Eye Movements in Autism Spectrum Disorder: Implication for Social Deficit

by

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Abstract

Autism spectrum disorder (ASD) is a developmental condition characterized by social communication deficits, often accompanied by perceptual and attentional atypicalities. Studies suggest that eye tracking has the potential to reveal strategies adopted by individuals with ASD when processing their environment; importantly, this technology is particularly useful for the study of young children and infants with ASD (Boraston & Blakemore, 2011; Falck-Ytter, Bölte, & Gredebäck, 2013). This article reviews how eye tracking has been used to explore these issues and to explain the underlying mechanisms of the social difficulties experienced by people with ASD. This review covers studies that investigate low-level eye movement characteristics, attentional processes and components, and processing of social information. The heterogeneity of the disorder, developmental changes and the effect of language ability have all contributed to the current discrepancies in findings. In addition, the methodological complexities that have contributed to the conflicting evidence are discussed, as well as areas where further investigation is required.
Introduction

Autism spectrum disorder (ASD) and autism are both general terms for a group of complex neural developmental disorders. A triad of symptoms characterizes these disorders: 1) difficulties in social interaction, 2) verbal and nonverbal communication, and 3) repetitive behaviors and/or restricted interests (American Psychiatric Association (APA), DSM V, 2013). Individuals with autism also often exhibit unique perceptual and attentional characteristics, such as biases to focus on visual details (see Simmons, Robertson, McKay, Toal, McAleer, & Pollick, 2009 for a review). This altered processing of visual information may influence on the way individuals with autism approach novel environments and navigate social situations, a set of deficits that appears to be unique to autism (Shic, Bradshaw, Klin, Scassellati, & Chawarska, 2011).

For many decades, eye tracking has been used to investigate gaze behavior in the typically developing population (see Hayhoe & Ballard, 2005 for a review). Recent studies have extended its use to individuals with autism (e.g. Pelphrey, Sasson, Reznick, Paul, Goldman, & Piven, 2002; Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Dalton et al., 2005). Eye tracking provides a non-invasive method for elucidating basic oculomotor functioning and a wide variety of cognitive processes, from visual-spatial attention and object perception to memory. Potential eye movement abnormalities would profoundly affect one’s ability to perceive and process stimuli crucial for appropriate behavioral responses (see Brenner, Turner, & Müller, 2007 for a review). For example, previous studies reported that saccade frequency may
be abnormally elevated in children with autism in the absence of a visual task (Kemner, Verbaten, Cuperus, Camfferman, & van England, 1998).

Furthermore, recording of eye movements is useful when combined with a test of cognitive performance, such as visual search, attentional cueing, and emotion recognition, because it provides extra information in addition to a person's overall score on the test. For instance, information about fixation patterns can provide insight into the strategies a person might have been using to complete the test (e.g. Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; O’Riordan & Plaisted, 2001; Jarrold, Burack, Shore, Mottron, & Enns, 2006).

In addition, eye-tracking measures shed light on the social deficits of individuals with autism by investigating how they process social information such as face recognition, emotion recognition, and attention bias (see Falch-Ytter et al., 2013 for a review). Commonly used stimuli include pictures of human faces, videos of social interactions, human voices, and abstract animations (e.g. Chawarska, Macari, Shic, 2012; Klin et al., 2009). Individuals with autism have marked deficits in face perception (see Schultz, 2005 for a review). Recently, the application of eye tracking techniques have allowed for evaluation of strategies and changes in gaze patterns in face processing (e.g. Dalton et al., 2005; deWit et al, 2008; Klin et al., 2008). Furthermore, studies have found that individuals with autism show unusual fixation trajectories: they fixated less on human faces compared to typically developing individuals when presented with complex social scenes (Klin, et al., 2002).

This altered viewing pattern of social stimuli has been found in infant siblings of children with autism as early as 6 months (see Falch-Ytter, et al., 2013 for a
review). The presence of atypical gaze behaviors in early development could potentially hamper a wide range of social learning and in turn result in the social interaction deficits that characterize autism (Csibra & Gergely, 2006).

This paper will provide an overview of eye tracking studies in populations with autism of all ages, and review how eye-tracking measures have contributed to the understanding of cognitive and social processes in autism. The first part of the review summarizes various experimental paradigms used in the eye tracking studies of autism. In each of the following sections, relevant eye-tracking studies are discussed in light of different cognitive aspects of the disorder, including oculomotor control, attention, and social cognition. The goal of the current review is to evaluate available evidence in eye tracking studies of autism, to highlight the limitations of this research method, and to identify the areas where further research is required. It should be noted that other reviews in the literature have also discussed eye-tracking studies in autism, including eye tracking in early autism (Falck-Ytter, Et al., 2013), the application of eye tracking techniques (Boraston & Blakemore, 2007) and a summary of recent findings (Benson & Fletcher-Watson, 2011). With a vibrant ongoing research in this field, the current review expands on the Benson and Fletcher-Watson review by discussing new studies and findings; additionally, the current review covers research from early development through adulthood in autism.
Common Assessment Tools for Autism Spectrum Disorder

Autism is characterized by impairments in social interactions and communication, and the presence of restricted and repetitive behaviors. The diagnosis of autism spectrum disorder (ASD) is based on behavior evaluations. Currently, there is no medical test available to diagnose the disorder. Onset of these symptoms is typically prior to the age of three, with delays or abnormal functioning in social interaction, social communication (e.g. use of language), or symbolic or imaginative play. ASD can be diagnosed as early as 14 months; however, diagnosis becomes increasingly stable over the first three years of life (Landa, 2008). In addition, individuals whose symptoms of autism were not detected by their caregivers or doctors during early childhood can also seek diagnoses later in adulthood (National Autistic Society, 2005). This section introduces several diagnostic instruments that are commonly used in autism research and clinical diagnoses of ASD.

*The Autism Diagnostic Interview-Revised, 3rd Edition (ADI-R; Lord, Rutter, & Le Couteur, 1994)*

ADI-R is a structured interview with a child’s principal caregiver used in the diagnosis of autism spectrum disorder for individuals with a mental age of 18 months or older (Ruter, LeCouteur, & Lord, 2003). The comprehensive interview assesses information related to language and communication, reciprocal social interactions, and restricted, repetitive, or stereotypical behaviors and interests. The interviewee is required to give detailed descriptions of the child’s behavior. Use of the ADI-R requires experience with the population and basic interviewing skills, as well as training specific to the ADI-R. Responses are scored based on a
diagnostic algorithm (Lord et al., 1994). The purpose of the ADI-R is to provide information that can support a diagnosis of autism spectrum disorders and to identify the needs of children and adults for intervention planning (Lord & Corsello, 2005). Interrater reliability for the scoring of the interview has been reported to be good (.90 or higher; Constantino et al., 2003).

*The Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000)*

This is a semi-structured assessment of communication, social interaction, and play/imagination. It uses standard activities such as free play, telling a story from a book, and symbolic imitation to elicit and observe behaviors that are important in the diagnosis of pervasive developmental disorders. The ADOS includes four modules, from which one is selected for evaluation of autistic symptoms depending on the individual’s expressive language level and chronological age (available for children ages 12 months through adults). The only developmental level not served by the ADOS is non-verbal adolescents and adults (i.e. age 12 years and older) with autism. The examiner rates behaviors as they occur, and these ratings are incorporated in a diagnostic algorithm. The ADI-R is often used as a companion instrument to provide comprehensive information on the subject’s full developmental history.

*Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001)*

AQ is a brief, self-administered instrument which measures where any given individual adult, with normal intelligence, lies on the continuum of autism spectrum disorder. It is comprised of 50 statements, which prompt subjects to
indicate how much they agree, from definitely agree to definitely disagree. These statements were designed to assess social skill, attention switching, attention to detail, communication, and imagination (e.g. I prefer to do things with others rather than on my own). These abilities were selected from the domains in the “triad” of autistic symptoms (APA, 1994) and from areas of cognitive abnormality in autism (Baron-Cohen et al., 2001). (See Baron-Cohen et al. (2001) for a complete list of questions.)

*Childhood Autism Rating Scale (CARS; Schopler, Reichler, & Renner, 1986)*

CARS is a behavioral rating that assesses children on a scale from one to four in various criteria, ranging from normal to severe. The scale is used to observe individuals’ performances in several aspects, including relationships with others, imitation, emotional response, body, object use, adaptation to change, visual response, listening response, taste-smell-touch response, fear/anxiety, verbal communication, non-verbal communication, activity level, intellectual response and general impressions. Raters can be clinicians, teachers, or parents, and the rating is based on subjective observations of the child’s behavior.

*Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; APA, 2013)*

DSM-5 is the current American Psychiatric Association’s (APA) classification and diagnostic tool for mental disorders, including autism. Deficits in three areas, 1) non-verbal communication, 2) social initiation and response, and 3) restricted, repetitive patterns of behavior, interests, or activities, characterize autism spectrum disorder (ASD). Symptoms must be present in early childhood
and together limit and impair everyday functioning. Diagnosis falls in different levels of severity depending on the existing symptoms. Further, unlike the International Statistical Classification of Disease and Related Health Problems (ICD; World Health Organization, 1992), there is not a separate diagnosis for Asperger Syndrome.
Research Paradigms

The most common saccade parameters measured in studies of autism are latency, amplitude, peak velocity, and duration. Saccade latency refers to the time between onset of stimulus and the initiation of a saccade. Typical latency is around 200ms (Carpenter, 1988) and a typical saccade lasts for about 20-200ms, depending on the saccade’s amplitude. However, saccade latencies are substantially affected by the nature of the stimulus. That is, even if the stimulus and response are constant, latency is very variable at a trial-by-trial level. It is thought that the saccade latency is a composite of the time to process the visual stimulus, the accumulation of a decision process, during which the brain has to determine ‘when’ to initiate a saccade and ‘where’ to position the saccade landing, and the final motor execution (see Gilchrist, 2011 for a review). The saccade amplitude is the angular distance the eye travels during the movement and is usually less than 15°. The peak angular speed of the eye during a saccade reaches up to 900°/s. Fixation describes the location on which a saccade lands and maintains visual gaze. Fixation duration is the total time of fixation on the location. Visual information at the fixated location is processed; processing of information from the periphery is also possible (Gilchrist, 2011). Recording of gaze behaviors thus indicates where in a visual scene a person is seeking detailed information.

Modern eye tracking techniques allow for an accurate recording of gaze behaviors. There are a variety of instruments available for tracking eye movements. One common approach is to illuminate the eye with an infra-red beam, and then record the reflected image. Two points are identified from the captured image: the reflection from the cornea of the eye, i.e. the brightest point
on the image, and the pupil, i.e. the second brightest point. In addition, eye tracking that uses only the position of the pupil reflection and that detect the position of the fovea directly are also available (Gramatikov, Zalloum, Wu, Hunter, & Guyton, 2007). Combining eye tracking with a test of cognitive performance provides additional information about the parts of the test stimulus on which a person fixates; further, the eye movement data can reveal the strategies that person might be using to complete the task.

Two common eye tracking data analysis approaches in the study of autism include 1) areas of interest (AOI) analysis, e.g. calculating and comparing the total fixation duration on a particular regions the stimulus, and 2) scanning pattern analysis, e.g. processing the data to find the regions of the stimulus on which the subject ‘fixated’ and viewing pathways. Eye movement data has provided insight into the linkages between basic oculomotor system, attention, and other cognitive mechanisms and the disorder. Various paradigms have been used to investigate eye movements in individuals with autism spectrum disorders. Tasks measuring eye movements used in research have included the anti-saccade task, memory guided saccade task, and the gap-overlap task. This section briefly introduces each of these paradigms.

Visually Guided Saccade Task

In a visually guided saccade task, participants are required to make an eye movement to a visual stimulus presented on the periphery of a screen. This task is used to examine the basic oculomotor functions of an eye movement, and is commonly used as a baseline condition in the anti-saccade task or memory guided saccade task. A stimulus-elicited saccade is often referred to as a reflexive saccade.
Typical measures include saccade latency, variability in latency, saccade amplitude and peak velocity, and fixation duration. Aberrations in these measures of saccade metrics reflect neurological deficits in the brain regions controlling eye movements, such as the cerebellum and the frontal eye field (see White & Fielding, 2012 for a review).

**Anti-saccade Task**

In an anti-saccade task, a visual stimulus is presented on the screen and participants are required to make an eye movement to the mirror position of the stimuli location (Munoz & Everling, 2004). Successful performance on the anti-saccade task involves top-down inhibition of a reflexive saccade to the stimulus location, and then a volitional eye movement to the mirror location of the stimulus. A volitional saccade depends more heavily on voluntary cognitive control process compared to a reflexive saccade (see Walker, Walker, Hsuan, & Kennard, 2000 for detailed discussion). Anti-saccades have longer latencies than saccades toward the stimuli location (Gilchrist, 2011). Additionally, participants make more erroneous saccades toward the stimulus location. Typical measures in the anti-saccade task are 1) saccade latency and 2) the number of directional errors. Increased numbers of directional errors suggests inhibitory deficit, which is a failure to suppress an inappropriate response due to problems with top-down regulation (Munoz & Everling, 2000).

**Memory Guided Saccade Task**

In a memory guided saccade task, participants are asked to look at a central fixation point on a screen. While participants are fixating, a target appears
at a location in the periphery. The participant is not supposed to make a saccade
towards the target but has to remember the target location. After the target
disappears, the participant needs to make a saccade towards the memorized
location of the target. The time between the disappearance of the target and the
moment the participant is allowed to make a saccade, the delay period, is
manipulated in order to change the visuo-spatial working memory load. Typical
measures in the memory guided saccade task include accuracy in remembering the
target location correctly; the number of anticipatory errors, which are failures to
inhibit reflexive saccade response to target in the periphery; and saccade latency.
This task is used to assess memory, inhibition, accuracy, and saccade latency (e.g.
Luna, Doll, Hegedus, Minshew, & Sweeney, 2007; Luna et al., 2002; Frith, 2003).

*Gap-overlap paradigm*

In the gap-overlap paradigm, a central fixation point is presented prior to
the appearance of a stimulus on either side of a screen. In the gap condition, the
central fixation point is removed before the onset of peripheral stimulus. In
contrast, in the overlap condition, the central fixation point remains on display
when the target stimulus presents. Measurement of saccade latency is used as a
proxy measure for the disengagement of attention and shift between fixation point
and target stimulus. Specifically, saccade latency tends to be longer in the overlap
condition as attention is still engaged at the fixation point and must then be
disengaged before the shift towards the target (Abrahams & Dobkin, 1994). In
contrast, latencies are shorter in the gap condition because attention is already
disengaged when the target stimulus is presented.
Scene Viewing Task

Eye tracking has also been used in studies of social attention in ASD. In a scene-viewing task, participants are usually presented with complex, naturalistic pictures or moving images while their viewing patterns are recorded. Typical measurements include fixation duration and scan pattern analysis. It is suggested that such methods have greater ecological validity than classic attentional paradigms like the Posner cueing task (Posner, 1980) and visual search tasks (see Chun & Wolfe, 2001 for a review), and thus provide a better understanding of how the attention of people with autism may be distributed in the real world (Ames & Fletcher-Watson, 2010).

Smooth Pursuit

Smooth pursuit eye movements involve the smooth oculomotor tracking of a small object in motion with a constant speed. The task requires the non-ballistic eye movement to continuously adapt the velocity to that of the moving object. Typical measurements of smooth eye movements include 1) gain, calculated as the ratio of eye velocity to target velocity, 2) root mean square error, the difference between target and gaze position, and 3) the number of compensatory saccades, which are indexed by the number of saccade necessary to catch-up with the moving object when the eyes do not reproduce the target motion (e.g. Takarae, Minshew, Luna, Krisky, & Sweeney, 2004; Brenner et al., 2007).
Saccadic Eye Movements in Autism

Oculomotor Dysfunctions

Individuals with autism have been consistently found to have abnormal saccadic movements during cognitive tasks (e.g. Ronsehall, Johansson, & Gillberg, 1988; Luna et al., 2007). Deficits in different types of saccades may provide information regarding impairments in the cerebellum and cortical regions, as well as pathways that involve various cognitive abilities (Rosenhall et al., 1988). This section reviews the important findings of reflexive and volitional saccade performances in autism. Oculomotor development trajectories and the different oculomotor deficits associated with language impairment in autism are briefly discussed in this section.

E.O.G. studies:

The earliest studies used electrooculography (E.O.G.) to study basic oculomotor functions in autism. Ronsenhall et al. (1988) performed a visually guided saccade task: subjects only make saccade to the periphery when a light emitting diode is illuminated, and remain fixated at the center of the screen for the rest of the trial. Eight of the 11 children with autism that participated in the study showed reduced accuracy and/or lower peak velocity compared to the control group, indicating impairment in the cerebellum vermis (lobules VI-VII) (Rosenhall et al., 1988). This region maintains the consistent accuracy of saccadic eye movements and plays an important role in correcting systematic errors in saccade amplitudes (Izawa, Pekny, Marko, Haswell, Shadmehr, & Mostofsky, 2012). The biggest limitation
in the Ronsenhall et al. (1988) study is that the study included a very small sample (n=11); moreover, it was unclear how many of the 8 participants with abnormal saccadic movements had both reduced accuracy and lower peak velocity.

