RELATIONSHIPS BETWEEN EYE TRACKING AND FUNCTIONAL OUTCOMES IN AUTISM SPECTRUM DISORDER

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Abstract

Autism spectrum disorder (ASD) is marked by social dysfunction with a wide range of impairment. Deficits in visual attention have been identified as a key mechanism involved in observed social difficulties. Children with ASD typically do not attend to pertinent areas when viewing social interactions, and therefore do not obtain crucial information for social learning. Over the course of development, this leads to compounding difficulty in acquiring and learning from social situations. Eye tracking studies provide a window into the child's visual attention that allows researchers to precisely identify what is being attended to. This dissertation includes three studies that examine visual attention in children with ASD through eye tracking studies. In the first study, I use a combination of eye tracking and a simple language measure to discriminate between ASD and related disorders. Linear discriminant analyses were used to demonstrate that eye tracking and language variables were able to differentiate groups at a comparable level to standard measures of autism. The second study uses eye tracking variables (i.e., proportion of time that attention is focused on the eyes) to longitudinally predict specific areas of social dysfunction. That is, it is proposed that deficits in visual attention mechanistically lead to social deficits, which results in observed behaviors that typify ASD which are most accurately predicted by eye tracking variables early in development (compared to non-core symptoms of ASD). Consistently, the variables best predicted by eye tracking at an early age were those at the core of ASD (i.e., eye contact, gaze integration, joint attention). Finally, in the third study, eye tracking variables are used to understand more nuanced social behaviour. Specifically, according to the Social Information Processing model, children with ASD first have difficulty encoding information (operationalized as eye tracking variables in this study), which leads to difficulties with interpretation (i.e., children's understanding of the situation). Generally, the pattern of results was consistent: those children, typically developing or with ASD, who

attended the least to informative areas formed the most problematic interpretations. These three studies highlight the impact of eye tracking on social dysfunction in ASD.

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Glossary of Abbreviations

ADHD – Attention deficit/hyperactivity disorder
ADI-R – Autism Diagnostic Interview - Revised
ADOS – Autism Diagnostic Observation Schedule
AOI – Areas of interest
ASD – Autism spectrum disorder
HR – High-risk (for autism)
ID – Intellectual disability
LD – Language delay
LR – Low-risk (for autism)
NDBI – Naturalistic developmental behavioural intervention
SIP – Social Information Processing
TD - Typically developing

Chapter 1: General Introduction

Autism spectrum disorder (ASD) is characterized by marked impairments in social communication and restricted and repetitive behaviours or interests (American Psychiatric Association [APA], 2013). The range of social dysfunction associated with ASD is large. Some people with ASD are able to make friendships and develop romantic relationships, while others struggle to communicate and use basic language (Lewis et al., 2006). Previously, language difficulties were required for a diagnosis of autistic disorder, though many children with intact language abilities are now diagnosed as being on the spectrum. Those children previously may have been identified as having Asperger's Syndrome, which is now subsumed under the autism spectrum disorder diagnosis (Smith et al., 2015). In order to understand the range of social symptomology seen in ASD, core mechanisms that underlie these social symptoms have been studied by researchers. One of those core mechanisms, impaired attention to social stimuli, as measured by eye tracking studies, has been identified as an area of marked difficulty in ASD. However, the specific impact of impaired attention on the development of the child is not well understood.

In order to understand visual attention (i.e., what individuals are looking at and orienting their attention to) in children with ASD, researchers have turned to eye tracking studies as a key paradigm. Researchers have long noted that children with ASD do not show the same eye movement patterns when watching social scenes compared with typically developing (TD) controls (e.g., Neumann et al., 2006). For example, Klin and colleagues (2002) reported that adolescents with ASD had significantly reduced fixation time on the eyes of individuals in naturalistic scenes compared to TD children. In addition, within the ASD group, fixation on the mouth predicted positive social outcome, while fixation on other objects predicted increased impairment. In order to fully elucidate the link between visual or social attention and social impairment, I will first turn to a discussion of the nature of social difficulties observed in ASD.

1.1 Social Impairment in ASD

ASD is by definition a disorder of social impairment; specifically, social communication must be disrupted for a diagnosis of ASD (APA, 2013). In terms of observable behaviour, clinicians often look for poorly integrated eye contact, difficulties with joint attention, language abnormalities and poor social reciprocity (Lord et al., 2000). Some social difficulty may be seen soon after birth (e.g., abnormal smiling; Zwaigenbaum et al., 2007); however, typically social difficulties emerge around 12 months of age or later. Once they emerge, a striking range of social difficulties may become apparent including impairments in visual attention (Ozonoff et al.,2008), in shifting attention (Zwaigenbaum et al., 2005), in responding to social overtures (Wu et al., 2010) and in nonverbal communication (Mitchell et al., 2006). Zwaigenbaum and colleagues (2005) reported that, while none of the children in their study exhibited all the social risk factors of ASD at 12 months, if several of these factors are present, children are far more likely to meet criteria for ASD later in life. The other diagnostic criterion of ASD is the presence of repetitive behaviours and/or severely restricted interests (APA, 2013). However, these latter difficulties are not typically observed very early in life (Bryson et al., 2007).

Despite some studies reporting differences in social attention between typically developing children and those with ASD very early in life (e.g., the first few months after birth),the majority of these studies rely on retrospective data (Tager-Flusberg, 2010). Prospective studies involving infants at risk have shown no reliable differences in social attention between TD children and children who later go on to develop ASD, in the first 6 months (Rogers, 2009). Some have even suggested that children with ASD show increased social communicative behaviours in that period of time compared to TD children (Ozonoff et al.,2010). These findings have led researchers to conclude that ASD symptomatology gradually develops as a result of altered brain development resulting from a variety of causes (e.g., genetic dispositions or epilepsy; Tager-Flusberg, 2010). Such patterns of behavioural findings correspond to patterns observed through brain imaging whereby at age 14 months, children are showing functional differences in the brain (Orekhova et al., 2014), for example hyper- connectivity on brain EEG. As children with ASD continue to develop, their social difficulties evolve into a host of behavioural characteristics such as difficulty with social orienting, joint attention, and the aforementioned language difficulties (Burnside et al., 2017; Franchini et al., 2017).

Social attention is a key area of impairment in ASD. Dawson and colleagues (2004) have identified social orienting and joint attention as important areas of deficits in children with ASD that distinguish them from TD children. In addition, in this study these areas were predictive of the children's language ability. Social orienting and joint attention deficits are reliably present by 3 to 4 years of age (e.g., Franchini et al., 2017). This complex developmental trajectory may begin with little to no impairment at birth in many children with ASD, to reliable difficulties with social attention in the first few years of life, to severely impaired social communication at the time of diagnosis, which demands considerable attention. Many researchers have recently turned to children's abnormal pattern of viewing visual information as a window to study this crucial developmental trend. Eye-tracking offers a powerful glimpse into this issue.

1.2 Eye Tracking and Social Impairment

Dawson and colleagues (2004) sought to identify predictive patterns for common deficits seen in ASD, especially for the social impairment described above. Specifically, they wanted to identify social difficulties that predicted language impairment. They constructed models that identified attention to distress and social orienting as indirect predictors of language, both having their effect moderated by joint attention. What stimuli the children focused on, and their ability to orient to social stimuli, had downstream effects on language. That is, children who showed early orienting difficulties had later difficulties with language. The Social Information Processing (SIP) model developed by Crick and Dodge (1994) suggested that TD children first encode information, then interpret this information. The next three steps in their model involve identifying goals and possible actions, then generating solutions with the final step beginning to act out a behaviour. The purpose of their model was to outline how children process information and act out behaviours in line with this processing. A visual depiction of this model can be found in this paper: https://doi.org/10.1037/0033-2909.115.1.74 (Crick & Dodge, 1994). As this model applies to language generation in ASD, key research (Dawson et al., 2004; Klin & Jones, 2002) suggests that children with ASD are not encoding social information properly. Over time, they fail to receive the appropriate social feedback and miss important social clues by failing to establish joint attention. Eventually, this cascade leads to the final steps in the Crick and Dodge model where children with ASD select and execute socially inappropriate or inadequate behaviours.

The eye tracking paradigm, such as that described in the Klin and Jones (2002) study, provides crucial information on what is being encoded by children with ASD. In the Klin and Jones (2002), as well as the other studies described in the dissertation, eye tracking refers to the method of capturing eye gaze patterns while people are viewing a computer screen. These eye movements are often captured by areas of interest on an image or video that allow the researcher to operationalize visual attention. That is, if eye movements are recorded within the area of interest of the mouth, the participant has “attended” to the mouth. Klin and Jones presented children with ASD scenes from a movie that involved conversation, gesturing and background items. Children with ASD, compared with TD children, paid much less attention to useful social information (i.e., the mouth or eyes of the actors or their gestures) and instead focused on items in the background.

The process for how attention to social stimuli develops is well known in typical development. Human newborns are responsive to direct gaze from their parents within the first days of life. This may be regulated via a sub-cortical system which precedes typical face processing later in life (Dimitriou et al., 2016). Johnson (2011) further surmised that, as infants continue to develop, different brain regions begin responding in tandem and further specialize by a process he calls “interactive specialization”. Indeed, Scherf and colleagues (2007) have with typically developing children demonstrated increased specialization in the visual processing of different stimuli with age. In their study, adults and adolescents demonstrated far more specialization in processing faces, objects and buildings compared with young children. That is, adults were more adept at detecting subtle differences in these stimuli than young children. Johnson (2015) concluded that as infants increasingly attend to particular information, their brains become increasingly specialized to process that type of information. For children with ASD, their brains appear to become increasingly specialized to process information other than faces or other socially relevant stimuli. For example, the fusiform face area which has classically been identified as showing increased activation when processing familiar faces in typical development (Kanwisher et al., 1997),instead in some cases shows activation in youth with ASD when processing their restricted interests (Foss-Fieg et al., 2016). In one case study, a child showed increased activation when responding to his favourite Digimon (a cartoon monster character; Grelotti et al., 2005). So, while children who develop typically may see and differentiate between many faces, children with special interests may instead have these areas of the brain respond to visual stimuli that are of interest to them.

1.3 Suggested Mechanisms whereby Eye Gaze may Affect Social Development

The mechanism by which the ASD brain engages particularly with non-social information is not well understood. Researchers have noted that high functioning children with ASD are often able to perform well on experimental social tasks (e.g., Dahlgren & Trillingsgaard, 1996), but struggle in many real-life social situations. To explain these differences, researchers have long posited that children with ASD have difficulty generalizing the skills learned (particularly cognitive and social skills) to other environments (e.g., Bebko et al., 2020; Ozonoff & Miller, 1995). For example, in the study by Bebko and colleagues (2020), children with ASD generally demonstrated an ability to learn memory strategies, but did not readily apply this learning to situations other than the one that they were trained in. Klin and colleagues (2003) suggested that individuals with ASD make sense of their world by using what they call the “enactive mind”. That is, rather than developmentally acquiring competencies that are regular and predictable as a rule, the child’s mind is differentially drawn to things in the environment. Differently salient stimuli in the child’s environment leave “cognitive traces” that continue to shape the development of the mind. Put simply, children attend to different stimuli based on genetic and environmental factors that shape the child’s mind throughout development. Species-specific gradients for attentional demands are present in all of the stimuli in our environments. A basic illustration is that, for example, a child who is lactose intolerant (most commonly a genetic trait) and has a history of negative interactions with ice cream (environmental experience) is unlikely to experience the same attentional demand from ice cream as many other children.

Klin and colleagues (2015) further suggested that two such demands are present in the typical development of children and are areas needing further study to understand the developmental difficulties seen in ASD. The authors noted that many studies have reported that children with ASD show difficulty in two areas: preferential attention to biological movement (referring to movement that approximates styles and patterns inherent in living creatures; e.g., Pierce et al., 2016) and preferential attention to people's eyes (e.g., Hironori et al., 2014; Jones et al., 2008). Rather than being the cause of ASD, Klin et al. (2015) suggested that differences in the salience of these stimuli represent the unfolding of social difficulty in ASD. That is, the attention focus of children with ASD may not prioritize social stimuli at a rate comparable to peers. Due to this, they lose valuable social experiences that accumulate in frequency and importance. Over time, their brains specialize in processing the types of stimuli that they have prioritized viewing or developed interest in, resulting in the sometimes profound, sometimes subtle social difficulties and differences observed over the spectrum of ASD.

This hypothesis has profound implications. First, there are the myriad of conditions that have long been associated with ASD (e.g., epilepsy, intellectual disability, attention deficit hyperactivity disorder). Researchers have spent considerable time trying to understand the causal pathways between other neurological conditions and ASD (for a review, see Baumer &

Sahin, 2016). In addition to the disorders named above, many other comorbidities have been associated with ASD. Johnson (2015) suggested that core to the ASD brain is diffuse brain pathology affecting multiple regions of the brain. Baumer and Sahin (2016) also concluded that the current research is trending in the direction of early synaptic plasticity that leads to distributed difficulties and disordered neural networks that develop behaviourally into ASD and neurologically (sometimes)into the other conditions described above.

Therefore, diminished attention to biological motion and to face areas relevant for social interaction (e.g., eyes or mouth) are possibly two foundational phenotypic difficulties that lead to the progressive accumulation of non-social experiences or impaired social experiences. Consistent with this theory, multiple groups of researchers have identified that toddlers with a propensity to attend to geometric motion over biological motion develop ASD at a higher frequency than children who do not show this propensity (Annaz et al., 2012; Pierce et al., 2016).

1.4 ASD Classification with Eye Gaze

The potential of monitoring eye gaze with this population includes understanding general developmental profiles, like diagnoses, as well as specific deficits. An emerging possibility in the diagnosis of ASD is the use of eye tracking measures as a screener or part of the diagnostic toolkit in identification of ASD. Eye tracking studies typically involve some apparatus that records children's eye movements as they are presented various stimuli on a computer screen (e.g., Klin et al., 2002). This procedure can allow researchers to identify different areas of interest (AOI) that children attend to. Current gold standard measures in ASD diagnosis include the Autism Diagnostic Observation Schedule – Second Edition (ADOS-2) and the Autism Diagnostic Inventory – Revised (ADI-R), which show good sensitivity and specificity (Zwaigenbaum & Penner, 2018). However, both measures have drawbacks. Foremost among them is the significant material and monetary investment, in addition to the considerable training required to reliably administer these instruments (Lai et al., 2014). Therefore, researchers and clinicians are examining other indicators of ASD to aid with the diagnosis.

The idea of eye tracking in screening or diagnosing ASD is not new (Klin et al., 2002; Zwaigenbaum et al., 2005). Since these studies were first published, a variety of research labs have used eye tracking for the purpose of aiding in the diagnosis of ASD. Wan and colleagues (2019) found good classification accuracy (~85%) using brief eye tracking trials compared with expert diagnosis. These experts were not using the ADOS or ADI-R, primarily due to the constraints mentioned above. That is, in China where the study was conducted, the ADOS and ADI-R are not widely available due to constraints in clinician training and resources, accordingto the authors of the study. Other studies in China using eye tracking have reported similar results using expert diagnoses as well (Liu et al., 2016).

Researchers are also seeking to develop eye tracking algorithms that may help to identify ASD (e.g., Vargas-Cuentas et al., 2017). Another popular methodology is to create an ASD risk index based on eye tracking at early ages (Frazier et al., 2016). Indeed, Jones and Klin (2013) have demonstrated that eye gaze early in life can predict ASD severity later in life, in this instance better than early life ASD severity itself. However, much research and clarification of the exact type of eye tracking trials that are most useful for discriminating between ASD and TD are required. Researchers have demonstrated that children with ASD show many differences in viewing patterns based on the type of trial and its social or linguistic content (Alli, 2016; Bebko et al., 2006; Stevenson et al., 2017).

1.5 Specific Deficits Associated with Eye Tracking

In addition to diagnostic and screening use in ASD, eye tracking may be beneficial in contributing to the identification of mechanisms for specific deficits seen in ASD. Eye tracking (which captures attention to social stimuli as recorded by eye movements) may offer a window into developmental mechanisms for the emergence of deficits seen in ASD (as proposed by Jones& Klin, 2013). It stands to reason that there are specific behavioural sequelae most affected by the difficulty accruing appropriate information. These sequelae should then be reflected in observable differences in ASD from typically developing children. Researchers are beginning to study these areas. In some cases, eye tracking is used to assess preferential looking (Bebko et al., 2006) and receptive vocabulary (Brady et al., 2014). Others have also noted that decreased looking time in particular areas is associated with reduced reading comprehension (Asberg Johnels et al., 2013), word processing accuracy (Chita-Tegmark et al., 2015) and referential word learning (Akechi et al., 2010) in children with ASD. Given the strong links between language development and the severity of ASD, the mechanisms underlying these language difficulties are crucial to understand (Bavin et al., 2014).

