recorded resting state differences in cerebral functioning.

Results and Analysis: The most important finding was that of underconnectivity between the certain regions in the ASD group.

Conclusions: Results suggest that there is dysfunctional integration of frontal and posterior regions of the brain as well as underconnectivity of neural patterns and during neural functioning in the brains of individuals with ASD.

Relevance to the current work: Sensory processing, attention, and predictability are all related to neural functioning. It is important to note that this study highlighted EEG results. With fMRI data, we will look to see if there are patterns of underconnectivity or overconnectivity.


*Objective:* This article aimed to review 26 different studies that examine executive function (EF) and its links to ASD and ADHD in children.

*Methods:* Researchers compared the studies with included 646 children with ASD and 789 children with ADHD ages ranging from 3-18 years old. Additionally, some studies included an ASD + ADHD group, as these diagnoses commonly cooccur. All studies used the *DSM-5* as diagnostic criteria.

*Results and Analysis:* All groups exhibited similarities in attention, working memory, and fluency. Both ASD and ASD + ADHD groups demonstrate difficulties with flexibility and planning and required more time to complete the working memory and fluency tasks.

*Conclusions:* Few of the studies have investigated the impairment in monitoring, preparatory process, and concept formation, all of which are EF domain. There was only one common result among these studies regarding monitoring, preparatory process, and concept formation, and it shows that the children in these groups struggle more with EF concepts than with typically developing children.

*Relevance to the current work:* Because we are investigating attention in relation to ASD, it is important to note the EF (which attention is a part of) is a higher-order process that is impaired in children with ASD. This could be contributed to poor top-down processing, which is what we want to investigate.

**Objective:** Researchers aimed to characterize the interactions of previously identified regions associated with task-control, initiation, maintenance, and adjustment using resting-state function connectivity fMRI data.

**Methods:** Using resting-state fMRIs researchers, tracked blood oxygen levels in the brain in 74 healthy young adults and compared the signals to each other in relation to goal-directed behavior and initiation.

**Results and Analysis:** Two distinct task control networks were identified. 1. The frontoparietal network that influenced the dorsolateral prefrontal cortex and the intraparietal sulcus which specialized in start-cue and error-related activity which shows these regions are responsible for initiating a task and adapting control on a trial by trial basis. The second network identified included the dorsal anterior cingulate/medial superior frontal cortex, anterior insula/frontal operculum, and anterior prefrontal cortex. These regions likely contribute to sustained attention and goal-directed behavior.

**Conclusions:** The brain possesses distinct networks responsible for initiating and maintaining behaviors.

**Relevance to the current work:** Our study aims to compare the different networks associated with attention, sensory processing, and predictability. The regions identified
by this study contribute to the attentional network and potentially contribute to the predictability network and will be analyzed in our study.

https://doi.org/10.1016/j.ijpsycho.2011.09.017

**Objective:** This review aimed to highlight the results from various studies that explain the neural bases underlying disorders such as ASD. The researchers explain that individuals with ASD struggle with flexibility and prediction. Using the results from the various reviews, they proposed that the dysfunction of predictability may be a result from impaired top-down influence over a variety of sensory and higher-level information processing.

**Methods:** Authors compared several studies that investigated ASD and its associated characteristics in light of the “proactive brain theory which aims to explain symptoms in ASD including resistance to change to a deficit in planning and social interaction.

**Results and Analysis:** Evidence from ERPs and fMRI, ASD participants demonstrated difficulty with flexibility and building predictions.

**Conclusions:** Difficulty with predictions leads to several consequences. If a child is unable to predict this can lead to inflexibility and difficulty with planning (EF functions). It can lead to repetitive and restrictive behaviors and interest in an effort to create predictable events. It may impair an individual’s ability to adapt quickly and result in stressful reactions that create a sense of overstimulation.
Relevance to the current work: This review explains how predictability is a critical component when trying to understand what is occurring in the autistic brain. Our study aims to analyze predictability and how it impacts attention and sensory processing.


