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RESEARCH ARTICLE

Basic oculomotor function is similar in young children with ASD and typically developing controls

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Abstract

A variety of eye tracking studies have demonstrated that young children with ASD gaze at images and movies of social interactions differently than typically developing children. These findings have supported the hypothesis that gaze behavior differences are generated by a weaker preference for social stimuli in ASD children. The hypothesis assumes that gaze differences are not caused by abnormalities in oculomotor function including saccade frequency and kinematics. Previous studies of oculomotor function have mostly been performed with school-age children, adolescents, and adults using visual search, anti-saccade, and gap saccade tasks that are less suitable for young pre-school children. Here, we examined oculomotor function in 144 children (90 with ASD and 54 controls), 1–10-years-old, as they watched two animated movies interleaved with the presentation of multiple salient stimuli that elicited saccades-to-targets. The results revealed that the number of fixations, fixation duration, number of saccades, saccade duration, saccade accuracy, and saccade latency did not differ significantly across groups. Minor initial differences in saccade peak velocity were not supported by analysis with a linear mixed model. These findings suggest that most children with ASD exhibit similar oculomotor function to that of controls, when performing saccades-to-targets or freely viewing child-friendly movies. This suggests that previously reported gaze abnormalities in children with ASD are not due to underlying oculomotor deficiencies.

Lay Summary

This study demonstrates that children with ASD perform similar eye movements to those of controls when freely observing movies or making eye movements to targets. Similar results were apparent across groups in the number of eye movements, their accuracy, duration, and other measures that assess eye movement control. These findings are important for interpreting previously reported differences in gaze behavior of children with ASD, which are likely due to atypical social preferences rather than impaired control of eye movements.

KEYWORDS
eye position, eye tracking, gaze, kinematic characteristics, movies, oculomotor control, saccade

INTRODUCTION

Atypical gaze behavior is one of the first manifestations of impaired social communication in many children with autism spectrum disorder (ASD). For example, reduced eye contact, joint attention, and looking at others are apparent already in 12-month-old children with ASD (Osterling & Dawson, 1994; Senju & Johnson, 2009). These gaze behavior abnormalities are indications for an ASD diagnosis according to the Diagnostic and Statistical Manual of Mental Disorders fifth edition (DSM-5) (American Psychiatric Association, 2013) and are

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measured by several items in the Autism Diagnostic Observation Schedule (Lord et al., 2000).

To further quantify abnormalities in gaze behavior, numerous studies have utilized eye tracking to record the gaze of children with and without ASD as they observe different images and movies. Several studies have demonstrated that typically developing infants and toddlers exhibit a strong preference for gazing at stimulus features that are important for social interaction, such as the eyes region in faces (Batki et al., 2000; Farroni et al., 2002; Frank et al., 2009; Haith et al., 1977; Johnson et al., 1991), faces in general (Frank et al., 2009; Johnson-et al., 1991) and biological motion (Simion et al., 2008). In contrast, children with ASD exhibit less fixations to the eyes region (Frazier et al., 2017; Jones et al., 2008; Jones & Klin, 2013), less fixations to the face in general (Chawarska et al., 2012; Frazier et al., 2017; Shic et al., 2011), and a weaker preference for biological motion (Klin et al., 2009; Todorova et al., 2019). Instead, individuals with ASD exhibit higher preferences for stimuli with moving geometric shapes (Pierce et al., 2016), stimuli with high audio-visual synchrony (Klin et al., 2009), and stimuli with higher low level saliency (Wang et al., 2015). It has been suggested that some of these gaze preference abnormalities may be useful biomarkers for assessing ASD risk at very early ages (Jones & Klin, 2013; Pierce et al., 2016).

The vast majority of eye tracking studies described above assume that differences in gaze behavior across groups are generated by differences in preference for certain stimulus categories versus others. However, differences in gaze behavior may also be generated by oculomotor impairments that alter the frequency of saccades, their velocity, latency, accuracy, and other kinematic variables. For example, an individual who makes more saccades per second is likely to scan visual stimuli more quickly and may potentially scan more locations in each stimulus. Alternatively, an individual who makes less accurate saccades may miss intended saccade locations/targets in specific stimuli. Such differences are likely to alter measures of gaze preference that often compare the total fixation time on specific locations or regions of interest in a stimulus (e.g., amount of time gazing at faces vs. other objects).

Previous studies examining oculomotor function in ASD have yielded mixed results. For example, while some have reported that older children and adolescents with ASD exhibit abnormally long saccade latencies (Goldberg et al., 2002; Wilkes et al., 2015), others have reported no significant differences across groups (Luna et al., 2007; Van der Geest et al., 2001). Similarly, some have reported lower saccade accuracy in ASD individuals (Luna et al., 2007) while others have not (Goldberg et al., 2002; Kovarski et al., 2019; Minshew et al., 1999). Most studies have reported equivalent saccade peak velocity and acceleration measures across ASD and control groups (Johnson et al., 2012; Kovarski et al., 2019; Minshew et al., 1999). A recent meta-analysis concluded that there were no significant differences in saccade latency, accuracy, or peak velocity across individuals with ASD and controls when performing saccades to targets. However, they suggested that consistent differences across groups were apparent in a saccade dysmetria measure, which quantified within-subject variability of saccade distance across trials, suggesting that individuals with ASD make more variable saccades (Johnson et al., 2016).