Social development in ASD is a complex phenomenon. Researchers have identified core social attentional deficits in young children who later develop autism. These deficits emerge as children begin to engage ineffectively with the social world (Jones & Klin, 2013). Recent developments in ASD research have highlighted cascading developmental consequences of attending to non- social information (Klin et al., 2015). Ranging from language development to many of the recognizable behaviours associated with ASD (e.g., poor eye contact), a developmental understanding of ASD must consider the effect of these difficulties engaging with the social world on concrete, defined and observable areas of deficit. Focusing on eye tracking offers a crucial opportunity to observe the patterns with which children with ASD understand their world. In this dissertation, I examine these ideas over three studies that will add significantly to our understanding of the relationship between attentional capabilities (measured through eye tracking) and social development in ASD. Each of these studies will be described below.

Chapter 2: Study 1

2.1 Introduction

Autism Spectrum Disorder (ASD) is a developmental disorder resulting in social communication difficulties and repetitive behaviours and/or restricted interests (APA, 2013). Diagnosis of ASD is a complicated process. A central factor in this is that children who are diagnosed with ASD often do not show the characteristic deficits before the first year of life (e.g., Ozonoff et al., 2010; Rogers, 2009). However, differences in social communication become progressively apparent after this period and begin with key areas of social development, namely social orienting, joint attention, and language difficulties (Dawson et al., 2004; Franchini et al., 2017). Therefore, it stands to reason that measures that assess these key areas of social development may be powerful in identifying children who are not developing typically, and might be on the autism spectrum.

The ADOS-2, a "gold standard" measure of ASD assessment, incorporates an evaluation of joint attention with the examiner, as well as orienting to where the examiner directs (Lord et al., 2012). However, standard (and gold standard) measures of ASD are often training- and cost-intensive and difficult to mobilize (i.e., they are not often used in countries outside of North America; Wan et al., 2019). To address the issues of cost and resource, this study examines the alternative of eye tracking as a tool to understand social development in children. Eye tracking provides a window into the attentional world of the child in regard to both orienting and attention. Eye tracking allows for researchers and clinicians to examine what children with ASD orient to, including in regard to social information, and what aspects are engaging or interesting for them, and thus more likely to be attended to in the future. In this study, I will examine the information gained by using eye tracking together with simple behavioural measures, the combination of which could provide a simple screening measure particularly when other diagnostic resources are unavailable.

2.1.1 Overview of ASD "Gold Standard" Measures

Ultimately, the ASD diagnosis that leads to the most stability over time occurs when conducting an assessment involving a multi-disciplinary team (MDT; Woolfendon et al., 2012). The systematic review by Woolfendon and colleagues (2012), using information available up until 2012, identified that the most comprehensive MDT diagnoses that lead to the greatest stability are time-intensive and resource-intensive. Despite this, researchers have noted in reviews that the true classification rates (based on diagnoses that remain accurate at follow-up) of even the best methods fall somewhere between 80 and 90% accuracy (Falkmer et al., 2013; Woolfendon et al., 2012). Therefore, researchers have identified that the combination of the two best instruments for approximating the success of the MDT are the ADOS and the ADI-R, with Falkmer and colleagues (2013) rating the ADOS and the ADI-R together as of comparable accuracy to an MDT in their review.

These measures have come to be considered "gold standards" (e.g., Wan et al., 2019). Other than strong statistical reliability of diagnosis, they both share certain features that promote success. The ADOS is used to assess a wide range of behaviours that are elicited using carefully designed tasks and activities with the child directly (Lord et al., 2012). In addition to core features of ASD (e.g., issues with joint attention, eye contact, repetitive behaviours, and language), it surveys a variety of other behaviours that are closely related to ASD, including gesture use, echolalia, creativity, conversational skills, etc. Further, it has developmentally appropriate modules to properly assess these behaviours.

The ADI-R, in contrast, is an extensive parent interview (Lord et al., 1994). Autism, as a disorder of development, requires an in-depth understanding of a child's developmental history, which the ADOS does not assess. In contrast, the ADI-R has many specific and general prompts for the caregiver of all the main areas that are related to ASD in order to fully understand the impact the autism symptoms may or may not have had in development. Together, these measures help the clinician to understand both the current behaviours, and the development of the child being queried for ASD.

2.1.2 Issues with Gold Standards

The gold standard measures of MDT, the ADOS and the ADI-R carry with them a series of problems in addition to their many strengths. In many situations, these problems are prohibitive of their use (Vargas-Cuentas et al., 2017). Primarily, the issue is one of resource. An MDT assessing the developmental, language, and medical concerns of the child could require several trained clinicians, spending hours with the child in order to provide a diagnosis. With the ADOS and ADI-R, a similar problem is present, to say nothing of the material cost of the kits needed to administer these measures. While neither test requires multiple clinicians, both do require a well-trained one. The ADOS and the ADI-R generally advise that the clinicians who administer the measures should be trained to "clinical reliability", although in recent practice, administration has become more common without training to the appropriate benchmarks (Lord et al., 2012; Lord et al., 1994). Difficulties with the ADOS are further complicated by even experienced, or lesser-trained clinicians, lacking the specialized training necessary to uphold the ADOS' strict standards for fidelity (Kamp-Becker et al., 2018). These issues are usually mitigated in North America, where the major cities have clinicians who are trained in the use of these measures, but startling gaps emerge in rural areas and around the world (Colombi & Ghaziuddin, 2017; Nowell et al., 2020). These problems are often exacerbated when clinicians do not have a nuanced understanding of differential diagnoses, which can often present in many ways as similar to the symptoms seen in ASD. The problem of differential diagnosis will be returned to later on.

Another consideration for the ADI-R, and to a lesser extent the ADOS, is the full reliance on subjective reports of behavioural symptoms or subjective assessments of behavioural symptoms (Havdahl et al., 2017; Lord et al., 1994;). Consequently, the integration of clinical judgements alongside accurate administration and scoring is vital to form an accurate clinical picture. In relying on these methods, clinicians must eschew objectivity. Havdahl and colleagues (2017) report that in parents who were not seeking an ASD diagnosis, sensitivity of identifying ASD with the ADI-R was only 57%. That is, for those parents that took part in the study, but were not concerned about their child's symptoms or did not believe symptoms to be in line with ASD, they often reported experiences in a way that seemed like that of a child whose development was typical to a clinician using the ADI-R. Using other measures, it was apparent that a large number of children who met criteria for ASD were not diagnosed because of the subjective nature of the ADI-R.

Especially with the additional limitations imposed in many countries by the COVID-19 pandemic, telehealth has been pushed to the forefront and many clinicians have had to weigh the gold standards with practical concerns, even in major cities in North America (Nowell et al., 2020). While the field is in its infancy, there is evidence that telehealth diagnoses are reasonably in agreement with face-to-face diagnoses and may be relied upon when necessary (Alfuraydan et al., 2020). The ADOS (but not the ADI-R) would be cumbersome to administer through an online process and much is lost in doing so. Even as the pandemic subsides and restrictions are eased, diagnosticians have begun to understand the need for increased flexibility in measurement and of having a range of options.

In summary, the major limitations of the measures often used as a gold standard of ASD diagnosis include a heavy drain on resources, the need to maintain strict standards of fidelity which ensure the accuracy of the measures, some difficulty with differential diagnosis, limitations with online administrations, and lack of training and availability in some parts of the world (including difficulty administering in rural locations). There is, of course, good reason for the continued use of and reliance on these measures, but in the instances where they are not available or less desired, steps may be taken to mitigate these issues.

2.1.3 Eye Tracking as a Screener and Diagnostic Aid

Eye tracking in ASD has become more prominent and it is used in a variety of ways. While there is a potential for eye tracking to aid in an accurate diagnosis, its utility in understanding the variance in ASD is understudied. For example, using eye tracking technology, researchers have been able to identify specific subtypes or groups in ASD (e.g., Pierce et al., 2011, Wan et al., 2019). In addition, some researchers have demonstrated that it provides comparable screening to other common measures of ASD (e.g., Wan et al., 2019; Vargas-Cuentas et al., 2017). However, key gaps exist in the eye tracking literature. Specifically, since ASD is such a heterogenous disorder, and one currently defined behaviourally (as opposed to having clear biological or genetic markers), using eye tracking as a screener would likely need to be supplemented by other information.

Being able to follow social information while watching videos using the eyes was identified as an area of deficit in ASD in the early 2000s (Klin et al., 2002; van der Geest et al., 2002). Since then, a plethora of studies have demonstrated significant differences from typically developing (TD) children (for a review, see Chita-Tegmark et al., 2016). Researchers have used algorithms to fully separate the differences between the way TD children and those with ASD view social scenes (Vargas-Cuentas et al., 2017). Vargas-Cuentas and colleagues created an algorithm that they used to calculate an accurate measure of gaze preference, accounting for distractions and other artifacts of data collection, so avoiding the need for calibration, training or having the children sit in a specific way. They used this to determine cut-off points for TD and ASD, thereby differentiating these groups. This was also done on a relatively inexpensive tablet. While the clinical application of eye tracking lags behind, researchers have begun to compare the effectiveness of eye tracking as a screening tool compared to other commonly used screeners.

Jensen and colleagues (2021) have used a gaze preference task, in addition to the Modified Checklist for Autism in Toddlers (M-CHAT; Robins et al., 2001), a commonly used screener for ASD in order to determine whether the gaze preference task adds to the utility of the M-CHAT. The gaze preference task (15 seconds in duration) was comparable to the M-CHAT and together with M-CHAT was significantly better than just the M-CHAT alone at differentiating children with ASD from the TD group. Jensen and colleagues (2021) have used machine learning algorithms to differentiate children with ASD from TD children with 89% accuracy compared with 78% and 76% for the M-CHAT and gaze preference task alone, respectively.

In addition to studies that specifically designate eye tracking methods as viable screeners, a wealth of studies have identified that eye tracking serves as a useful biomarker for ASD (e.g., Frazier et al., 2021; Wagner et al., 2016;). Researchers have identified that there is good convergent validity with other measures of social attention (Murias et al., 2018). In addition, researchers have begun to use eye tracking as an outcome measure indicating not only propensity for a response to treatment (i.e., to predict whether children will improve at targeted skills, in this case social engagement and communication), but also as one of the functions improved as a result of the treatment (Bradshaw et al., 2019). Due to the burgeoning use of eye tracking, it must be established that not only does eye tracking offer real value in regard to efficiency and expediency of screening or diagnosis of ASD, but also that the use of eye tracking can assist with differential diagnoses.

2.1.4 Importance of Early Diagnosis in ASD

Early diagnoses are vital in the case of ASD. Diagnosis in Western countries typically happens at 3 – 4 years of age or later (Brett et al., 2016; Habayeb et al., 2021; Jo et al., 2015). However, the years of infancy are seen as a critical period in the development of ASD and the associated traits (Petinou & Minaidou, 2017; Schaer et al., 2014;). While a diagnosis in these crucial years is important, the stability of such a diagnosis of the disorder leaves much to be desired. Before autism was subsumed under the category of autism spectrum disorder, Rondeau and colleagues (2011) noted in a meta-analysis that before three years of age, autism had a stability of 76% (i.e., the likelihood of having the diagnosis at a later time) whereas some of the other parts of the spectrum had much lower rates. Pervasive developmental disorder – not otherwise specified (now considered ASD) had the lowest rates of stability at 35%. Part of the issue here is that the severe developmental, especially communication, difficulties seen in children with some of the other diagnoses now in the spectrum, improve with age. Some researchers suggested that combining autism and other related entities in "ASD" would bring with it increased variability (Camarata, 2014). Another, more recent study found similar stability as the Rondeau et al. meta-analysis with 75% of the children diagnosed before 48 months, continuing to meet criteria at a one year follow up and the remainder of the children continuing to show neurodevelopmental issues (Benedetto et al., 2021). This variability is certainly present in the diagnosis of ASD, but this does not undermine the importance of early identification.

Researchers have demonstrated that even young children with ASD traits who are later found not to have a diagnosis of ASD benefit from intervention (Vietze & Lax, 2020; in this case <40 months). Many of the common interventions used with infants have approaches that focus on symptoms common to many developmental issues (e.g., language, social skills, adaptive skills; Machalicek et al., 2021). A further problem exists, at least in the United States, where many agencies are able to screen for ASD but do not follow up with a full diagnostic assessment, due to a lack of resources (Williams et al., 2021). Still, early screening that identifies developmental issues likely to lead to further problems, but not limited to ASD are important and necessary even in the absence of a stable early diagnosis.

Screening using eye tracking offers a relatively inexpensive and low-training way to identify a crucial developmental problem in ASD: that of low levels of social engagement (Jones & Klin, 2013; Pierce et al., 2016). Screening for ASD using eye tracking would not only add to the confidence of a diagnosis but may allow specific skills to be targeted even when a diagnosis in unsure.

2.1.5 Current Study

The currents study used date from an online database. The original study by Pierce and colleagues (2016) demonstrated the diagnostic utility and predictive validity of eye tracking. In a preferential looking paradigm where a child is presented with two or more options on a screen at which they can freely choose to look, toddlers with ASD had increased looking time toward geometric images over social images. Using cut-offs derived from their measure, the authors' positive predictive value for arriving at the correct diagnosis was 86%, though their cut-off showed poor sensitivity (21%). That is, their cut-offs maximized specificity (98%) so that children without ASD would not be routinely identified. In addition, they reported that the children with ASD who spent the most time looking at the geometric images showed poorer outcomes in terms of cognition and language.

One consideration mentioned earlier when using the ADOS and other diagnostic measures is that these are somewhat non-discriminant. For example, children have been incorrectly identified as being on the autism spectrum, who in fact are anxious (Stadnick et al., 2015), have an eating disorder (Kerr- Gaffney et al., 2020), or have an intellectual disability (Sappok et al., 2013). Pierce and colleagues (2016) used the predictive power of eye tracking to separate groups of children with ASD from children with other developmental issues, but as was demonstrated by Jensen and colleagues (2012), a combination of variables may be more effective, especially as there is good reason to use complementary screeners (i.e., different developmental issues being queried).

I hypothesize that a combination of variables that can be quickly assessed and easily used (i.e., simple language and cognitive measures) have the potential, when combined with eye-tracking, to most effectively discriminate between groups of children with ASD, developmental delays, language delays and those that are typically developing. As described earlier, in the instance when eye tracking is combined with other measures, the combination often leads to greater utility than the measures individually (i.e., the M-CHAT; Jensen et al., 2021). The purpose of the first study, reflecting the current need in this field, is to identify whether a combination of variables, including eye tracking and language measures, is able to offer classification accuracy on par with gold standard measures to discriminate ASD from other related disorders.

2.2 Methods

2.2.1 Participants and Procedures

The Pierce and colleagues (2016) dataset was re-analyzed to determine the efficacy of eye tracking, cognitive, and language measures in separating children with ASD, language delay, and developmental delay or intellectual disability (ID) into distinct diagnostic groups. This is in contrast to Pierce and colleagues' (2016) original analysis, which examined eye tracking in isolation and generally only examined differences between ASD and all other groups combined. This dataset, obtained through the National Institute of Mental Health's National Data Archive, includes 49 children with a final diagnosis of ASD, 19 with developmental delay, 46 with a language delay, and 70 typically developing children (122 males and 42 females). The following description of the sample and their procedure has been summarized from Pierce and colleagues (2016).

The children were aged 12 – 36 months (M = 24.00, SD = 9.21) at the beginning of testing. These children were recruited via two sources: a community referral and a general community level screener. All children were assessed by psychologists. The children were given tests of early cognitive ability and language (Mullen Scales of Early Learning; Mullen, 1995), the Vineland Adaptive Behavior Scales (Sparrow et al., 2017), as well as the appropriate module of the ADOS-2 (Lord et al., 2012). Then they were presented with short video clips called the Geometric Preference Test for Autism (Pierce et al., 2011). The clips consisted of the presentation of dynamic geometric images (e.g., a square being elongated into a rectangle) on one side and dynamic social images on the other side (e.g., children playing). During the presentation of this clip, children's eye movements were recorded. The children were later given a final diagnostic assessment after the age of 3, and when appropriate, given a diagnosis. The final diagnosis was made using a combination of the ADOS and clinician judgement alongside the DSM criteria.

2.2.2 Materials

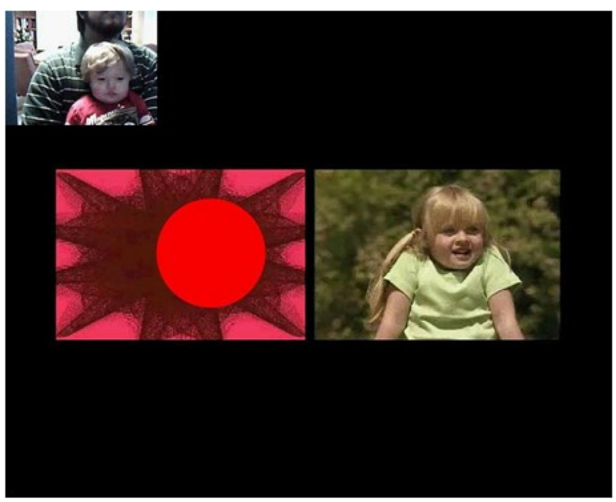
Autism Diagnostic Observation Schedule – 2nd Edition (ADOS; Lord et al., 2012). The ADOS consists of series of tasks designed to elicit behaviours that may be impaired or atypical in ASD. These tasks are adjusted based on the developmental level and age. For example, older children are asked questions about social interactions, whereas younger children are shown bubbles being blown (where the aim of the task is to see if they request more). The entire series of tasks takes between 30 and 60 minutes to administer and requires clinician training and fidelity. The clinician then rates the child's behaviour. For this study, children were given either Module 1, 2 or the Toddler module and assigned a diagnosis according to the ADOS Module Algorithm, referred to as "ADOS total" in *Table 1*.