Objective: Study aimed to investigate resting-state salience network connection and how neural functioning patterns associate with abnormal brain response to basic sensory input. Researchers looked for sensory processing patterns and their correlation to sensory overresponsivity (a common characteristic of individuals with ASD).

Methods: fMRI data from 61 youth (8-17 years; 28 with ASD and 33 IQ typically developing youth) was analyzed to determine potential correlations between resting-state salience network connectivity and brain response to tactile and auditory stimuli. These results were compared to parent-rated sensory overreactivity symptoms.

Results and Analysis: Sensory over-responsivity in youth with ASD was related to functional connectivity between the SN and brain regions associated with attention and sensory processing (visual, auditory, etc.).

Conclusions: Results support an association between brain connectivity and brain regions associated with primary sensory processing and attention.

Relevance to the current work: Sensory processing and attention are highly correlated. It is important to consider this with individuals with ASD because the amount
they are able to control their attention could influence how they process sensory information.


**Objective:** These authors proposes a theory that sensory over responsivity (SOR) is defined by responding to too much for too long of a time and an inability to habituate input. The authors study examined the role of the amygdala in SOR and how it affected ASD in light of several different studies.

**Results and Analysis:** Results from the various studies show that there is involvement of the amygdala in SOR in ASD and therefore suggest that SOR is related to increased attention, attribution of salience, and/or emotional response to sensory stimuli. Children who have reported higher levels of SOR have greater resting-state function connectivity between the salience network, sensory cortex, and the amygdala. The results reported suggest that there is not amygdala impairment, rather the amygdala is unable to form habituation over time.

**Conclusions:** Research should focus on ASD in relation to attention and regulation systems rather than just simply sensory input. Likely, excitation-to-inhibition theory of sensory processing is related to an amygdala-drive attentional alerting mechanism in relation to SOR.

**Relevance to the current work:** Our study aims to address how attention is related to other salience networks as well as predictability. This review provides a framework of
systems to investigate as well as theories to consider while looking at functional
connectivity between the different brain regions.

Jao Keehn, R. J., Pueschel, E. B., Gao, Y., Jahedi, A., Alemu, K., Carper, R., Fishman, I., &
with sensory abnormalities in autism spectrum disorders. Journal of the American
https://doi.org/10.1016/j.jaac.2020.02.007

Objective: Researchers investigated the functional connectivity between the anterior
insula cortex (AI) and primary somatosensory regions in the brain. They aimed to
investigate the functional connectivity in the autistic brain and how it relates to autism
symptomology.

Methods: fMRI was used to examine resting-state functional connectivity patterns
of salience networks to A and AI to visual regions in children and adolescents diagnosed
with ASD and compared to a matched control group. Data from the fMRI was compared
to behavioral measures.

Results and Analysis: Data showed underconnectivity between the AI and salience
networks as well as atypical visual sensory profiles. Functional connectivity was
positively correlated with behaviors of social motivational responsivity from the
behavioral measures reported by parents.

Conclusions: Reduced functional connectivity between the AI, salience networks,
and visual networks in the ASD group could indicate deficits in selecting salient
information to attend to.
Relevance to the current work: Attention (directed by the AI) is correlated with sensory processing. If the functional connectivity is low, there would be difficulty selecting and attending to salient information.


Objective: The Dorsal Attention Network (DAN) controls selective attention that allows the brain to process information that is relevant and suppress information that is irrelevant. This study aimed to investigate the role of the DAN in the suppression of distractions.

Methods: fMRI data was collected in 24 healthy subjects who participated in selective attention tasks (i.e., selecting numbers while irrelevant distractors were cooccurring).

Results and Analysis: Results showed higher activation levels of the DAN when distractors were present during the tasks as opposed to when they were not present.

Conclusions: The DAN plays a pivotal role in suppressing distractions and directing attention towards a specific goal.

Relevance to the current work: Functional connectivity of the DAN will play an important role in attention, sensory processing, and predictability. If a brain has a low ability to suppress distractions, it will struggle to know what to attend to and the attentional network will be overridden leading to breakdowns.
Objective: This study aimed to explain sensory behaviors in Autism by correlating behavioral measures such as overfocused behavior, difficulty shifting focus (resulting in perseverative preoccupation), and an exceptional memory for self-selected material to sensory overreactivity.