The vast majority of oculomotor studies described above were performed with adolescents and adults using relatively complex tasks such as pro-saccade gap, anti-saccades, and visual search that usually require compliance with specific instructions (Johnson et al., 2016). Such studies are not possible with young children or with participants who have relatively high autism severity and/or low cognitive abilities. One recent study examined oculomotor function in individuals with ASD, 6–30 years-old, as they freely viewed movies. This study reported that individuals with ASD performed saccades of significantly shorter duration and distance, while there were no significant differences across groups in saccade peak velocity, number of fixations, or fixation duration. Furthermore, the study reported that combining multiple measures of oculomotor function enabled classification of ASD and control participants at accuracy rates that were similar to those reported by eye tracking studies of social preference (Bast et al., 2021).

Our goal was to assess oculomotor function in younger children with ASD using a child-friendly experimental design that would enable inclusion of a heterogeneous community sample including those with relatively severe ASD symptoms and low cognitive abilities. We, therefore, examined oculomotor function in young 1–10-year-old children with ASD and controls as they freely viewed two child-friendly animated movies interleaved with the presentation of salient visual stimuli (twinkling stars) that elicited saccades to predefined locations. This enabled us to quantify and compare a variety of oculomotor measures across groups during both a "naturalistic" free-viewing condition and a structured saccade-to-target condition.

METHODS

Participants

We analyzed data from a total of 144 children (Table 1) including 90 children diagnosed with ASD (mean age: 5.17 years old ±1.6, 70 [78%] males), and 54 typically developing controls (mean age: 4.4 years old ±1.8, 36 [67%] males). There was no significant difference in gender ($X^2[1.144] = 2.14$, $p = 0.14$) across the two groups. However, there was a significant difference in age ($t[105.3] = 2.61$, $p = 0.01$, $d = 0.46$). We included age

TABLE 1 Characteristics of children included in the analysis of oculomotor function during free viewing of movies

	ASD ($n = 90$, 70 males)		Control ($n = 54$, 36 males)	
	Range	Mean ± SD	Range	Mean ± SD
Age (years)	1–8	5.17 ± 1.6	1.4–10	4.41 ± 1.8
Total ADOS score	5–27	15.16 ± 6.1		
Cognitive score	50–128	83.1 ± 15.9		
SRS score			11–66	35.3 ± 13.4

Note: The mean and standard deviation of the children's age, ADOS, cognitive, and SRS scores are presented.

TABLE 2 Characteristics of children included in the analysis of oculomotor function during saccade to targets on discrete trials

	ASD ($n = 54$, 41 males)		Control ($n = 32$, 19 males)	
	Range	Mean ± SD	Range	Mean ± SD
Age (years)	1.7–8	5 ± 1.9	1.4–8.4	4.34 ± 1.7
Total ADOS score	5–28	16.5 ± 6.9		
Cognitive score	50–107	79.1 ± 14.5		
SRS score			19–57	34.2 ± 12.2

Note: Same format as Table 1.

and gender as co-variates in our statistical model (see below).

The analyzed sample included most of the 196 children (131 with ASD and 65 controls) who participated in eye tracking studies at the National Autism Research Center of Israel (Dinstein et al., 2020; Meiri et al., 2017) between 2016 and 2019. We included children who viewed at least 50% of each of the presented movies (i.e., at least 180 s of valid data) in the main analysis (Table 1). This relaxed inclusion criterion was used to maximize the power of the study, but we also re-analyzed the data while selecting two alternative sub-samples with more stringent data quality criteria (see data quality section below). The analysis of saccades-to-targets was performed with data from 86 children (54 with ASD and 32 controls) who performed saccades in at least 50% of the trials (Table 2). There were no significant differences across groups in age ($t[74.6] = 1.9$, $p = 0.07$) or gender ($X^2[1.86] = 2.6$, $p = 0.1$) in the saccade to target sample.

ASD severity was assessed using the Autism Diagnostic Observation Scale-2 (Lord et al., 2012) by a trained clinician with over 5 years of experience. Cognitive abilities were assessed by a licensed developmental psychologist using the Wechsler Preschool and Primary Scale of Intelligence (Wechsler, 2002) or the Bayley Scale of early development (Albers & Grieve, 2007). Parents of all control children completed the social responsiveness scale (SRS) (Constantino & Gruber, 2012) to ensure that SRS scores were below clinical concern cut-offs (i.e., maximum of 75) (Moody et al., 2017). The study was approved by the Soroka Medical Center Helsinki committee and the Ben Gurion University internal review board committee. Written informed consent was obtained from all parents.

Eye tracking

Left eye gaze position was recorded at a sampling rate of 500 Hz using an EyeLink 1000+ head-free eye tracking system (SR Research Inc. Canada). Children were seated approximately 60 cm from the screen on an adapted car seat with straps or on a comfortable chair (depending on their physical size). The screen was mounted on an adjustable arm from the wall and the eye tracker camera was located below the screen. A head tracking sticker was placed on the forehead of the child which enabled the eye tracker to track the head of the child. The eye tracker was calibrated by presenting five brief salient stimuli at the center and four points on the screen. The accuracy of calibration was reassessed before and after each segment in the experiment using a single target, and re-calibration was performed when the error exceeded 2°. Data was acquired and analyzed using Experiment Builder and Data viewer (SR Research Inc., Canada). Additional analyses were performed using Matlab (Mathworks Inc., USA).

Experimental design

Children freely viewed 2–3 short movies (each 1.5 min long) and each movie was presented twice. In the current study we analyzed data from the two movies that were presented to all children (the third movie was presented to only a sub-sample of the children). The first contained a 1.5 min segment of the Pixar animation "Jack-Jack Attack." The segment depicts the adventures of a babysitter who is trying to take care of an infant with supernatural powers. The second contained a segment of the Walt Disney animation "The Jungle Book." In the chosen segment a boy (Mogli) meets the Monkey king who sings and dances while interacting with other monkeys. Movie presentations were separated by segments with presentation of 10 targets that were presented on a white background in fixed locations such that the distance between consecutive targets varied from 7° to 23° of visual angle. Each target (a twinkling star presented with an auditory "ding") was presented for 250 ms and followed by an inter-stimulus interval of 450 ms. A total of 50 targets were presented to each child throughout the experiment.