Mullen Scales of Early Learning (Mullen 1995). This test consists of 5 subscales that assess Gross Motor, Visual Reception, Fine Motor, Receptive Language and Expressive Language domains. The Mullen takes between 15 and 30 minutes to administer, for children aged under 3. A composite score that excludes the Gross Motor subscale is considered to be an early measure of IQ. That is, a "Cognitive Sum" was calculated based on scores in the Visual Reception, Fine Motor, Receptive Language, and Expressive Language subscales, a method sometimes used as an indicator of cognitive ability (e.g., Duvall et al., 2020). This was used in the Pierce and colleagues (2016) study and was used in this study for consistency. The test uses a series of simple activities and queries that are designed to provide developmentally accurate assessments of the child's functional age in the various domains assessed.

Apparatus and Stimuli for Eye Tracking. Eye tracking data in Pierce et al. (2016) were captured by using a 120 Hz Tobii T120 eye tracker and processed with Tobii Studio software. Children were oriented to the eye tracking task by having them attend to images like a cartoon cat, and toy sounds. The eye tracker was calibrated using this information and sufficient trials were presented to ensure low rates of errors. Dynamic areas of interest (AOIs) were created to encapsulate the stimuli presented (i.e., either the geometric or social stimuli), and total looking time at both AOIs were recorded and analyzed. The children were seated on a parent's lap approximately 60 cm away from the screen. The geometric clips involved the movement of different shapes with a variety of different colours. The social clips involved children playing, usually in a field or backyard, engaging in activities like jumping, shrugging, dancing, or falling. An example is provided in Figure 1. Each clip lasted approximately 4 seconds and there was a total of 60 seconds of viewing time including all clips.

Figure 1

Sample Image Taken from Video Presented On-Screen During Eye Tracking



Note. The image shows a geometric stimulus (left side) and a child playing (right side).

2.2.3 Analysis

A linear discriminant function analysis was conducted using eye tracking (i.e., percentage of looking time at the social image, or "the fixation percentage"), cognition, and language as the predictor variables in order to see which combination of these variables best predicted all available diagnostic groups (note: there were no collinearity issues found between the Mullen variables and variance inflation factor was close to 1). The eye tracking variable had percentages that were normally distributed. The "Cognitive Sum" variable, of course was skewed negatively (with children with developmental delays in the sample), but passed normality tests. There were no outliers for Mullen variable (i.e., 2.5 SD above or below the group mean). The efficacy of the combination of variables was compared with diagnosis as given by the ADOS (after 3 years of age), in terms of an overall percentage agreement.

2.3 Results

Several linear models were constructed to better understand the relationship between ASD symptoms, eye tracking and related variables such as language and intelligence. Table 1 below shows the group averages and standard deviations on the Mullen, ADOS and eye tracking task in terms of fixation percentage towards the social stimuli using the samples from this study. An ANOVA revealed a group effect for fixation percentage ($p < 0.001$), and follow-up Tukey's HSD revealed that the ASD group was significantly different from all other groups ($p < 0.001$, $p = 0.003$, $p = 0.022$ for TD, Language Delay and ID respectively). An ANOVA also revealed an effect for the Cognitive Sum ($p < 0.001$) with follow up tests indicating significant differences between the TD group and all other groups (all $p < 0.001$), as well as between the ASD group and the language delay group, but not the ID group ($p < 0.001$ and $p = 0.896$ respectively). Finally, an ANOVA revealed a group effect for the ADOS ($p < 0.001$) with significant differences between ASD and all other groups (all $p < 0.001$).

A linear regression with the variables from the Mullen revealed no significant predictors of ASD symptoms on the ADOS (i.e., visual reception, receptive language, overall language, cognitive ability; all not significant [N.S.]). Visual fixation on the social stimuli was also not a predictor of ASD symptomatology within the ASD group ($p = 0.067$), though it approached significance.

Table 1

Means and Standard Deviations for all the Diagnostic Groups on Key Study Measures

Group (n)	TD (70)	ASD (49)	Language Delay (46)	ID (19)
Social AOI Fixation (%)	81.34 (13.62)	62.26 (27.26)	77.28 (16.89)	79.55 (17.52)
ADOS total	3.27 (2.84)	17.00 (5.37)	5.31 (3.98)	4.79 (2.49)
Receptive Language	54.15 (9.60)	30.57 (15.50)	42.44 (10.93)	36.93 (7.45)
Expressive Language	51.22 (6.45)	30.33 (13.82)	34.77 (7.26)	28.79 (8.65)
Cognitive Sum	210.67 (21.69)	138.17 (46.97)	180.18 (28.31)	145.14 (24.46)

Note. TD = typically developing, ASD = autism spectrum disorder, and ID = intellectual disability.

Two major linear discriminant analyses (LDA) were conducted to understand the combination of variables that is best able to discriminate among the groups (i.e., between ASD, ID and language delay). The first LDA had variables from the Mullen (receptive language, expressive language, and cognitive ability) as well as the eye tracking variable (fixation duration on social stimuli). The second LDA had the same variables from the Mullen as well as the ADOS total score. It is important to note here that the ADOS was eventually also used as a categorical variable to diagnose the children with ASD; therefore, there is likely to be a high correlation between the ADOS at time 1 and time 2. Since it was used as a measure of symptoms at time 1 and diagnostically later, the ADOS has an advantage in its predictive power in this case. In contrast, the eye tracking and other measures have no *a priori* advantage as predictor variables. The analyses must be considered in light of these facts.

Both analyses produced linear combinations that were able to effectively separate the groups. The LDA with the eye tracking variable and the Mullen was able to do this with 70% accuracy (i.e., able to place the child in the proper diagnostic group), while the LDA with the ADOS was able to do so with 73% accuracy. The overall sensitivity of the first LDA (eye-tracking plus Mullen) in identifying ASD among the 4 groups was 60%. Sensitivity and specificity for all groups are presented in Table 2. It is important to know that these numbers represent separation from all the groups, not just from TD. That is, the number reflects accurate identification (as an example in the case of sensitivity for the ASD group) of ASD, from TD, ID or Language Delay, not just ASD vs. TD.

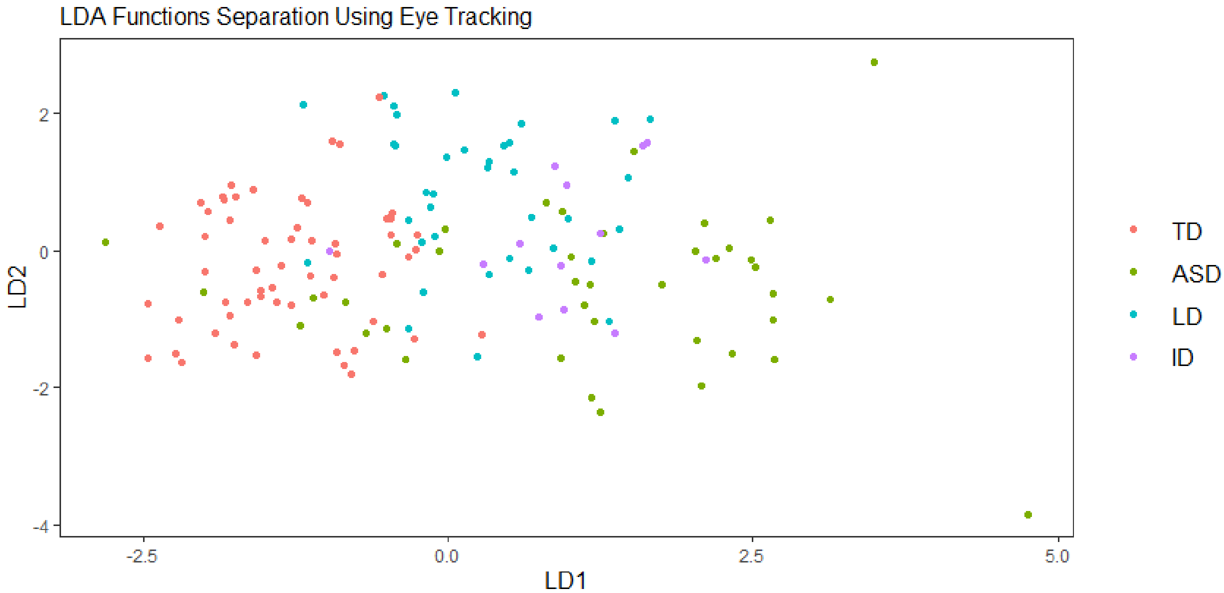
Table 2

Sensitivity and Specificity Based on LDA Using the Eye Tracking Variable and Mullen

	Sensitivity	Specificity
Typically Developing	94.9%	77.8%
Autism Spectrum Disorder	59.5%	62.5%
Language Delay	64.1%	65.8%
Developmental Delay	14.3%	33.3%

Figure 2

Plot Showing Differentiation of the Groups Using the First Linear Combinations Generated Using the Eye Tracking Variable in Addition the Mullen to Examine Group Differences

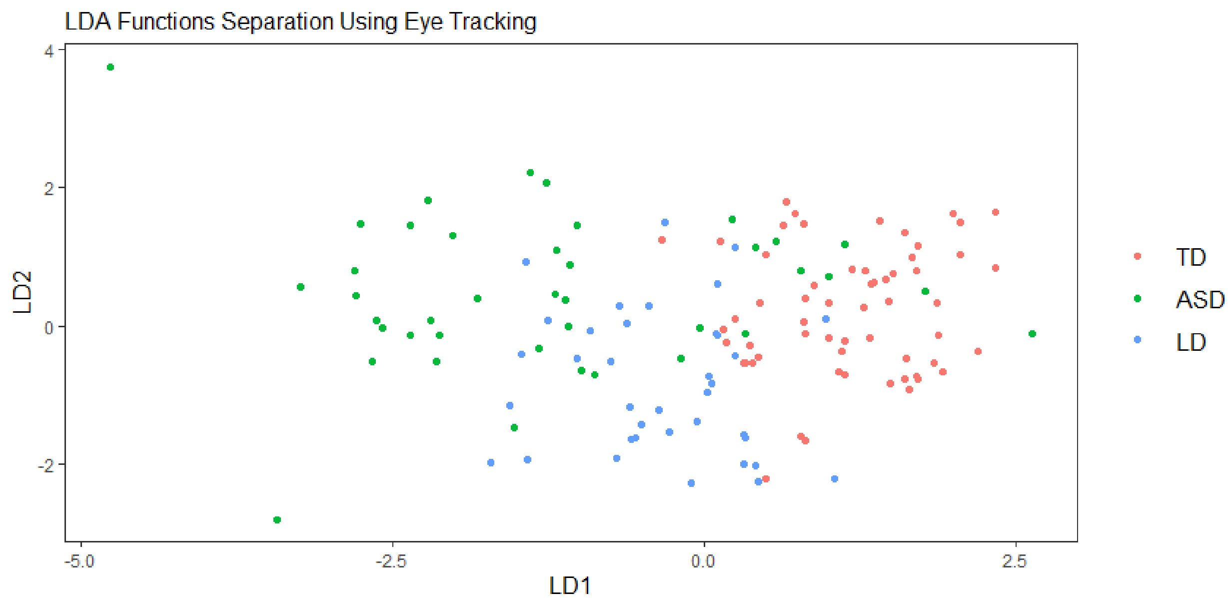


The most common analysis in eye tracking studies compares ASD populations to TD children. Comparable analysis was completed to be consistent with previous studies. A linear combination was identified to separate only the TD and ASD groups. In this case, the overall accuracy of separation in the LDA was 88%. Sensitivity overall for this combination was 97% and specificity was 74%.

In order to determine whether the increase in accuracy in the second LDA was due primarily to one of the other diagnostic groups being excluded (i.e., Language Delay or ID), a third LDA was used to see how the language delay group was affecting the model. In particular, it seemed that the combination of eye tracking and the Mullen was adept at separating ASD from language delay. Removing the ID group from the analysis and including the Language Delay group, yielded an accuracy of 76.6% using the eye tracking variable and Mullen, compared with 78.7% using the ADOS and the Mullen. The LDA using the eye tracking variable and the Mullen had a sensitivity of 64.1% and a specificity of 75.8% for the language delay group. With the ADOS, it provided an overall sensitivity of 58.9% and specificity of 65.5%.

Figure 3

Plot Showing Differentiation of the Groups with the ID Group Removed Using the Eye Tracking Variable and the Mullen



2.4 Discussion

Eye tracking representing social attention is becoming increasingly important with regards to the screening, diagnosis and understanding of ASD (Chita-Tegmark et al., 2016). It is quick, increasingly cost-effective and relatively objective. Despite this, many areas and uses of eye tracking require clarification. The primary goal of this study was to examine eye tracking with two important differences from the typically studied context. To do this, data from the Pierce and colleagues (2016) database were reanalyzed. First, one of the key goals of the Pierce study was retained: to examine ASD in relation to related disorders, and not in isolation. Secondly, eye tracking was examined in conjunction with other measures. Even as screeners, two or more measures are often used in tandem and, in order to understand phenomena as complex as

ASD, this may be a useful strategy. In addition, given high enough sensitivity, a tiered approach to screening may be useful before a full diagnostic assessment. Before a discussion, it is important to note that the goal of the study was not to identify screeners for ASD; rather, it was to narrow the direction in which to direct our efforts with eye tracking. That is, in what way and in combination with which other variables can eye tracking provide useful information for the screening and/or diagnosis?

This study extended the findings of Pierce and colleagues (2016). The latter sought to obtain high specificity for the eye tracking variables in order to reliably identify what they called a subtype for ASD. This subtype showed severe symptoms overall. In the current study, linear discriminant analyses were used in order to identify the combination of the eye tracking variables and variables from the Mullen assessment that were most effective in maximizing sensitivity and specificity between the diagnostic groups present in the sample. The Mullen was chosen both because it was a useful and available data point, but also due to it being easy to administer and providing valuable information in areas where the eye tracker provides no/little information (i.e., language and cognitive information). This combination showed promise. The overall accuracy of the combination of the Mullen and eye tracker in distinguishing between groups was high (70%). Both the sensitivity and specificity of identifying ASD was approximately 60%.

It is important to note that in the present study, the overall fixation time on a social vs. non-social stimuli was the eye tracking variable used. Other studies have used a more complex stimulus (even with young children) that requires the participant to trace the social interaction across a dynamic situation (e.g., Hosozawa et al., 2012; Jones & Klin, 2013). These dynamic social scenes provide several benefits over the paradigm followed in this study. First, they allow for researchers to present naturalistic scenes that the child may encounter in everyday life.

Secondly, they allow for more variety and complexity. There have been some indications that eye tracking can also provide a window into intelligence very early in life. These ideas will be re-examined in the limitations below.

Early diagnoses of ASD, intellectual disability and language delay are highly unstable (i.e., before 3 or 4 years of age depending on the studies; Lemcke et al., 2013; Rondeau et al., 2011). Most studies in the field seek to differentiate children with ASD from TD. Eye tracking in combination with the Mullen assessment were able to do this very effectively in this study. Most importantly, the accuracy of the ADOS and the Mullen together in separating these groups is very comparable (73%) to using the eye tracker and Mullen together instead of the ADOS. That is, much information is provided by using a combination of eye tracking and Mullen, but little more classification information is gained if the ADOS is substituted. While the reverse is also true (i.e., little is gained using the eye tracker in addition the ADOS), the eye tracker has many advantages - described above - which include being a more efficient screener (with regards to being time-efficient and with low training thresholds), more objective measure, and more accessible. The task of eye tracking research in ASD with regards to screening remains to identify what information is gained, and how to target the remaining variance that remains unaddressed. That is, a task that remains is to identify how to disentangle the source of the variance and then to develop a measure or battery to address or predict this variance.

Using the sensitivity and specificity information from this study may help us develop some insight into what information remains to be targeted effectively, or the sources of the remaining variance. The combination of the two measures, eye tracking variable and Mullen Cognitive Sum, provides a largely accurate identifier of typical development. That is, this combination of assessment measures is able to group accurately with few false positives or true negatives those children that are TD. Of course, such an assessment does not offer a complete picture of development, but may be a step towards a parsimonious screening measure. However, this same assessment offers little insight into intellectual disability. Foremost among reasons for this is that in early development, it is difficult to separate language delay and a more generalized disability. Often the first signs of developmental impairment are expressed in the language domain (Mitchell et al., 2006). As with ASD, eye tracking may offer some further insight into developmental or intellectual delay, but a more robust screener of language and cognitive delay may be needed.