Methods: Data was gathered from 222 parent reports of children with ASD. Parents were asked to complete a sensory questionnaire, report the extent of their child’s memory, list scores for the DSM-V, the Kinsborne Overfocusing Scale, and the Vineland Adaptive Behavior Scale.

Results and Analysis: Data from the surveys were analyzed and considered in relation to overfocused behavior, difficulty shifting focus (resulting in perseverative preoccupation), and an exceptional memory for self-selected material and correlated with sensory overreactivity. A cluster analysis was used. Results confirmed their hypothesis that sensory overreactivity was positively correlated to previously outlined behavioral measures.

Conclusions: They suggest that sensory seeking is compensatory. It moderates arousal when it rises to uncomfortable heights (e.g., sensory overreactivity). However, repetitive movements (linked to sensory input) were also prominent in underreactive, low-functioning participants with ASD.

Relevance to the current work: Sensory processing and behavioral measures are strongly correlated. When considering sensory processing, it is crucial to consider
behavioral measures. The behavioral measure of difficulty in shifting focus could make it difficult for people with ASD to avert their attention from an aversive stimulus, which could cause an overload on the attentional system.


**Objective:** The aim of this article was to review the current literature on sensory processing in Autism.

**Methods:** Authors compared auditory sensory processing, tactile sensory processing, visual sensory processing, low-level multisensory integration, higher-order multisensory integration, attentional shift, and selective attention.

**Results and Analysis:** Authors explained, “Our ability to attend appears to have a limited capacity (i.e. there is a finite quantity of information that can be considered simultaneously), and we, therefore, need to selectively concentrate on one aspect of the environment while ignoring other features to effectively and efficiently process sensory input.” The reported data showed that the ASD brain differs in connectivity when it comes to the various types of processing.

**Conclusions:** As data continues to accumulate, the authors suggest that sensory processing differences are the causes for autistic traits and features such as language delay (auditory processing) and difficulty reading emotions (visual processing).

**Relevance to the current work:** This information is key in understanding the impact attention has on ASD processing. These conclusions illuminate the importance of considering sensory processing, attention, and autistic traits together when researching
the autistic brain. By knowing how these domains function together, we are able to consider autism as a whole rather than its individual characteristics.

https://doi.org/10.1016/j.tics.2011.08.003

**Objective:** Review examines recent developments which are contributing to the current paradigm shift in how researchers look at psychopathology.

**Methods:** The author summarizes the current findings, both conceptual and methodological, and provides novel insights into dysfunctional brain structure.

**Results and Analysis:** Large-scale brain networks play an important role in how ASD is understood, particularly the AI is an integral hub that mediates the interactions between the other large-scale networks involved in externally orienting attention and self related mental process.

**Conclusions:** The author proposes a triple network model which includes the central executive network, the DMN, and the Salience network (SN). These discoveries point support a model in which the SN has an integral role in saliency detection, attentional capture enhanced by error signals and dynamic cognitive control.

**Relevance to the current work:** Our study aims to identify how salience networks and attention are intertwined and affect predictability and function in the world. This model supports our current theory that attention is an integral part of sensory processing.

https://doi.org/10.1038/nrn.2017.112
**Objective:** Researchers in this study argue that sensory traits have important implications for developing brains. They considered how sensory processing difficulties may relate to other domains in behavior associated with ASD.

**Methods:** Studies relating to ASD and sensory processing were reviewed. Categories of sensory processing included visual detection, temporal synthesis of sensory signals, tactile perception, auditory perception, and multisensory binding.

**Results and Analysis:** Visual detection: individuals with ASD may have superior detection/discrimination thresholds that aid in their ability to focus on details. Temporal synthesis of sensory signals: Research suggests that processing of local sensory signals is slower, while some suggest this is due to over-connectivity. Tactile perception: Studies report mixed perception of high, low, and no difference. Auditory perception: Individuals with ASD showed delayed evoked neural responses to auditory tones which suggest impairment in higher-order control.