In the second E.O.G. study, Minshew, Luna and Sweeney (1999) recorded the saccade velocity, latency, and accuracy of 26 autistic adolescents (verbal- and full scale-IQ> 80 on the Wechsler Intelligence Scale) during reflexive (e.g. visually guided saccade) and volitional saccade (e.g. anti-saccade and memory-guided saccade) tasks. They found no difference between the autism group and the age- (± 2 years) and gender-matched healthy controls in accuracy, velocity, and latency during the visually guided saccade task. On the other hand, the autism group showed deficits in volitional saccade control as indexed by more response suppression errors in both the anti-saccade task and the memory-guided (delayed-response) saccade task. These findings shed new light on the pathophysiology of autism; in addition to a dysfunctional cerebellum (Rosenhall et al., 1988), deficits in volitional saccade control, as the authors suggest, are reflective of the intrinsic dysfunction of neocortical circuitry in autism (see also Courchesne et al., 1994 for a similar finding). Since this study, further research has identified other brain areas and pathways that may be associated with oculomotor abnormalities in autism (see Brenner et al., 2007 for a review).
Visually guided saccade and saccadic dynamics

Individuals with autism show subtle differences in their saccadic characteristics, including increased variability of saccadic velocity, longer latency, and unstable fixations, throughout development (Pensiero, Fabbro, Michieletto, Accardo, & Brambilla, 2009; Goldberg, et al., 2002; Luna et al., 2007). Pensiero et al. (2009) compared the eye movements of 14 male children with autism (age 5-12) with an age-matched control group of 20 male children without autism during a visually guided saccade task. A light target was randomly moved in a visual range of +/- 20 degrees at different amplitudes. Unlike children with typical development who consistently and correctly followed the stimulus, the autistic group showed poorer tracking. The tracking patterns of the autism group were characterized by stillness, gross errors in movement direction, and fixation instability. Furthermore, the autistic group showed a reduction of the peak saccade velocity. The observed abnormal ocular behaviors are consistent with findings of cerebellar disruption linked to autism.

On the other hand, there is conflicting evidence concerning the altered saccadic movement profile in autism, i.e. longer latency (Goldberg, Lasker, Zee, Garth, Tien, & Landa, 2002), reduced peak saccade velocity (Pensiero et al., 2009) and hypometria (Minshew et al., 1999). Johnson and colleagues (2012) compared the performances in a visually guided saccade task of 25 children (age 9-14) with high functioning or non-high functioning autism, and 12 age-matched typically developing children. A green target was presented centrally, 5 degrees or 10 degrees from center in either visual field for each trial, and participants were expected to direct their gaze to the target
when it appeared in the periphery (5/10 degree) and then redirect gaze back
to the center when the stimulus reappeared in the center. The time to initiate
visually guided saccade (latency) and the saccade velocities were similar
between the autism group and the control group (see also Minshew et al.,
1999; Takarae et al., 2004 for a similar finding). Additionally, the same study
confirmed previous reports of hypometria (too small/short saccades) at
large saccade amplitudes (e.g. 10 degree target in the Johnson et al (2013)
study), but not at small amplitudes (e.g. 5 degree target [Johnson et al. 2013])
in children with high functioning autism (see Takarae et al., 2004; Stanley-Cary, Rinehart, Tonge, White, & Fielding, 2011 for a similar finding).

Although the dysfunctional cerebellum theory in autism is well
supported by empirical evidence, further investigations are needed to specify
the disrupted regions or pathways in the cerebellar network in individuals
with autism. It is also possible that the heterogeneous groups of individuals
with autism may be distinguished by their oculomotor performance, which
would affect the developmental trajectories as a result of different levels of
functional disturbance of the cerebellum. Further studies are needed to
investigate the associations between the various symptoms of the disorder
and the functional impairments of the cerebellum.

*Volitional saccade: Anti-saccade & memory guided saccade*

The ability to perform volitional saccades has also been examined
using anti-saccade tasks and memory guided saccade tasks in autism.
Volitional saccades involve controlling of multiple cognitive domains, such as
executive functions and goal directed behaviors, and uses both spatial
working memory and response inhibition (Luna et al., 2007, 2002; Frith, 2003). Therefore, abnormal saccadic movement might be an indication of impairments in relevant regions and pathways in the cerebral cortex.

Two recent studies assessed children with autism on two oculomotor executive functional tasks, the memory guided saccade task and the anti-saccade (Luna et al., 2007; Goldberg et al., 2002). Luna et al. (2007) compared the performances on these two tasks between 61 autism participants and 61 age-and IQ-matched typically developing individuals. All participants were required to have an IQ of 80 or above, as assessed by the Ammons’ belief vocabulary test (Ammons & Ammons, 1962). This study attempted to establish a developmental progression from childhood to early adulthood in a cross-sectional design with subjects ranging in age from 8 to 33 (Luna et al., 2007). In the other study, eleven adolescents with high functioning autism (age 12-18 years) and eleven age-matched healthy controls were assessed with the same functional saccade tasks mentioned above with similar experimental conditions (Goldberg et al., 2002).

In the anti-saccade task, subjects must inhibit the response to look to the target in the periphery (8, 16, 24 degree; right and left visual field) and direct their gaze to the mirror position of the target. Feedback was provided by a light that appeared at the location where subjects should have been fixating. The autism group in both studies showed more errors to suppressing reflexive saccades and generating a saccade away from the stimulus throughout childhood into adulthood. The increase in suppression errors indicates inhibition deficits in autism.
The evidence of saccade latency differences during the anti-saccade task is inconsistent. While Goldberg and colleagues (2002) found no difference in saccade latency between the autism group and the control group, the other study demonstrated that young autistic subjects were faster to initiate saccades than controls, but that the abnormal saccadic latency appeared to stabilize when entering adolescence (Luna et al., 2007). The authors further suggested that the reduced latency may be too short for autistic subjects to execute inhibition, which therefore increased their suppression errors. In addition, individuals with autism showed improvement in anti-saccade task performance, as well as similar saccade latency as the control group upon reaching adolescence, indicating that cognitive development in autism may be intact. If this is true, individuals with autism could potentially benefit from interventions that target different cognitive abilities. Indeed, previous studies on typically developing populations suggest that, although the basic brain circuitry of voluntary response is functional by childhood and adolescence, adults continue to develop, and demonstrate increased activation of distant brain regions known to underlie preparation of correct anti-saccades and cognitive processes related to timing and learning (Luna, Garver, Urban, Lazar, & Sweeney, 2004).

The memory guided saccade task required subjects to maintain central fixation while simultaneously encoding the peripheral locations of a stimulus. A target light appeared in the periphery (9, 18, 27 degree; right and left visual field) and then disappeared after a short delay (1, 2, 4, or 8 sec). Subjects first inhibited the response to look at the target, then after the
designated delay, directed their gaze to the 'remembered' target location. In addition to voluntary response inhibition, the second task involved spatial working memory and motor response planning. Both research groups found increased response suppression errors during the task. Additionally, one study found the autism group showed higher response latencies than the control group, but no differences in saccade accuracy (Goldberg et al., 2002). In contrast, Luna and colleagues (2007) found no effect in latencies, but that the autistic participants were less accurate in directing the saccades to the correct positions. The authors suggested that spatial working memory may be impaired, and such a limitation compromises the ability to plan goal directed behaviors. Their findings concur with earlier neuroimaging evidence indicating impaired brain function in the dorsal lateral prefrontal cortex (DLPFC) in autism, which is associated with the maintenance processes of spatial working memory (Luna et al. 2002).

Further functional brain studies are needed to confirm the specificity of the deficits associated with abnormal memory-guided saccades. The ability to choose a task-appropriate response and prevent inappropriate reflexive responses, as well as the ability to hold information in memory to guide behavior, is essential to the executive control of behavior. Therefore, the study of volitional saccades will contribute to the understanding of the cognitive ability profile in autism.

Subtypes of Oculomotor Profile in Autism

Individuals with autism are at increased risk of language impairment (Loucas et al., 2008). The additional language impairment attached to autism
is thought to represent a distinct neurocognitive phenotype which shares etiological and neurobiological risk factors with specific language impairment (SLI) (Tager-Flusberg & Joseph, 2003; Tomblin, 2011). Several recent studies demonstrated that abnormal oculomotor performances may be associated with specific symptoms of autism, including language impairment (Kelly, Walker, & Norbury, 2013; Takarae, Minshew, Luna, & Sweeney, 2013). One study compared saccade behaviors during a visually guided saccade task of 46 high functioning individuals with autism, either with or without delayed language acquisition, and 104 age- and IQ-matched controls (Takarae et al., 2013). Only individuals with autism and without delayed language development showed saccadic hypometria in visually-guided saccade tasks. Saccadic hypometria refers to undershooting the intended location due to lack of eye movements coordination (Isotalo, 1999). The authors suggested that pathophysiology at the level of the cerebellum in autism may differ depending on an individual’s history of language development.

In another study, Kelly et al. (2013) found normal control and speed of reflexive eye movements in 73 children aged 8-14 years from four distinct groups: autism language normal (n=18), autism language impaired (n=17), language impaired non autistic (n=16) and typically developing (n=22). The study further demonstrated that both autistic and non-autistic individuals with language impairments showed higher suppression inhibition error rates compared to typical developed individuals in an anti-saccade task. The results indicate that deficits in the volitional control of saccadic movements
were not specific to ASD. (see also Tager-Flusberg & Joseph, 2003 for a similar finding).

The extension of oculomotor deficits to non-autistic children with language impairment provides further support for the notion that the additional language impairment represents a distinct neurocognitive phenotype, and that distinct oculomotor control deficits are associated with language delay in autism (Takarae, et al., 2004). This raises concerns about the exclusion of Asperger’s disorders (AD) in the newest DSM-V. AD was differentiated from autism by the absence of clinically significant delays in language, and no delays in cognitive development (American Psychiatric Association, 2013). Previous functional brain image studies also found more severe disruption to the oculomotor vermis-fastigial nuclei in high function autism than AD (Courchesne, et al., 1988; Catani et al., 2008). This may account for the functional differences in primary saccade accuracy. Moreover, Kelly and colleagues reported movement errors in children with autism, but not AD (Kelly et al., 2013). The abnormal oculomotor performance associated with language development thus suggests a deficit in motor function rather than visual attention (Takarae et al., 2013). Future investigations of oculomotor behaviors in specific groups of autism are needed to further parcel the pathophysiology of the disorder and to further improve the diagnostic criteria for autism.
**Attentional Disengagement**

Visual attention acts in three steps: disengagement of attention from its current focus, moving attention to a new target, and engagement with that target (Posner, Walker, Friedrich, & Rafal, 1984). Impaired attentional disengagement has been thought to be a prime suspect for the etiology of autism (Landry & Bryson, 2004). Deficits in basic visual attention and visual orienting may underlie the atypical social-communicative development characteristic of autism (Fischer, Koldewyn, Jiang, & Kanwisher, 2013). Eye movements and visual attention processes are closely related. Attention includes overt and covert orienting. Overt attention selectively attends to an item or location over others by moving the eyes to point in that direction (Posner, 1980), while the latter involves mentally shifting one's focus without corresponsive eye movements (Eriksen & Colegate, 1971). Saccadic fixation involves overt attention, whereas visual cues from the periphery demands covert attention.

Visual orienting tasks are commonly employed in studies of attentional disengagement in individuals with autism (e.g. van der Geest, Kemner, Camfferman, Verbaten, & van England, 2001; Goldberg et al., 2002; Elsabbagh et al., 2009). During the task, a fixation point is displayed at the center of a visual field on a screen while a target is displayed on one side of the visual field. There are two possible conditions. First, in the gap condition, the fixation point disappears before the onset of the target. Second, in the overlap condition, the fixation point remains throughout the presentation of the target. In both conditions, subjects are instructed to direct their gaze to
the target as soon as possible. The overlap condition involves disengagement (from the center fixation point) whereas the gap condition only requires attention shifting. In the gap-overlap paradigm, saccadic reaction times (latencies) are influenced by the presence of an initial fixation stimulus (e.g. center point). The latencies of reflexive saccades toward the target are much shorter in the gap condition than in the overlap condition, which requires disengagement from the current fixation point (see Saslow (1967) for example). The difference in latencies between the two conditions is called the gap effect. Visual orienting studies on autism showed conflicting results: some found similar gap effect in autistic and healthy populations (e.g. Goldberg et al., 2002), and other studies found a reduced gap effect in individuals with autism (e.g. van der Geest et al., 2001).

Van der Geest et al., (2001) assessed 16 high-functioning autistic children (aged about 10 years) and 15 age- and IQ- matched control children without autism with the visual orienting task in gap and overlap conditions. They found a reduced gap effect in the autism group compared to the control group. A reduced gap effect would support their hypothesis that children with autism have a weaker attentional engagement to visual stimuli. However, they did not observe shorter overall saccadic reaction times in the autism group, which would be expected as a result of weak attentional engagement. Furthermore, a second study using a similar visual orienting task found no group difference in gap effect between the disengage trials, in which the center fixation point remains as the peripheral target is presented, and the shift trials, in which the center fixation point is removed as the peripheral target is presented (Goldberg, et al., 2002). On the other hand, van
der Geest et al. suggested that their results point to a general rather than
domain-specific (i.e. social) deficit in autism because they used non-social
stimuli in the study. Landry and Bryson (2004) also used non-social stimuli,
e.g. colored geometric shapes (red, green and yellow rectangles; purple,
brown and blue triangles) in the disengage/shift task to assess disengage
impairment in children with autism (n= 15; average 6 year-old). While both
the autism group and the age- and IQ-matched control group showed the gap
effect with longer latency in disengage (overlap) trials compared to shift
(gap) trials, the autism group spent 3 times as long as typically developing
controls to disengage attention from the visual stimulus. An important
limitation to these studies is their relatively small sample size.

One recent study addressed the limitation of small sample size in
previous studies by testing a large group of high functioning children with
autism (n=44) and age- and IQ- matched typically developed children (n=40)
in a free-viewing visual orienting task (Fischer et al., 2013). The stimulus
categories chosen in this study provided a broad sampling of both social (e.g.
a face) and nonsocial (e.g. a fruit, vegetable, or train) images that might elicit
attentional differences between the autism group and the control group, thus
providing a strong test of whether stimuli of interest could interfere with
disengagement in children with autism. Their data showed no interactions
between groups (autism vs. control) with any factor, including trial types
(disengage vs. shift) or stimulus types (social vs. nonsocial). Disengage costs
(longer latency for disengage trials than shift trials) did not differ across
groups. High-functioning children with autism showed no disengagement
impairment as indexed by saccadic eye movements (see Kelly et al., 2013;
Kicuchi et al., 2011 for a similar finding; See also Table1). Furthermore, Fischer and colleagues (2013) speculated that the discrepancies between their findings and prior findings, which reported significantly slower disengagement in children with autism, may be due to other factors, such as the low IQ of participants (Kawakubo et al., 2007), or repetition priming of the stimulus (Elasabbagh et al., 2009), rather than disruption of the attention system. In that regard, their study further challenged the idea that disruptions of core attentional abilities lie at the root of autism [Menon, 2011]. Future studies should investigate a variety of functions associated with attention in autism as well as whether atypical social functioning modulates other core attentional functions (e.g. disengagement). This will clarify whether the crux of the matter in autism lays in the general impairment or domain-specific deficits.

**Smooth Pursuit**

The smooth pursuit system supports voluntary foveation of a stimulus that is moving (Luna et al., 2007). Unlike the rapid movements of saccades, smooth pursuit involves slow eye movements that approximate the velocity of a moving target and allows focus on the visual image to fall on the fovea. Although a few studies exist, smooth pursuit in autism has not been well documented (see Brenner, Turner, & Müller 2007; Rommelse, Stigchel, & Sergeant 2008 for a review). To track a moving target, a saccade occurs after the onset of target motion so that the eyes can catch up to the moving target, i.e. open-loop, and follow the target with smooth pursuit, i.e. closed-loop. The open-loop stage is driven by sensory input; on the other hand, the closed-
loop stage requires the use of internally generated feedback about performance accuracy and the prediction of target motion.

One important paper by Takarae et al. (2004) compared pursuit eye movements of 60 high-functioning individuals with autism and 94 IQ-, age- and gender-matched controls during a foveofugal step-ramp task, a pure ramp task, and a oscillating task. In the foveofugal step-ramp task, targets were displayed at the center, and then jumped 3° to the left or right, and started moving in the same direction at constant speed (4, 8, 16, 24°/s). Subjects were instructed to follow the target until it disappeared after reaching ±15°. In the pure ramp task, the target moved at the same speed and direction as the foveofugal step-ramp task, but differed from that paradigm in that the target began moving smoothly from the center without first stepping abruptly from the center. This task allows examination of pursuit initiation before the occurrence of catch-up saccade, which is a necessary first step in the foveofugal step-ramp task. In the third task, the oscillating target task, the target oscillated back and forth (between ±12° and ±17° of visual angle from the center). The target accelerated or decelerated throughout the cycles. Pursuit gain (the ratio of average velocity of pursuit eye movement to target velocity) was measured for all conditions.

The autistic group showed reduced pursuit gain in both open-loop and closed-loop phases. The reduction in pursuit gain in the closed-loop phase was more pronounced after mid-adolescence (age= 16), suggesting reduced maturational achievement of the pursuit system in autism. The findings were consistent with maturational disturbances in the frontal lobe, especially the frontal eye field, and the executive function deficits on oculomotor tests,
reported in autism (Goldberg et al., 2002). Furthermore, lower open-loop pursuit gain toward a rightward moving target relative to matched controls was found in family members (57 first degree relatives of individuals with autism) of individuals with autism (Mosconi et al., 2010). Previous studies in schizophrenia suggested that the closed-loop pursuit abnormalities also affect up to 80% of patients with schizophrenia and their nonpsychotic first-degree relatives (Levy, Sereno, Gooding, & O’Driscol, 2010; O’Driscol & Callahan, 2008). In contrast, the open-loop pursuit deficit in autism was not found in first-degree relatives, and has not been reported in any neuropsychiatric illness (Masconi et al., 2010). The observed deficits in executive functions indicated alterations in prefrontal systems that are associated with autism may be familial, providing evidence of a genetic prototype in autism. More studies are needed to specify the genetic phenotypes linked to oculomotor deficits. Moreover, the distinct open-loop pursuit deficits associated with autism may be useful for future diagnostic purposes.
Attention

Visual Search

Atypical visual processing in autism is often expressed in the form of enhanced performance relative to non-autistic individuals (O’Riordan & Plaisted, 2001). For example, superior performance on visual search tasks has been found in toddlers, children, and adults with autism (Kaldy, Kraper, Carter, & Blaser, 2011; O’Riordan, Plaisted, Driver, & Baron-Cohen, 2001; O’Riordan, 2004). In a typical visual search task, an observer looks for a target item among an array of distractors and responds by indicating whether a target is present or absent. Two common methods to examine visual search performance are the Embedded Figure Task and the Block Design Task (Plaisted, O’Riordan, & Baron-Cohen, 1998). These tasks require either a ‘feature’ search, in which the target is the same color as one set of distractors, but is unique in shape (e.g. pick out a red circle located within a group of red squares), or a ‘conjunction’ search, in which the target shares color with one set and shape with another set of distracters. The first part of this section briefly summarizes studies of visual research in autism covered in a recent review by Simmons et al., (2009). The second part discusses more recent visual search eye tracking studies in autism that were not covered by the Simmons et al. review.