Data-analysis

Eye tracking data from the movie presentations was preprocessed by removing segments with eye blinks

(i.e., brief extreme gaze position values) and segments in which gaze position was missing (i.e., the child was not looking at the screen). Saccades were detected using custom-written code, which identified segments of consecutive gaze velocity values that were larger than two standard deviations above the mean. The point of peak velocity was identified according to the maximal value. Saccade onset and offset were defined as the first and last point that exceeded a threshold of 40° of visual angle per second respectively. Saccade duration was defined as the time between saccade onset and offset, and saccade distance was defined as the distance between eye position at saccade onset and offset. Segments of gaze position between saccades were defined as fixations, and their duration was calculated accordingly. We then calculated the number of fixations per second, number of saccades per second, median fixation duration, median saccade duration, median saccade peak velocity, and median saccade distance across all saccades identified during the two movie presentations. We used the median since saccade measures are known to exhibit a right skewed distribution (Canice McGivern & Mark Gibson, 2006; Harris et al., 1988; Van Loon et al., 2002; van Opstal & van Gisbergen, 1989) and in such cases the median is a more robust measure of central tendency.

Eye tracking data from the saccade-to-target segments were analyzed similarly using equivalent custom-written code. The initial saccade, executed within 50–700 ms of target presentation, was identified according to velocity, and saccade onset and offset were defined as described above. In addition to the oculomotor measures described above, we also calculated saccade latency and accuracy for the initial saccade in each trial. Saccade latency was defined as the time between stimulus presentation and saccade onset. Saccade accuracy was measured in three ways. We first computed the trajectory of the saccade at peak velocity (relative to saccade onset) and then calculated its difference in degrees from the trajectory of the actual target (relative to saccade onset). This yielded a measure of the trajectory error at peak velocity in degrees for each trial, which was averaged across trials for each child. We then computed the error in saccade extent as the difference between the distance of the initial saccade and the distance to the target (relative to saccade onset). Finally, we also computed the absolute saccade error as the Euclidian distance between the saccade end-point and the target location.

Only children with recordings that contained at least 25 valid saccade-to-target trials (i.e., 50% of the trials) were included in these analyses. Trials were excluded using the following criteria:

1. Trials where a saccade was not identified within 50–700 ms of stimulus presentation.
2. Trials with missing data due to eye blinks or instances where the child did not look at the screen.
3. Trials where the initial saccade trajectory was $\pm>90°$ from the trajectory of the target, indicating that the child made a saccade to an irrelevant direction.
4. Saccades with extreme peak velocity values that exceeded 1000° per second, which are impossible physiologically and were likely the product of measurement error (Bahill et al., 1981; Boghen et al., 1974; Fukushima et al., 2000). This criterion accounted for 1.5% of the saccades discarded in the ASD group (146 out of 9966 saccades) and 2.3% in the control group (106 out of 4564).

Statistics

Between group differences were assessed using two samples, two-tailed, *t*-tests with unequal variance. Correlations between saccade distance and velocity were calculated using Pearson linear correlations. Statistical significance was set to a *p*-value of 0.05 for all tests and we did not correct for multiple comparisons in order to increase sensitivity. We also calculated Cohen's *d* to assess effect sizes of differences between groups and the Bayes Factor (BF) or its inverse (inverse BF = 1/BF) to estimate the strength of evidence for the alternative or null hypotheses, respectively. A BF larger than three means that the alternative hypothesis is three times more likely than the null hypothesis, while an inverse BF larger than three (i.e., BF < 0.33) means that the null hypothesis is three times more likely than the alternative hypothesis. This is often suggested as a threshold for the existence of moderate/substantial evidence for accepting or rejecting either hypothesis (Lee & Wagenmakers, 2014).

In a final analysis, we used linear mixed modeling to assess potential oculomotor differences across groups during observation of the two movies, while combining multiple measures in a single statistical model. This approach has the advantage of accounting for individual differences across children (i.e., random effects) while also addressing the potential effects of nuisance variables such as data quality and age when quantifying differences across groups (i.e., fixed effects) (Henderson, 1973). We built a separate linear mixed model for each of the independent oculomotor variables (number of fixations, median fixation duration, number of saccades, median saccade duration, median saccade distance and median saccade peak velocity) while including group identity (i.e., ASD or control), age, gender, calibration error, percentage of valid eye-tracking data, and movie identity as dependent variables. All variables were standardized into *z*-scores to facilitate comparison across measures.

Power analysis

We assessed statistical power using G*power version 3.1.9.4 (Faul et al., 2007). The power of the current study

to identify significant differences across groups using a two tailed t-test, assuming a medium effect size of $d = 0.5$ across groups, was 82% for the full sample (90 children with ASD and 54 controls) and 60% for the saccade-to-targets experiment sample (54 children with ASD and 32 controls).

Data quality

Calibration errors were slightly larger in the ASD group (t[134. 7] = 1.63, $p = 0.11$, $d = 0.24$) as were the drift correction values throughout the experiment (t[166.5] = 1.69, $p = 0.09$, $d = 0.23$). To ensure that these marginally significant differences did not impact our findings, we performed an additional analysis with a sub-group of 95 children (55 ASD and 40 controls) who had a calibration error <1.5°. Furthermore, to ensure that the results were not due to our relaxed inclusion criteria (i.e., children who viewed 50% of the movies), we also re-analyzed data from a sub-group of 103 children (55 ASD and 48 controls) who viewed at least 70% of each of the movies (i.e., at least 252 s of valid data). Finally, we included the percentage of valid data and calibration errors of individual children as predictors in the linear mixed model analysis.