When trying to distinguish children with ASD from children who are typically developing, the combination of eye tracking and the Mullen provided a high positive predictive value, identifying nearly all the children with ASD (97%). Specificity is relatively lower at 74%, but the first purpose of the screener is to identify all the children who *might* have ASD. In addition, the combination continues to provide valuable information in separating children with ASD from those who have a language delay, indicating that the major limitation present in the LDA models explored in this study is differentiating ASD from intellectual disability.

As summarized above, the importance of early diagnosis and intervention with regard to ASD cannot be overstated. Children who are diagnosed at an earlier age have much better outcomes than children with the same level of ASD severity who are diagnosed later in life (Schaer et al., 2014). A primary reason for this is the effective intervention techniques that have been developed for ASD. However, a fundamental problem remains – diagnosis before 4 years of age can be unreliable and the possibility of a different diagnosis being made at a later age is significant. The field of ASD research and the researchers and clinicians must adapt to this problem in two ways. The first, which is explored in the present study is to continue to pursue techniques that may help with earlier diagnoses of ASD. The second is to explore what possible avenues for treatment exist without a clear diagnosis of ASD.

If a reliable test of eye tracking were to be constructed as a screener, it would have several clear advantages over or in conjunction with the ADOS. While the eye trackers used in research studies are often large and expensive, the technology is continually being made more efficient in terms of size and cost. Reliable eye tracking technology exists that is usable with smartphones and iPads and this technology is now being studied in the context of ASD (Strobl et al., 2019). In addition, eye tracking tasks are easy to administer, objective and do not require very extensive training or qualification., An eye-tracking task that lasts minutes and could be used by anyone with a smartphone anywhere in the world is an achievable dream for ASD screening.

Symptom level interventions, in contrast to disorder-specific programs are gaining in popularity (Talbot & Miller, 2020). Effective interventions exist that emphasize the shared commonalities present in a range of disorders that affect the development of the child (Adams et al., 2012; Soorya & Halper, 2009). Efforts are also underway to examine the commonalities that exist in and underlie a range of neurodevelopmental disorders (Talbott & Miller, 2020). These approaches point to new opportunities in the treatment of ASD symptomatology. The method described in this paper allows us to highlight social attention that is atypical compared to typical development and, in combination with language and cognitive function, indicate the need for intervention, especially given evidence suggesting children who miss important social cues develop more serious ASD symptoms (Jones & Klin, 2013). Symptom level interventions that target these problems in recognizing social cues may allow us to treat the underlying issues seen even without a reliable diagnosis at an early age. A quick screener to identify the combination of eye tracking differences and language or cognitive issues could help identify areas that require specific and targeted intervention. At the level of intervention, programs have already been developed where children's eye gazes towards the appropriate stimuli are rewarded in a game like setting thereby reinforcing their attention to socially important targets (Sosnowski et al., 2021). This intervention was found to be effective in improving emotion recognition scores in the aforementioned study, but can be applied to a wider range of social phenomena.

2.4.1 Limitations

One of the primary limitations of this study is the type of video stimuli used for the eye tracking condition. In this study, simple and short videos of children playing was presented. As discussed earlier, there is significant evidence that more complicated but naturalistic scenes can be used, even with young children, to have better discrimination using eye tracking tasks between TD and ASD (Klin & Jones, 2013). In the present study, the TD, language delay, and ID groups were not significantly different from each other in their fixation percentage toward the social stimuli. While the information provided was still useful in separating the groups, a more nuanced eye tracking task (as present in both Study 2 and Study 3, which follow) may provide greater separation between the groups.

One reason that there may be better separation would be because more nuanced tasks allow for many more contextual social features to be addressed. For example, pointing, gestures, gaze direction, and shifting focus are all more likely to be present in a typical social reaction. For infants, these scenes may be overwhelming, but using developmentally appropriate videos that contain these nuances may be useful. In addition, these nuances also become more important when considered as a whole (i.e., the social situation), which is often identified as a difficulty for children with ASD. There is some evidence that children with ID may struggle with tasks that require integration (Dube & Wilkinson, 2014). Therefore, the judicious use of dynamic social scenes may allow researchers and clinicians to observe degrees of difference that fit one or another diagnosis better.

The separation afforded by the cognitive measure was not adequate to separate the ID group from the other groups. Often, measures of intellectual function with very young children rely on language (Mullen, 1995; Vlasblom et al., 2019). Therefore, children with language delay or ASD may also appear to have intellectual difficulties, even if language is eliminated. There is emerging evidence that children who have intellectual difficulties sometimes demonstrate eye tracking differences when viewing some types of videos that have complex sequences of information (Boot et al., 2013; Dube & Wilkinson, 2014). In line with what was stated earlier, if these eye-tracking differences were explored and clearly differentiated from ASD, there may be greater utility for the use of eye tracking.

This study demonstrates that eye tracking, in combination with commonly used assessment measures, is an effective way to screen for ASD and ASD symptoms. This remains the case when examining some of the other presentations that are commonly found in clinical settings (e.g., language delay and intellectual disability). In this study, the eye tracking measures were able to achieve comparable levels of accuracy to the ADOS.

Since there are unreliable diagnosis of infants with currently used tools, clinicians and caregivers who focus on interventions that target symptoms (i.e., focusing on issues with social engagement) can use information from eye tracking and simple language and cognitive measures to target issues that could lead to progressively disordered behaviour. In addition, the screening methods reviewed in this study are still emerging and with further refinement (and perhaps in combination with other measures) offer a tantalizing window into the mind of a developing child.

The greater utility of more nuanced eye tracking methods is explored further in Study 2 and to an even greater degree in Study 3. These studies will help us to develop a more complete grasp of the utility and limitations of employing eye tracking methods with children with ASD.

Chapter 3: Study 2

3.1 Introduction

Autism has been defined as a neurodevelopmental disorder affecting both social communication and behavioural patterns in the form of repetitive behaviours or restricted interests (APA, 2013). "Neurodevelopmental" indicates that there is a progressive accumulation of disruption to the typical process of a child's development. According to Jones and Klin (2013), ASD is a developmental adaptation that manifests as a result of the child acquiring atypical learning experiences over time. In their study, Jones and Klin suggest that a child with ASD could be watching an interaction with two other children and be focused on a door that the other children are opening and closing rather than the children themselves. In doing this, they may miss the vital nature of the interaction (i.e., playful) and not develop or strengthen a schematic understanding of what play can look like. Beginning first with the encoding of cues in the world around them, the child accumulates these atypical learning experiences that lead to downstream consequences in the processing of information. Studies of ASD have reliably established that the social domain is the primary area where the consequences of these learning experiences are manifested in the child with ASD (e.g., Constantino et al., 2017; Klin et al., 2015). If this theory about the process of accruing dysfunction is accurate, it is expected that young children who have atypical learning experiences (e.g., children who are not attending to the age-appropriate social information) first acquire those deficits that are most linked with the particular information that is missed. For example, the children who do not follow the eyes of a caregiver might not learn as efficiently the importance of following someone's gaze.

The propensity to not attend to social information but have some ability to sustain attention with regards to other non-social stimuli has long been noted in ASD (e.g., Osterling &

Dawson, 1994). The methods of quantifying the specific amount of attention and to exactly which stimuli have substantially progressed with the development of eye tracking methods (Papagiannopoulou et al., 2014). Rudimentary eye tracking involved examining the child's eyes using a recording and coding the approximate areas where the child was attending. Using this method, Klin and colleagues (2002) had children with ASD watch a scene from a movie and noted significant differences between them and TD controls. The scene required children to attend, notice, and understand social aspects of everyday life such as speech, gestures, and emotion. Children with ASD struggled to track the social information effectively, often focusing on irrelevant or seemingly random information.

Since then, many researchers have demonstrated fundamental differences in the way the children with ASD track visual social information relative to their peers (Brown-Lavoie et al., 2011; Kylliainen & Hietanen, 2004; Papagiannopoulou et al., 2014; Swettenham et al., 2003). A proposed mechanism to understand these differences is the propensity in typical development to prefer biological motion over other types of stimuli (Klin et al., 2009). That is, when given a choice to view motion that behaves in a biological way (e.g., shapes appear to be walking), TD children have a tendency to focus on this information. Even when movement is not strictly biological, typically developing children will impose biological intentions onto otherwise neutral stimuli (Klin, 2000). In the Klin (2000) study, children with ASD did not show this tendency, referring to what they were viewing in the strictly plain sense terms of what they observed (e.g., "a square was moving", rather than attributing or imagining a biological explanation like a character leaving his house).

While the consensus in the field is that, unlike in typical development, children with ASD do not preferentially attend to social information (New et al., 2018), the proposed mechanism of how this affects their development is not well understood. As mentioned earlier, Jones and Klin (2013) argue that this lack of preferential attending leads to progressively greater amounts of formative learning experiences that are missed, which then leads to observed social and behavioural deficits. I will now turn to discussion of a social information processing model in order to contextualize the steps from improper encoding (from not attending to a stimuli) to behavioural outcomes, before returning to this idea.

The Crick and Dodge (1994) model of social information processing (SIP) is an influential model that has been used in the context of aggressive behaviours (Fontaine & Dodge, 2009), bullying (Camodeca et al., 2003), and ASD (Ziv et al., 2014), among many others. For this discussion, certain steps of the model will be emphasized, but an overview of the model will be helpful. Though the model has been revised, the initial model is widespread because of its explanatory power (Crick & Dodge, 1996). The first step in processing information is the encoding of relevant cues in a social interaction. By encoding, it is meant the attention needed to relevant stimuli for these stimuli to make an impression on the mind. Second, one makes interpretations of these cues. Third, (for the purposes of this discussion), a child will select a goal based on that interpretation. Fourth, the child will generate possible responses or behaviours. Fifth, the child will evaluate these responses and finally, or sixth, the child will enact a behaviour. In the model, it is emphasized that the child's behaviour will then impact the encoding of cues and the model is typically depicted as a cycle, presented in Figure 4. This cycle does not happen in isolation, but Dodge later emphasized the role of the individual's data base (Dodge & Rabiner, 2004). This database includes memories, rules, and schemas as well as social knowledge or understanding that impacts each piece of information received by the child. For example, a child hears a loud voice, and the child's internal rule for loud voices is anger or impending violence. This limits the interpretation in the second step (the interpretation step), which thereby limits all further steps. A child with a different schema and a wider base of social knowledge could presume that there are many reasons for loud voices, and could possibly come to a different interpretation, therefore having more possibilities for each further step including alternate goal selections and response selections.

In the context of the SIP model, eye tracking allows us unique insight into the first step of the model, the encoding of cues. If the wrong cues are encoded, the responses that are enacted (or observed behaviours), will be limited by the information that the child has. Since the cycle depicted in the model is an iterative process, with each “revolution” leading to the development of further social knowledge, schemas, and memories, a significant impairment in the encoding of cues will lead to on-going deficits in response enactment, not to mention mistaken intentions, lack of options for responses, and difficulties with response evaluation. All of these deficits have been observed in ASD (Flood et al., 2011). The iterative process of the SIP model also lends itself to a core hypothesis as to how the dysfunction in ASD should emerge. That is, the children who struggle to encode social information should also demonstrate deficits with behaviours that are part of the enactment stage. The areas of first or greatest impairment in ASD should be those that are part of the 6th step of the chain represented in the model, stemming from the particular issues seen with encoding in ASD. To examine this further, I will first turn to a discussion of the literature of emerging social deficits seen in ASD.

Beginning with eye tracking, researchers have identified that, very early in development (e.g., before 2 months: Jones & Klin, 2013; before 6 months: Young et al., 2009), children who later develop ASD, do not demonstrate tracking deficits. In conjunction with this, while there are some studies that identify early differences (e.g., Sacrey et al., 2015) children at these young ages also do not typically display any consistent, measurable social differences (Donati et al., 2020). This is one of the reasons why reliable diagnoses are so difficult to make very early in development. In some studies, babies who later go on to develop ASD show more eye contact with their mothers than those who do not (Jones & Klin, 2013). Johnson (2015) proposed that the children who develop ASD, for a variety of primarily biological, but also social reasons, are overwhelmed with the amount of information needed to process social interactions. Therefore, ASD becomes an alternative developmental pathway for these children with brains that are better attuned to processing other types of information (i.e., perhaps not types of social information). With regards to the SIP model, the children who develop ASD seem to be able to encode the right cues as young infants. As they get older (possibly around 6 months of age; Zweigenbaum et al., 2007), the amount of information that needs to be integrated becomes more difficult for these children in social situations. Therefore, they turn to other non-social stimuli which leads to improper encoding of social cues at this young stage.

3.1.1 Emergence of Difficulties with Eye Contact

Eye contact (or lack thereof) has been identified as one of the core symptoms of ASD (Zweigenbaum et al., 2005). Proposed mechanisms for the development of this problem have included atypical subcortical infrastructure that would allow for the detection of faces and eyes (Senju & Johnson, 2009). Since this is a deficit that emerges early in development, it is likely that iterative processes that require greater and greater interaction between face and eye detection and other brain regions involved in interpretation of cues, as well as inputs from sounds, smells and other sensory domains lead to issues of integration as Johnson suggests (2015). The issues of integration in turn ensure that areas that would normally become specialized for purposes such as face recognition, do not. Consistent with this, Wang and colleagues (2018) have noted that eye contact is particularly avoided when emotional facial expressions are present compared to less emotional expressions. That is, when there are emotions to process in addition to the typical visual cues in social information, children with ASD avoid eye contact all the more, which could be explained by a difficulty with integrating emotional and visual information.

Deficits in eye contact have been noted as some of the first symptoms to emerge in infants who develop ASD (Zweigenbaum et al., 2015), but as noted earlier these deficits are not consistently present at 2-6 months of age (Jones & Klin 2013). Zweigenbaum (2007) noted that deficits with eye contact are not present in the first few months of life, but then do become apparent, by the first year of life. Much more common are studies that examine deficits at around age 12 months, and these show reliably observed deficits in eye contact (e.g., Filliter et al., 2015; Gammer et al., 2015; Gangi et al., 2018).

3.1.2 Emergence of Language Issues

Language issues are another common indicator of ASD in both the receptive and expressive domains. Miller et al (2017) found that children who did not orient to their names well in the first year of life were far more likely to receive a diagnosis of ASD. They noted that children began showing this tendency at age 9 months, though there were no appreciable differences at 6 months. Many independent research groups have identified differences in vocalization in the 12 – 15-month window among children who develop ASD (Heymann et al, 2018; Lazenby et al., 2016; Parlade & Iverson, 2015;). Lazenby and colleagues identified deficits in both expressive (beginning with vocalizations) and receptive language in the ASD group, which also mirrors some of the findings in the first study of this paper. Ozonoff and colleagues (2010) also found group differences by 12 months in the number of vocalizations. This difference was not found at 6 months. Hudry and colleagues (2014) also saw a similar profile with less frequent vocalizations present at 14 months, but not at 7 months. Liu and colleagues (2020) reported on brain differences from their typically developing peers in the resting state fMRI during natural sleep of infants who later developed ASD. They noted changes in brain connectivity as early as 1.5 months; by 9 months, they reported hyperconnectivity in auditory and somatosensory areas.

3.1.3 Emergence of Problematic Behaviours (e.g., Repetitive Behaviours, and Difficulties with Gesture Use, Pointing)

Restricted or repetitive behaviours are also part of the diagnostic profile of ASD. Stereotyped behaviours, such as rocking or hand flapping, tend to emerge with the core symptoms described above around 12 months of age (Elison et al., 2015; Wolff et al., 2014). Other behaviours are less well understood. Gesture use (part of the diagnostic algorithm of the ADOS) among children with ASD was limited in one study (Gordon & Watson, 2015), but further analyses revealed the relationship was mediated by language. In another study, the high-risk group that was later diagnosed with ASD showed more deictic gestures at 8 months (West et al., 2020). After this, they showed far less growth in gesture use than the other groups, showing fewer gestures by 14 months suggesting that gesture use fails to accrue at the rate of typically developing peers, possibly being affected by ongoing deficits in other areas. With regards to pointing, Sansavini and colleagues (2019) report that children who are later diagnosed with ASD do not point (primarily classified as pointing to request) as much as their typically developing peers at 18 months.

While many of the distinguishing symptoms of ASD develop early, the presence of social attention deficits captured through eye tracking represents a crucial window into the accrual of learning difficulties. Jones and Klin (2013) identified that eye tracking at age 2 is a strong predictor of ASD severity at age 5, better than even ASD symptom severity at 2 years. Therefore, it is hypothesized that those behaviours that are more related to eye tracking will begin accruing symptomatic concerns before, or at a greater rate, than other areas. Following the SIP model of information processing (Crick & Dodge, 1994), the iterative process of improper encoding must be addressed. The symptoms that form the immediate "responses" include eye contact, gaze integration and joint attention. That is, if a child encodes the wrong cues, they may not select the appropriate behavioural response (i.e., in this case, to meet a parent's eyes). In contrast, other behaviours seen in ASD such as gestures, pointing, giving and other abstract difficulties, such as the lack of imaginative play, may constitute responses that emerge from consistently missing the cues that are present in earlier life. The deficits seen in these behaviours (e.g., gestures), while they may be linked with eye tracking, should be seen later in life or to a lesser extent than the first group (e.g., eye contact).