**Conclusions:** Difficulties with sensory input do not seem to stem from individual primary sensory systems. Difficulties appear to stem from impairments in higher-order processing.

**Relevance to the current work:** Our study aims to determine how higher-order systems are impacting sensory processing and predictability. By understanding that each sensory system contributes different factors to sensory integration as a whole, it helps us to see sensory processing as a more top-down experience rather than bottom-up.

Objective: The aim of this article was to review current ASD data in the frame of the Predictive Impairment in Autism theory (PIA).

Methods: Authors reviewed and analyzed current data in relation to difficulties with dynamic objects, understanding humor, insistence on sameness, sensory hypersensitivities, islands of proficiency, and difficulty with theory of mind while considering PIA implications in these areas.

Results and Analysis: PIA could affect the outlined categories in many ways. For example, a child could participate in self-stimulating behaviors when they feel overwhelmed to provide some element of predictability to their mind. However, other factors could be contributing to the difficulty in these areas.

Conclusions: Using PIA to understand individuals with Autism could bring some unanimity to a group that is often characterized as too heterogeneous to understand. It could explain several traits at one time, not just one trait.

Relevance to the current work: An individual’s ability to predict would affect what receives attention. If a child cannot predict what sensory input is going to happen next, their attention would become overwhelmed and unable to attend.


Objective: Researchers investigated the role of goal-directed actions vs. habit formation.
Methods: They studied habit formation when rats were reinforced for pressing a lever while a discriminative stimulus cooccurred. During the experiment, different lengths of aversion were used to determine habit compared to goal-directed behavior.

Results and Analysis: Results found that true habits were formed when the reinforcer became predictable. When the rat knew a stimulus was coming at a certain time interval, it knew to press the lever before it occurred. It was able to predict the time when a stimulus was about to take place.

Conclusions: This contradicts previous theories that repeated reinforcement creates a habit (as in the law of effect). They concluded, “Organisms pay less attention to their own behavior, as they pay less attention to signals associated with predicted reinforcers in Pavolian conditioning.”

Relevance to the current work: Predictability greatly impacts where attentional resources are allocated. In order to prevent an attentional system from becoming overwhelmed, predictability helps the DAN to suppress unimportant external stimuli.


Objective: Researchers aimed to describe patterns of sensory processing found in children with ASD.

Methods: 400 children with ASD with a wide range of symptoms and severity participated in the study. They were matched with age and gender to the current prevalence statistics. All participants completed the Short Sensory Profile. An
exploratory factor analysis was completed to identify patterns of sensory processing of individuals with ASD.

*Results and Analysis:* Data was categorized into 6 factors which included: low energy/weak, tactile and movement, smell/taste and auditory and visual sensitivity along with sensory seeking and hypo-responsivity factors.

*Conclusions:* Researchers concluded that these 6 factors are the strongest contributors to sensory processing in ASD. By targeting these areas, professionals can have a more thorough analysis and treatment.

*Relevance to the current work:* The SSP can be a valid measure for determining sensory processing symptoms in individuals with ASD. As we determine what behavioral and sensory measures to correlate to brain activity, we want to use a valid measure to capture sensory measures.

https://doi.org/10.1001/jamapsychiatry.2013.104

*Objective:* Researchers aimed to examine the connectivity of large-scale brain networks and determine whether the specific function of the networks can distinguish children with ASD from typically developing children and indicate the severity of ASD symptoms.

*Methods:* 20 children aged 7-12 years old with ASD were age, gender, and IQ matched with 20 typically developing children in this study. Specific brain networks between the two groups were compared using fMRI data.
Results and Analysis: Researchers found that there was higher functional connectivity between the large-scale brain networks in children with ASD than the TD group. The hyperconnectivity included salience, default mode, frontotemporal, motor, and visual networks. Using the data maps, children with ASDS could be classified with 75% sensitivity and 80% specificity, with the salience network being the most accurate indicator. There was not strong enough sensitivity to indicate behaviors or symptom severity in the ASD group.