Findings from previous research seemed to agree that individuals with autism show superior performance in both feature and conjunction search tasks as compared to typically developing matched controls. O’Riordan et al. (2001) found that children with autism showed no decrease in reaction time in the conjunction task compared to the feature task, and were in fact faster at finding the
conjunction target than the controls. The results were also replicated in adults with autism (O’Riordan, 2004). Jarrold, Gilchrist and Bender (2005) increased the difficulty of a feature search task by making the feature quite similar to the distracters (e.g. a red clown extending both arms and legs into X-shaped-body amongst green clowns extended only both arms [T-shaped body] and red-T-shaped clowns). Similar to other findings, task performance was better in the group of children with autism than in the typically developing control group.

FMRI studies provided further evidence of superior performance in visual search. Individuals with autism showed different activation patterns, which involved a network of the frontal, parietal, and occipital cortices, when performing visual search tasks, whereas typically developing controls showed less extensive activation mostly limited to occipito-temporal regions. (Keehn, Brenner, Palmer, Lincoln, & Mueller, 2008). On the other hand, atypical visual research has also been linked to oculomotor abnormalities (see Brenner et al., 2007 for a review), enhanced discrimination (O’Riordan & Plaisted, 2001), and enhanced memory (Takeda & Yagi, 2000). Further investigations are warranted to identify the underlying causes of atypical visual processing in autism.

In a typical search task (e.g. feature search, conjunction search), search efficiency is estimated by varying the number of items in the search array (set size), measuring the time needed to complete the search and respond, and computing the slope of the reaction time by set size function. High efficiency searches yield slopes approaching 0 ms/item, whereas inefficient searches have slopes in the range of 20-60 ms/items as a result of multiple deployments of attention (Joseph et al., 2009). It is well known that the shifting of attention in space while searching for an object is followed by eye movements (Findlay, 2004).
Recent studies on visual search also used eye-tracking techniques, which allow for further examination of spatial distribution of fixations and of different strategies during search. Two common eye movement measures that have been used to study the spatiotemporal evolution of visual search in autism are fixation frequency and fixation duration.

Joseph et al. (2009) examined the influence of memory on visual search superiority in autism by adopting the dynamic search paradigm (Horowitz & Wolfe, 2003). In a dynamic search, targets and distractors are relocated randomly every 500ms within a trial. As a result, memory of the locations of previously inspected items does not benefit search efficiency. That is, if memory contributes greatly to searching, search efficiency would be markedly diminished in the dynamic condition. Previous findings in typically developing individuals suggested that visual search normally proceeds via sampling with replacement and that memory for prior attentional deployments makes at most a limited contribution to search efficiency (Horowitz & Wolfe, 2003). Children with autism (n=21) and age- and IQ-matched typically developing (TD) children (n=21) were asked to look for a T among Ls that appeared in four orthogonal orientations under both the dynamic condition and the static condition. The study involved both target present and target absent trials. Children with autism showed shorter reaction times than the TD group. Importantly, the autism group showed a significant advantage on dynamic and absent trials. Also, search efficiency was worse in dynamic and target absent trials compared to static and target present trials for both groups. These findings indicate that memory contributes no more to the search skills of children with autism than to those of TD children. Furthermore, both groups were similar in fixation frequency, indicating that enhanced memory
is not associated with the superior visual search in the autism group because otherwise, lower fixation frequency would be expected. On the other hand, children with autism had shorter fixation durations, while the number and spatial distribution of eye movements did not differ markedly between the two groups, indicating children with autism adopted similar search strategies but made stimulus discriminations more quickly than the TD group (see Kemner, Van Ewijk, Van England, & Hooge, 2008 for a similar finding).

While superior ability in visual search is consistently reported in individuals with autism (e.g. Joseph et al., 2009; O’Riordan & Plaisted, 2001), slower response has been reported in contextual cueing studies. Contextual cueing paradigms induce attentional guidance or facilitation effect by maintaining certain regularities in the visual world across repeated trials. For example, a target is repeatedly surrounded by the same objects, or by objects in the same locations. Contextual cueing visual search tasks require experience-driven attention that is formed by previous experience, and that in turn speeds visual search (Jiang, Swallow, Rosenbaum, & Herzig, 2012). Individuals with autism were slower to respond compared to TD individuals, indicating that they were less able to make use of context during visual search (Barnes et al., 2008; Kourkoulou, Leekam, & Findlay, 2012). A recent study further analyzed fixation frequency and fixation duration during the contextual cueing task, which allowed for the examination of the spatial and temporal aspects of visual search strategies (Kourkoulo et al., 2012). The participants were asked to look for a T among Ls that appeared in four orthogonal orientations. Further, the experimenters contrasted a “whole context” condition in which the entire display is repeated across blocks, with a “local context” condition in which only two items located immediately adjacent to the
target were repeated. Sixteen trials were administrated in the ‘learning’ phase, and then followed by the ‘transferring’ phase, in which half of trials from the learning phase were repeated and the other half was newly generated. Both the autism group and TD group detected the target faster in whole and local context trials compared with novel trials, and this benefit in search time showed contextual cueing in both groups. Nonetheless, the autism group was slower both in ‘whole context’ and ‘local context’ conditions compared to the TD group by 195msec on average, indicating that the overall magnitude of contextual cueing was greater in TD participants than the autism group.

Further, eye movement data analysis revealed that the longer reaction time in the autism group was driven by duration of fixations. This finding was inconsistent with the bulk of previous research, according to which individuals with autism show superior visual search because they have enhanced discrimination as indexed by shorter fixation durations (O’Riordan & Plaisted, 2001). It is possible that the differences in the demands of various tasks resulted in this discrepancy. It has been argued that previous experience works by making the decision to respond faster in contextual cueing task (Hout & Goldinger, 2012). Further analysis of the distribution of fixation time across the search stages showed that group differences in fixation durations were found in the later stage of “gaze duration in the target region,” which, as the authors indicated, encompasses the decision making component, i.e. the time it takes from detecting the target to making a motor response.

Thus, if participants’ performance on this later stage of the task was driven by prior experience, then slower search in ASD would suggest that prior experience does not bias search behaviors as much as it does for typically
developing individuals (see Pellicano & Burr, 2012 for a similar finding). Saccadic eye movements involve a high level decision that the brain has to make to determine when to initiate a saccade (Ludwig, Gilchrist, McSorley, & Baddeley, 2005). It was suggested that such temporal delay was related to preparing eye movements as indexed by longer first saccade latency. Secondly, one could also infer that the slower search in autism in the contextual cueing task was due to difficulties in disengaging attention. However, due to the small samples in the study, it is difficult to make a definitive inference. Furthermore, unlike a stronger learning effect on ‘whole context’ trials found in typically developing individuals, the autism group showed a similar magnitude of learning effect in ‘whole context’ and ‘local context.’ Such a finding would suggest either difficulties with processing of the whole context or enhanced processing of the local context in autism during learning. These findings clearly demonstrate that individuals with autism utilize contextual information in a different manner. Future studies will need to elucidate these findings further to understand how people with autism learn and how learning modulates attention.

Early emergence of a different attentional processing has also been demonstrated in 2 year old toddlers with autism—the age by which many children will first receive a diagnosis of autism spectrum disorder. Kaldy et al. (2011) modified the classic feature and conjunctive search tasks by 1) using a familiar object (e.g. red apple vs. blue apple-shapes and red rectangular-shape distractors); and 2) presenting the target (e.g. a red apple) before each trial began to grab the participant’s attention and fixation. In each trial, the target and distractors were presented in a different spatial configuration. This paradigm eliminated the need for verbal instructions as toddlers with autism are known to fall behind in
receptive language skills at young age (Perryman, Carter, Messinger, Stone, Ivanescu, & Yoder, 2012). The results demonstrated that children with autism (n=17; mean age= 29.5 months) tended to spend the most time looking at the target during each trial, where trial length was fixed, whereas the fixation pattern of typically developing children (n=17; mean age=29.6 months) was more evenly distributed among the objects in the display. This finding suggested that toddlers with autism were more successful than TD toddlers of the same age at locating a target amidst distractors in a feature and conjunction search. Further, toddlers with autism scrutinized more items than TD toddlers during search.

Literature on older children and adults with autism has suggested enhanced discrimination facilitates visual search (e.g. O’Riordan & Plaisted, 2001; Kemner et al., 2009; Joseph et al., 2009; See also Table2). If this is true, the differences in visual search processes at the earliest age when diagnosis is typically made would support the view that differences in these processes are part of the nature of the disorder, and not a result of abnormal social development. Importantly, atypicalities in visual perception and attention may contribute to abnormal social-communicative development. Although preliminary, Joseph et al. (2009) found a positive correlation between enhanced visual perception and symptom severity. Longitudinal behavioral research with young children with or at risk for autism will provide a clearer view of causal relationships among the developmental characteristics in autism.

**Gaze Following**

One of the earliest manifestations of autism is a deficit in joint attention behaviors with social partners (Baron-Cohen, Cox, Baird, Swettenham,
Joint attention is defined as the ability to share the attention of another person, such as following the direction of another person’s gaze to what they are looking at (e.g. Mundy & Burnette 2005; Frischen, Bayliss, & Tipper, 2007). The deficit in joint attention is thought to restrict a child’s opportunities for social learning, impairing subsequent social and communication development (Baron-Cohen et al, 1996; Klin, Jones, Schultz, & Volkmar, 2003).

Attention orienting in response to gaze cues has been investigated using the Posner type cueing task (Posner, 1980). In this paradigm, participants are required to fixate on a central point, and are instructed to look at the target on either side of the screen indicated by certain cue (e.g. color change) of the target fixation point. In one variant of this task, a ‘distractor’ face is presented in the center, whose eye gaze shifts either to the right or the left during fixation (on the center). That is, the distractor’s eyes either point in the same direction as the indicated target (congruent trials) or the opposite direction (incongruent trials). Results have found a cueing effect in which participants were slower at initiating eye movements on incongruent than on congruent trials, and typically made more errors on incongruent trials in typically developing adults (Kuhn & Benson 2007; Ricciardelli, Bricolo, Aglioti, & Chelazzi, 2002). In the study of autism, further manipulations involved the presentation of varied directional cues (e.g. an arrow, eye gaze) at central fixation point in order to examine attentional orienting in response to social versus symbolic cues (e.g. Chawarska, Klin, & Volkmar, 2003; Senju, Tojo, Dairoku, & Hasegawa, 2004).

In a recent review on attention in autism, Ames and Fletcher-Watson (2010) concluded that children with autism do orient reflexively in response to both eye gaze and arrow cues (e.g. Chawarska et al., 2003; Senju, et al., 2004).
However, individuals with autism showed a comparable cueing effect for both eye gaze and arrow cues, whereas typically developing controls showed greater cueing in response to eye gaze (e.g. Senju et al., 2004; Vlamings, Stauder, van Son, & Mottron, 2005). Specifically, typically developing individuals demonstrated a slower reaction time in response to eye gaze cues than to arrow cues, while individuals with autism reacted similarly to both types of cues (Chawarska et al., 2003). This is thought to be an indication of insensitivity to social stimuli, such as eye gaze cues, in autism.

Eye tracking provides additional information about the timing, as well as the direction, of saccades correctly executed toward the target, and of saccades incorrectly executed toward the opposite side of the target. Kuhn et al. (2010) employed this technique to investigate possible abnormalities in gaze cueing to eye-gaze and symbolic cues (e.g. arrows) in high-functioning individuals with autism. The experiment involved a Posner cueing task with two types of distractor cues, eye gaze and arrow, that indicated either the identical or the opposite direction as the target. Further, a schematic face, rather than images of real faces, was used in the study. The distractor cue appeared either at the same time when the target changed color or at 600ms before the color change.

Kuhn et al. (2010) reported that typically developing individuals (n=12; mean age=22.4 years) and their age- and IQ-matched counterparts with autism (n=11; mean age=26 years) showed similar cueing effects for both types of distractors (eye gaze and arrow). Both made significantly more directional saccades errors in incongruent than in congruent trials, and their saccade reaction times in the congruent trials were faster than in incongruent trials. As mentioned, typically developing individuals demonstrated a slower reaction time in response
to eye gaze cues than to arrow cues, while individuals with autism reacted similarly to both types of cues (Chawarska et al., 2003). Inconsistent with previous findings (see Ames & Fletcher-Watson, 2010), there was no size differences in cueing effect between arrows and eye gaze for both TD and autism participants.

A growing body of evidence has now been gathered in support of cognitive systems specialized for human gaze perception (e.g. Baron-Cohen, 1995; Haxby, Hoffman, & Gobbini, 2002). Specifically, reflexive orienting to eye gaze is thought to be associated with brain regions specialized for face processing, including the fusiform face area (Kingston, Friesen, & Gazzaniga, 2000). Downing, Dodds and Bray (2004) demonstrated that non-eye gaze cues (e.g. tongue) could elicit a cueing effect; however, only eye gaze cues produced automatic shifts of attention sufficient to overcome a 4:1 probability in favor of the target appearing at the uncued location in typically developing individuals. Therefore, the schematic face used in the Kuhn et al. (2010) study may not reflect the nature of human eye gaze, but, nonetheless, it elicited attentional cueing irrespective of social processing. A naturalistic scene viewing study would therefore be a more ecologically valid approach to uncover subtle differences in gaze cueing in autism.

Riby and Doherty (2009) examined gaze direction detection in autism with images of real faces. The stimuli contained photographs of a female’s face and an array of 4 or 6 items that were easily nameable for young participants, e.g. duck, sheep, person, pig, and car. The two different numbers of items in an array served to differentiate the difficulties of the task. Items were spaced evenly and separated into two groups (i.e. 2 items each; 3 items each) on the right and left to the center
of the table and the female actor appear to look at the target item at the center from her eye level. In each photograph, the female actor either turned both her head and eye toward the target item (‘head-and-eye condition’) or only directed eye gaze toward the target item and with head directed forwards (‘eye only condition’). All participants were asked to name each item in the array, and then, were asked to name the item being looked at in the photograph. The photograph was divided into three areas of interest (AOI) including actor’s face, correct side for target item and correct target item.

Similar gaze patterns were found in the 4-item-array and 6-item-array. Children with autism (n=13; average age=10.75 years) were significantly less accurate than their nonverbal-ability-matched typically developing counterparts (n=15; average age=6.8 years) when naming the target item. Both groups were not affected by cues from eyes alone versus head and eyes. Although the amount of time spent fixating on the target item did not differ across groups, the numbers of fixations to detect the target was much higher for autistic participants (6th fixation was on target on average) than for typically developing participants (3rd fixation). Consequently, the autism group took a longer time to complete each task by naming the target item.

The task in the Riby and Doherty (2009) study required participants to look at the actor’s face to detect a gaze cue, then to follow this cue to the target item. A lack of preference for face viewing has been consistently reported in autism (e.g. de Wit et al., 2008; Klin et al., 2002), and could therefore cause the delay. Further analysis also revealed that the autism group was slower at first

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1 Raven's Progressive Matrices (Raven, Court, & Raven, 1990) was administered to the participants to assess their nonverbal abilities, including the ability for reasoning and "meaning-making."
fixation to the face than typically developing counterparts (Freeth, Ropar, Mitchell, Champman, & Loher, 2011). It has been suggested that individuals with autism are intact in their ability to make exogenous shifts of attention. Exogenous orienting is thought to be under the control of stimulus, which often are presented in the periphery (peripheral cues). Such cues often result in a reflexive saccade, even when individuals are aware that the cue will relay accurate information about where a target is going to occur (Kuhn & Benson 2007). Indeed, Iarocci and Burack (2004) reported that children with autism and children with typical development showed similar cueing effects in the exogenous cueing task, which was similar to the Posner attention orienting task (1980) (see Townsend et al., 1999; Townsend et al., 1996 for a similar finding).

On the other hand, failure to utilize eye-gaze cues naturally, despite their sensitivity to the directional information conveyed in cues, may reflect a difficulty involving general processing, or the absence of the typical preference for faces, in people with autism (Leekam, Lopez, & Moore, 2000; Charawska et al., 2003). Additionally, it was unclear whether the ‘gaze wandering’ observed in individuals with autism before fixating on the target was directly associated with deficits in gaze detection. Different experimental design such as limited cueing time could prevent exhaustive scanning and the gaze patterns may vary from the current findings as a result. It is also possible that the poorer performance in naming the target item reflected some deficit in verbal ability rather than gaze following ability. It is known that language impairment is often associated with the disorder (Lindgren, Folstein, Tomblin, & Tager-Flusberg, 2009). Although all participants were able to name each item before proceeding to the task, official language assessment was not part of the pre-screen criteria for participating in the study.
In a recent study, Riby, Hancock, Jones and Hanley (2013) explored how individuals with autism attended to an actor’s eye gaze cues within a social scene. An actor appeared in different settings (e.g. an office, kitchen and lounge) and the actor’s gaze was directed to a target item in the complex scene. Each image was divided into several areas of interest (AOI) including the actor’s face, the eye region, the target item, plausible items, and implausible items. Plausible items were the ones that lay in the line of sight of the target item, and implausible items were either in the wrong direction (i.e. not in the line of sight) or behind the actor. The experiment consisted of two phases: 1) the spontaneous phase, in which the participants viewed the scene freely and 2) the cued phase, in which the participants were told ‘detect and name what the actor is looking at.’ The scene was viewed for only three seconds in each phase in order to avoid exhaustive scanning (Riby et al., 2009). Furthermore, the time restriction simulated real-life gaze following, in which cues indicating the target of a person’s attention are often fleeting.