The objective of my second study will be to understand the effect of eye tracking impairment on specific characteristics seen in ASD. A crucial question that remains important to address is the relationship between social attention and specific domains of impairment in ASD. Pierce and colleagues (2016), among a handful of others (e.g., Liu et al., 2020), have demonstrated links between social attention and language deficits, but this area is not well understood. In order to target this objective, a dataset collected by Volkmar and his colleagues (2007) at the Yale Centre for Excellence in Autism is analyzed here. Primarily, the analysis of this data set will focus on the predictive ability of social attention captured through eye tracking with regards to behaviours commonly affected in ASD, for example eye gaze, gaze integration, joint attention, which are considered immediately related to the encoding of social information, and gesture use, pointing, giving and imaginative play which are not immediately related. An example would be investigating whether the children who pay the least attention to the eyes when viewing a social scene show inappropriate eye contact on the ADOS. The Volkmar database provides information collected at the time of the eye tracking testing, as well as approximately 8 months later. These data provide a glimpse into the putative downstream consequences of impaired eye tracking on specific items, as discussed with the SIP model. That is, will eye tracking indicators at Time 1 (encoding) predict behavioural difficulties at either Time 1 or Time 2 (behavioural enactment). The goal of this study is to understand whether social attention can predict change in severity of ASD symptoms, such as those mentioned above. I predict that those behavioural areas that are directly affected by improper encoding will be the most affected at time 1 and continue to show an effect at time 2, whereas more distal areas of behavioural difficulty seen in ASD, may only show mild effects at the second time point. The methods described below will allow us to examine change in these symptoms over time and the potential utility of eye tracking ability.

3.2 Methods

This study focused on theoretically driven, specific deficits associated with poor social attention. The Volkmar database (2007) contains data collected at several time points, two of which will be analyzed for this study. Two cohorts of children that were classified based on their risk of developing autism were recruited for this study. The first group of children, the high-risk group (HR) were recruited by contacting mothers of children with ASD, who were pregnant with another child. These mothers were recruited through pediatric centres, general advertisement, and prior clinical evaluations at the Yale Child Study Centre. Another group, the low-risk group, was recruited through the Yale OB-GYN and pediatrics departments.

3.2.1 Participants

This study reported on 69 children in the HR group and 32 children in the LR group (78 males and 23 females) . Longitudinal analyses were conducted only with the HR group, since some data (e.g., the ADOS) were only collected for that group. Though 69 children in the HR group had data available at time one, only the children that had data available at both time points were used for longitudinal analyses in the present study. At the first time point, these children (final n = 59), who were between the ages of 12 months and 24 months (M (mean age) = 20.47, SD = 2.94), participated in a session including eye tracking and were given measures including the ADOS and the Mullen Scales of Early Learning. These children were again tested an average of 8 months later (M (mean age) = 28.16, SD = 2.94). Cross-sectional analyses were only completed at time point 1; that is, the HR group was compared with the LR group (M =19.45, SD = 2.93).

3.2.2 Materials

Both groups of children were given the Mullen (1995; described in Study 1) at time 1, along with a variety of other measures not reviewed or examined here (for a description, see Klin & Jones, 2013). At time 2, the children were tested again and given the same measures. The HR group were also given the ADOS (Lord et al., 2012; also described in Study 1) at both time points (one of the Toddler, module 1 or 2, depending on their verbal ability and age).

Eye Tracking Task. The children were presented with the scenes in the infant and toddler labs at Yale (described below), using a monitor and eye tracker collecting data at 60 Hz. The hardware and software needed to collect the data were created by ISCAN. Flashings lights and cartoons were used for calibration of eye position. Animated targets were shown between trials to ensure the child stayed focused on the stimuli. Participants were given an eye tracking task with short videos playing, consisting of a woman on a screen performing a naturalistic caregiver interaction (i.e., the woman was speaking to the child either by making sounds or saying short phrases; mean length = 20.99s, *SD* = 5.94s). Areas of interest were programmed to capture each child's looking time in the following areas: mouth, eyes, the woman's body, or the background in the image. Proportion of looking time was calculated for each area. The methods are described by some of the investigators of the database in Klin and Jones (2013).

3.2.3 Analysis

Logistic regressions with eye tracking as the predictor variable were constructed with the categorical variables of interest. This analysis does not depend on normally distributed variables (rather, the variable of interest has two or three levels). No multicollinearity was detected among the predictor variables (variance inflation factor close to 1) and there were no extreme outliers (+/- 2.5 SD). Specifically, categorical variables that logically derive from poor social attention (i.e., difficulty with social attention, indicating a lack of overall looking time at the mouth or eyes) were used to predict hypothesized downstream consequences. The categorical outcome variables used in the logistic regression :eye contact, joint attention, and social orienting are derived from the ADOS. These are given incremental scores by the clinician conducting the test that represent levels of dysfunction (i.e., for eye tracking "0" indicated normal eye contact and a "2" indicating abnormal eye contact). In these cases, the logistic regression provides the odds of moving "up" in severity on the ADOS as a function of eye tracking difficulty. In other instances, typical regression models were constructed. Key continuous outcome variables of interest include gesture use, receptive language, and expressive language. Furthermore, since the data were collected at two time points, the predictive value of eye tracking in explaining the variance in the outcomes described above prospectively was also examined.

3.3 Results

The LR group and HR group were compared at time 1. The change in the symptoms of the HR group was also compared at time 1 and time 2. The results of the comparison between the groups at time 1 are reported first.

3.3.1 Time 1 Analyses

Proportions of looking time at each of the four areas of interest were calculated (presented in Table 3 below). The four areas were the mouth, eyes, the woman's body, or the background of the scene. The LR group spent a significantly higher proportion of their time looking at the woman's eyes, t(99) = 2.971, p = 0.004, and the HR group spent a significantly higher proportion of their looking time at the background than the LR group, t(99) = -3.347, p = 0.001. The other two areas had no significant group effects (both p > 0.10).

Table 3

Proportion of Looking Time by Areas of Interest (AOIs)

Group (n)	TD (LR; 69)	ASD (HR; 32)	Cohen's d
AOI 1 (mouth)	26.65	33.58	0.34
AOI 2 (eyes)	55.69	42.73*	0.61
AOI 3 (body)	13.45	14.85	0.16
AOI 4 (background)	4.19	8.83*	0.63

Note. * Indicates a significant difference between the TD and ASD group at the 0.01 level.

Logistic regression models predicting group membership (i.e., LR vs. HR) were conducted in order to determine if eye tracking alone was able to distinguish between these groups. The time looking at the eyes and looking at the background were again significant predictors of group membership (p = 0.009 and = 0.018). The correct classification rates of the two areas were 66% and 68% respectively. Two final models predicting group membership were created including the language indices from the Mullen as predictors (T-scores for expressive and receptive language). Model 1 included the AOI including the eyes and the Mullen variables as predictors whereas Model 2 included the AOI including the background and the Mullen variables as predictors; the predictive accuracy of both of the models was increased to 76%. Significantly more variance was predicted by the models with the Mullen variables (p = 0.023). These analyses were done as a partial replication of Study 1. Odds ratios presented in *Table 4* below show that an increase in time (1 percentage point increase) spent at a social area (eyes) is associated with a 3.1% percent decrease in the odds of being in the ASD category. A single T-score increase on receptive language is associated with 5.4% decrease; for receptive language it is a 5.9% decrease. For Model 2, a percentage increase in time spent looking at a non-social area is associated with 6.5% increase chance of being in the ASD category. The relevant decreases associated with the Mullen are 4.8% and 5.5% respectively.

Table 4

Odds ratios and accuracy of models using the Mullen variables

Model 1	AOI 2	Receptive Language	Expressive Language	Accuracy
Odds Ratios	0.969	0.946	0.941	76.2%
Model 2	AOI 4	Receptive Language	Expressive Language	Accuracy
Odds Ratios	1.065	0.952	0.945	75.8%

Many of the HR group did not meet criteria for the ASD diagnostic criteria on the first ADOS administered. That is, even though at time 2, they had enough symptoms to indicate a likely ASD diagnosis, at time 1, these symptoms did not exceed the diagnostic threshold. In this analysis, there were 32 TD children, 34 children with ASD, and 35 children who were not definitively in the “autism” category on the ADOS at time 1. Given that these children did not definitively meet criteria for ASD, a further logistic regression was conducted that excluded these 35 children from the sample. When distinguishing between these remaining children, the regression model revealed 92% accuracy in predicting children who were TD or had ASD at Time1 with the eye tracking variable alone.

3.3.2 Time 2 Analyses

The majority of the analyses were conducted at time 2 to determine whether eye tracking measures could predict ASD symptoms over time. Specifically, in line with the features of the SIP model and as described earlier in the study, eight outcome variables on the ADOS were chosen to be examined from a theoretically driven understanding of the consequences on the child with ASD. The 4 areas that were predicted to be affected the most were eye contact, gaze integration, and joint attention, subdivided as on the ADOS into initiation of joint attention and response to joint attention. These were termed “near effects”. Four areas were also chosen that were predicted to be theoretically downstream (and were therefore called “downstream effects”) of the initial failure to attend to social information. These areas were imaginative play, gesture use, pointing, and giving.

3.3.3 Near Effects

Logistic regression or multinomial logistic regression models were constructed for each of the near effect variables. Age of the child was controlled for in all models. Based on the initial analyses, time spent looking at the eyes and the background were combined to create the primary eye tracking variable. At time 1, the eye tracking variable was not a significant predictor of the ADOS deficits in the eye contact variable (p = 0.312; again, this item is scored “0” or “2”).

However, eye tracking at time 1 was a significant predictor of ADOS eye contact at time 2 (p = 0.036). Odds ratios are presented in Table 5 for each of the logistic regression models. Therefore, the odds of having difficulty with eye contact at time 2 are about 26% (from the odds ratio = 1.259) greater for every percentage point increase in the amount of time spent looking at non-social information At time 1, this likelihood is only 5% greater.

For all variables other than eye contact, a child could be assigned on the ADOS a score of "0" (indicating no difficulty), a "1" (indicating some differences or more difficulty than what is expected in typical development) or a "2" (indicating significant difficulty). Therefore, multinomial logistic regression models were constructed for these variables. All of the odds ratios are presented in Table 5. For integration of eye gaze, the eye tracking variable was not a significant predictor at time 1, but at time 2 it was a significant predictor from both a score of 0 to 1, and 1 to 2. The odds ratios indicate that a percentage point increase in the eye tracking variable (e.g., one percent more time looking at the appropriate stimuli) predicts a 25% and 29% greater likelihood of going from a score of 0 to 1 and 1 to 2 respectively. For initiation of joint attention, at time 1 the increase from 1 to 2 was significant; however, neither of the increases were significantly predicted by eye tracking at time 2. For response to joint attention at time 1 and 2, an increase from 1 to 2 was significantly predicted, as well as 0 to 1.

Table 5

Odds Ratios Indicating the Likelihood of More Symptomatic Presentation

	Time 1				Time 2			
	0 to 1	*p*-value	1 to 2	*p*-value	0 to 1	*p*-value	1 to 2	*p*-value
Eye contact	1.055	0.312			**1.259**	**0.036**		
Gaze Integration	1.036	0.450	1.060	0.080	**1.249**	**0.024**	**1.288**	**0.013**
Initiation of Joint Attention	1.054	0.205	**1.124**	**0.007**	1.005	0.450	1.052	0.080
Response to Joint Attention	**0.208**	**0.001**	**1.056**	**0.027**	**1.164**	**0.002**	**1.088**	**0.027**

Note. A higher category indicates more symptomatic presentation on the ADOS. Eye contact only has a score of 0 or 2 and so these data are placed in the 0 to 1 column. Further description provided in text.

3.3.4 Downstream Effects

Only multinomial regression models were constructed for far effect variables since all of these variables had 3 levels (i.e., scores of "0", "1" or "2"). These downstream effect variables are Imaginative Play, Gesture Use, Giving and Pointing. The age of the child was again controlled. These results are presented in Table 6 below. For imaginative play, neither the likelihood of being given the "1" score, nor the "2" score were significant at time 1. Unlike some of the near effects, these continued to be non-significant at time 2. At both time points, eye tracking predicted either a negative or a very low likelihood of having a higher score (i.e., more problematic symptoms). As these values were non-significant, they are best interpreted as the eye tracking variable not being a significant predictor of the likelihood of the severity of the deficit. Similar patterns were observed for gesture use, giving, and time 1 of pointing. At time 2, pointing was significantly predicted by eye tracking, both from 0 to 1 (16% greater likelihood) and 1 to 2 (18% greater likelihood).

Table 6

Odds Ratios Indicating the Likelihood of More Symptomatic Presentation

	Time 1				Time 2			
	0 to 1	*p*-value	1 to 2	*p*-value	0 to 1	*p*-value	1 to 2	*p*-value
Imaginative Play	0.943	0.231	1.033	0.230	0.964	0.232	1.023	0.273
Gesture Use	1.003	0.458	1.002	0.479	1.032	0.175	1.036	0.191
Giving	1.008	0.411	1.025	0.279	1.057	0.123	1.018	0.385
Pointing	1.019	0.331	1.028	0.246	**1.163**	**0.043**	**1.185**	**0.027**

Note: Bolded values indicate significance at the $p = 0.05$ level.

3.4 Discussion

The goal of this study was to identify predictive value of eye tracking in understanding later difficulty emerging in the core symptoms and more peripheral symptoms of ASD. To this end, a dataset of young children (age <3 years) who were at high risk of developing ASD, and had been given the ADOS at two time points, was re-analyzed (Chawarska & Volkmar, 2007). These children also had their visual attention patterns analyzed using an eye tracker when they were watching a naturalistic caregiver scene. As in previous studies, the high-risk group of children (i.e., those children who were more likely to be diagnosed with ASD because they were siblings of children already diagnosed with ASD) showed significant differences from the low-risk group, focusing on non-informative parts of the scene (i.e., the background) whereas children who were in the low-risk group focused on the eyes of the caregiver. Regression models using eye tracking and the Mullen as in Study 1 were reasonably accurate at detecting group membership (76%). It is important to realize that unlike the previous study, this analysis was not predicting final diagnosis, but rather group membership at time 2 since this study only distinguished between and high and low risk groups. When the children who could not definitively be diagnosed with ASD were removed from the sample (these children had a score reflecting no diagnosis or broader spectrum on the ADOS), the accuracy was 92%. This reinforces the findings of Study 1 that a simple combination of measures, including eye tracking, may be effective in predicting the emergence of ASD at a later time point.

One reason for the effectiveness of eye tracking in predicting a diagnosis of ASD may be due to the effect of attention to social stimuli on the developing brain. As discussed, the Crick and Dodge (1996) social information processing model (SIP) posits that there are later effects from the improper encoding of cues. These effects could be one factor that leads to the accumulation of atypical learning experiences, such as those proposed by Klin and Jones (2013). For example, children who do not attend to a social interaction between two children on the playground where one is asking the other to play for the first time, later may not be able to effectively deal with a friendly advance directly towards themselves.

The propensity to give preferential status to biological stimuli may be impaired in ASD (Li et al., 2021), leading to the lack of typical social learning seen in typically developing peers of children with ASD. Johnson (2015) suggests that, for a variety of reasons, the brain of the child with ASD is not able to keep up with the high frequency and complexity of social information. This may lead to the brain's development in ways in which it can effectively process information (i.e., by not attending to the more confusing or problematic social information). That is, according to Johnson the style of attending seen in children with ASD may be due to a preference to reduce the input or load of information.

I proposed here that given these arguments, it should be expected that those functions that are impaired in ASD should be predicted by the logical application of the Crick and Dodge (1994) model. That is, if the child improperly encodes cues, we should observe the most deficits in those areas that follow from the missing cues. Eye contact, gaze integration, and joint attention were selected as those areas are most likely to be affected (or affected first) in the developing brain of the child with ASD. Eye tracking may serve as a strong marker of differential encoding of social stimuli. According to the SIP model, encoding serves as the first step in a chain of events that can manifest as different behaviours (e.g., not making good eye contact). In contrast, other issues associated with ASD, but logically “downstream” from the initial disturbances would follow at a later time or with decreased severity.

In line with these propositions, children in the high-risk group in this study showed more difficulty with the eye tracking task than the children in the low-risk group. Further, at Time 1 the children who had more time spent looking at something in the background as opposed to areas with more social information such as the eyes or mouth, showed a higher risk of displaying more difficulty with joint attention and response to joint attention at the first time point. These deficits were particularly entrenched by time 2 as these children had a higher risk of showing difficulty with eye contact, gaze integration and response to joint attention. These effects were generally large; for example, a single percentage point increase in the time spent looking at the background indicated a 26% greater likelihood of being rated as having low levels of eye contact.