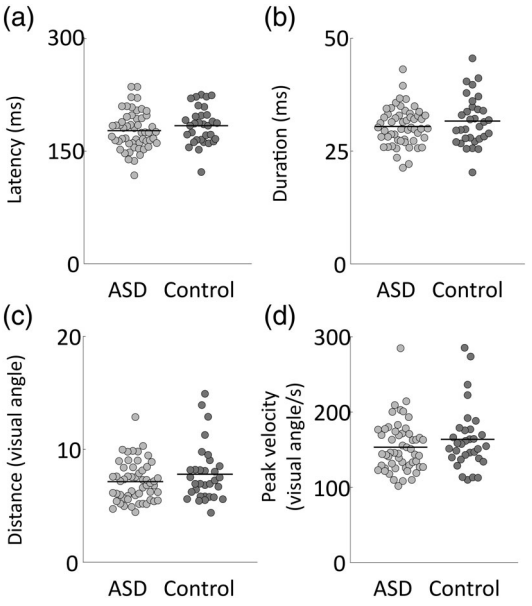

FIGURE 1 Saccades to targets. Bee-swarm plots of saccade kinematics from the initial saccade after target presentation: (a) Latency, (b) Duration, (c) Distance, (d) Peak velocity. Light gray: ASD children. Dark gray: Control children. Each circle represents a single child (mean across all trials). There were no significant differences across groups ($p > 0.05$, two sample t-test with unequal variance)

RESULTS

Saccades-to-targets

The initial saccades performed on trials containing a salient target (twinkling star) did not differ significantly across ASD and control groups in their latency (t[65.9] = −1.2, $p = 0.24$, $d = -0.27$, inverse BF = 2.32), duration (t[52.5] = −1.07, $p = 0.29$, $d = -0.26$, inverse BF = 2.44), distance (t[49.4] = −1.3, $p = 0.2$, $d = -0.32$, inverse BF = 1.78), or peak velocity (t[54.5] = −1.21, $p = 0.2$, $d = -0.29$, inverse BF = 2.12) (Figure 1). There were also no significant differences in the number of saccades per trial (t[70.5] = −0.28, $p = 0.78$, $d = -0.06$, inverse BF = 4.16) or the percentage of valid trials (t [64.5] = −0.21, $p = 0.84$, $d = -0.05$, inverse BF = 4.16).

Saccade accuracy

Saccades to targets did not differ across groups in their accuracy. This was apparent in the probability density functions (pdf) of individual trajectory error distributions (Figure 2a,b). While there was considerable heterogeneity across children of either group (i.e., some children made more accurate saccades than others), the mean pdf of the ASD group was entirely overlapping with the mean pdf of the control group demonstrating that trajectory errors were similar across groups (Figure 2c). There were no significant differences across groups in the magnitude of absolute trajectory errors (t[55.0] = 0.14, $p = 0.89$, $d = 0.03$, inverse BF = 4.35, Figure 2d), extent errors (t[54.8] = −1.15, $p = 0.23$, $d = -0.27$, inverse BF = 2.27, Figure 2d), or in the mean Euclidian distance between the saccade end-point and the target (t[61.7] = −1.14, $p = 0.25$, $d = -0.26$, inverse BF = 2.38, Figure 2f).

The isochrony principle (main sequence)

A basic feature of motor control is that the peak velocity of a movement scales with its distance such that movement duration remains similar (Viviani & McCollum, 1983). Saccades made during presentation of the salient targets varied in their distance in a manner that was significantly correlated with their peak velocity (Figure 3). This was similarly apparent in saccades made by children with ASD (r[2730] = 0.69, $p < 0.0001$) and controls (r[1589] = 0.70, $p < 0.0001$). Examining this relationship within each subject revealed that the correlation coefficients were heterogeneous across individual children, yet did not differ significantly across groups (t [61.2] = −0.73, $p = 0.46$, $d = -0.20$, inverse BF = 3.45).

Saccades while freely viewing movies

Similar results were found when analyzing saccades identified during movie viewing (Figure 4 and Table 3). There