Rigy et al. (2013) compared the gaze patterns between typically developing children (n=22; average age 9.15 years) and children and adolescents with autism (n=22; average age 11.25 years) with comparable nonverbal ability during the task. Analysis of the gaze duration on each AOI revealed that despite the fact that the autism group shifted their attention towards and fixated the face, they failed to show a transfer to the correct target as the TD group did in the cued phase. During spontaneous viewing, the autism group spent a shorter amount of time fixating on the face, the eye regions, the target item, and the plausible items as compared to the TD group. Several limitations to the study should be mentioned: mainly, that the small sample size prevented further exploration of the
variability of gaze behavior within the autism group. Secondly, accuracy of target item naming was not taken into consideration in the eye movement data analysis, and therefore, whether there was an interaction between gaze pattern and accuracy remains unknown. Lastly, the face area occupied a relatively small portion of the whole image. Some individuals may have used visually larger information in scenes of this nature, such as full face/head, to cue their gaze direction, rather than limiting their gaze to a smaller eye region. Nonetheless, previous research had demonstrated that individuals with autism were capable of following gaze both when eye and head regions were congruent (toward the same directions) and incongruent (Rigy et al., 2009; See also Table3).

As eye gaze plays a central role in communication, atypical orientation to the gaze of others, and the social information it provides, may impact social functioning throughout development (Longton & Bruce, 1999). In accord with this view, Rigy and colleagues (2009) found a negative correlation between task performance and CARS score, an assessment of the level of functioning in autism. Previous research has also indicated that CARS scores are correlated with attention to faces in autism (Rigy, Doherty-Sneddon, & Bruce, 2008); however, it is worth noting that this report was from the same research group. Therefore, these results should be further validated with other measurements of functioning, such as the Autism Diagnostic Observation Schedule (ADOS) as well as by different research groups. Moreover, inconsistent findings have been reported with high functioning individuals with autism. Some showed a reduced likelihood to spontaneously follow an actor’s gaze within a social picture (Fletcher-Watson, Leekam, Benson, Frank, & Findlay, 2009); yet, other research has reported typical gaze cueing (Freeth, Chapman, Ropar, & Mitchell, 2010a). Differences in the
processing of gaze behavior seemed unrelated to the level of functioning, at least in the case of high-functioning individuals with autism.

**Attention Bias**

Attention describes our ability to selectively process a small subset of the sensory information in the environment. An early attentional bias toward nonsocial information has been repeatedly reported in autism, and is thought to impact the cognitive development of individuals with autism. Specifically, a bias for visually exploring nonsocial information could contribute to the development of restricted and perseverative patterns of behaviors and interests (Pellicano, Smith, Cristino, Hood, Briscoe, & Gilchrist, 2011). Covered in a recent review by Benson and Fletcher-Watson (2011), previous studies investigating visual preferences in autism reported that social information appeared less salient, or that non-social information is more salient, for young children with autism (e.g. Klin et al., 2009; Pierce & Courchesne, 2011; Sasson, 2006). South, Ozonoff and McMahon (2005) further demonstrated subcategories of non-social images that represent a diverse range of objects (e.g. trains, computers) related to circumscribed interest in autism. An early bias toward non-social information could potentially direct development. Indeed, development of neural specialization related to many social information processing abilities are experience-dependent (Leppanen & Nelson, 2009; Sasson, 2006; Schultz, 2005), and therefore, heightened salience of non-social aspects of the environment may adversely affect development when the quantity and quality of visual experience with social stimuli is abnormal.
Social orienting impairment is a widely embraced account for the etiology of autism. According to the social orienting hypothesis, the failure of individuals with autism to prioritize social information gives rise to the social communication deficit that characterizes the disorder (e.g. Klin et al., 2003; Schultz, 2005). However, evidence for the hypothesis is inconsistent (see Dawson et al., 2004 for a review). A recent study tested a large group of children with autism (n=44) and age- and IQ-matched typically developing children (n=40) in a free-viewing visual orienting task to further investigate social orienting impairment in autism (Fischer et al., 2013). In the experiment, a stimulus appeared at the center of the screen for 1 or 2 seconds. The central stimulus then disappeared at the onset of the peripheral stimulus at 14 degrees in the periphery. The stimuli categories chosen provided a broad sampling of both social (a face) and nonsocial (a fruit, vegetable, or train) images that might elicit attentional differences between the autism group and the control group. The experiment involved two trial types: in ‘shift’ trials, the central stimulus disappeared at the onset of the peripheral stimulus; in ‘disengage’ trials, the central stimulus remained on the screen for the entire trial duration. Saccadic reaction times showed no interactions between groups (autism vs. control) with any factor, including trial types (disengage vs. shift) or stimulus types (social vs. nonsocial). Both groups were significantly faster to saccade to the social stimulus.

Furthermore, the two groups did not differ in the total time spent looking at either social or nonsocial peripheral images. The data indicated that high-functioning children with autism did not suffer from across-the-board impairments in attentional orientation to social stimuli. This result concurred with mounting evidence that the root of autism does not stem from disruption of core attentional
abilities, including working memory, top-down cognitive control, and bottom-up saliency processing, as described by Knudsen (2007) in a recent review. For example, Ozonoff and Strayer (2001) reported normal performance in autism on working memory task (see also New et al., 2010 for a finding on intact low level visual processing; Sheth et al., 2011 for a similar finding in social processing).

On the other hand, various aspects of attention have been reported to be atypical in individuals with autism (see Ames & Fletcher-Watson, 2010 for a review). One possible contributing factor to social impairment could be an abnormal focus of attention on low-level, bottom-up visual properties of complex stimuli. Freeth, Foulsham and Chapman (2011) compared the influence of visual saliency on high-functioning individuals with autism (n=24; aged from 11-16 years) and a group of age-, gender- and IQ-matched typically developing participants (n=24) when viewing natural scenes. Participants’ eye movements were recorded while looking at sixteen photographs of everyday indoor and outdoor scenes. Visual saliency maps were created for the stimulus images. Mean visual saliency was higher at the fixated areas compared to non-fixated areas for all participants. Further analysis confirmed that mean saliency at fixations did not differ between the two groups (see Fletcher-Watson et al., 2009 for a similar finding).

This result demonstrated that highly visually salient areas of the scenes captured greater attention (e.g. higher number of fixations) than non-visual salient areas in both the TD and autism group, indicating that visual saliency similarly affected the gaze behaviors of individuals with autism and TD individuals. Furthermore, the social aspects of the scenes received greater attention than other properties related to visual salience in both groups of
participants. Importantly, the autism group was slower to fixate on highly salient social stimuli, such as faces, compared to typically developing individuals, supporting the hypothesis that individuals with autism lack a strong preference for social information when presented with complex stimuli (Freeth et al., 2010b). While the reason for this absence of rapid attention to social aspects of stimuli remained unclear, the study demonstrated that attention capture by the low-level, visually salient properties of stimuli is unlikely to be a causal factor. On the other hand, individuals with autism are known to take a special interest in certain categories of nonsocial objects such as cars and computer equipment (Sasson, Turner-Brown, Holtzclaw, Lam, & Bodfish, 2008). It would be interesting for future research to investigate whether these types of items rapidly capture the attention of individuals with autism in a similar manner to the way in which social stimuli capture typically developing individuals.

Furthermore, while studies of attention in autism have examined individuals from early development through adulthood, previous studies mostly were restricted in the age range examined. Hence, little is known about how these processes progress over the course of development. Elison, Sasson, Turner-Brown, Dichter and Bodfish (2011) recently examined the age trends in visual exploration of social and non-social information in children with autism. In the cross-sectional study, 43 typically developing children and 51 children with autism ranging in age from 2 to 18 were compared in their performance on a visual exploration task (VET) (Sasson et al., 2008). The VET consisted of 12 static arrays, each comprised of 24 individual color images distributed around the screen space. Each array consisted of images of either “social+object” (e.g. images of people and objects) or “object only.” Social images depicted males and females of various
ages and ethnicities, and presented either a face in isolation or a full head and body. Object images were chosen from nine non-social categories that previous research (South et al., 2005) has indicated are either common target of circumscribed interests in autism, e.g. ‘high autism interest’ (HAI) such as trains, planes, and computer equipment, or from ‘low autism interest’ (LAI) such as clothing, furniture, and food. The combination of LAI and HAI was counterbalanced across a set of image–type ratios (5:1; 3:3; 1:5) in both ‘social+object’ and ‘object only’ arrays. Visual attention patterns of participants were examined by analyzing three discrete attentional variables: 1) exploration, 2) perseveration, and 3) detail-oriented visual scanning as indexed by number of images fixated upon, average fixation time per image explored, and number of discrete fixations per image explored, respectively.

The results from the Elison et al. (2011) study revealed a significant age effect in both typically developing and autism group; exploration increased with age while perseveration and detail-orientation decreased. However, although children with autism showed an increase in exploration, the age effect was much smaller than the typically developing (TD) children. Specifically, children with autism exhibited less of an age-related increase in the exploration of HAI stimuli relative to TD comparison children. The finding indicated a disproportionate attentional bias for certain nonsocial information may exist in autism since very early in life; yet, visual exploratory behavior can increase with age. Given the developmental differences in visual exploration observed in the study, longitudinal studies in autism appear are warranted for characterizing trajectories. Moreover, evidence supporting these findings has the potential to elucidate optimal timing and viable targets for early interventions in autism (See Table4).
Change Blindness

Change blindness is a phenomenon whereby an individual fails to detect changes in a visual display when the view is briefly interrupted (Rensink, O’Regan, & Clark, 1997). This phenomenon has been commonly demonstrated by the ‘flicker’ paradigm, in which alternating images are presented in the same location on a screen, but are separated by a brief blank screen (Rensink et al., 1997). Research using this paradigm has found that changes to objects in the ‘center of interest’ of a scene are detected more readily than peripheral or ‘marginal interest’ changes (e.g. Simons, 2000). It is thought that focused attention must be directed to the site of change in order for the change to be detected (Rensink, 2002). Change detection methods have been used with various populations to illustrate the influence of expertise and preference on the direction of attention (e.g. Jones, Jones, Smith, & Copley, 2003; Werner & Thies, 2000). Whilst this review focuses on eye tracking studies in autism, the varied aspects of cognition that were examined have also been investigated with change detection paradigms. Specifically, in the study of autism, this method has been used to demonstrate the atypical attentional preferences of people with autism when viewing complex, naturalistic scenes, and can therefore increase understandings of how individuals with autism attend to the real world (e.g. Smith & Meline, 2008; Fletcher-Watson, Collis, Findlay, & Leekam, 2009). For the purpose of this

2 For example, a central item might be a fountain at the front of a scene, while a marginal one could be a tree (one of many) in the background. Typically developing individuals detect change of a central item more rapidly than that of a marginal item (Fletcher-Watson et al., 2012).
review, it is therefore necessary to consider studies of attention in autism with different methodologies.

In the first study of change detection in autism, Fletcher-Watson, Leekam, Turner and Moxon (2006) examined how the semantic role of items in the scenes influenced change detection in adults with autism. The experimental stimuli were color picture pairs of real-world scenes. Each pair consisted of pictures that were virtually identical except for a single difference in the color, presence, or location of a particular object or area. The modified object or area was either of high semantic importance (central interest) or of low semantic importance (marginal interest). The level of interest of a particular item or area was determined in a previous study in which the images were originally used. In that original study (Rensink et al., 1997), an object or area in an image was defined as central interest when mentioned by three or more observers in their verbal descriptions of the image, whereas marginal areas or items were mentioned by one person or less.

Stimuli were presented in a ‘flicker’ paradigm (Rensink et al., 1997)–the paired images were presented alternately in the same location on a screen, but separated by a brief blank screen (e.g. 120ms). Participants were instructed to search for a change during the display and to respond as fast as possible when they saw the change. Young adults with autism (n=19; aged 17-26 years) detected a change in items of central interest more rapidly and accurately than in marginal interest items. This pattern was similar to that of a matched typically developing group (n=19; aged 17-32 years) (see Smith & Milne, 2008 for a similar finding). The autism group was slower to detect changes in marginal items as compared to the typically developing group. This finding, as the authors proposed, reflects a
difficulty switching attention between items in the scene in autism that leads to a delay in the searching process.

Furthermore, research has investigated the effect of context and attention to detail on change detection (e.g. Loth, Gomez, & Happe, 2008; Fletcher-Watson et al., 2006). The study conducted by Loth et al. (2008) presented a scene consisting of a contextually appropriate object (e.g. a pot in the kitchen) which was replaced by either 1) another appropriate object in the same location (e.g. a cup); 2) an inappropriate object (e.g. a pair of shoes); or 3) an object of the same category as the original object (e.g. a different pot). The authors proposed that attention to context would produce shorter reaction time to inappropriate objects. Conversely, detail-focused processing would result in enhanced detection of object change under the same category. The results showed the typically developing participants (n=20) detected contextual changes more rapidly than categorical changes. In contrast, the IQ- and age-matched participants with autism (n=20) showed a similar response pattern in both conditions.

The weak central coherence theory (Happé & Frith, 2006) predicts some of the features of autism, including a tendency to focus on parts of objects, extreme sensitivity to small changes in the environment, and circumscribed interests. This model proposed that these features could be explained by a failure or absence of holistic processing of information. The hypothesized type of processing in autism is characterized by seeing stimuli in terms of disparate parts rather than a coherent whole. Supporting the view of weak central coherence in autism, this result provided evidence of a weaker influence of global-level contextual information on attention in autism. On the other hand, the result indicated no enhanced detail processing in participants with autism.
In contrast to the findings in the Loth et al. (2008) study, there has been
evidence from change detection paradigms that support theoretical models
emphasizing the local processing bias in autism (See Ames & Fletcher-Watson,
2010 for a review). For example, Smith and Milne (2008) demonstrated that
individuals with autism detected both central and marginal changes more rapidly
in a dynamic film scene. A recent study further investigated enhanced detail
processing by children with autism in a change blindness paradigm (Fletcher-
Watson et al., 2012). Eleven children with autism (aged 11-16 years) participated
in the experiments replicated from the Fletcher-Watson et al. (2006) study
described above. Children with autism responded quicker than typically
developing children (n= 20; aged 10-12 years) to all types of changes on marginal
items, which indicates enhanced local processing bias. One possible explanation
for these discrepancies in findings is that the differences in methodology – for
example, moving versus static stimuli, complex versus simple content – impact
the responses. Additionally, participants in different studies represented a
heterogeneous population with autism with a wide range of IQ and age. Therefore,
the discrepancies in the results may in fact reflect that people with autism adopt
different mechanisms, either individually or at different stages throughout
development.

In addition to examining general issues in attention such as local
processing and contextual effects, change detection methods have also been used
in studies of attention to social information. Sheth et al. (2013) compared change
detection responses under six conditions, which included 1) target change in a ‘no
human presented’ scene; 2) target change not connected with humans; 3) target
change connected with humans; 4) a human looking at target change; 5) a human
gaze at an object that was not target change; and 6) change of facial expressions or gaze. The images were displayed in the ‘flicker’ paradigm. The results showed no reliable differences in any of the social or non-social attention conditions between children with autism (n=22; average age: 10.5 years) and their IQ- and age-matched typically developing counterparts (n=18), in line with past studies on adults with autism (see also New et al., 2010; Freeth et al., 2010b). The current research on social attention using change detection paradigms provided preliminary evidence that the social impairment that characterizes autism may not be attributed to a low-level difference in social perception and attention. Instead, the evidence seemed to point to non-perceptual reasons (e.g. complexity of social stimuli, a lack of preference for social stimuli) that underlie the profound deficit in social processing associated with autism. Furthermore, whilst eye-tracking measures have consistently shown atypical patterns in attending to the eye region in people with autism (e.g. Klin et al., 2002), individuals with autism were as adept as typically developing participants at detecting changes to items being fixated on by another person (e.g. Sheth et al., 2013). To resolve the discrepancies, future research should attempt to specify how methodological designs of experiments vary, and in which people with autism demonstrate different abilities.

**Section Summary: Attention**

The studies reviewed in this section illustrate the value of eye tracking measures for understanding aspects of attention, including visual search, gaze following, and attentional bias in autism spectrum disorder. Atypicalities in visual perception and attention may contribute to the
abnormal social-communicative development which characterizes the disorder. In visual search research, it is generally agreed upon that individuals with autism show superior search performance compared to typically developing individuals (e.g. O’Riordan & Plaisted, 2001; O’Riordan et al., 2001). Kaldy et al. (2011) recently demonstrated that toddlers with autism were more successful than TD toddlers at locating targets during search tasks. Furthermore, consistent with a growing corpus of literature indicating an atypical enhancement of visual perceptual abilities (see Motton, Dawson, Soulieres, Hubert, & Burack, 2006 for a review), Joseph et al. (2009) concluded that superior visual search performance by individuals with autism is caused by enhanced discriminations as indexed by shorter fixation durations.

In contrast, individuals with autism performed worse at modified visual search tasks involving more complex decision-making processes such as context dependence (Kourkoulo et al., 2013). The study by Kourkoulo et al. (2013) reported that individuals with autism have difficulty processing the whole context during visual search tasks, supporting the weak central coherence hypothesis (Frith & Happe, 2006). Previous results from change paradigms also provided evidence of a weaker influence of global-level contextual information on attention in autism; however, there was no indication of enhanced detail processing associated with autism (Loth et al., 2008).