In contrast, the downstream effects were more attenuated with only difficulties in pointing showing a significantly higher risk based on eye tracking, and this was only at time 2. The other areas studied here (i.e., imaginative play, gesture use, and giving) showed much smaller increases in risk, and none of these were statistically significant. Therefore, the results of this study indicate that eye tracking specifically predicts core ASD dysfunction. In addition, these results mirror the developmental pattern of deficit presentation in ASD (Gordon & Watson, 2015; Miller et al., 2017; Sansavini et al., 2019; Zweigenbaum et al., 2015). However, the downstream effects are generally not predicted by the eye tracking durations, indicating as hypothesized that these behaviours are not part of the initial dysfunction arising from lack of proper attention. It may be that these behaviours are affected later – that is, given more time, these behaviours would be predicted by eye tracking. It may also be that these behaviours are mediated by another variable. Some researchers have found in previous studies that these may be mediated by language ability (Gordon & Watson, 2015).

The findings in the study have two major implications. First, they reinforce the suggestions of Jones and Klin (2013) that eye tracking which captures attention to social stimuli and improper attentional patterns to informative social areas lead to compounding atypical learning experiences that lead to some of the core dysfunction seen in ASD. The problematic encoding and the resulting behavioural dysfunction are predicted by the Crick and Dodge model (1994) of social information processing. Secondly, the findings suggest that the core of ASD dysfunction emerges in an interconnected manner with social attention, whereas other symptoms of ASD (i.e., the "downstream" effects) do not. This largely reflects the ASD literature in that many studies describe other symptoms (i.e., these downstream effects) emerging at different or later ages (Gordon & Watson, 2015; Miller et al., 2017; Sansavini et al., 2019; Zweigenbaum et al., 2015).

Our understanding of the emergence of ASD symptomatology is developing and, as Johnson (2015) suggests, it seems likely that ASD is a reflection of a combination of compromised brain areas/connectivity and atypical learning experiences. Any of the brain areas implicated in social understanding, social processing, language, or the integration of information could lead to difficulties for children in being able to attend to complex social information of these types. The child learns to focus on material that we predict that he or she does not find overwhelming, or at least is less complex. One likely reason that social information may be overwhelming are difficulties in multi-sensory information processing that have been identified with ASD (Bebko et al., 2014) That is, there are noted difficulties for people with ASD with integrating verbal and visual information that are inherently part of social interactions. Over time, this change in focus leads to specialization in areas that are predictable or comforting and resulting in a lack of understanding of the broader social rules required in life and/or competence in the use of language. This study helps to put in context how those areas of dysfunction might emerge. The child with ASD who does not focus on the caregiver's face, over time does not learn to make crucial social leaps such as integrating their gaze with action and the interplay of joint attention. These problems are exacerbated over repeated cycles depicted in the SIP model to the point where eye contact (or the other "near" areas) become increasingly dysfunctional.

3.4.1 Clinical Implications

The first implication for the use of eye tracking mirrors the conclusions of the first study. Eye tracking is an effective, relatively inexpensive way to screen for markers of potential social encoding difficulties, which is associated with the core symptoms of ASD (e.g., eye contact, joint attention, and gaze integration). While the optimization of the video and administration method need further study, its benefit as an aid to understanding ASD should be considered. It may be implemented economically; already many smartphones and iPads contain rudimentary eye trackers, and these have already begun to be studied in conjunction with ASD (Strobl et al., 2019) As technology becomes more widely available and more efficient, the mass screening of children who have access to these devices can one day be simple and effective. For a more thorough exploration, see Study 1. In developing countries and in remote countries, it could be helpful to identify children in need of early intervention whether it be children with ASD or other social impairments (e.g., Patel, 2019).

Secondly, this study in conjunction with the findings and conclusions of Johnson (2015) and Klin and Jones (2013) suggests interventions that target and encourage social engagement may be vital in helping to accumulate *typical* learning experiences. That is, if a child can be engaged in effective social interactions, the symptoms that develop in ASD may be altered to some extent early on in this cascade of events. The SIP model (Crick and Dodge, 1994) examined in this study suggests that without repeatedly failed social learning experiences, the internalized "database" of the child may reflect different social schema, knowledge, and rules about how to interact with the world. Indeed, many ASD interventions have incorporated this proposition into clinical practice. For example, Naturalistic Developmental Behavioral Interventions (NDBIs) are a group of interventions that seek to provide naturalistic contexts in which to engage and develop children's social interactions and focus on key principles including engaging the child in parent-child activities (Schreibman et al., 2015). Parents are given a variety of strategies by which to capture their child's attention, first to draw it to themselves and then to redirect it towards relevant stimuli in their environment. By doing this, the child with ASD learns to interact with their environment by attending to the most important and informative pieces. Applied Behavioral Analysis include techniques such as reinforcement for proper eye contact (Mundy et al., 1990), but some NDBI's seek to use the social engagement with the caregiver as the context in which to learn (Ingersoll & Wainer, 2013). The impact of these strategies may be fundamental in the developmental trajectory of ASD and could amplify their effect over repeated experiences, compared with strategies that work by teaching sets of skills.

3.4.2 Future Directions

There is a good foundation for understanding the developmental pathway by which some of the symptoms seen in ASD emerge. However, much work remains in understanding the nuances of this pathway, especially given the diversity seen in ASD. Longitudinal research that focuses on the development of symptoms of ASD and how these relate to eye tracking is possible with the myriad of well-funded, multisite studies that are currently underway in North America (e.g., Chawarska & Volkmar, 2008; the first study from an expanding database used by these studies). These studies may be able to clarify crucial questions about how the developing brain is affected by insufficient attention to the social world. Complex models that require many participants and incorporate the role of mediating variables (such as language) will be invaluable in understanding how the "near" effects affect the other symptoms seen in ASD.

While there is some evidence that the difficulties identified by eye tracking (i.e., engagement) lead to appropriate and useful strategies for intervention, specifically targeting these areas will reveal further information about the development of ASD symptomatology. For example, Johnson (2015) argues that some of the core reasons why the child with ASD focuses on non-social information is because social information is unpredictable and overwhelming. Future studies that examine whether social scenes that have more predictable information or information with fewer cognitive demands are more engaging will help further clarify the efficacy of intervention targets derived from these premises.

Chapter 4: Study 3

4.1 Introduction

Autism Spectrum Disorder (ASD) is a developmental disorder associated with social communication difficulties and repetitive behaviours and/or restricted interests (APA, 2013) and it is associated with a range of interpersonal difficulties, including higher rates of bullying victimization (Rowley et al., 2012). In order to understand some of the perpetuating factors of these difficulties, this study examines the way information processing may affect a child's response to bullying.

According to the Social Information Processing (SIP) model (Crick & Dodge, 1994), first children must encode age-appropriate social information. However, Crick and Dodge (1994) also propose downstream consequences as a result of improper encoding. For example, one would expect children who encode the wrong information to have difficulty understanding and appropriately interpreting the information (second step in the model). Naturalistic scenes containing social interactions can provide much information about the myriad of ways a child with ASD may miss information (e.g., Klin et al., 2002). This study was designed to determine whether eye tracking can predict errors in interpreting nuanced social situations, such as those found in bullying situations.

While the way in which children with ASD process information can be examined through a variety of observable behaviours, bullying situations offer several compelling reasons for study. Children with ASD experience higher rates of bullying victimization than typically developing (TD) children and children with cognitive impairments (Rowley et al., 2012; Schroeder et al., in prep). The study of eye tracking in the context of social information processing could be used to examine whether children with ASD are particularly likely to fail to encode the most appropriate information, and as a result, form biased interpretations of their experiences. These interpretations could, in part, help to explain the differences observed in rates of bullying.

The failure to encode information is particularly likely given that eye tracking patterns seen in the literature show that children with ASD are less likely to focus on critical areas of social interaction (Jones & Klin, 2013). Failure to encode the appropriate social information also may lead to deficits in children with ASD with selecting the most socially appropriate responses, which could help to explain the differences in rates of victimization observed. That is, if children are unable to encode vital information (e.g., the eyes of a person making a joke), then it follows that they are more likely to misinterpret the situation (e.g., thinking nothing funny was said), leading to them selecting an action that is socially inappropriate (e.g., not laugh when everyone else is laughing), which may lead to them being singled out or teased. The goal of this study is to evaluate the first two steps of the SIP model: do children with ASD fail to encode appropriate cues in dynamic social situations (first step), leading to problematic interpretations (second step)?

4.1.1 Bullying and ASD

Children with ASD are bullied at a rate higher than their peers (Maiano et al., 2016; Nowell et al., 2014). For these children, the type of bullying more often than for their peers involves social bullying as opposed to physical violence (Kloosterman et al., 2013). One study examining the experiences of 279 children with ASD found that while factors such as "meltdowns", hygiene, rigid adherence to rules, and self-injury were predictive of negative peer experiences, while other factors such as repetitive behaviours or tics were not (Adams et al., 2020). This suggests that the social characteristics of ASD likely represents a greater part of the association seen with bullying when compared with restricted and repetitive behaviours. Indeed, Nowell and colleagues (2014) found that higher cognitive ability and less severe ASD symptomology were predictive of bullying experiences, rather than the opposite, though this is controversial (c.f., Tanaka et al., 2014). Further, there is evidence that suggests that as a result of bullying experiences, children with ASD are more likely to develop internalizing issues such as anxiety or depression, which then place these children at even greater risk of victimization (Adams et al., 2014). Taken together, the conclusions of these articles suggest that one of the reasons why children with ASD may be victimized is a difficulty with social nuances rather than overtly bizarre or odd behaviours.

4.1.2 Understanding of Bullying Experiences

The role of the child's social understanding of bullying in ASD is not well understood. Roekel and colleagues (2010) showed no differences in understanding of social scenes involving bullying between typically developing children and those with ASD. However, in their study, the children were presented with straightforward scenes with explicit bullying. That is, in the scenes the children who were depicted as bullies would clearly perform aggressive actions (e.g., yelling, hitting) toward another child. In these conditions, the children with ASD were able to identify the presence and type of bullying. In order to examine more nuanced understanding of bullying in children with ASD, Hodgins and colleagues (2020) showed children ecologically valid scenes of bullying, that is, scenes more like those that a child might encounter in everyday life. These scenes depicted classroom or similar experiences that contained instances of bullying but were more subtle expressions thereof (e.g., laughing at another child, intimidation rather than violence, threat of exclusion). In addition, the children were also asked to identify aggressors or bullies. Under these circumstances, children with ASD showed less understanding of these social situations than their typically developing peers.

4.1.3 Bullying in Typically Developing Children

In order to understand the relationship between autism and bullying, I will first turn to the wider literature on bullying. Predictors of victimization provide us an important clue into these common childhood experiences. While the victims are, of course, not to blame, there are predictable sets of variables that may make children more vulnerable to bullying experiences. Foremost among these include loneliness and disconnection from peers (Acquah et al., 2016). In direct and cyber-bullying examples, lower self-esteem is an important variable (Brighi et al., 2012). Kollerova and Smolik (2016) conducted a study with 512 young adolescents. They found that peer rejection and male gender were highly associated with victimization experiences. Fear of victimization was also related to victimization. The handful of studies here illuminate that bullying is a complex social phenomenon that often occurs where social rejection and poor self-esteem are present. Social rejection often occurs in situations where the peer at risk is not able to conform with the rest of the group (Gordon et al., 2018)**.** Children with ASD specifically often struggle to understand social nuances as well as other children, are more likely to be male (4:1; Constantino et al., 2012), and often possess traits associated with rejection (i.e., loneliness, lower self-esteem; e.g., McCauley et al., 2019).

4.1.4 Social Information Processing and ASD

Children with ASD often have great difficulty interpreting nuanced social situations (Parish-Morris et al., 2019). The social information processing model (SIP; Crick and Dodge, 1994) offers insight into the developmental processes behind these interpretive difficulties. Crick and Dodge sought to explain the sequential nature of social information processing in their model (1996). First, social information is encoded, followed by successive steps of interpretation, goal selection, response generation, response evaluation, and finally, enactment.

While much work has focused especially on the enactment of behaviours, we stand to learn much by understanding the process leading to problems in these enacted behaviours. In bullying situations, the middle steps, especially interpretation of the encoded cues, are important. There are many behaviours which could be interpreted as friendly or as an instance of bullying depending on context. A child making a joke about another child can be an instance of playfully connecting with that child, bullying that child, or doing anything in between.

Children's interpretation of bullying experiences is crucial for parents, teachers and the children themselves to understand (Barone & Barone, 2021). In some cases, the willingness to intercede (as caregivers or teachers) in a situation depends on the interpretation of the situation (Ireland et al., 2020). Samnani (2013) has noted that in subtle cases of bullying, the victims may find it more difficult to defend themselves. In addition, bystanders are more likely to be confused as to how and if to intervene in these situations. Even more problematically for the child, Prinstein and colleagues (2005) noted that the children who are presented with ambiguous peer clues (i.e., clues that could be mean or harmless depending on context) are more likely to make self-critical attributions, which can lead to more depressive symptoms.

A possible pathway for understanding the difficulties experienced with bullying by children with ASD is outlined below: first and foremost, these children may be less likely to understand the social cues present in the bullying situations that they face. Especially in more ambiguous instances of bullying, these children may be making more self-critical attributions than others who have a better understanding of the cues (e.g., as in Prinstein et al., 2015). For example, a child who does not know why another child knocked over their board game may have a thought like "I must have made them angry because I don't understand the rules" or "I must be no fun to play with" rather than "they are behaving in an aggressive way because they do not know how to handle disappointment". These thoughts and distorted or maladaptive attributions can lead to significant internalizing symptoms such as anxiety and depression, which are found at a higher rate in children with ASD compared with their peers (Acquah et al., 2016).

4.1.5 SIP, Eye Tracking, and ASD

A few studies have examined the relationship between social information processing and ASD. Consistent with the previous research presented, children with ASD have difficulty detecting socially inappropriate behaviours (Loveland et al., 2001). In addition, children with ASD are more likely to forget facts that they originally remembered after viewing social exchanges, suggesting that they are not encoding the information as easily (Channon et al., 2001). Some researchers have also identified problems with the response selection stage of the model, when asked to choose a response to a presented social scene (Bernand-Opitz et al., 2001; Channon et al., 2001). Hodgins and colleagues (2018) have also demonstrated that children with ASD have more trouble detecting bullying compared with their peers. A promising method of examining the relationship between social information processing and social attention is to use eye tracking technology to examine what information children are encoding. Using eye tracking, we are able to examine the relationship between the initial encoding of the event and the child's understanding of the intent of the offender. If a link between the encoding and this interpretation is determined through eye tracking, this would help to identify a pathway to better understand the specific struggles we see in ASD regarding bullying. In order to understand the relationship between the encoding of the cues and the interpretation of the event (i.e., in this case the intent of the bully), I will re-examine data from a study previously conducted in my lab (Schroeder, 2014). In this study, Schroeder collected data from children with ASD and typically developing children (TD) about their bullying experiences. She confirmed that children with ASD experienced more instances of bullying than their peers (both self-reported and parent-reported). In addition, she noted that children in the ASD group were less likely to look at faces than children in the TD group, more likely to miss vital information about emotions and motivations, and that this difficulty with encoding was linked to victimization. However, there is a crucial middle step in this proposed process that yet to be explored. The purpose of the present study is to determine which encoding errors lead to problems in interpretation of the event.

Through the exploration of the current literature and the social information processing model, I hypothesize that those children who have the most difficulty with encoding the most pertinent relevant social information, will also have the most difficulty understanding the intent of a bully. Social information usually includes facial expressions but can also include other factors (e.g., the body, posture, relevant actions) depending on the specific context of the interaction. If this is the case, as Prinstein and colleagues (2015) noted, those children who miss the type of information described above are more likely to make negative self-attributions, potentially leading to greater isolation from peers and internalization problems. As reviewed at the beginning of this study, these conditions leave one particularly vulnerable to bullying. While the theoretical pathway leading from the encoding of cues to the greater vulnerability to bullying is complex and largely unexplored, in this study, I hope to establish a link in the early steps of the pathway, namely the encoding of cues (e.g., the relevant cues identified above, which could include faces, posture, etc.) and the understanding of the intent of the offender. Further, to properly understand the encoding of cues, the eye tracking information gathered by Schroeder (2013) was re-analyzed. Key areas in complex social scenes were identified and areas of interest were created over these socially informative areas to determine the child's attention to these social cues. While the previous analysis relied only on the encoding of faces (Schroeder, 2014), new and dynamic areas of interest were identified that change depending on the socially directed focus of the scene. That is, areas of interest were created with the complexity of social interaction in mind. Rather than focusing solely on faces, the areas of interest followed the direction of social cues (e.g., a point would mean that the next AOI is at the terminus of the point) and these are described in further detail below.

4.2 Methods

4.2.1 Participants

This methods section was adapted from Schroeder (2014). Participants included 24 children with ASD as well as 24 typically developing children, ranging from 6 – 14 years of age. Most of the ASD participants were in a regular classroom with special accommodations. 83% of the ASD group were males and 79% were males in the TD group. Participant groups were matched based on age as well as IQ (Table 7). There were no significant group differences in age between the ASD group (M = 11.25 years) and the TD group (M = 10.10 years; $t(45) = -1.53$, p = 0.13). There were no significant group differences in verbal intelligence (VIQ) standard score between the ASD group (M = 104.00) and the TD group (M = 109.63), or performance intelligence (PIQ) between the ASD and TD (M = 102.43 and M = 105.65 respectively; $t(31.82) = 1.11$, $p = 0.28$ and $t(30.94) = 0.54$, $p = 0.47$ respectively).