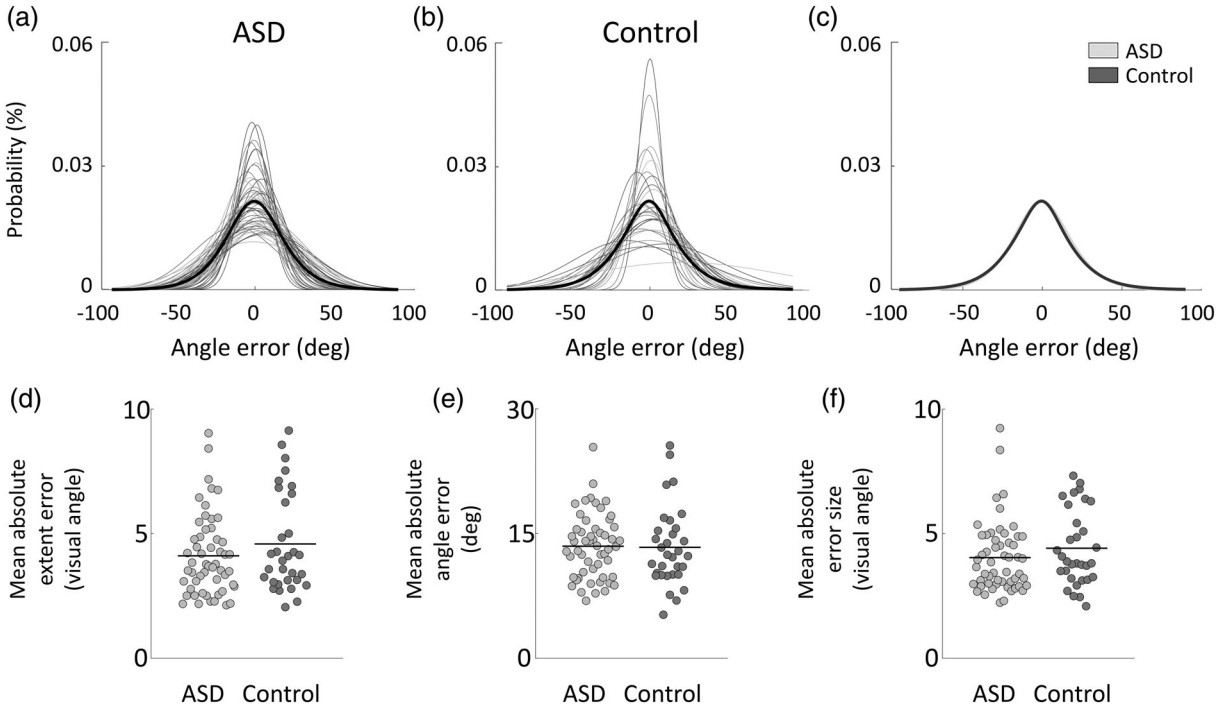

FIGURE 2 Saccade accuracy. (a) Probability density function of saccade trajectory errors for each of the children in the ASD group. Target trajectory was set to 0°. Gray lines: Individual children. Bold black line: Mean across the group. (b) Same as a for control children. (c) Mean probability density function for the ASD and control groups. (d) Bee-swarm plot of the absolute extent error of individual children. (e) Bee-swarm plot of the absolute trajectory error. (f) Bee-swarm plot of the absolute error size (i.e., Euclidian distance between saccade endpoint and target). Light gray: ASD children, dark gray: Control children. Each circle represents a single child. There were no significant differences across groups ($p > 0.05$, two sample t-test with unequal variance)

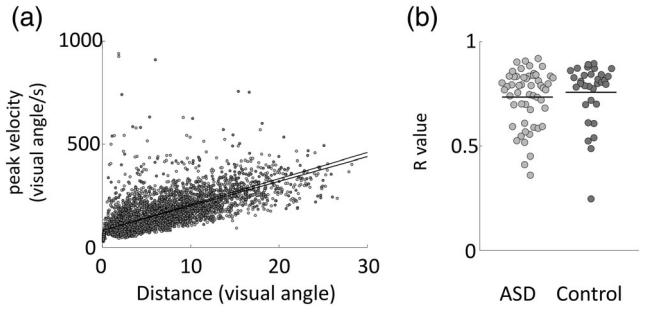

FIGURE 3 The isochrony principle (main sequence). (a) Scatter plot of all saccades made by children with ASD (light gray) and controls (dark gray). Strong and significant correlations were apparent between peak velocity and distance. Lines: Least squares linear fit for the two groups. (b) Bee-swarm plots of the Pearson's correlation coefficients computed separately for each child in the ASD (light gray) and control (dark gray) groups. Horizontal line: Mean value of the group. There were no significant differences across groups ($p > 0.05$, two sample t-test with unequal variance)

were no significant differences across children with ASD and controls in the number of saccades per second ($t[85.1] = -0.92$, $p = 0.36$, $d = -0.17$, inverse BF = 3.45), number of fixations per second ($t[95.6] = -0.13$, $p = 0.89$, $d = -0.02$, inverse BF = 5.26), saccade duration ($t[128.7] = 0.26$, $p = 0.79$, $d = 0.04$, inverse BF = 5.26), or saccade distance ($t[94.8] = 1.71$, $p = 0.09$, $d = 0.31$, inverse BF = 1.26). Children with ASD, however, exhibited a trend for shorter fixation durations ($t[89.9] = -1.88$, $p = 0.06$, $d = -0.35$, BF = 1.15) and significantly higher peak velocity ($t[102.1] = 2.22$, $p = 0.03$, $d = 0.39$, BF = 1.94). Note that we did not correct any of these analyses for multiple comparisons to increase their sensitivity.

To determine the reliability of these findings we reanalyzed data from a sub-group of the children who had higher quality recordings with smaller calibration errors (i.e., <1.5°) and a sub-group who had a higher percentage of valid data (i.e., 70%). For continuity we also reanalyzed data from the sub-group of children who participated in the saccades-to-targets analyses described above (Figure 5).

There were no significant differences across ASD and control groups in any of the examined oculomotor measures when examining the sub-groups of children with higher calibration quality, higher percentage of valid data, or the sub-group of children in the saccades-to-targets analyses. This was true for the number of saccades per second ($|t| < 1.76$, $p > 0.08$, $|d| < 0.41$, inverse BF > 0.98), the number of fixations per second ($|t| < 1.90$, $p > 0.06$, $|d| < 0.43$, inverse BF > 0.9), saccade duration ($|t| < 1.48$, $p > 0.14$, $|d| < 0.36$, inverse BF > 0.22), fixation duration ($|t| < 1.42$, $p > 0.16$, $|d| < 0.29$, inverse BF > 1.88), saccade distance

($|t| < 1.89$, $p > 0.06$, $|d| < 0.41$, inverse BF > 0.85), and saccade peak velocity ($|t| < 1.75$, $p > 0.08$, $|d| < 0.40$, inverse BF > 1.15).