Attentional bias was previously thought to account for social communication deficits in autism (e.g. Klin, et al., 2003; Schultz, 2005). Studies investigating visual preferences in autism reported that social
information seemed less salient, or that non-social information more salient, for young children with autism (see Benson & Fletcher-Watson, 2011 for a review). However, new evidence suggested that children with autism did not suffer from across-the-board impairments in attentional orientation to social stimuli; for instance, Fischer et al. (2013) found both ASD and TD children were significantly faster to saccade to a social stimulus, e.g. a face, than a non-social stimulus, e.g. a fruit. Similarly, individuals with autism did not show deficits in reflexive orientation in response to both eye gaze cues and symbolic cues (e.g. Chawarska, et al., 2003; Senju et al., 2004). However, results by Chawarska et al (2003) suggested that individuals with autism might be less sensitive to social stimuli, e.g. eye gaze, compared to TD individuals. They found that while typically developing individuals had a slower reaction time in response to eye gaze cues than to arrow cues, individuals with autism reacted similarly to both types of cues. Furthermore, individuals with autism performed especially poorly at detecting eye gaze directions when the stimulus involved images of real faces (e.g. Riby & Doherty, 2009; Riby, et al., 2013). Together, these findings suggest a failure to process social stimuli, e.g. faces, meaningfully in a naturalistic context for individuals with autism.

In conclusion, mounting evidence has indicated that the root of autism does not stem from a disruption of core attention abilities, including working memory, top-down cognitive control, and bottom-up saliency processing (Knudsen & Eric, 2007). Instead, research findings point to the possibility of disruptions in social processing from early development for individuals with autism.
Social Cognition

Face Processing

Face recognition deficits are common among individuals with autism spectrum disorder (see Weigelt, Koldewyn, & Kanwisher, 2012 for a review). Previous behavioral observations in the literature have demonstrated that autism is implicated in impaired attention to faces in general and to the eye regions in particular. Avoidance of eye contact could lead to poor face recognition performance, emotion processing, and poor representation of encountered faces in memory throughout development (Schultz, 2005). Recently, eye tracking has been applied to the study of face recognition in autism (e.g. Dalton et al., 2005; de Wit et al., 2008; Hedley, Young, & Brewer, 2012; Yi et al., 2013). Eye tracking allows for evaluation of strategies used and changes in gaze patterns, and also provides an objective and quantitative assessment of face processing.

Dalton et al. (2005) found decreased gaze fixation on the eye regions of the face in people with autism (n=14) as compared to age-matched typical controls (n=16) in a face recognition task. Participants were asked to decide whether a face was familiar, using photographs of family members or friends and photographs of novel faces. No main effect for “familiarity” was found in both the control group and the autism group. The two groups showed a similar pattern of fixation on the mouth region and the face region in general. Diminished gaze to the eye region was also found in other studies on face recognition in autism (see Pelphrey et al., 2002; Spezio, Adolphs, Hurley, & Piven, 2007 for detail of the studies; for contrary findings see Chawarska & Shic 2009; De wit et al, 2008, Nakano et al, 2010).
Klin et al. (2008) investigated gaze patterns in viewing dynamic social scenes of an infant with autism, an age-matched typical developing infant (age 15 months), and a verbal-age-matched typical developing infant. The infant first presented symptoms that met criteria for autism on both standard diagnostic instruments and clinician-assigned diagnosis at 15 months, and then was re-evaluated at 23 and 34 months for confirmatory diagnosis and characterization. Videos showing a female actor playing the role of caregiver were presented to the participants. On-screen fixations were coded relative to four regions of interest: eyes, mouth, body, and surrounding objects. The infant with autism not only showed reduced fixation on the eye regions, but also showed a viewing preference for the mouth region relative to the typical developing infants (Klin et al., 2008). This study indicates that disruption in face processing may present as early as the first year of life, prior to the time in which developmental concerns typically lead to clinical referrals (Chawarska & Volkmar, 2007). Note further that Dalton and colleagues (2005) did not find longer fixation on the mouth compared to eye regions in the autism group as reported in the Klin et al. study. One explanation for the discrepancy is the different types of stimulus used in the two studies: dynamic social scenes (Jones et al., 2008) versus static face photographs (Dalton et al., 2005).

Additionally, Klin and colleagues (2008) presented the infant with eight point light animations (Allison, Puce, & McCarthy, 2000), each emulating age appropriate social experiences. The animation appeared with an audio track of the social event and with an upright point-light figure on one half of the computer screen and an inverted (i.e. upside-down) figure on the other. While the infant with autism did not show preference for upright point-light biological motion
animations over the inverse version, the infant made more fixations to the hand regions when the “figure” represented a clapping motion. The results were later replicated in another study from the same research group on two-year-olds with autism (see Klin et al., 2009). The authors hypothesized that this pattern of looking in autism would suggest seeing the world, and even people, as a collection of physical contingencies, unmoored from their social context. Therefore, in viewing a dynamic social scene, the children may focus more on the mouth because of its physically contingent properties, and so this preference would not be observed in static photograph stimuli. In a recent review, the authors concluded that the age of the subjects might affect their viewing patterns of faces (Falk-Ytter & von Hofsten, 2011). Specifically, a number of studies found excess mouth/diminished eye gaze pattern in adolescents and adults with autism (see Klin et al., 2002; Corden, Chilvers, & Skuse, 2008; Nakano et al., 2010; Speer, Cook, & McMahon, 2007 for a similar finding). Only one study replicated the excess mouth/diminished eye gaze pattern in children (defined as 12 years or younger) with autism (Jones, Carr, & Klin, 2008; see also van der Geest et al., 2002; Chawarska & Shic, 2009; de Wit et al., 2008; Nakano et al., 2010 for contrary findings).

In particular, social perceptual skills (e.g. the ability to perceive facial identity and facial expressions) provide important scaffolding for social skill development during childhood. De Wit, Falck-Ytter and von Hofsten (2008) reported differences in face scanning patterns between ASD and TD children. Their study compared the visual scanning patterns in a group of 3- to 6- year-old children with autism (n=11) and a 5-year-old control group during exploration of faces showing positive and negative emotions. Areas of interest (AOI) included
the eyes, nose and mouth, which were identical in size for all the emotional expressions. The ASD group looked less at the AOIs compared to non-AOI areas on the screen, and spent less time scanning the mouth. Importantly, the time looking at the mouth was negatively related to the severity of social and communicative impairments (see Klin et al., 2002 for a similar finding). Furthermore, both groups displayed differential scanning patterns for faces displaying positive or negative emotions, e.g. extended scanning of the eye region when looking at faces with negative emotions. It is thought that directing gaze to the eyes of other people is important for extracting emotional information (Adolphs, Gosselin, Buchanan, Tranel, Schyns, & Damasio, 2005). These findings suggest that the two groups did not differ in visual scanning of emotional facial expressions, though the ASD group used different viewing strategies for faces in general.

The AOI approach, which measures fixations that fall within a predefined area of interest, is commonly used in face recognition eye tracking studies. While AOI provides a reliable estimate of participants’ looking pattern at specific AOIs, it could fail to reveal potential differences in fixation patterns within the area. Yi et al. (2013) addressed this issue in their study by generating a fixation heat map, which allows for comparisons of the differences between groups. Twenty children with ASD (aged between 5–11 years), 21 chronological-age-matched typically developing children, and 20 IQ-matched typically developing children participated in an old-new face recognition task. The task included one familiarization phase and three test-review phases. In the familiarization phase, subjects viewed 12 photos of Chinese adult female faces, three if which were targets and the other nine were foils, for three seconds. All faces were front facing...
and matched in overall brightness and luminance, as saliency modulates visual attention (Ungerleider, 2000). The task asked subjects to remember the three target faces. During the test-review phase, either a target or a foil face was presented one at a time and the subject responded to the question, “Have you seen this face before?” Feedback was given after each response. In the target trials only, the target face reappeared for three seconds after feedback. The researchers defined five AOIs, including the whole face, left eye, right eye, the nose and the mouth. Total fixation durations from the familiarization, test, and review phases were recorded for each AOI. This study was the first study using scan paths analysis for analyzing TD and children with autism’s face scanning data. Saccade path analysis counted the frequencies of gaze shifts from one AOI to another (Salvulcci & Goldberg, 2000), by dividing the frequency of each saccade path by the total number of saccade paths on the whole stimulus.

Yi and colleagues (2013) found significantly shorter fixation on the face in the autism group compared to the age- and the IQ- matched control. They also found a smaller proportional duration: that is, the proportion of fixation duration on the right eye region of the face to total fixation duration on the stimuli, compared to the control. A heat (saliency) map was created to further analyze participants’ fixation distribution during the task. Both the autism group and typically developing controls fixated mostly in the central triangular area of the face (e.g. the region between the two eyes and the mouth). However, the results of subtracting the fixation map for typically developing group from the autism group revealed that the autism children scanned less often than age-matched control between the eyes, eyes and nose, and nose and mouth. In contrast, no differences were found between the autism group and IQ-matched control for the above scan
paths. These findings together would suggest that reduced proportional saccade paths might not be ASD specific, but rather reflect a developmental delay.

Interestingly, there was no difference in either the proportional duration of the left eye or of left/right eyes combined between the autism group and the two control groups. When fixation data from the autism group were contrasted with those from both TD groups, the autism group fixated more on the left eye. The authors further suggested that the left eye bias found in the autism group concurred with the deficits in understanding facial expressions and emotions reported in previous studies (Baron-Cohen et al., 1999; Dalton et al., 2005). In a recent review, Powell and Schirollo (2009) also found that the right side of the face (from the observer’s view) was found to be more emotionally expressive than the left side (See Table5). Further investigations are needed to probe the potential link between emotion perception and face scanning patterns.

Furthermore, brain-imaging techniques such as fMRI have provided insight into the face perception deficit in autism. It has been argued that activity within the fusiform face area (FFA) represents both perceptual and social conceptual processes. Thus, hypoactivation of the FFA often observed in individuals with autism may also be responsible for their face perception deficits (see Schultz, 2005 for a review). It will be important for future research to integrate brain imaging evidence and behavioral data to understand the underlying mechanisms of facial perception in autism.
Animacy: Processing of Social Information in Animated Triangles

Individuals with autism have shown differential eye movements in social situations, which may reveal difficulties with extracting relevant cues from social agents (see Fletcher-Watson et al., 2008 for a review). A number of recent studies used non-human stimuli to examine the ability of autistic individuals to detect social agent cues through movement alone. Simple geometric shapes can elicit the attribution of complex internal states by their pattern of contingent movements (Heider & Himmel, 1994). High functioning individuals with autism showed impaired ability to attribute mental states as indexed by a lack of intentionality in their verbal descriptions of geometric shape animations involving social agents (Abell, Happe, & Frith, 2000; Klin & Jones, 2006). Recently, eye tracking has been used to capture systematic differences in behavior while viewing such animations without interference from the subject’s verbal impairment. Specifically, geometric shape animations that involve social agents invited longer fixations compared to those with random movements in neurotypical participants (Klein, Zwickel, Prinz, & Frith, 2009).

One common stimulus used to study how individuals process animacy is the Frith-Happe animations (Abell et al., 2000; Castelli, Frith, Happe, & Frith, 2002). The animation shows two triangles interacting in different scenarios. These stimuli reliably reveal differences in verbal descriptions from participants with autism and controls (Abell et al., 2000), as well as in brain activities in the regions associated with theory of mind, including medial prefrontal cortex and superior temporal sulcus (Saxe & Kanwisher, 2003; Castelli et al., 2002).

In the Frith-Happe animations, a small blue and a big red triangle interact with each other in three different conditions: moving randomly (R), moving in a
simple goal-directed fashion (GD) and moving in complex interaction sequences (theory of mind condition, ToM) (See Castelli, Happe, Frith, & Frith, 2000 for an example). The patterns were designed so that the number of cues to social agentic behavior increases from the R to GD to ToM animations. Samples of the stimuli can be seen at http://sites.google.com/site/utafrith/research.

Zwickel, White, Coniston, Senju and Frith (2011) first demonstrated that individuals diagnosed with Asperger’s (AS) showed the same differential gaze patterns as neurotypical adults when watching the animated triangles in all the three conditions (Klein et al., 2009). Specifically, the experiment compared the eye movements of 19 adults with Asperger’s and 18 age-and IQ-matched neurotypical controls when viewing the Frith-Happe animation (Abell et al., 2000). Four different clips from each condition in the Frith-Happe animation served as stimuli. Fixation duration was different between GD and ToM compared to R animations. In addition, “triangle time” was calculated as the time when eye gaze fell within a circle of 3° around the center (of mass) of either triangle. Triangle time was compared to the total viewing time of the background, as an indication of the importance attributed to the triangles. Participants were asked to give verbal descriptions about each presentation.

Zwickel et al. (2011) found fixation duration increased from R to GD to ToM in both groups. Both groups also showed similar increments from R being the lowest to ToM being the highest in triangle time. On the other hand, while the AS group demonstrated the capability of mental state language, such as attributing intentionality to the triangles, their descriptions were generally less appropriate in the context (see Abell et al, 2000; Senju, Southgate, White, & Frith, 2009 for a similar finding). Together, these results indicated that the detection and early
processing of social agent information are intact in autism, and that their difficulties lie in producing a coherent and fitting description of the animations. Further, the authors proposed that their results might also apply to individuals with high functioning autism, given that differences between the clinical categories rest solely on the absence of early language and cognitive delay, and not on current signs and symptoms.

**Biological Motion Processing and Social Development**

The perception of biological activity, such as body language and facial expressions, is important to interacting with others (Allison et al., 2000). A number of studies have demonstrated a disruption in the perception of point-light displays of biological motion in children with autism, including perception of emotion from point-light displays (Moore, Hobson, & Lee, 1997) and a lack of preferential attention toward biological motion over object motion (Kaiser, Delmolo, Tanaka, & Schiffrar, 2010; Annaz, Campbell, Coleman, Milne, & Swettenham, 2012). 5- to 10-year-old children with autism showed deficits in discrimination of biological motions from scrambled motion; the impairments were more severe with children who demonstrated more symptoms of autism (Blake, Turner, Smoki, Pozdol, & Stone, 2003). Furthermore, preferential attention to social stimuli, such as faces, the sound of language, and human biological motion, start to present in early development (Cassia, 2004; Farroni, Csibra, Simion, & Johnson, 2002; Fox & McDaniel, 1982). Visual sensitivity to biological motion emerges in infants as early as two days old (Simion, Regolin, & Bulf, 2008). The development of social interactions with others relies on attention
to others’ movements in cues such as gaze direction or facial expression, and therefore impairment in such a mechanism may be a potential precursor for subsequent abnormal social development in individuals with autism (Frith & Frith, 1999).

Klin, Lin, Gorrindo, Ramsay and Jones (2009) designed a point-light animation of biological motions, e.g. playing ‘peek-a-boo’ or ‘pat-a-cake’ to investigate how two-year-old children with autism process such biological motion in a preferential-looking paradigm. In each animation, an upright figure was placed with an inverted figure (i.e. rotated 180° from upright) with an accompanying soundtrack matching the actions of the upright figure. The inverted presentation disrupts perception of biological motion in typically developing young children (Pavlova & Sololov, 2000). Visual scanning was measured with eye tracking equipment to determine if subjects showed a preference between biological motion (upright figure) or perceptual matching of sound and action (inverted figure). The autism group (n= 21) demonstrated random viewing patterns between the upright and inverted presentation; however, the age- and mental age-matched typically control and non-autistic developmentally delayed control group showed strong preference for the upright presentation.

Furthermore, in Klin et al. (2009), the autistic toddlers (aged 2 years) showed a significant preference for sound and movement contingent figures, e.g. clapping hands and sounds. Increased sensitivity to synchrony in the presence of biological motion stimuli could explain increased fixation on the mouth region in autism during face viewing (Schultz, 2005). On the other hand, the results from this study only demonstrated that the audio-visual contingencies override the biological motion as an orienting cue. To examine whether a lack of preferential
attention to biological motion presented independently in autism, Annaz et al. (2012) created a new stimulus: a point-light walker without accompanying sound and a scrambled version, which was created by taking the motion trajectories of each dot and playing them temporally out of phase with each other. The scrambled presentation removes any temporal relationship between dot and movements, which was kept in an inverted biological motion (Klin et al., 2009). Secondly, the walker motion excluded any social gestures within specific actions, such as the “play games” motion used in another study (Klin et al., 2009), which could be a confounding factor when children with autism specifically chose to ignore such social stimuli.

In the Annaz et al. (2012) study, 17 children with autism and 17 typically developing, age- and IQ- matched children were presented with a point-light walker alongside a scrambled point-light walker. Only the typically developing controls showed preference for biological motion. When a point-light walker was displayed alongside a point-light spinning top created from a clockwise-turning object, the autism group showed a significant preference for the spinning top over biological motion with larger percent fixation time on the spinning-top over the total fixation time per trial (See Table6).

A reduced sensitivity to biological motion presents great difficulties in social interaction and could lead to diminished expertise in social skills found later in life in autism. From the neural perspective, the lack of input from social stimuli could result in a lack of specialization in brain regions normally associated with social processing, and sometimes referred to as ‘the social brain’, including the amygdala, an emotion hub, the fusiform face area, dedicated to face recognition, and the superior temporal sulcus (STS), which has been implicated in
mood regulation (Schultz, 2005). A recent fMRI study measured the brain responses to biological motion in a group of children with autism (aged 4-17 years), unaffected siblings of children with autism, and age-matched typically developing children. The results suggested a possible neuroendophenotype of autism, as both the autism group and unaffected siblings showed a distinct brain response in the STS to biological motion compared with the controls (Kaiser et al., 2010). The current research provided preliminary evidence for a causal relationship between a lack of attention preference for social stimuli, e.g. biological motion, and the deficits of higher-level social cognition, such as theory of mind, in autism.