Table 7

Means and standard deviations of the IQ and age for the ASD and TD groups

	VIQ	PIQ	Age
TD (n = 24)	109.63 (12.17)	105.65 (9.94)	10.10 (2.66)
ASD (n = 24)	104.00 (20.29)	102.43 (17.61)	11.25 (2.49)
Cohen's d	0.33	0.23	0.45

A previous diagnosis of autism spectrum disorder was required to be placed in the ASD group. Previous ADI-R or ADOS scores were reported for 44% of participants in the ASD group and all these participants met criteria for autism. The CARS-2 was used to assess severity of ASD symptoms for everyone in the ASD group and scores generally fell in the mild range of ASD symptoms ($M = 27.13$, $SD = 3.18$, range = 20.5 to 34.5).

4.2.2 Stimuli

Participants were shown nine videos (of which, four are reported on for the present study) from the Social-information Processing Application (SIP-A), commercially available videos by innovation Research & Training (2009). Each video begins with a brief 30 second depiction of explaining a social interaction between two or more children involving a potential bullying situation. These first-person perspective videos allow participants to view the scene in the role of the primary actor, thereby increasing the likelihood of identifying with the child.

After the first video (a training video), the videos used in this study consisted of one clearly hostile video (a bully grabs homework out of the hand of a child, throws it on the floor, and steps on it), two ambiguous videos (a peer is losing a game of chess, and then appears to knock the game board over, but it is difficult to ascertain intent; another child places a Gameboy on a ledge and another child is seen heading over to the ledge, and the Gameboy disappears).

Videos were shown to the children on a 66 cm television in front of which they sat with their eyes at the approximate midline of the screen, approximately 60 cm away. The eye movements were recorded using a Tobii X60 at a rate of 60 Hz. The children were shown a training video to orient them to first-person perspective, where they would view actions from the point of view of the camera recording the scene. After this, they were shown the testing videos which continued to be in first-person perspective. After this, they were asked open-ended and closed-ended questions about the video. The children's responses were coded depending on the video. This coding is described in the "Results" section following the description of the looking patterns that were expected and observed in each video. The intent of the child in the video was determined by asking: "Do you think the other child meant to be mean?". The children were given a Likert response scale, with a 1 being defined as definitely mean, a 3 being maybe mean, maybe not mean, and a 5 being definitely not mean.

4.2.3 Analysis

AOIs are created by superimposing a 2-dimensional area over the original scene while eye gaze patterns were recorded. That is, a section of the image on screen is identified as an area of interest, then is frame by frame altered to match the movement in a video. An eye gaze within the AOI is recorded each frame, and the total time spent looking within the AOI is tabulated by the software. For example, if a backpack was identified as a potential target for eye gaze, a rectangular area of interest was superimposed on the backpack, and moved frame-by-frame as the backpack moved. The previous analysis of the videos consisted of areas of interest (AOIs) created on the characters' faces. No other AOIs were used. However, these scenes are fast-paced scenes with shifting of camera angles in order to focus on different parts of the characters (e.g., someone's hand for pointing, or the foot of a bully stepping on homework). The focus of the scene (i.e., the first-person camera perspective) also shifted onto non-social aspects of the scene (e.g., the Gameboy, the homework). For the current study, in the scenes mentioned above, new AOIs were superimposed on those parts of the scenes that convey the most important information in the scene (e.g., character's faces, the focal point of their actions). These AOIs were created to dynamically shift based on the most important social information in the scene. Cues such as pointing, gaze shift, verbal cues, and others were considered. Two researchers independently created AOIs over these scenes. The focal points of the AOIs were found in 100% of the other researcher's AOIs indicating strong agreement between the researchers. Then, using eye tracking software, the amount of time children with ASD spent looking at these parts of the scenes was compared with the time spent by TD children. The aggregate of this looking time was the new variable, considered as time spent encoding, and these times were compared with the intent attribution of the child to the actions of the children in the scene.

4.3 Results

The results of the scenes are presented one at a time. In the tables are presented total looking time, which represents the full amount of time looking at the screen, including time not spent looking at any of the AOIs.

4.3.1 Gameboy Scene

The first of the three scenes (not including the training video) was the Gameboy scene. In this scene, there was not a significant difference in overall looking time between the ASD and TD groups ($p = 0.322$). In this ambiguous scene, the child who is the presumed thief was shown from the viewer's perspective at first. His face and classmates' reaction provided the primary social clues as to what happened in the scene. The Gameboy was placed by the observer on a windowsill, after which the observer turned to face a classmate. Outside of the focus of the scene, a child (the presumed thief) walked by, and the gaze of one of the classmates standing nearby shifted towards the now empty windowsill, as well as the presumed thief's backpack. Examining the areas described in this paragraph that were in focus, the AOI around the Gameboy and the classmate showed no group differences between the typically developing children and the children with ASD ($p = 0.120$ and $p = 0.454$, respectively). The AOI focused on the thief showed no significant difference in looking time ($p = 0.259$). However, the social cue directed area (defined by the glance of the classmate), the backpack, did show a significant difference ($p = 0.007$) with the children with TD viewing this informative area more. In contrast, the children with ASD paid more attention to an empty windowsill where the Gameboy was in the past. They did not show scanning (i.e., looking around the window), but focused (more than the TD children) on the AOI in the location where the Gameboy had been ($p = 0.043$). The total looking times are presented in the Table 8 below, with the following scenes presented in Table 9 and 10. Again, total looking time represents looking time at the AOIs and time spent looking elsewhere on the screen.

For this video, where it is truly ambiguous whether the child stole the Gameboy (there were also other people walking in the crowded hallway), the answers to the intent question were coded as insightful (a sample response "you can't tell who did it"), showing some insight ("it was confusing with all the kids") or no insight ("it was probably one of the kids in the hall". A multinomial logistic regression showed that overall looking time at the AOIs in the scene was a significant predictor of "showing some insight" over "no insight" ($p < 0.001$) and was in the marginal range for the "insightful" responses over "showing some insight" ($p = 0.063$). In addition, for the backpack (i.e., a social cue directed stimuli), looking time was a significant predictor of the difference between the “no insight” and “showing some insight” category (p = 0.049). The odds ratios from these analyses are present in Table 11 below. A chi-square test revealed no significant differences between ASD and TD with regards to insight ($X^2(2) = 0.027$, $p = 0.870$).

Table 8

Looking Time in Seconds During the Gameboy Scene for ASD and TD Group

	ASD	TD	t(df)	p	Cohen’s d
Total	74.760	78.923	0.47(22.83)	0.322	0.21
Gameboy	27.010	34.577	1.22(22.26)	0.120	0.47
Backpack	4.883	9.954	2.71(21.08)	0.007*	1.08
Thief’s face	4.907	3.680	0.642(16.70)	0.259	0.16
Classmate	2.377	2.637	0.11(18.38)	0.454	0.05
Windowsill	2.563	1.514	1.74(15.42)	0.043*	0.71

Note. * Denotes a significant difference between the groups ($p < 0.05$)

4.3.2 Chessboard Scene

The second scene, also an ambiguous scene, was that of a chess game between the viewer and the potential bully (presented in Table 9 below). The potential bully seems to be losing the game and knocks over the game with his arm. While this could be an accident, it seems, based on his facial expressions, that it was a deliberate act. The difference between the ASD and TD groups was not significant with regards to overall looking time ($p = 0.086$). In the scene, the opposing child’s arm knocks over the chessboard, but the movement of the arm may be deliberate or unintentional. The arm provides little information about the intention and there was not a significant difference between the groups ($p = 0.162$). The chessboard similarly is not illuminating of intention, but there was a significant difference here with the TD group looking more at this AOI ($p = 0.008$). The player's face provides clear information on his intention and again the TD group had more looking time at this AOI ($p = 0.011$). Despite the importance of looking at the face, none of the AOIs for this video were significantly predictive of insight using multinomial logistic regression models into the scene using the same coding as above ($p > 0.05$). These analyses are presented in Table 12 below. However, simple correlations revealed the proportion of looking time toward the child's face was correlated with insight into the scene (r = 0.373 $p = 0.050$). A chi-square test revealed no significant differences between ASD and TD with regards to insight ($X^2(1) = 0.024$, $p = 0.876$).

Table 9

Looking Time in Seconds During the Chessboard Scene for ASD and TD Group

	ASD	TD	*t*(df)	*p*	Cohen's d
Total	53.209	64.909	1.47(12.97)	0.086	0.75
Hand	17.818	12.680	1.04(13)	0.162	0.53
Face	2.560	11.891	2.42(6.43)	0.008*	1.29
Chessboard	0.813	2.966	2.64(8.63)	0.011*	1.39

Note. * Denotes a significant difference between the groups ($p < 0.05$).

4.3.3 Ruined Homework Scene

In the ruined homework scene, the intention of the bully is apparent. The bully took the homework out of the viewer's hand and threw it on the ground. He then stepped on it and moved his foot around. Although this scene was obviously hostile, there were still several children who did not provide insightful answers. The TD group spent much more time looking at the bully's face and the homework than the ASD children ($p = 0.014$ and 0.013 respectively; presented in

Table 10). The other AOIs showed no significant difference in looking time and there was no difference in overall looking time between the two groups ($p = 0.401$). The logistic regression models revealed a significant effect of looking time at the bully's foot on "Insight" ($p = 0.028$). That is, the children who looked most at the bully's body during the act where the bullying happened, were the most likely to identify that the child was being hostile. These analyses are presented in Table 12 below. *A* chi-square test revealed no significant differences between ASD and TD with regards to insight ($X^2(1) = 1.246$, $p = 0.265$).

Table 10

Looking Time in Seconds During the Homework Scene for ASD and TD Group

	ASD	TD	t(df)	p	Cohen's d
Total	65.660	67.771	0.25(16.32)	0.401	0.10
Bully	7.157	7.498	0.26(18.15)	0.399	0.11
Foot	0.090	0.542	1.32(10.47)	0.107	0.56
Homework	14.917	28.280	2.38(18.88)	0.013*	1.00
Bully's face	0.830	1.716	2.26(11.35)	0.014*	0.96
Bully's foot	2.760	2.251	0.28(16.25)	0.493	0.10

Note. * Denotes a significant difference between the groups ($p < 0.05$).

Table 11

Exponentiated regression coefficients showing odds ratios showing likelihood of greater insight for Gameboy Scene

Gameboy AOI	Odds Ratio (0-1)	*p*	Odds Ratio (1-2)	*p*
Total	1.061	0.000	1.010	0.063
Gameboy	1.013	0.350	0.989	0.360
Backpack	1.346	0.049	0.939	0.302
Thief's face	1.055	0.365	1.138	0.154
Classmate	1.480	0.096	0.624	0.103
Windowsill	0.578	0.174	1.319	0.169

Table 12

Exponentiated regression coefficients showing odds ratios showing likelihood of greater insight for Chessboard and Ruined Homework scenes

Boardgame AOI	Odds Ratio	*p*	Homework AOI	Odds Ratio	*p*
Total	1.016	0.576	Total	1.012	0.597
Hand	1.090	0.176	Bully	1.149	0.367
Face	-1.030	0.658	Foot	0.580	0.466
Chessboard	1.806	0.274	Homework	0.990	0.752
			Bully's face	0.717	0.500
			Bully's foot	2.083	0.028

4.4 Discussion

In this study, a series of complex and ecologically valid videos about potential bullying situations were shown to children with ASD and TD peers. There were three experimental scenes; one was a scene depicting an obvious bullying situation, in another, the intent of the offender was likely aggressive, and in the last, the intent was not clear. I examined eye gaze patterns in each of these scenes to understand whether children with ASD would look to the informative, socially directed parts of the scene where their TD peers would look. Second, I also examined whether these patterns of looking would predict insight into the behaviour of the potential offender. ,Contextualized in the Crick & Dodge's (1996) social information processing model (SIP), this study examines the relationship between encoding of cues and the interpretation of events, the first steps of SIP, in children with ASD. The pattern of results shows clear differences in the types of stimuli that TD children and ASD children attend to. TD children were more likely to attend to the faces captured by the areas of interest (AOIs). These AOIs were created to capture the most informative parts of the scene in understanding what was happening and in order to understand the intent of the characters. Often, these AOIs were social parts of the scene (e.g., a character's face) or directed by social cues (e.g., following a point). Indeed 2/3 of AOIs that contained a character's face showed significantly higher looking times for TD children. However, it is interesting to note that this increased focus was not restricted to social stimuli. TD children also looked at some key non-social stimuli, for example a backpack (where a stolen item may have been hidden), a chessboard (the main item towards which the possible bully expresses his aggression) and homework (the clearly targeted item of a bully's aggression). These areas could be vital in understanding the intent of a possible aggressor. These differences suggest that children with ASD may not simply fail to encode social stimuli, but may also not identify the social implications of a scene and may also fail to look at non-social stimuli that are cue directed. That is, while they may look at the relevant child who may be a potential bully in some situations, they may have more trouble with following the sequence of events and may not understand the importance of cues that are socially indicated (e.g., by a glance of a classmate) than a typically developing child may.

In addition, the duration of the time spent looking at some of these AOIs were significant predictors in whether the child understood the intent of the aggressor or not. This is not to say that children viewing this scene were all inattentive, but that the most inattentive children were the most likely to make interpretation errors across the groups. In one presented scene, the bully is clearly aggressive and stomps on a piece of paper that is the child's homework. Here, if the child was paying less attention to the bully's foot, they were less likely to identify the intent of the bully (i.e., to be a bully). Likely, this indicates that if a child misses this component of the scene, they might miss a pertinent detail in understanding intent. This is the focal point of the action in the scene, indicating that children who missed this were looking away from this part of the scene, perhaps because they were inattentive, or it was uncomfortable to watch. Indeed, children with Attention Deficit Hyperactivity Disorder and other attention issues are more likely to get bullied than TD children (Simmons & Antshel, 2021) and these results help us understand one of many possible explanatory pathways. That is, inattentive children may miss key details which are likely to lead to misunderstanding social situations.

In another ambiguous scene (i.e., it is not explicit that the other child is a bully), but given the context cues (i.e., the other child shows frustration on their face and knocking over the board looks like a deliberate arm movement) it was likely that the child is intentionally aggressive. In this scene, none of the AOIs were predictive using logistic regression models of understanding intent. However, this was likely at least partially a power issue. Due to technical limitations (e.g., situations where the eye tracker did not record information correctly or the children left their seat), only 15 children were recorded during this scene. In addition, there is a significant correlation between looking time at the possible bully's face and insight into the bully's behaviour. This suggests that the proper encoding of the cues is a crucial step in understanding this situation better. As suggested by the Crick and Dodge SIP model (1996), it is reasonable that missing the cues and problematic understanding of intent are likely to lead to ongoing downstream issues that may contribute to bullying experiences. A growing collection of research studies indicates that those children who do not understand the nuances of social situations are more likely to be bullied (Hodgins et al., 2020; Swearer & Hymel, 2015). This study suggests a possible first step in this pathway: these children may be less adept at following and attending to complex social interactions. While with other scenes, they may attend occasionally to a face, in situations like this, they may have more difficulty understanding that it is vital to attend to the face. In addition, the fact that children with ASD are overall less likely to attend to faces (McPartland et al., 2015), means that vital seconds of important social cues are missed, leading to problematic interpretations.

Finally, another scene, the *Gameboy* scene, depicted a complex social situation, where it appears that a child may be responsible for stealing the main actor's toy. This scene presents several items that may provide clues (i.e., the other child's face, his backpack where he may be keeping the toy and the windowsill from where the item was taken). In this scene, children who attended to all the different aspects of the scene were most likely to provide insightful comments into what may have happened. Unlike the other scenes, it was not a single item or AOI that predicted insight but the entirety of their attention towards the scene**.** Again, the findings from this scene reiterate that in complex social situations, it is imperative that children attend to and keep track of multiple crucial bits of information at a time in order to understand the intent of others. In simple cases, looking at the focal point of the scene is enough. However, in situations where the intent is unclear, it requires carefully attending to all parts of the interaction. These videos and the eye tracking data provided here suggest that since attention to relevant cues (often of a social nature) is so often compromised in children with ASD, there is a likely sequential pathway of accumulating missteps in the steps of the SIP model, which may account for the increasing difficulty seen in nuanced social situations. Some evidence suggests that children with ASD are able to identify straightforward social conflict as readily as TD children, including instances of bullying (Bellesi et al., 2018; Nah & Poon, 2011). The evidence presented here suggests that it is in complicated situations where multiple parts of the scene require attention that children with ASD may be more affected.