Since multiple factors may have influenced comparisons of oculomotor function across ASD and control groups (e.g., age, gender, quality of data, etc.), we performed a final set of linear mixed model analyses using the full dataset (Table 4). We included movie type, age, gender, calibration error, and percentage of valid data as covariates when attempting to identify group differences in each of the oculomotor variables. All variables were standardized into z-scores to facilitate comparison of predictor parameter estimates across measures. The linear mixed models revealed no significant differences in the number of saccade per second ($F[1, 74] = -0.13$, $p = 0.46$), number of fixations per second ($F[1, 74] = -0.13$, $p = 0.45$), median saccade duration ($F[1, 74] = -0.15$, $p = 0.28$), median fixation duration ($F[1, 74] = 0.001$, $p = 0.99$), median saccade distance ($F[1, 74] = 0.11$, $p = 0.51$), or median peak velocity ($F[1, 74] = -0.16$, $p = 0.30$). Furthermore, no significant effects for movie type, age, gender, calibration error and percentage of recorded data were found across groups.

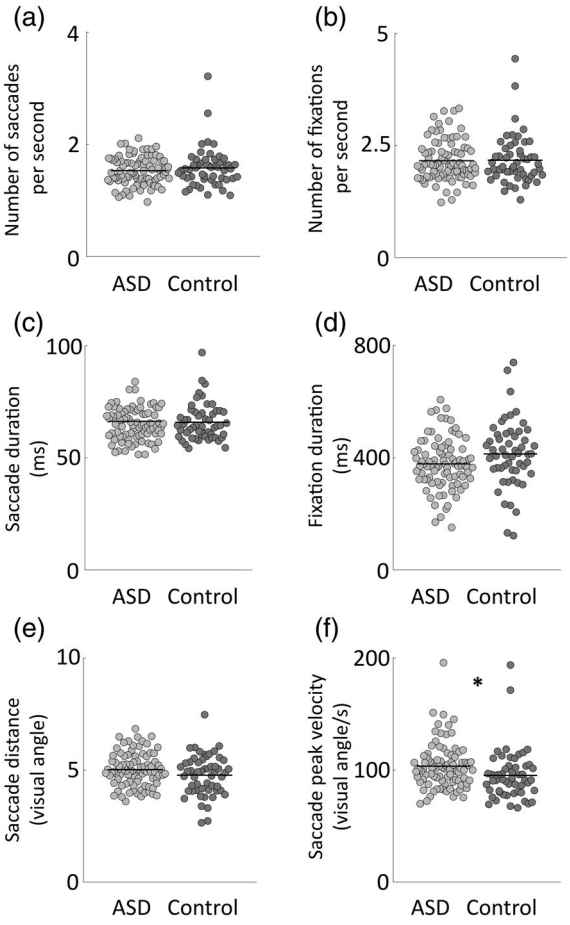

FIGURE 4 Saccade kinematics when freely viewing movies. Beeswarm plots of the number of saccades per second (a), number of fixations per second (b), saccade duration (c), fixation duration (d). Saccade distance (e) and peak velocity (f). Light gray: ASD children, dark gray: Control children. Each circle represents a single child (mean across saccades or fixations in all movie presentations). Asterisks: Significant differences across groups ($p < 0.01$, two sample t-test with unequal variance)

DISCUSSION

Our results revealed that basic saccade and fixation characteristics of young children with ASD were statistically indistinguishable from those of controls when examining either saccades-to-targets in a structured experiment (Figures 1–3) or recordings of naturalistic free-viewing of movies (Figures 4 and 5). Characteristics included the number of fixations per second, the number of saccades per second, fixation duration, saccade duration, and saccade distance. A minor significant difference was apparent in saccade peak velocity, which was larger in the ASD group when analyzing the entire data set without correcting for multiple comparisons. But this difference did not appear in re-analyses of the data using more stringent data quality criteria (Figure 5) or when including potentially confounding co-variates in a linear mixed model analysis (Table 4). Finally, the isochrony principle (main sequence), whereby peak velocity scales linearly with saccade distance (Robinson, 1964; Viviani & McCollum, 1983), was similarly evident in the saccades of children in both groups (Figure 3).

TABLE 3 Characteristics of saccades and fixations while freely viewing movies

	ASD ($n = 90$, 70 males)			Control ($n = 54$, 36 males)		
	Median	Mean ± SD	Range	Median	Mean ± SD	Range
Number of saccades per second		1.53 ± 0.25	0.97–2.11		1.58 ± 0.35	1.10–3.22
Number of fixations per second		2.16 ± 0.45	1.23–3.33		2.17 ± 0.54	1.29–4.44
Saccade duration (ms)	66.3	78.8 ± 10.0	51.5–109.2	65.9	77.5 ± 8.23	54.25–97.0
Fixation duration (ms)	378.1	562.9 ± 90.9	151–607	413	585 ± 119	122–740
Saccade peak velocity (visual angle/s)	5.02	6.14 ± 0.73	3.60–6.85	4.78	5.80 ± 0.89	2.65–7.48
Saccade distance (visual angle)	103.4	103.9 ± 20.1	69.9–195.8	95.2	113.3 ± 22.4	66.3–193.0

Note: The median, mean, SD, and range are presented for the oculomotor measures.