**Visual Scanning of Naturalistic Scenes**

Atypical viewing patterns have been consistently identified in individuals with autism when they view social stimuli, such as dynamic scenes portraying human interactions (e.g. Zwagenbaum, Bryson, & Garon, 2013). Additionally, individuals with autism show attenuated reliance on information from the eye regions, and appear to rely too heavily on information from the mouth region when performing emotional expression tasks (Klin et al., 2003). This section begins with a brief summary of a recent review by Falck-Ytter et al. (2013), which focused on how young children with autism look at semi-naturalistic scenes. Then, the section moves on to discuss additional eye tracking studies that adapted varied paradigms in the study of naturalistic scene viewing in autism across a wide range of ages.
Two studies found that children with autism looked less at faces when viewing videos containing social features, including interactions between people and verbal communication (Chawarska et al., 2012; Hosozawa, Tanaka, Shimizu, Nakano, & Kitazawa, 2012). A similar pattern was observed in 6-month-olds who later received diagnoses for autism spectrum disorder and infants at high-risk for autism (siblings of children with autism) (Chawarska et al., 2012; Shic, Macari, & Chawarska, 2013). However, two longitudinal studies demonstrated no indication that the infants diagnosed with autism looked at their mothers’ faces in an atypical way (Young, Merin, Roger, & Ozonoff, 2009; Elsabbagh, Bedford, Senju, Charman, Pickles, & Johnson, 2013). Furthermore, shorter looking time at the faces was found to be associated with having a better expressive single-word vocabulary than receptive language capacity, a language profile that is typical for children with autism (Chawarska et al., 2012; Luyster, Kadlec, Carter, & Tager-Flusberg, 2008). On the other hand, two studies provided evidence of both shorter looking time and longer looking time at the hand/object area in children with autism (Shic et al., 2011; the latter: Chawarska et al., 2012). Finally, a recent eye tracking study suggested that only when objects belonged to categories such as trains, vehicles, and airplanes did the children with autism prefer to look less at the face compared to typically developing controls (Sasson et al., 2008). In summary, reduced looking time at people and faces appears to emerge as early as first year of life in individuals with autism. In toddlers with autism, altered looking patterns across facial features such as the eyes and mouth have also been found. On the other hand, inconsistent evidence has also been reported in different research paradigms and experimental designs. Hence, the authors concluded that integration of explorative naturalistic approaches and experimental measures is
needed, as well as with more advanced analytic approaches that can constrain interpretations.

Eye tracking technology, along with a free-viewing paradigm, allows for a measure of a person’s spontaneous reaction to complex social situations, as the ability to appreciate many crucial social cues occurs very rapidly in everyday life. Individuals with autism consistently show performances different from those of healthy controls on the experimental tasks that adopted the free-viewing paradigm in a variety of social stimuli, such as dynamic social scenes (video) and photographs portraying social interactions (Klin et al., 2003). The results of this study consistently pointed to atypical gaze patterns in autism across different ages (e.g. Klin et al., 2002; Klin et al., 2003). The atypical gaze patterns may implicate a general failure in assessing the meaning of entire situations, thus precluding adaptive reactions in autism. Here, the section discusses additional eye tracking studies that examined naturalistic scene viewing in autism across a wide range of ages, which were not covered in the Falck-Ytter et al. (2013) review.

Rice, Moriuchi, Jones and Klin (2012) examined patterns of variability in social visual engagement in a heterogeneous sample of school-aged children with autism spectrum disorder (ASD). The stimuli contained two 5- to 7-minute films of everyday social scenarios with age-appropriate social interactions in a visually complex environment. Specifically, one film offered a narrative of a girl trying to fit in and make friends at school (edited from Welcome to the Dollhouse (1995)). The other film displayed a group of boys playing baseball on a summer day (edited from The Sandlot (1993)). Children were shown a series of video clips and animations while the elicited eye movement behaviors, e.g. fixation durations on each of the regions of interest (ROI: eyes, mouth, body, and surrounding objects)
were measured. Between group comparisons revealed attenuated orientation to socially salient aspects of the scenes, such as faces, in the autism group (n= 37; mean age = 10.2±3.2 years) compared to typically developing controls (n= 26) matched by gender, age, and IQ (see Chawarska et al., 2012; Hosozawa et al., 2012 for a similar finding). The autism group instead spent a longer time fixating on body and object regions (see Jones et al., 2008; Klin et al., 2002 for a similar finding; for contrary finding, see Shic et al., 2011).

Inconsistent with the findings reported in previous studies on toddlers (Jones et al., 2008) and adults with ASD (Klin et al., 2002), the school-aged children with ASD did not exceed typically developing controls in percent mouth fixation (Rice et al., 2012). This discrepancy may be due to the nature of the stimuli used in the study. When viewing dot-animation of biological motions, individuals with autism showed a preference for physically contingent objects, such as hands and clapping sounds (Klin et al., 2009). The stimuli contained dynamic social scenes composed of complex interactions between sounds, movements, and the environment, and thus may not particularly appeal to these children with ASD. Furthermore, a lack of preference for physically contingent objects, e.g. mouth, may be interpreted as general processing difficulties for complex social scenes in children with ASD. Therefore, these discrepancies underscore the fact that visual fixation patterns relative to faces or social scenes may be paradigm specific. That is, specific experimental demands in the research paradigms could be a contributing factor to the differential scanning patterns. When comparing different eye-tracking studies, a conclusion based only on absolute percent fixation times on ROI could be misleading. Clarifying specific demands in the paradigms could thus potentially reveal what aspects of social
processing are impaired in autism. Furthermore, the study examined a large and heterogeneous sample of children with autism that represented a wide range of IQ (Group 1: n=37, mean IQ=112±15.2; Group 2: n=72, mean IQ=88.7±19.8). The researchers found that higher percent object fixation predicted more severe social disability. Visual scanning of dynamic social scenes might therefore, as the authors suggested, be informative of the heterogeneity of the disorder. Note further that despite the wide IQ variability in the sample, all the participants were non-intellectually disabled, so these results should not be generalized to the population of intellectually disabled children with autism.

It has been argued that verbal reports provide insights into experiences and beliefs and can reveal which aspects of stimuli are attended to (Smilek, Bimingham, Cameron, Bischof, & Kingston, 2006). In an attempt to develop comprehensive accounts of the cognitive processing of social stimuli in autism (ASD), Freeth et al. (2011) incorporated subjective verbal reports into the analysis of visual scanning patterns of naturalistic scene. As noted by Ames and Fletcher-Watson (2010), spontaneous reports may facilitate a broader understanding of ASD to complement behavioral measures such as eye movement data. A series of photographic scenes, each containing a person with a neutral expression, was presented to 26 normal verbal acuity adolescents with ASD (aged 11–16 years) and 24 gender- and IQ- matched typically developing controls. The person in the photo either looked straight toward the participant or directed their gaze to an object in the photo. Four regions of interest were defined in each photo: upper face, lower face, body, and the three main objects that appeared in each scene. Participants were instructed to ‘have a good look at the photo’ while the fixation locations and durations were measured during the 15-second-free-viewing
window. A screen prompt then requested that participants gave a ‘short description’ of the scene, which remained visible in this phase. Inconsistent with the findings reported in other studies (Rice et al., 2012; Chawarska et al., 2012; Hosozawa et al., 2012), the proportion of overall viewing time spent fixating the person as well as the face of the person did not differ between the autism group and the typically developing group. However, participants with autism were slower than typically developing controls to first fixate on the person. In other words, ASD participants did not prioritize attending to the person in a scene. Furthermore, the autism group mentioned ‘the person’ in their verbal description less frequently compared to the typically developing controls. Together, these results indicated that the saliency of the person in each scene was reduced for participants with autism (see Jones et al., 2008; Riby & Hancock, 2008 for a similar finding; See also Table 7).

Importantly, the data reported in the study conducted by Freeth et al. (2011) demonstrated that eye movement data alone, despite revealing whether a stimulus is attended to, might not be able to determine whether it is encoded and processed in a meaningful way. Verbal description analysis in this study provided insight into how visual input was processed differently by individuals with autism. It should be noted that the study recruited only high functioning and normal verbal ability individuals with autism in the interest of analyzing their verbal description. Therefore, the findings can not be generalized to a larger population with autism, such as those with language impairments. Secondly, even though the autism group was high functioning and the stimuli did not contain complex social information such as multiple people interacting and conversing together (see Klin et al., 2002; Riby & Hancock 2008 for an example), the ASD group nonetheless showed a
reduced saliency of the person in the photograph overall. This observation further demonstrated the robust difference in the nature of social processing in individuals with autism.

Current research is mostly in agreement that individuals with autism process social stimuli differently as indexed by atypical gaze patterns on social stimuli (see Falck-Ytter et al., 2013 for a review). It is known that frontal lobe abnormalities, including increased white matter (Herbert, Zeigler, Makris, Filipek, Kemper, & Normandin, 2004) and reduced grey matter (McAlonan, Daly, Ekmari, Crichley, van Amerloort, & Suckling 2002), are associated with the disorder. The frontal lobe dysfunction also affects higher cognitive functions (Smith & Jonides, 1999) and oculomotor control (Pierrot-Deseilling, Milea, & Muri, 2004). Benson, Piper and Fletcher-Watson (2008) speculated that atypical gaze patterns in naturalistic scenes in ASD may be modulated by the altered top-down processing, i.e. perceptual processing problems, rather than social cognition dysfunction. They recorded the eye movements of participants while they viewed the picture ‘Unexpected Return’ (1884) painted by the Russian artist Ilya Repin. The picture was divided into three domains of interest: head region, whole person (head and body), and background objects. Prior to each presentation, participants were given either a material instruction (‘Estimate the material circumstances of the family’) or a social instruction (‘Estimate how long the unexpected visitor has been away’). The different types of instruction elicited different fixation patterns on the same picture in typically developing participants (n=9, mean age 18 years). Specifically, they fixated more often and longer (proportion to total viewing time of the picture) on heads and whole person after given a social instruction compared to a material instruction. Then, they showed increased amount of
fixations on the objects in response to a material instruction. Such ‘task effect’
was not found in the age-matched participants with autism (n=7, mean age 19
years); they showed similar fixation patterns for both instructions. As
comprehension of the different task instructions was tested by verbal questioning
following each inspection, and all ASD participants demonstrated a clear
understanding of each task requirement, a lack of differential distribution of
fixation patterns between the different scene elements implicated an impaired top-
down control of saccades. Such deficits may have an impact on domain general
attentional difficulties (Allen & Courchesne, 2001) or any specific social attention
problems (Mundy & Newell, 2007). These findings are in support of the
speculation that social processing impairments in autism are not associated with
social cognition deficits per se, but rather may be the result of aberrations in
oculomotor control. One limitation to this study was the relatively small sample
size. Similar to the limitations mentioned in the studies discussed above, these
results did not represent a larger population with autism, e.g. those with language
impairment.

Norbury, Brock, Cragg, Einav, Griffiths and Nation (2009) compared the
fixation durations on the eye regions and mouth and the latency of first fixation
among a group of teenagers with autism and language impairment (n=13), with
autism and language normal (n=14) and a group of age- and non-verbal IQ-
matched typically developing participants (n=18). The stimuli contained social
interactions between 2-3 characters with spoken dialogue and minor emotional
responses. Interestingly, only individuals with autism and with normal language
abilities spent less time viewing the eye regions and were slower to fixate to the
eyes than typically developing controls. The language impaired autism group
showed similar viewing patterns as the control group. One interpretation of these findings is that the different viewing patterns of people with autism sub-groups reflect underlying cognitive or perceptual differences that co-vary with language status. Secondly, all participants with autism were in full-time special education, which included a social skills curriculum emphasizing the importance of eye contact in social interaction. Therefore, the more typical viewing patterns evident in many participants with autism may be a consequence of explicit learning (Itier, Vallate, & Ryan, 2007). Indeed, a recent study used virtual reality technology that provided real-time feedback based on a person’s gaze patterns in social scenarios, and showed that social intervention could directly influence fixation patterns in ASD (Lahiri, Warren, & Sarkar, 2011). Specifically, there was an increase in the number of fixations on face areas after social intervention.

Additionally, participants fixated longer on faces displaying emotions, either positive or negative, compared to neutral facial expression, suggesting an improvement in emotion recognition represented by facial expression (see also Hsiao & Cottrell, 2008). A limitation to the Norbury et al. (2009) study was the small sample of each sub-group. Whether these fixation preferences relate to the diagnostic status or language ability could not be confirmed from the current results. Future research should validate the typical viewing patterns of dynamic social stimuli in language impaired individuals with autism and establish how typical viewing patterns may be related to the atypical social interactions and understandings that characterize the sub-groups of ASD.

To sum up, individuals with ASD showed reduced visual attention to the face area compared to typically developing population (e.g. Rice et al., 2012; Klin et al., 2002; Jones et al., 2008) when viewing social stimuli in a naturalistic
context. Whether distinct viewing patterns such as increased fixation on the mouth are associated with the disorder remains unclear. It has been suggested that the nature of the experimental stimuli may cause the discrepancy in findings (Rice et al., 2012; see also above for a discussion). It is also possible that the atypical social viewing is not caused by social cognition deficit, but rather a cascade effect of the general cognitive function alteration associated with ASD, as demonstrated in the Benson et al. (2008) study. Importantly, there is a lack of research on a proportion of the heterogeneous ASD population, as the majority of naturalistic assessments of eye movements and attention to complex realistic stimuli in autism focused on high-functioning and normal verbal subgroups. Future works should address these issues by exploring in what ways eye tracking data represent cognitive processing in autism, and implement research methods that accommodate the specific symptoms that are affected by autism.

Summary: Social

The studies reviewed in this section illustrate the value of eye tracking measures for understanding aspects of social cognition in autism. Current research points to the possibility of general disruptions in social processing in autism. Atypical gaze patterns toward social stimuli (e.g. faces and naturalistic contexts) in individuals with ASD presented from early childhood (see Falck-Ytter et al., 2013 for a review) through adulthood (e.g. Benson et al., 2008; Klin, et al., 2002). Further, the lack of preferential attention towards biological motion was found in 3-7 year olds with autism, suggesting an atypical developmental course (Klin & Jones, 2008; Annaz et al., 2012). Such attention bias could potentially lead to
deficits of higher-level social cognition, such as theory of mind, in autism; however, future investigations are needed to establish the causal relationship.

Attention to the face is a major area in which there appears to be differences in people with autism. ASD individuals showed attenuated visual attention to the face area compared to the typically developing population (e.g. Rice, et al., 2012; Klin et al., 2002; Jones et al., 2008). Evidence has further pointed to the possibility that deficits in social perceptual skills (e.g. the ability to perceive facial expressions) may account for the atypical face viewing in autism (de Wit et al., 2008; Yi et al., 2013). For instance, Yi et al. (2013) reported that children with autism fixated less on the right eye, which was found to be more emotionally expressive than the left (Powell & Schirollo, 2009). Furthermore, inconsistent findings have been reported regarding increased fixation on the mouth region of the face in ASD (e.g. Klin et al., 2008; Corden et al., 2008; see also Dalton et al., 2005; Nakano et al., 2010 for a contrary finding).

The nature of the experimental stimuli may cause the discrepancy of findings in this area. One explanation for the increased mouth fixation is the physically contingent properties of mouth (e.g. movement and voice). Consequently, this preference as indexed by increased mouth fixation would not be observed in a static photograph stimulus (Dalton et al., 2005) or dynamic social scenes with complex interactions between sounds and movements (Rice et al., 2012). Secondly, atypical social viewing may not be caused by a social cognition deficit, but rather a cascade effect of the general cognitive function alteration associated with ASD. Benson et al. (2008) demonstrated that individuals with autism lack the top-down control of saccades toward relevant social stimuli while processing verbal information with social content. It is also possible that atypical
viewing behaviors are reflective of general processing difficulties for complex and
dynamic everyday social interactions. If this is true, clarifying specific
experimental demands in a paradigm could potentially identify aspects of social
impairments in autism.

Lastly, there is a lack of studies on a proportion of the heterogeneous ASD
population in current research. Previous studies found that atypical viewing
patterns of social stimuli co-vary with language status (e.g. Norbury et al., 2009)
and developmental delay (e.g. Yi et al., 2013), indicating that the perceptual
difficulties might not be ASD specific. Furthermore, the majority of the studies
reviewed in this section focused on high-functioning and normal verbal subgroups
in autism. Future works should address these issues by exploring in what way eye
tracking data represents cognitive processing in autism, or implement research
methods that accommodate the specific symptoms that are affected by autism.
**Autism in Early Childhood Development**

The eye tracking technique has been used in studies of early autism, ranging from research that involves viewing naturalistic scenes to highly experimental designs (e.g. Klin et al., 2002; Jones et al., 2008; Hosozawa et al., 2012). As compiled in a recent review by Falck-Ytter et al. (2013), research has found that reduced looking time to people and faces is characteristic of young infants and toddlers with autism (e.g. Chawarska et al., 2012, 2013; Shic et al., 2011).

Furthermore, early differences between children at high risk of autism and typically developing children are not restricted to social tasks. Young infants have demonstrated altered visual orienting (Elison et al., 2013), and impaired joint attention behaviors such as gaze following (Elsabbagh & Johnson, 2007) and atypical visual processing of biological motion (Falck-Ytter, Rehnberg, & Bölte, 2013). Importantly, results of these eye-tracking tasks have been able to discriminate between children with autism and non-autistic children (Pierce, Conant, Hazin, Stoner & Desmond, 2011; Falck-Ytter, von Hofsten, Gillberg, & Fernell, 2013); for instance, altered visual orienting patterns of toddlers were found to be associated with high levels of autistic symptomatology at two years of age (Elison et al., 2013).