The examination of reactions to the series of videos presented in this study offer several explanatory pathways for the misinterpretation of social interactions. First, as shown using the *Homework* scene, a child may miss crucial information due to inattentiveness. In this scene, children were not all inattentive, but the ones that were the most inattentive were most likely to misinterpret the scene. Significant amounts of research indicate that children with ADHD are more likely to be bullied (Simmons & Antshel, 2021). It is also important to note that children with ASD often have co-morbid attention issues (Tye et al., 2014). Second, as shown using the *Chessboard* scene, children with ASD classically demonstrate a difficulty in attending to faces. Often, the most relevant social information is found by examining another's face, an act that children with ASD may find difficult. Finally, as in the *Gameboy* scene, some interactions require efficient gaze patterns, switching between multiple types and sources of information. Children with ASD often struggle to attend to information in this way and they showed crucial differences compared with TD children during this task. Rather than a simplistic model showing lack of attention to faces leading to problematic downstream consequences, this study identifies several pathways that can lead to ongoing misinterpretation of social situations (i.e., through attention, through face processing, and through integration of information in nuanced situations). While these may appear to be three unique problems, a more parsimonious explanation is that these are, at least, related difficulties.

The steps of the SIP model (Crick & Dodge, 1996), have at their core a feedback loop with each step of the model. These steps are posited by the authors as continuously updating the internal schema of the child and the schema are involved in modulating each step of the model.

With the difficulties outlined above, it is likely that these internal schemas are implicated in the impaired pathways suggested by Crick and Dodge in their model. Cue selection is an internal task (e.g., near automatic, based on previous experience) that incorporates attentional demands (Gottwald et al., 2002). That is, the more competing information there is to process, the more difficult the task of selecting the most appropriate cues becomes. In the case of children with ASD, cue selection may underlie the three types of difficulty identified. This may help to explain the differences identified in the introduction of this study, where children with ASD are able to distinguish bullies in some situations, but not in others (Hodgins et al., 2020; Roekel et al., 2010). The naturalistic setting presents many more competing points of information or noise, and Johnson (2015) suggests that autism is a developmental response to an inability to process multiple streams of information efficiently. There is evidence that particular brain regions are often involved in the selecting of appropriate cues, including the cerebellum (Gottwald et al., 2002). People with ASD overwhelmingly show differences compared with controls in this region of the brain (Townsend et al., 2001), indicating that this task (selecting the appropriate cue based on the situation) is one that may be of great difficulty for these children. Future studies may be able to systematically vary the information involved in tasks of cue selection and examine whether children with ASD are more affected in their attentional abilities under these demands.

It is important to note that children in the two groups did not show significant differences with regards to insight in their intent attributions. There are several possible explanations for this including the small sample size and concerns with attention or total looking time in both groups. It is possible that the pattern of encoding and interpretation persists regardless of diagnostic group (i.e., children who do not encode the proper cues are more likely to form incorrect attributions). The relevance for ASD remains that these children have demonstrated deficits in these crucial patterns in the wider literature base (i.e., more attention issues, more face processing issues, and issues following complex social scenes; Pavlova et al., 2017; Souchay et al., 2013; for a review see Campatelli et al., 2013; Jones & Klin, 2013).

4.4.1 Clinical Implications

The results of this study highlight several possible avenues for interventions. A plethora of social training programs exist for ASD (for reviews, Dubreucq et al., 2021; Shukla-Mehta et al., 2010). Many interventions focus on responding to various types of behaviour from peers and some deal with identifying other people's intentions. However, this study suggests that there are several initial factors (i.e., at the encoding or attentional level) that make it more difficult for children to interpret the scenes. Crick and Dodge (1996) also suggest that if the first steps of information processing are missed, then the following steps will be impacted and over time these mistakes are solidified through repetition and create problematic response patterns. Therefore, it may be beneficial for social training programs to focus on the encoding of cues or in training attention, by focusing on paying attention and trying to increase knowledge of where to attend. For example, a clinician could play a scene, pause, and have children identify where it would be important to attend to pick up important information.

Johnson (2015) suggests a few more avenues for helping to train focus on important parts of scenes. Some of the reasons why children with ASD may learn not to direct their focus in social situations effectively are because they find the scenes unpredictable and overwhelming. Both of these difficulties could be addressed. Introductions and explanations of social situations may help to make them more predictable for verbal children and pictures or other visual stimuli may serve the same purpose for nonverbal children (Johnson, 2015). Having social situations with fewer aspects or elements to keep track of may also help reduce how aversive they are found to be. These are commonly made recommendations when working with children with ASD but may specifically help children direct their attention to the appropriate areas. In addition, outlining the specific social cues to attend to may be an obvious step in helping with direction of attention through something like the 'pause and reflect' method described earlier.

This study also reiterates the importance of early intervention with children with ASD. Children who do not attend to these cues very early in life will likely continue to accrue problematic patterns of viewing and therefore problematic patterns of interpretation. According to Crick and Dodge (1996), this will continue to lead to further errors (e.g., response selection, behavioral responses, etc.). Naturalistic Developmental Behavioural Interventions (NDBIs) are commonly used interventions with young children with ASD (Schreibman et al., 2015). NDBIs focus on drawing the attention of children and engaging them in play using ASD specific strategies and this helps develop skills like joint attention, eye contact, and gaze integration (Schreibman et al., 2013). Given the findings of the current study, these types of intervention are crucial in helping children with ASD take the first step to better interpretation of the social world around them.

4.4.2 Limitations and Future Directions

The foremost issue identified above is the small sample size of this study. Particularly due to the challenges inherent in using technology such as eye tracking hardware and software, there were several children who were not assessed accurately. Eye trackers continue to become more simplified and streamlined and so this becomes a rapidly changing consideration. However, for studies of this kind, further consideration needs to be given with regards to the power of the study to detect differences between the groups.

Other sample characteristics are also vital. For example, if attention is important in understanding the complexity of scenes, children's attention abilities need to be carefully considered and controlled for. An ADHD group can also provide valuable information as to the role of attention in later interpretation of stimuli. Measurement of attention characteristics (i.e., ability to sustain attention) can also be useful variables in understanding the problems posed in this study. Understanding how attention variables covary with the social attention variables (i.e., attentional difficulties in addition to a lack of disposition to view social scenes) can help researchers understand the added impact of attention difficulties on social learning.

Furthermore, the videos used in this study were chosen due to their ecological validity. That is, they are naturalistic scenes with many moving parts similar to what a child might see in real life. However, this also comes with some important considerations. The different characteristics of the scene were qualitatively determined for the purposes of this study. For example, acts of aggression, the focal points of the scene and the intent of the potential bully, though they may be obvious, were not systematically controlled *a priori*. That is, the videos were not designed to address these specific problems (though they were made to be ambiguous or not). A video, or a control condition, with specific acts of aggression, a clear and directed focus, where actors are told to act in very specific ways (by the researchers) would lead to more systematic control over the factors that may affect interpretation.

Chapter 5: General Discussion

As this dissertation explores eye tracking across three different studies, the discussion will begin by exploring the various uses of eye tracking in the studies described above, as well as an exploration of the possibilities for future research more generally. These considerations will be contextualized in the three studies discussed in the dissertation.

In the first study, eye tracking was examined as a potential adjunct tool to support the accuracy of placement into different diagnostic groups. Overall, eye tracking, alongside information about language and cognitive development, provided valuable information for diagnostic purposes that proved comparable to what could be learned from a full ADOS administration. The second study examined whether eye tracking would be able to predict the development of later core ASD pathology. In this study, eye tracking more accurately predicted effects that are part of the core presentation of ASD compared to other, more distant variables. Finally, in the third study, I examined whether an eye tracking variable was useful in understanding the cascading patterns of difficulties seen in ASD. The differences in tracking between typically developing children and those with ASD in complex scenes were critical in helping to understand what social cues and other information were prioritized by these children for further analysis and subsequent responses.

5.1 The Future of Eye Tracking

While the three studies had quite different research goals, overlapping themes were evident. These studies address the future of eye tracking with regard to: the types of visual stimuli that would be useful to develop; the population to be considered for its use; its use as a potential screener in a diagnostic context. Our findings suggest that eye tracking could serve as a rich source of information when it comes to understanding social development in ASD and beyond.

5.1.1 Types of Stimuli

Eye tracking studies employ a wide range of visual stimuli. “Classic” paradigms employ a preferential looking approach where (usually) children are presented with two screens which vie for their interest (Bebko et al., 2006; Pierce et al., 2011). This approach was employed for the data that were reanalyzed in the first study. The second study utilized one stimulus that was divided by areas of interest into the mouth, eyes, body, and the background in order to examine which areas the child would be focused on, another commonly employed approach. The third study relied on a more ecologically valid virtual social scene with dynamic interactions that have their own drawbacks but have been used in eye tracking in very early and pivotal research (Klin et al., 2002) and often since. In all three approaches, the purpose of using an eye tracking measures is to discriminate between typically developing children (or children with other developmental issues) and children with ASD. The three studies follow a common approach to eye-tracking methodology, which is typically calibrated to the developmental level of the child, usually in the order of preferential looking for the youngest children, then a single stimulus, then dynamic images (e.g., Bebko et al., 2020; Jones et al., 2008; Pierce et al., 2011). However, there are variations to this progressive approach (Hironori et al., 2014).

The studies in this dissertation have highlighted that the use of eye tracking variables and stimuli need not be constrained by typical research designs. For example, most studies that examine eye tracking as a screener use it in isolation. It may be more useful to identify what information in a screening is required, and how tools can be used most efficiently to access that information. Eye tracking may be an efficient, objective, and specific (e.g., in Pierce et al., 2011) component of a screener. As ASD rates continue to rise and screening of larger populations becomes a consideration, eye tracking technology has also become increasingly accessible (Strobl et al., 2019). Many studies use a sample of videos (e.g., 3 second clips and 30 videos) to assess visual preferences. An important question to consider is whether a combination of the stimulus types described above enables better discrimination between groups compared to the single type videos used in most research. A simple battery of 5 – 10 minutes of video combined with the eye tracking technology present in most tablets could be a means of quick and efficient screening, with certain patterns of responses leading to further assessment. Combined with simple information about language proficiency, an efficient system of widespread screening becomes more attainable.

One further consideration is the ability of eye tracking to detect other developmental issues. This was the goal of the first study in this dissertation. A prior study found that those with intellectual disability (ID) showed much less attention to the relevant traffic related stimuli (Earl et al., 2019). Another study identified deficits in route learning using an eye tracking measure in children with Williams Syndrome (Farran et. al., 2016). What these studies reveal is that complex stimuli that require reasoning or adaptive abilities for navigation could be used with eye trackers to discriminate between TD and intellectual disability. The next step, then, requires tasks to be constructed that allow for discrimination among the three major pathways of early development: ID, ASD, and TD. Not only would these be useful as screening tools, but they may also help us better understand additional features of the developmental issues that are impeding social or cognitive development, for example visual attention to and interpretation of social cues. As the social information processing models suggests, difficulties with encoding and interpretation of relevant cues will likely lead to downstream consequences in behaviour. This theoretical stance is supported by the second study of this paper, as well as in previous ASD research (e.g., Jones & Klin, 2013).

5.2 Social information processing in ASD

The studies in this dissertation have used the social information processing model (SIP) put forth by Crick and Dodge (1996). The third study most specifically examined the specific steps of the model, by analyzing the effect of the first step in the model (encoding of cues) on the second step of the model (interpretation of cues). The second study in this dissertation examined proposed downstream consequences of improper encoding at the final stage of the model (behavioural enactment) by examining the core areas of dysfunctional behaviour seen in ASD. Both of these studies could help one better understand the mechanisms by which social dysfunction emerges in ASD. However, there is much that remains to be explored in working with the SIP model in ASD.

No researcher has yet examined the effect of the improper encoding of cues in every step of the SIP model for those with ASD. It is important to clarify the effect of disordered social attention in each of the steps in the model not explored in this dissertation (i.e., step 3: clarification of goals, step 4: response access, step 5: response decision). Understanding each of the steps outlined in the model in response to situations can help researchers determine the mechanisms by which the behaviours typical to ASD emerge. Each of these SIP steps have been identified as areas of difficulty in ASD. Children with ASD often do not select the same superordinate goals as other children, even if they are trying to avoid the same consequences (e.g., Romanczyk et al., 2017). Response access and faulty decision making have been studied in a plethora of studies, and many possible mechanisms of disorder have been identified in these studies (e.g., poor strategy use, memory difficulties, lack of generalization from previous experiences; Bebko et al., 2020). Examining the problematic pathway by which these difficulties might emerge can help with our understanding of the nature of these issues and with knowing where to intervene.

Based on the findings of study 2, it will be important for the field of ASD research to clarify the long-term effects of the consequences of learned patterns implemented at each step in the model. Crick and Dodge (1996) suggested that each step in the model affects what they termed the “database” where memories of past events as well as social rules and schemas are developed and clarified over time. These rules and memories in turn, also shape the processing that is occurring in each of the steps. The long-term effects of improper encoding appear to be significantly problematic, and some have suggested that these issues are more predictive of long-term symptomology than even ASD severity at a younger age (Jones et al., 2008). The second study of this dissertation described the effects of encoding in the prediction of core ASD symptoms. Studying each step of the model at several points can clarify the interactions between the steps themselves as well as proposed elements of the Crick and Dodge (1996) model including the database and the schema that guides behaviour and thinking.

5.3 Eye Tracking as Detection of Processing Differences

After examining the evidence gleaned from eye tracking in the studies of this dissertation and the wider evidence-base, an important question arises. Is social attention a marker of difficulties that are emerging, or does eye tracking provide a window into the reason why these difficulties emerge? Put another way, is the eye tracker detecting a symptom or the cause of some of these issues? Jones and Klin (2013) argue that the attentional processes captured by the eye tracker are detecting processing differences whereby children progressively accumulate atypical learning experiences. These atypical learning experiences then influence the behavioural output of the child. Johnson (2017) posits that there is an "overly focal style of attention in autism… that means it is beneficial to restrict sensory input to a single channel or area of input". That is, due to widespread changes in the developing brain of the child with autism, attention has to be "focal" in order to ensure that the child does not become overwhelmed with information. Consistent with this, emotions are considered a source of information that is overwhelming for the brain of the child with ASD (Wang et al., 2018). Therefore, what the eye tracker is detecting is not the biomarker of the degree of impairment, but the process by which the child's learning is made atypical. The child attends to the limited information and thereby misses out on learning what another child without ASD might learn in that instance (i.e., thereby reinforcing avoidance of overwhelming stimuli and preferential attention toward more neutral stimuli). Over time, these missed experiences may lead to the behavioural differences observed in children with ASD.

Given the framework of altered attention leading to progressively atypical learning, the studies covered in this dissertation take on new and profound meaning. The child who may hypothetically be screened by a procedure analogous to that used in Study 1 is not only identified as showing an atypical attentional pattern, but rather is differentiated from a peer as likely not having learned what he or she should have from that experience. That is, the child is losing a potential learning experience by not attending to the biological stimuli. In the second study, at time 1, a child is showing the attentional differences by which he or she will later develop or worsen in their ability, for example, to look another child in the eyes. Early eye tracking differences, then, are not only biomarkers of existing dysfunction (though, this is partially true), but also an opportunity for intervention so that a child's development may be affected (i.e., intervention focused on drawing the child's attention to relevant stimuli). Study 3 most clearly lays out this principle: eye tracking is detecting the process by which the entire SIP model begins to fail. The child did not attend the face (or the posture, or some other relevant social detail) and therefore, did not understand the intent of the aggressor. Over hundreds or thousands of these experiences, the very schema formed will be problematic, impacting many other pieces of information of which the child attends to or tries to make sense of.

The pattern suggested by these studies is not bleak. The future goals of researchers using this powerful methodology should be to identify the types of intervention that can remediate the issues that can be identified. Several methods have been suggested in the various studies, but a few overarching ideas will be reviewed. Foremost among these is the idea that perhaps the demands affecting a child's visual input can be altered. For example, if as Johnson (2015; 2017) suggests, the child is being overwhelmed by the various inputs that are coming in, can these be systematically altered in order to direct the child's attention toward relevant social information? Indeed, some have suggested that the processing of multiple sensory modalities at once is impaired in ASD (Dahary et al., 2018). Therefore, if some other modalities of information (e.g., sound) can be reduced, or the intensity of the primary modality changed (e.g., the intensity of the light or the presence of multiple stimuli in a scene), can children be drawn toward processing simple unimodular social information? These intervention ideas are not new ideas, but the present studies reinforce the importance of these considerations regarding structuring the environment and surround stimuli or greater success. In conjunction with this, researchers have yet to determine whether these changes, namely reducing the amount of surrounding stimuli, which may make it easier for the child to focus on relevant stimuli will then affect later steps of the SIP model, for example the interpretation of cues, and acting on the latter.

The future of eye tracking in ASD research is promising. From helping with screening or diagnosis, to understanding the core difficulties and differences seen in ASD, to highlighting potential areas for intervention, the researcher can use this tool in a plethora of ways. The studies comprising this dissertation highlight evidence for the value of eye tracking as an indicator of attentional differences between ASD and typical development. These differences can lead to efficient identification of a problematic developmental pathway. The SIP model helps to situate the attention/encoding problem in ASD within a multistep multidirectional cycle. This cycle offers many avenues for intervening with the core clinical issues that challenge practitioners who work with children with ASD. From the evidence reviewed in this dissertation, it appears that the future of eye tracking studies stands to provide much in the way of addressing clinical issues in ASD and beyond.

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