Conclusions: Salience network hyperconnectivity may be an indicator of ASD in a child. Biomarkers may help indicate a diagnosis and predict severity of symptoms.

Relevance to the current work: Our study aims to investigate the functional connectivity of the salience network to other higher-order systems in the brain. This study shows that there is a relation to hyperconnectivity in the brain and in ASD. Our study will build on this and attempt to correlate behavioral data with fMRI data.


Objective: Author aims to explain that deficits in executive function (EF), theory of mind (ToM), and central coherence in people with ASD can all be understood as a consequence of an inability to makes and test predictions and errors that result from incorrect predictions cause an override of their cognitive system resulting in difficulties with EF, ToM, and central coherence.
Methods: Authors review current research and how attention and EF, perceptual processing, social functioning, sensorimotor abilities, multisensory integration all are affected when predictive coding is impaired.

Results and Analysis: Focusing on attention, results from various studies suggest that when prediction and variability are key components of a task, children with ASD struggle more than their peers, but when a task is clearly predictable, children with ASD do not exhibit much deviation from their typically developing peers.

Conclusions: There may be more coherence in the ASD symptom clusters than previous authors have assumed because prediction plays a role in all of the symptoms related to ASD.

Relevance to current work: Using this model, we can assume that attention and predictability are essential in understanding the sensory behaviors in ASD. As predictive ability increases, attentional resources are spared and can be allocated to other avenues.


https://doi.org/10.1044/1092-4388(2011/10-0029)

Objective: Researchers aimed to examine the patterns of sensory responsiveness in terms of hyperresponsiveness, hyporesponsiveness, and sensory seeking and how they may account for the variability in social-communicative symptoms in ASD, such as language, social skills, and conversational development in relation to children with developmental disabilities (DD).
Methods: Seventy two autistic children and 44 DD children participated in a protocol that measured sensory response patterns, social communication, language, and autistic traits.

Results and Analysis: Researchers found that hyporesponsiveness was positively correlated with social-communicative symptom severity with no group difference. Hyperresponsiveness had no significant association with social-communicative severity. For sensory seeking, there was a positive association for autistic children, but no difference for the DD group. Hyporesponsiveness and sensory seeking was negatively associated with language and social skills in both groups.

Conclusions: Sensory processing may play a role in the pathogenesis of ASD as well the rate of acquisition of language, social, and communication skills.

Relevance to the current work: This study supports one of the foundational tenets of the study, which explains that children with altered sensory processing may experience difficulties with language, social, and communication skill development.
APPENDIX B

Consent/Institutional Review Board Approval Letter

Memorandum

To: Garrett Cardon
Department: BYU - EDUC - Communications Disorders
From: Sandee Aina, MPA, HRPP Associate Director
      Wayne Larsen, MAcc, IRB Administrator
      Bob Ridge, Ph.D., IRB Chair
Date: September 23, 2022
IRB#: IRB2022-339
Title: Sensory processing, prediction, and attention in autistic children

Brigham Young University's IRB has approved the research study referenced in the subject heading as expedited level, categories 4 and 7. The approval period is from 09/23/2022 to 09/22/2023. Thereafter, continued approval is contingent upon the submission of a continuing review request that must be reviewed and approved by the IRB prior to the expiration date of the study. Please reference your assigned IRB identification number in any correspondence with the IRB.

Continued approval is conditional upon your compliance with the following requirements:

1. A copy of the approved informed consent statement and associated recruiting documents (if applicable) can be accessed in iRIS. No other consent statement should be used. Each research subject must be offered a copy or provided a way to access the consent statement.
2. Any modifications to the approved protocol must be submitted, reviewed, and approved by the IRB before modifications are incorporated into the study.
3. All recruiting tools must be submitted and approved by the IRB prior to use.
4. All data, as well as the investigator's copies of the signed consent forms, must be retained for a period of at least three years following the termination of the study.
5. In addition, serious adverse events must be reported to the IRB immediately, with a written report by the PI within 24 hours of the PI's becoming aware of the event. Serious adverse events are (1) the death of a research participant; or (2) serious injury to a research participant.
6. All other non-serious unanticipated problems should be reported to the IRB within 2 weeks of the first awareness of the problem by the PI. Prompt reporting is important, as unanticipated problems often require some modification of study procedures, protocols, and/or informed consent processes. Such modifications require the review and approval of the IRB.