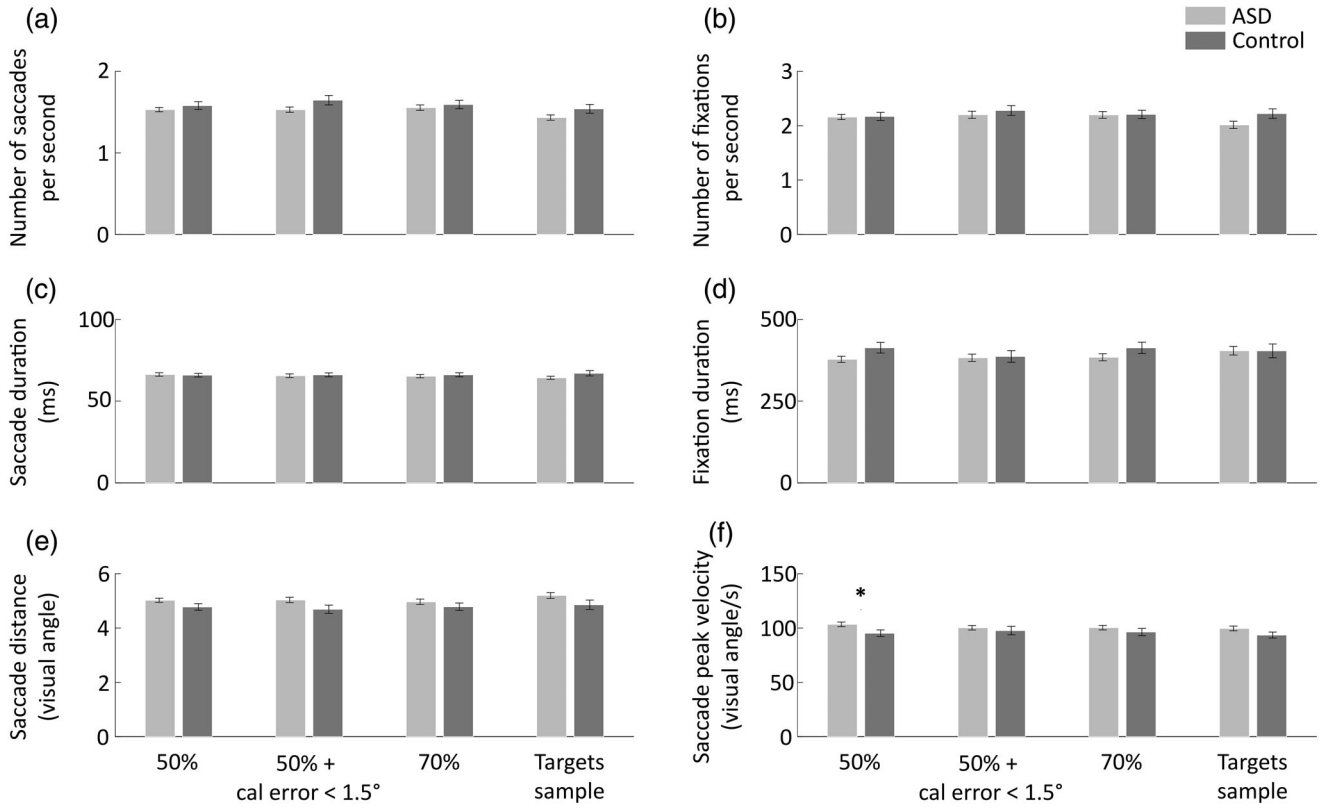

FIGURE 5 Oculomotor function in multiple sub-samples of the data. Bar graphs present the number of saccades per second (a), number of fixations per second (b), median saccade duration (c), median fixation duration (d), median saccade distance (e) and median peak velocity (f). Light gray: ASD. Dark gray: Controls. Results are presented for the entire sample that viewed at least 50% of the movies (90 ASD and 54 controls, 50%), a sub-group of these children who had calibration errors <1.5° (55 ASD and 40 controls, 50% + cal error <1.5°), a sub-group of children who viewed at least 70% of the movies (55 ASD and 48 controls, 70%), and the sub-group of children from the saccade-to-target analyses (53 ASD and 32 controls, targets sample). Asterisks: Significant differences across groups, two sample *t*-test with unequal variance (* = $p < 0.05$)

TABLE 4 Predictor parameters estimates from the linear mixed models

	Number of saccades	Number of fixations	Saccade duration	Fixation duration	Saccade peak velocity	Saccade distance
Intercept	0.232	0.255	−0.027	−0.22	0.046	−0.126
Group	−0.134	−0.131	−0.153	−0.001	−0.159	0.11
Movie type	0.019	0.036	−0.06	−0.062	−0.05	−0.121
Age	0.057	0.002	0.193	−0.16	0.128	0.144
Gender	−0.219	−0.233	−0.113	0.129	0.002	0.173
Calibration error	−0.188	−0.119	−0.613	0.258	−0.123	−0.497
Percentage of recorded data	0.036	0.12	−0.151	0.036	−0.17	0.084

The current study had 60%–82% power to detect medium sized effects (i.e., Cohen's $d = 0.5$). The fact that none of the oculomotor measures differed significantly across groups suggests that differences, if they exist at all, are likely to be small. To further assess the strength of evidence in favor of the null hypothesis (i.e., that there was no difference across groups), we also reported inverse BFs for each of the comparisons in the study. In most analyses of the saccades-to-targets data, the inverse BFs was between two and four, indicating that the null hypothesis was two to four time more likely than the alternative hypothesis (Stefan et al., 2019). In the movie analyses inverse BFs were smaller indicating that there was weaker evidence in favor of the null hypothesis, but still no evidence in favor of the alternative hypothesis. Taken together these results suggest that oculomotor function in young children with ASD is characterized by similar saccade and fixation characteristics to those of controls.

In contrast, previously reported social gaze abnormalities were of larger effect sizes (Hedges $g > 0.5$) that appeared consistently across multiple studies (Frazier et al., 2017) and enabled relatively accurate identification of individual young children with ASD (Jones & Klin, 2013; Pierce et al., 2016). Our results suggest that these abnormalities in gaze behavior are not generated by basic oculomotor deficiencies.