Further, some studies used eye tracking to characterize sub groups (e.g. language impaired and language intact) with autism (Rice et al., 2012). However, the wide range of eye tracking studies of early autism, both those that involved viewing naturalistic scenes and those with highly experimental designs, also produced mixed results. Falck-Yetter et al. (2013) concluded that explorative naturalistic approaches should be integrated with experimental paradigms and
measures, as well as with more advanced analytical approaches that can improve the specificity of interpretations. Furthermore, the authors suggested that eye tracking has the potential to be used as an integrated part of screening and diagnostic assessment. However, atypical eye movement behaviors in autism are poorly understood in relation to diagnostic status and heterogeneity of the disorder. This section reviews new longitudinal eye-tracking studies that investigate eye movements in early autism, in an attempt to evaluate the possibility of applying eye tracking to the early detection of autism.

How infants selectively attend to various features of the environment influences the development of their social and communication skills (Mundy, Card, & Fox, 2000). Elsabbagh et al. (2013) conducted a longitudinal study of infants from families with and without a history of autism to explore associations between face scanning and the degree of emerging autism symptoms, as measured by the Autism Diagnostic Observation Schedule (ADOS). 54 infants at-risk and 50 low-risk infants participated in the eye-tracking task when they were 6-10 months old, and again when they were 12-15 months old. Participants were screened for autism at 36 months and were classified as having ASD, other developmental concerns, or as typically developing. Infants were presented with videos of female faces exhibiting different communicative signals typically found in an infant’s environment. The stimulus contained four trial types: 1) eyes gaze shift while no other face part is moving; 2) mouth movement while no other face part is moving; 3) hand movement while no other face part is moving and 4) the eye, mouth and hands moving in a ‘peek-a-boo’ sequence. Areas of Interest (AOIs) included eyes, mouth, hands and all other areas of the face. An eye-mouth
index (EMI) was calculated as follows: (looking time towards the eyes – looking
time towards the mouth)/ total viewing time.

In the Elsabbagh et al. (2013) study, eye tracking data showed that across
both ages, when a peripheral feature was moving (the hand condition) or when
multiple features were moving (peek-a-boo scenes), infants preferentially looked
at eyes. This result confirms a general tendency to look more towards the eyes
relative to the mouth across both age groups. On the other hand, infants who were
overly driven by exogenous factors, such as mouth motion in single feature scenes,
were likely to later develop poor expressive language. Indeed, excessive scanning
of the moving mouth in the mouth condition was associated with a more severe
emerging social and communication impairment as measured by the ADOS. In
contrast, more looking at the mouth in complex scenes with multiple moving parts
was associated with better social communication development across groups.
Specifically, peek-a-boo EMI predicted later expressive language ability in
children both at-risk and control (see Young et al., 2009 for a similar finding).
Peek-a-boo scenes encompass concurrent signals from both the face and the
hands; these complex scenes required a high degree of endogenous control to
enhance the ability to select relevant features in the environment. Thus, individual
variation in endogenous and exogenous orienting affect scanning behaviors.

As such, attentional influences on social communication development are
likely modulated by a combination of default biases and subsequent learning that
modifies these biases over development. Importantly, the study was constrained
by the limitation of group analysis. For instance, the group of at-risk infants who
developed ASD (n=17; at-risk n= 54) was highly variable in their EMI. This could
have been used to discount the relevance of these data to the development of
infants at risk of autism. Furthermore, it was unclear whether the observed association between peek-a-boo EMI and later expressive language ability was specifically related to autism, as it held across low-risk and at-risk groups.

On the other hand, early development of gaze following has also been speculated to be a precursor to social and communication difficulties in autism. Bedford et al. (2012) employed eye-tracking to record gaze following longitudinally in infants with and without a family history of autism spectrum disorder (ASD). At-risk infants all had an older sibling with clinical diagnosis of ASD; the low-risk group had at least one older sibling and had no first-degree family members with ASD. Infants were tested at 7 months and then again at 13 months. At each testing, infants (at-risk n=35; low-risk n=38) were presented with short videos of a model turning to look at one of two objects. The videos begin with two objects on a table and a female model ‘looking down,’ then looking up and ‘directly gazing,’ and finally turning her head to look at one of the objects. The turning marks the beginning of the ‘shift’ phase. The object looked at by the model during ‘shift’ is defined as the congruent object, and the other object as the incongruent object. A previous study found that the number of first looks$^3$ and looking time to a congruent object was significantly greater than that to the incongruent object in 6-month-old typically developing infants (Senju & Csibra, 2008). It is suggested that the length of first look reflects the infant’s ability to follow the direction of another person’s gaze to its target. Further, the measure of looking time reflects not only the infant’s ability to follow a gaze, but also their subsequent engagement with the target of another person’s gaze (Brooks &

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$^3$ In this study, proportion of the first looks to the congruent versus incongruent object (Moore & Corkum, 1998) was chosen as the primary measure of gaze following behavior.
Meltzoff, 2005).

In the Bedford et al. (2012) study, first look and looking analysis at 7 months showed that gaze following was neither influenced by risk status nor by later emerging social and communication difficulties as measured by the ADOS, suggesting that the early mechanisms for automatic orienting to another’s gaze are intact in autism (see Elsabbagh & Johnson, 2010; Rogers, 2009; Yirmiya & Charman 2010 for a similar finding). In contrast, by 13 months, at-risk infants (n=35) who went on to an ASD or an atypical development outcome at 3 years (n=12) showed reduced looking time to the congruent object after gaze following, compared to the typically developing group. This indicates that whilst at-risk infants were able to orient correctly in response to the gaze shift, they might not be sensitive to the referential nature of gaze (see also Brook & Meltzoff, 2005). Importantly, such reduced looking time was found in infants with later social-communication problems, both those with autism and atypical development, indicating that this effect is associated with autistic-like social communication difficulties in general, rather than the clinical diagnosis of autism. These results should be interpreted with caution because social deficits this early in infancy have been especially difficult to demonstrate (Ozonoff et al., 2010). Together, these findings demonstrate that early automatic orienting to another’s gaze is not impaired in the autism phenotype in infancy, nor is it a predictor of autism outcome. Nonetheless, the subtle emergence of difficulties in joint attention in infancy may be related to ASD and other atypical outcomes.

Clinical conditions with a purely behavioral diagnosis such as ASD typically lack good information about the very first months of life (Happé & Frith, 2013). The eye tracking technique is a non-invasive and easy way for subjects to
be tested, and thus it is ideal for the study of young children and infants. However, current behavioral studies of genetically at-risk infants (the siblings of children with ASD) have produced mixed results (see also Falck-Ytter et al., 2013). Additionally, long-term studies are warranted to investigate the relationship between early eye movement behaviors and developmental trajectories of autism symptoms into later childhood, which could potentially allow for early diagnosis and intervention.
Conclusion

This review of literature, while focusing on the application of eye-tracking techniques in the study of autism, has revealed the array of theoretical standpoints and a range of both consistent and contradictory findings in the field. Eye tracking allows for direct, objective, and quantitative measurements of eye movements. As shown in the studies reviewed in this article, it can be used to investigate the cognitive mechanisms underlying abnormal brain activity (Dalton et al., 2005), and reduced task performance (Riby & Doherty, 2009).

Most eye tracking studies have shown that individuals with autism look at social stimuli differently: attenuated fixation on the eye region of the face (e.g. Pelphrey et al., 2002; Dalton et al., 2005), increased fixation of the mouth region (e.g. Klin et al., 2002; see Pelphrey et al., 2002 for a contrary finding), reduced fixation on faces in naturalistic scenes (e.g. de Wit et al., 2008 & Yi et al., 2013), and failure to orient to biological motion (Annaz et al., 2012). Several of the identified attention studies revealed that individuals with autism might lack social preference (e.g. Klin et al., 2003). Specifically, they failed to process social stimuli, e.g. faces, meaningfully in a naturalistic context (e.g. Fischer et al., 2013; Riby et al., 2013). Importantly, the findings suggested intact attention abilities, including cue orienting (Kuhn et al., 2010), bottom-up saliency processing (Freeth et al., 2009) and working memory (Joseph et al., 2009); instead, they pointed to the possibility of general social processing problems in ASD.

One common limitation to these studies is the relatively small subject groups. Larger studies would further clarify earlier findings such as attenuated eye fixation and increased fixation of the mouth (e.g. Klin et al., 2002). Further, ASD
encompasses a wide variety of disorders, and so it is possible to observe a wide range of verbal, non-verbal, and social abilities. Indeed, individuals with ASD demonstrate different cognitive capacities (e.g. attention) and variation in the severity of their clinical symptoms. At present, it is unclear how aspects of cognitive processing interact with each other and with the characteristics of this neurodevelopmental disorder, particularly, the social deficits. As such, there may be differing genetic, neurological, and cognitive pathways that lead to behavior associated with ASD (Ames & Fletcher-Watson, 2010). If this is true, specifying skills and aspects of impairment associated with the disorder may be crucial for future autism research, including our understanding of the impact of cognitive processes on social cognitive development.

A further complicating factor in the current research is the choice of stimulus, ranging from naturalistic scenes to highly experimental designs (e.g. Chawarska et al., 2003; Klin et al., 2002). While it has been argued that approximating stimuli with real-life situations can enhance ecological validity (Klin et al., 2002), some limitations remain. Firstly, individuals with autism may show atypical responses to more naturalistic stimuli because of the social anxiety they provoke, rather than processing difficulties or lack of interest (see also Dalton et al., 2005). Secondly, to what extent experimental studies resemble real-life situations requires further exploration. For example, when investigating features such as fixation to the eye region, people in the video do not ‘look back’ at the subject, whereas a real person would. Furthermore, stimulus content for experiments to explore the processing of social information is not well defined. For instance, the word ‘social’ has been used to describe a wide array of stimuli from cartoon pictures of faces (Kuhn et al., 2010) to moving human figure dot-
lights (Klin et al., 2009), which contain no visible human. Integration of explorative naturalistic approaches with experimental paradigms would allow for a more comprehensive picture of the disorder; more advanced analytical approaches can improve the specificity of interpretations from studies, both benefiting future research greatly.

The eye tracking method can address a dazzling array of questions (see Holmqvist, Nyström, Andersson, Deshurst, Jarodzka, & van de Weijer, 2011 for a review). More and more studies have extended its use to individuals with autism (see Boraston & Blakemore, 2007 for a review). The method is also ideal for the study of young children and infants, since it is non-invasive and requires no more than the ability to move the eye. Eye tracking tasks have been able to discriminate between children with autism and typically developing children (Falck-Ytter et al., 2013; Pierce et al., 2011). Other studies have used eye movement data to identify subgroups with autism (Rice et al., 2012), which may be useful for understanding the heterogeneity of the disorder. In fact, researchers have started to investigate the possibility of integrating eye tracking into screening and diagnostic assessments (e.g. Chawarska, Macari, & Shic, 2013; Klin et al., 2002). However, future research is warranted before the clinical application of eye tracking in autism.

In summary, although eye tracking has some limitations, there is a great potential to develop this technique further in studies of autism. Eye tracking provides links to understanding the underlying neurocognitive networks, as well as the everyday function and dysfunction associated with ASD. Many intriguing and often contradictory findings have been reported and an increasingly clear picture of the cognitive characteristics of ASD is emerging. This review seeks to
identify the main topics discussed in eye tracking studies in autism, and to describe the important findings and methodological issues. A lack of clear theoretical position unifying the cognitive characteristics and clinical features in ASD presents in the current research. Future work to investigate aspects of cognitive processes and their relationships with clinical symptoms in ASD and other neurodevelopmental phenotypes would be very helpful for understanding the roots of the social deficits and to develop targeted interventions.
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Rensink, R., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. Retrieved from: pss.sagepub.com.


Walther, D., & Koch, C. (2006). Modeling attention to salient proto-


## Appendices:

Table 1: Studies on Oculomotor Control

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Groups</th>
<th>Age (yr.) (SD)</th>
<th>IQ (SD)</th>
<th>Task</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
</table>
| **Goldberg, et al., 2002**   | 11  | HFA    | 13.8 (1.5)     | 99.4 (11.31) | AS; MGS; gap/overlap; predictive saccade task       | Saccade latency; amplitude; velocity | 1. HFA showed greater latency variance in predictive task.  
2. AS error rate: HFA>TD (p<.001).  
3. MGS error rate: HFA>TD (p=.003)  
4. HFA made less expressive saccade.
|                              | 11  | TD     | 14.4 (1.5)     | 112.6 (13.9) |                                                                                                     |                                 |                                                                                     |
| **Johnson et al., 2012**     | 10  | HFA    | 11.2 (1.44)    | 95.9 (15.22) | Visually guided saccade task                         | Saccade metrics: gain, error, latency and velocity. | 1. HFA made more errors than TD (p=.011); no difference between AD and TD.  
2. HFA showed hypometric and greater variety FEP.  
3. No group differences in latency and peak velocity.                                                                                     |
|                              | 15  | AD     | 12.8 (3.5)     | 104.2 (14)  |                                                                                                     |                                 |                                                                                     |
|                              | 12  | TD     | 11.6 (1.6)     | 108.5 (11.1) |                                                                                                     |                                 |                                                                                     |
| **Kelly et al., 2013**       | 18  | ALI    | 11.45 (2.12)   | 96.16 (16.36) | Gap/overlap task; AS task; search distractor task.       | Saccade latency and accuracy.       | 1. All group showed gap effect.  
2. AS task: directional errors: ALI=LI>TD=ALN.  
3. Search task: ALI and LI made more post-target fixations than TD (p<.002), which ALN did not.                                                                                   |
<p>|                              | 17  | ALN    | 11.3 (1.95)    | 106.31 (12.95) |                                                                                                     |                                 |                                                                                     |
|                              | 16  | LI     | 12.39 (1.99)   | 88.5 (10.29)  |                                                                                                     |                                 |                                                                                     |
|                              | 22  | TD     | 10.97 (1.36)   | 112.79 (14.23) |                                                                                                     |                                 |                                                                                     |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
<th>Group 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luna et al., 2007</td>
<td>ASD (61)</td>
<td>Control (61)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8-33 (Range)</td>
<td>8-33 (Range)</td>
<td>110.74 (±16.84)</td>
<td>110.95 (±13.75)</td>
<td>Visually guided saccade (VGS) task; AS task and MGS task.</td>
</tr>
<tr>
<td></td>
<td>8-33 (Range)</td>
<td>8-33 (Range)</td>
<td></td>
<td></td>
<td>Saccade metrics (velocity, latency, amplitude).</td>
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<td></td>
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<td>Cross-sectional analysis.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1. VG accuracy: ASD&lt;Control (no difference in velocity; latency)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. MGS latency: ASD&lt;Control;</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3. AS accuracy: ASD&lt;TD Both improved in latency and inhibition with age.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1. VG accuracy: ASD&lt;Control (no difference in velocity; latency)</td>
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<td></td>
<td></td>
<td></td>
<td>2. MGS latency: ASD&lt;Control;</td>
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<tr>
<td></td>
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<td></td>
<td>3. AS accuracy: ASD&lt;TD Both improved in latency and inhibition with age.</td>
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<td></td>
<td>1. VG accuracy: ASD&lt;Control (no difference in velocity; latency)</td>
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<td></td>
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<td></td>
<td>2. MGS latency: ASD&lt;Control;</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3. AS accuracy: ASD&lt;TD Both improved in latency and inhibition with age.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1. VG accuracy: ASD&lt;Control (no difference in velocity; latency)</td>
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<td></td>
<td></td>
<td></td>
<td>2. MGS latency: ASD&lt;Control;</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3. AS accuracy: ASD&lt;TD Both improved in latency and inhibition with age.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penseiro et al., 2009</td>
<td>ASD (14)</td>
<td>TD (20)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.1 (No rep.)</td>
<td>8 (No rep.)</td>
<td>IQ&gt;60</td>
<td>IQ&gt;60</td>
<td>MGS task; predictive task</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Saccade metrics (amplitude, duration, latency, velocity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. ASD did not show alterations in saccade profile.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Evidence of velocity variations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Takarae, et al., 2013</td>
<td>ALI (28)</td>
<td>ALN (18)</td>
<td>Control (10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.5 (11.73)</td>
<td>14 (7.86)</td>
<td>19.76 (11.48)</td>
<td></td>
<td>VGS task</td>
</tr>
<tr>
<td></td>
<td>103.57 (14.61)</td>
<td>110.44 (15.69)</td>
<td>107.53 (12.96)</td>
<td></td>
<td>Saccade metrics (velocity, latency, gain)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Accuracy: ALM &lt; Control; ALI = Control (Both autistic groups had greater variety in accuracy than Control).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. No group difference in velocity and latency.</td>
<td></td>
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</tr>
</tbody>
</table>

Notes: ¹expressive saccade – saccade with shorter latency; ²The FEP was defined as the fixation position reached following the primary saccade plus any corrective saccades. Abbreviations (HFA: high functioning with autism; MGS: memory guided saccade; AS: anti-saccade.)
Table 2: Studies on Visual Search

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Groups</th>
<th>Age (yr) (SD)</th>
<th>IQ</th>
<th>Task</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joseph et al., 2009</td>
<td>21</td>
<td>ASD</td>
<td>14.6 (2.7) 14.2 (2.9)</td>
<td>107 (10)</td>
<td>Static vs. Dynamic search paradigm</td>
<td>Reaction Time (RTs); Search efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaldy et al., 2011</td>
<td>17</td>
<td>ASD</td>
<td>29.6 (mth.) (4.8) 29.5(mth.) (2.5)</td>
<td>Not rep. Not rep.</td>
<td>Feature &amp; conjunction search task</td>
<td>Success rate design (Regression)</td>
<td>Main effects of Set size and Group in conjunction trials. Success rate: ASD&gt;TD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kemner et al., 2008</td>
<td>7</td>
<td>ASD (HA)</td>
<td>21.2 22.1</td>
<td>114.0 (106.7)</td>
<td>Feature search task (vertical vs. tilted targets)</td>
<td>RTs; Nb of fixations; fixation duration (ANOVA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Kourkoulou et al., 2013</td>
<td>15</td>
<td>ASD</td>
<td>19 (1.6) 21 (4.1)</td>
<td>101.3 &lt;br&gt; (12.4) 102.7 &lt;br&gt; (9.5)</td>
<td>Contextual cueing paradigm</td>
<td>RTs; Nb of fixations; fixation durations (ANOVA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Note: IQ refers to general (full scale) IQ unless otherwise specified; *nonverbal IQ measured with the Kaufman Abbreviated Intelligence Test (Kaufman & Kaufman, 2004); **search efficiency reflects the reaction time cost of each additional distractor and it determined by the rate of attentional shifting between items and the ability to filter out irrelevant items; †performance IQ assessed by WAIS-III (1997); ‡trial length is fixed, and performance is measured by the proportion of trials on which the target is found. Abbreviations (Mth: month; No rep.: not reported; HA: high functioning; Nb: number; Avg: average.)
### Table 3: Studies on Attention Cueing