If it is necessary to continue the study beyond the expiration date, you will need to complete the continuing review form and attach associated documents to renew the study. Continuing review documents should be submitted no later than two months before 09/22/2023. More information regarding the renewal process and lapses in approval can be found on the IRB website FAQ #8.

There is no grace period beyond the expiration date. In order to avoid lapses in approval of your research and the possible suspension of subject enrollment, please look for notifications prompting you to initiate a continuing review request. You will receive two prompts from iRIS to renew this protocol, the IRB requires time to review your documents so please be aware that requests made close to or on the expiration date will not be accepted.
Phase 1 Consent Form

Implied Consent

Your child is being invited to participate in a research study of sensory and attention functioning in children.

Their participation in this study will require the completion of the attached survey. This should take between 30-45 minutes of your time. Your participation will be anonymous, and you will not be contacted again in the future, unless you wish to participate in future phases of the study. This survey involves minimal risk to you. The benefits, however, may impact society by helping increase knowledge about real-world aspects of sensory and attention function and related behaviors in people between the ages of 8-11.

You will be asked at the end of the survey if you’d like to participate in future phases of the study, at which time you’ll be provided a place to enter your contact information. Participants who qualify for phase 2 of the study will be asked to schedule a research appointment and complete two simple tasks with one of our research team members. Those who elect to participate in this part of the study will be compensated for their time. Please complete this survey on behalf of your child.

You do not have to be in this study if you do not want to be. You do not have to answer any question that you do not want to answer for any reason. We will be happy to answer any questions you have about this study. If you have further questions about this project or if you have a research-related problem you may contact our research coordinator, Courtney Hunter, at court115@student.byu.edu or Principal Investigator, Garrett Cardon, at garrett.cardon@byu.edu.

If you have any questions about your rights as a research participant you may contact the IRB Administrator at A-285 ASB, Brigham Young University, Provo, UT 84602; irb@byu.edu; (801) 422-1461. The IRB is a group of people who review research studies to protect the rights and welfare of research participants.

The completion of this survey implies your consent to participate. If you choose to participate, please complete the attached survey. Thank you!
Phase 2 Consent Form

Parental Permission for a Minor

Title of the Research Study: Sensory processing, prediction, and attention in autistic children
Principal Investigator: Garrett Cardon
IRB ID#: IRB20222-339

Introduction
This research study is being conducted by Professor Garrett Cardon and research staff at Brigham Young University to determine the relationships between attention and understanding of sound and other sensory signals in autistic individuals. Your child was invited to participate because they are between the ages of 8-11 and have a confirmed diagnosis of autism. They must have no history of epilepsy, head injury, neurological disorders, Fragile X Syndrome, or traumatic brain injuries.

Procedures
If you consent for them to participate in this study, your child will be asked to do the following:

Answer questions about attention and how they deal with and understand sounds, sights, smells, tastes, and other sensory inputs.

- Participate in a short computer task about attention
- Participate in an eye-tracking experiment, in which they will be seated in front of a computer screen and we will record their eye movements in response to simple stimuli presented on the screen.
- All research activities will take place at the John Taylor Building on the BYU campus in the principal investigator’s laboratory. We anticipate that your research appointment will last approximately 1 hour. You will be given as much time as you need to familiarize yourself with the building, room, and personnel involved in the study, ask questions, as well as breaks during the research activities.

Risks/Discomforts
There are no known significant risks involved in this research study, but there is always a possibility a small, unknown risk may exist to this or any test (i.e., discomfort related to questions or activities). However, we believe that we have taken reasonable precautions to ensure your safety. None of the questions we will ask or procedures related to the study are overtly distressing or meant to cause discomfort or offense. If you have any questions about your safety in this experiment, please feel free to discuss them with us at any time. There is a risk that people outside of the research team will see your research information. We will do all that we can to protect your information.