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Groups</th>
<th>Age (yr) (SD)</th>
<th>IQ</th>
<th>Task</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
</table>
| Kuhn et al., 2010      | 12 | ASD        | 26.0 (10.5) 22.4 (9.7)  | 109 (12.5) 108 (22.9) | Gaze cueing (cartoon face eye gaze vs. arrow) | Saccadic reaction times (SRTs) (ANOVA)                        | 1. No group effect on cueing effects (SRTs: gaze<arrow).  
2. No correlation between AQ scores and difference from distractor types. |
|                        | 12 | Control    |                          |          |                                              |                                                             |         |
| Kyllianen et al., 2004 | 12 | ASD        | 9.3 (2.9) 9.4 (2.8)      | 91 (17) 106 (7) | Gaze cueing (images of real face) SOA design | SRTs: congruent vs. incongruent vs. neutral (ANOVA)           | 1. Main effects on gaze congruency (p<.002); SOAs (SRTs: 200ms < 800ms)  
2. Group X Main effects interactions is non-significant. |
|                        | 12 | Control    |                          |          |                                              |                                                             |         |
| Riby & Doherty, 2009   | 15 | ASD        | 10.8 (no rep.) 6.8 (no rep.) | 12a (No rep.) 12a (No rep.) | Gaze cueing (real face) | Accuracy; initial fixation latency, duration. (ANOVA) | 1. ASD is less accurate (ASD=74% vs. TD=90%)*  
2. Time to First fixate on face region: TD<ASD**; Face fixation duration: TD>ASD*; time to fixate on target: TD<ASD**  
3. Negative correlation between accuracy and functioning b (p<.01). |
<p>|                        | 15 | TD         |                          |          |                                              |                                                             |         |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Sample</th>
<th>Age (mean ± SD)</th>
<th>Repetitions</th>
<th>Task</th>
<th>Measure</th>
<th>Results</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vlaming et al., 2005</td>
<td>19</td>
<td>ASD</td>
<td>22.5 (4.96)</td>
<td>No rep.</td>
<td>Gaze cueing (eye gaze vs. arrow)</td>
<td>Accuracy; SRTs (ANOVA)</td>
<td>1. Both groups find congruency effect (SRTs: congruent &lt; incongruent &lt; .001).</td>
<td>1. Both groups find congruency effect (SRTs: congruent &lt; incongruent &lt; .001).</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Control</td>
<td>23.0 (3.70)</td>
<td>No rep.</td>
<td></td>
<td></td>
<td>2. Only Control showed different congruency effect between tasks, not ASD.</td>
<td>2. Only Control showed different congruency effect between tasks, not ASD.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. SRTs congruent: ASD &gt; Control*</td>
<td>3. SRTs congruent: ASD &gt; Control*</td>
</tr>
<tr>
<td>Bedford et al., 2012</td>
<td>35</td>
<td>At risk</td>
<td>7.3; 13.8; 24.4;</td>
<td>No rep.</td>
<td>Gaze cueing (real face)</td>
<td>Accuracy, fixation duration.</td>
<td>7 Month No difference in gaze behaviors between groups.</td>
<td>7 Month No difference in gaze behaviors between groups.</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>Low risk</td>
<td>38.4 (Assessed four times; Month)</td>
<td>No rep.</td>
<td></td>
<td></td>
<td>13 Month Reduced looking time in at-risk group with ASD siblings and AT siblings compared to TD siblings and Low-risk group.</td>
<td>13 Month Reduced looking time in at-risk group with ASD siblings and AT siblings compared to TD siblings and Low-risk group.</td>
</tr>
</tbody>
</table>

Note: * Ravens Coloured Progressive Matrices (Raven, Court, & Raven, 1990); *CARS; * group effect on accuracy is non-significant; ** significant (p < .001); IQ refers to general (full scale) IQ unless otherwise specified. Abbreviations (SOA: onset of the reaction signal (stimulus-onset-asynchrony); AT: atypically developing; ADOS-G: Autism Diagnostic Observation Schedule–Generic.
Table 4: Studies on Attention Bias

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Groups</th>
<th>Age (yr) (SD)</th>
<th>IQ (SD)</th>
<th>Task</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
</table>
| Elison et al., 2011           | 51 | ASD    | 9.3 (3.6)     | 94.9 (18.77)  | Visual Exploration Task     | Fixation durations; Nb of fixations per image, total; Nb of fixated images (Regression model) | 1. Age effect: fixation durations; Nb of fixations; Nb of fixated images in both groups.  
2. Limited age-related increase in visual exploration of social stimuli in ASD group. |
|                               | 43 | TD     | 8.2 (4.2)     | 112.77 (13.74) |                             |                                                                                               |                                                                        |
| Fischer et al., 2013          | 44 | ASD    | 9.2 (1.7)     | 108.8 (16.2)  | Gap-overlap paradigm        | Saccadic reaction time (SRTs) (ANOVA)                                                             | 1. Both groups showed disengagement cost for social vs. nonsocial (both p<.001; d>1).  
2. No Group X Stimulus type effect.                     |
|                               | 40 | TD     | 8.6 (2.1)     | 113.6 (13.2)  |                             |                                                                                               |                                                                        |
| Freeth, Foulsham, et al., 2011| 24 | ASD    | 13.8 (1.37)   | 97.0 (13.6)   | Natural scenes viewing task | Nb of fixations; saliency value of fixations (ANOVA)                                             | 1. Saliency effect in both groups.  
2. ASD group reached at peak saliency fixation slower (F(4,184)=2.39, p=.05). |
|                               | 24 | TD     | 14 (1.37)     | 95.5 (9.53)   |                             |                                                                                               |                                                                        |

Note: – significant (p<.05) negative correlation; + significant (p<.05) positive correlation; a Performance IQ assesses perceptual organization and processing speed; included in the Wechsler Adult Intelligence Scale–III (1997); b the Kaufman Abbreviated Intelligence Test (Kaufman & Kaufman, 2004.); IQ refers to general (full scale) IQ unless otherwise specified. Abbreviations (SD: Standard deviation; Yr: year; Nb: number)
Table 5: Studies on Face Processing

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Groups</th>
<th>Age(yr) (SD)</th>
<th>IQ</th>
<th>Task</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
</table>
| Dalton et al., 2005  | 14 | ASD             | 15.9 (4.71)  | 94⁴     | Facial emotion discrimination task; Facial recognition task | RTs; Accuracy; Gaze patterns                               | 1- ASD showed longer RT to discriminate emotional faces, but not neutral faces.  
|                      | 12 | Control         | 17.1 (2.78)  | (19.47)  |                                           |                                                           | 2- Recognition task accuracy: TD>ASD                                   
|                      |    | No rep.         |              |          |                                           |                                                           | 3- ASD spent less time fixating on face in both tasks**.              |
| de Wit et al., 2008  | 13 | ASD             | 5.2 (1.8)    | No rep.  | Emotional faces viewing patterns           | Gaze pattern (AOI: eyes, mouth and nose)                   | 1- ASD looked less at all AOIs compared to TD.                         
|                      | 14 | TD              | 5.0 (0.1)    | No rep.  |                                           |                                                           | 2- Both groups showed increased eye scanning for faces with negative emotions. |
| Hedley et al., 2012  | 26 | ASD             | 20.12 (9.54) | 107.69⁵ | Implicit facial recognition task           | Fixation durations; Nb of fixations (ANOVA: stimulus type X condition X group) | 1. Eye movements did not differ between groups at implicit recognition.  
|                      | 41 | Control         | 24.76 (7.42) | 109.88⁵ |                                           |                                                           | 2. ASD performed worse at explicit face recognition.                  |
| Klerk et al., 2013   | 44 | high risk       | 37.8 (1.7)   | 117⁶    | Facial recognition task- scanning pattern  | AOIs: eyes, nose, mouth, and surrounding.                  | 1. High risk group switched less between face features**.             
|                      | 40 | Low risk        | 37.3 (1.7)   | 106.5⁶  |                                           |                                                           | 2. Eye movement measures did not correlate with face recognition performance. |
| Yi et al., 2013 | 17 | ASD (Age) | 7.85 (1.59) | 77.16 (19.55) | Facial recognition task- scanning pattern | AOIs: whole face, left eye, right eye, nose and mouth. Saccade path analysis |
| | 18 | TD (IQ) | 7.73 (1.51) | 89.42 (11.23) | | |
| | 18 | TD (Age) | 5.69 (0.83) | 98.11 (7.01) | | |

1. Recognition Performance: ASD< both TD groups**.
2. ASD looked significant less at right eye.
3. ASD scanned less frequent between eye-eye and eye-nose than TD(Age)**.
4. No significant correlations between accuracy and eye movement measures.

| Sterling et al., 2008 | 18 | ASD | 23.5 (7.19) | 107.12 (13.31) | Facial recognition task-scanning pattern | AOIs: head, face, eyes, nose and mouth. |
| | 17 | Control | 24.24 (6.86) | 109.94 (13.25) | | |

1. Both groups showed greater percentage of Nb of fixations on eyes than mouth fixation.
2. Total fixation durations Eye: ASD<TD; mouth: ASD=TD
3. Recognition accuracy did not differ between groups.

Notes: ' not significantly different from the standardized average of 100 (SD=15) reported for the normal population; ** significant, p<.05; ' full scale IQ (group mean, standard deviation, and range of MSEL ELC scores, Mean = 100, SD = 15); b Raven standardized score. Abbreviations (RTs: reaction time; Nb: numbers of; Mon.: month; TD(Age): chronological age matched; TD(IQ): IQ matched TD.)
Table 6: Studies on Social Processing of Animation

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Group</th>
<th>Age(yr) (SD)</th>
<th>IQ</th>
<th>Task</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annaz et al., 2012</td>
<td>17</td>
<td>ASD</td>
<td>5.6 (1.1)</td>
<td>62a</td>
<td>Preferential Viewing</td>
<td>Fixation time (%) on each stimuli</td>
<td>1. Only TD showed viewing preference toward “walker.”</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>TD</td>
<td>5.6 (1.1)</td>
<td>79a</td>
<td>(point-light walker vs. scrambled vs. spinning top)</td>
<td></td>
<td>2. %fix Group effect: walker: ASD&lt;TD** scrambled: ASD&gt;TD** spinning top: ASD&gt;TD**</td>
</tr>
<tr>
<td>Klin et al., 2009</td>
<td>21</td>
<td>ASD</td>
<td>All groups are two-year-olds</td>
<td>No rep.</td>
<td>Preferential Viewing</td>
<td>Fixation time (%) (up-right vs. inverted version)</td>
<td>1. Only TD showed preferential viewing towards all social upright figures (p&lt; .01).</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>TD</td>
<td>No rep.</td>
<td>No rep.</td>
<td>(point-light figures engaging social activities vs. inverted versions)</td>
<td></td>
<td>2. The level of audiovisual synchrony is highly correlated with preferential viewing in ASD**, is uncorrelated with TD and DD.</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>DD</td>
<td>No rep.</td>
<td>No rep.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zwickel et al., 2012</td>
<td>19</td>
<td>AS Control</td>
<td>37 (No rep.)</td>
<td>117b</td>
<td>Frith-Happe Animation (R vs. GD vs. ToM)</td>
<td>Verbal report (intentionality analysis); fixation durations</td>
<td>1. ASD under-attributing intentionality in GD and ToM animations*.</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>Control</td>
<td>39 (No rep.)</td>
<td>115b</td>
<td></td>
<td></td>
<td>2. ASD over-attributing intentionality to R.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. No group interactions in fixation duration pattern: R&lt;GD&lt;ToM</td>
</tr>
</tbody>
</table>

Notes: *nonverbal mental age equivalent in months measured by British picture vocabulary scale (Dunn, Whetton, & Burley, 1997); ** verbal IQ by Wechsler adult intelligence scale (Wechsler, 1997); ** significant p<.05 * not significant; IQ refers to general (full scale) IQ unless otherwise specified. Abbreviations (R: random; GD: goal directed; ToM: theory of mind; DD: developmentally delayed but non-autistic; AS: Asperger’s Syndrome.)
<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Groups</th>
<th>Age(yr) (SD)</th>
<th>IQ</th>
<th>Tasks</th>
<th>Measures (Statistical Analysis)</th>
<th>Results</th>
</tr>
</thead>
</table>
| Benson et al., 2008         | 7  | ASD      | 19 (No rep.) | 88  | Viewing task (social vs. material instructions) | Fixation durations (fix.%) (AOI: people and the scene)                | 1. Only TD showed task effect on fixation % ➞ material: object>people; social: people>object.  
2. Fixation on head region: ASD<TD** |
|                             | 9  | TD       | 18 (No rep.) | 103 |                                            |                                                                       |                                                                        |
| Freeth, Ropar, et al., 2011 | 24 | ASD      | 14.9 (1.4)  | 101.3| Human gaze viewing task                    | Verbal description; fixation duration, latency (AOI: face and object) | 1. TD mentioned 'person' in the scene more times than ASD**  
2. No group difference in "person" and "face" fixation duration.  
3. ASD is slower to first fixate on "person" ** |
|                             | 24 | TD       | 14.8 (1.3)  | 98.3 |                                            |                                                                       |                                                                        |
| Klin et al., 2002           | 15 | ASD      | 15.4 (7.2)  | 101.3| Social scene viewing                       | Fixation duration (AOI: mouth, eyes, body and objects)               | 1. ASD focused 2 times more on the mouth region, body and object; 2 times less on the eye region.**  
2. Social functioning bcorrelated with mouth fixation(+) and object fixation(-) in ASD. |
|                             | 15 | Control  | 17.9 (5.6)  | 102.5|                                            |                                                                       |                                                                        |
| Norbury et al., 2009        | 14 | ALI      | 14.9 (1.2)  | 81.9a| Social video viewing                       | Fixation time(%) (AOI: eyes, mouth, body, and others)                | 1. Fixation Eyes: TD>ALN**; No group difference between TD and ALI, t < 1.  
2. ALN was slower to fixate the eye region than TD and ALI**.  
3. Increased eye fixation in negatively correlated with communication ability** ** |
<p>|                             | 14 | ALM      | 14.9 (1.4)  | 101.9a|                                            |                                                                       |                                                                        |
|                             | 18 | TD       | 14.5 (0.9)  | 111.6a|                                            |                                                                       |                                                                        |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Group</th>
<th>Autism</th>
<th>TD</th>
<th>Social video viewing</th>
<th>Fixation time (%) (AOI: eyes, mouth, body, and objects)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice et al., 2012</td>
<td>37</td>
<td>ASD</td>
<td>10</td>
<td>2.3</td>
<td>112 (15.2)</td>
<td>Face(eyes+mouth) fixation: TD&gt;ASD**.</td>
<td>1. Face(eyes+mouth) fixation: TD&gt;ASD**.</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>TD</td>
<td>9.5</td>
<td>2.2</td>
<td>110.4 (15.9)</td>
<td></td>
<td>2. Mouth fixation: TD&gt;ASD**.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASD</td>
<td>112</td>
<td>(26)</td>
<td>110.4 (15.9)</td>
<td></td>
<td>3. Object fixation is positively correlated with social disability as measured by ADOS**.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td>9.5</td>
<td>(22)</td>
<td>110.4 (15.9)</td>
<td></td>
<td>4. Mouth fixation is positively correlated with ADOS in ASD group of IQ&gt;98**.</td>
</tr>
<tr>
<td>Chawarska et al., 2012</td>
<td>54</td>
<td>ASD</td>
<td>21.6</td>
<td>2.9</td>
<td>21.6 (2.9)</td>
<td>ASD looked less to the face region.</td>
<td>1. ASD looked less to the face region.</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>DD</td>
<td>20.1</td>
<td>3.5</td>
<td>20.5 (3)</td>
<td>All groups looked more that eyes.</td>
<td>2. All groups looked more that eyes.</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>TD</td>
<td>20.5</td>
<td>3.5</td>
<td>20.5 (3)</td>
<td>ASD looked more to hands/act than both DD and TD.</td>
<td>3. ASD looked more to hands/act than both DD and TD.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASD</td>
<td>21.6</td>
<td>2.9</td>
<td>21.6 (2.9)</td>
<td>Correlation between %Valid and ADOS-G score (p&lt;.05).</td>
<td>4. Correlation between %Valid and ADOS-G score (p&lt;.05).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DD</td>
<td>20.1</td>
<td>3.5</td>
<td>20.5 (3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Notes: No rep.: not reported; ALI: autism language impaired; ALN: autism language normal; IQ refers to general (full scale) IQ unless otherwise specified; a verbal IQ derived from the Wechsler Intelligence Scale for Children, 3rd edition (WISC-III), and the Wechsler Adult Intelligence Scale, 3rd edition (WAIS-III); b As measured by the Vineland Adaptive Behavior Scales, VABS (Sparrow, Bella, & Cicchetti, 1984/21) and Autism Diagnostic Observation Schedule, ADOS; ‘overall attention to the scene; * significant, p<.05; + significant positive correlation; - significant negative correlation. Abbreviations (AOI: area of interests; DD: developmental delay.)