Benefits
There will be no direct benefits to you. However, this study is designed for the researcher to learn more about the social interaction styles of young adults. This study is not designed to treat any illness or to improve your health. We will not release any clinically un-interpretable results.
Confidentiality
Brigham Young University and the research team have rules to protect information about you. Federal and state laws including the Health Insurance Portability and Accountability Act (HIPAA) also protect your privacy. This part of the consent form tells you what information about you may be collected in this study and who might see or use it. We cannot do this study without your permission to see, use and give out your information. You do not have to give us this permission. If you do not, then you may not join this study.

We will see, use, and disclose your information only as described in this form. We will do everything we can to keep your records a secret. It cannot be guaranteed.

The use and disclosure of your information has no time limit. Data will always be stored on password protected computers, in filing cabinets in locked offices on the BYU campus, and/or with a secure cloud storage service (Box). You can cancel your permission to use and disclose your information at any time by writing to the study’s Primary Investigator, at the name and address listed below. If you do cancel your permission to use and disclose your information, your part in this study will end and no further information about you will be collected. Your cancellation would not affect information already collected in this study.

Garrett Cardon
Brigham Young University
Department of Communication Disorders
1190 N 900 E 130 TLRB
Provo, UT 84604

Both the research records that identify you and the consent form signed by you may be looked at by others who have a legal right to see that information. The participant’s name will immediately be replaced with an identifying code in order to protect your confidentiality. Other identifying information will only be used to make calculations (such as chronological age) or contact you, if you provide permission (see below), but will never be used in any publication, presentation, or other form of communication with anyone other than you.

Federal offices such as the Food and Drug Administration (FDA) that protect research subjects like you. People at the Brigham Young University Institutional Review Board (BYUIRB), the study investigator and the rest of the study team.

Information about you that will be seen, collected, used, and disclosed in this study:
- Name and Demographic Information (age, sex, ethnicity, address, phone number, etc.)
- Research Visit and Research Test records
- Diagnoses that have been given to you or your close family members, such as anxiety, Autism Spectrum Disorder (ASD), or Attention Deficit Hyperactivity Disorder (ADHD)

What happens to Data that is collected in this study?
The scientists on the research team work to discover new information about autism. The data collected from you during this study is important to this study and to future research. If you join this study:
- Both the investigators and any sponsor of this research may study your data
- Any product or idea created by the researchers working on this study will not belong to you.
• There is no plan for you to receive any financial benefit from the creation, use or sale of such a product or idea.

**Data Sharing**
We will keep the information we collect about you during this research study for analysis and for potential use in future research projects. If the study data contain information that directly identifies subjects: Your name and other information that can directly identify you will be stored securely and separately from the rest of the research information we collect from you. De-identified data from this study may be shared with the research community, with journals in which study results are published, and with databases and data repositories used for research. We will remove or code any personal information that could directly identify you before the study data are shared. Despite these measures, we cannot guarantee anonymity of your personal data.

**Compensation**
You will receive $10/hour (or any portion thereof) in the form of Visa gift cards for your participation in this study. There will be no monetary cost to you for participating in this study.

**Participation**
Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without any risk to you whatsoever.

**Questions about the Research**
If you have questions, concerns, or complaints, you can contact the Principal Investigator, Garrett Cardon, 303-241-6666, garrett.cardon@byu.edu or study coordinator, Courtney Hunter, court115@student.byu.edu

**Questions about Your Rights as Research Participants**
If you have questions regarding your rights as a research participant contact Human Research Protections Program by phone at (801) 422-1461; or by email: BYU.HRPP@byu.edu.

**Participation**
Participation in this research study is voluntary. You are free to decline to have your child participate in this research study. You may withdraw your child's participation at any point without affecting his/her study benefits.

Child's Name: __________________________________________

Parent Name: ___________________ Signature: _______________ Date: __________