Oculomotor function in saccade tasks

Previous studies, mostly carried out with older children, adolescents, and adults, have reported mixed findings regarding oculomotor function in individuals with ASD. For example, while some studies reported that individuals with ASD exhibit longer saccade latencies than controls (Goldberg et al., 2002; Wilkes et al., 2015), others reported no significant differences across groups (Luna et al., 2007; Van der Geest et al., 2001). Indeed, a recent meta-analysis examined data from 28 different studies where the mean age of participants was 8–34 years-old (Johnson et al., 2016). They concluded that there was no consistent evidence across studies for differences in saccade latency, peak velocity, or accuracy (i.e., saccade gain) between individuals with ASD and controls. There was however evidence for difficulties in the inhibition of anti-saccades, poorer accuracy in smooth pursuit eye movements, and larger saccade dysmetria (i.e., larger variability in saccade trajectories and extents) in individuals with ASD. Note that most of the tasks that were used in these studies are not suitable for young children and some of the tasks, such as the anti-saccade task, require that participants comply with specific instructions, thereby limiting participation to high-functioning individuals with ASD.

Our results extend this research to younger ages, by demonstrating that saccades-to-targets did not differ significantly in their latency, duration, distance, peak velocity, or accuracy across 1–10-year-old ASD and control children (Figures 1–3). In contrast to previous studies, we did not find any evidence of saccade dysmetria in the children with ASD who exhibited statistically indistinguishable trajectory and extent error distributions relative to controls (Figure 2). Our simple child-friendly experimental design did not enable us to study inhibition of anti-saccades or smooth pursuit eye movements. We presented child friendly twinkling stars with an auditory ding on individual trials and assume that these salient targets elicited saccades through mechanisms of covert exogenous spatial attention (Müller & Rabbitt, 1989), which involve fast involuntary responses (Anton-Erxleben & Carrasco, 2013). This design enabled us to include children with severe ASD and low cognitive scores (Table 2) who are often excluded from other eye-tracking studies.

Oculomotor function during free viewing of movies

To the best of our knowledge, only one study to date examined oculomotor function during free viewing of movies and was performed with a large cohort of 6–30-year-old participants with ASD (Bast et al., 2021). This study reported that there were no significant differences across groups in the number of fixations per second, number of saccades per second, fixation duration, saccade peak velocity, pupil dilation, or main sequence. However, they did report that the ASD group exhibited significantly shorter saccade duration and amplitude/distance (i.e., saccade dysmetria).

Our results, based on a cohort of younger 1–10-year-old children with ASD who viewed child-friendly movies, did not reveal any consistently significant differences across groups in the number of fixations per second, number of saccades per second, saccade duration, saccade distance, saccade peak velocity, or main sequence. Hence, both studies demonstrate that most measures of oculomotor function were statistically indistinguishable across groups who freely viewed movies.

Several potential causes may explain the differences in results regarding saccade dysmetria across the two studies. First, it is important to note that in the univariate comparisons performed by Bast et al., there were no significant differences across ASD and control groups in either of these measures (their Table 4). It was only after performing a linear mixed model analysis with multiple co-variates that significant differences across groups emerged. One of the limitations in the Bast et al. study was that the data were integrated across multiple sites, using different eye trackers, operating at different sampling rates, and yielding mixed data quality. These between-site and between-subject differences, while included as co-variates, may have introduced a variety of biases into the data that are difficult to account for and may potentially lead to misleading results. In contrast, our study was performed at a single site with a single eye tracker, thereby reducing the potential for such factors to influence our results.

A second difference was that our study included younger children than Bast et al., raising the possibility that saccade dysmetria emerges at older ages. Third, the video content of the two studies differed and may have affected the ability to identify differences in saccade dysmetria across groups. Finally, our study included a smaller sample (90 children with ASD and 54 controls) than the Bast et al. study (142 participants in each group) and, therefore, had weaker statistical power.

Abnormal gaze behavior in children with ASD

A prominent theory of ASD suggests that young children with ASD have a weaker innate preference for gazing at

social stimuli during early development and that this reduces their exposure to social interactions and impairs their ability to learn social skills (Shultz et al., 2018). This theory is supported by numerous studies, which have demonstrated that when presented with images or movies of people interacting, toddlers and young children with ASD spend less time fixating on areas of social interest including the eyes region in particular (Jones et al., 2008; Jones & Klin, 2013; Kliemann et al., 2010; Moriuchi et al., 2017; Papagiannopoulou et al., 2014) and faces in general (Chawarska et al., 2012; Chita-Tegmark, 2016; Riby & Hancock, 2009; Rice et al., 2012; Shic et al., 2011).

This reduced preference for social stimuli may be due to an aversion of looking at the eyes of others (Kliemann et al., 2010) or to increased preference for other types of stimuli such as stimuli with higher saliency (Wang et al., 2015), moving geometric shapes (Moore et al., 2018), or stimuli with audio-visual synchrony (Klin et al., 2009). Reduced preference for social stimuli may also be due to a passive lack of interest (Moriuchi et al., 2017), which is likely to create more variable and idiosyncratic gaze behavior (Avni et al., 2019; Nakano et al., 2010; Wang et al., 2015).

Alternatively, differences in social gaze behavior may be due to deficiencies in oculomotor function. Our study is the first to directly assess oculomotor function during free viewing of child friendly movies in young children with ASD at the age range corresponding to many studies of social gaze preferences. We suggest that the results of the current study (i.e., lack of difference across groups) are important for substantiating the interpretation of previous social gaze behavior studies (Frazier et al., 2017).

Limitations

The current study has several limitations. First, our sample size was limited by considerations of data quality, a common issue when studying young children with ASD. In particular, we excluded ~50% of our initial sample (54% of the ASD group and 49% of the control group) from the saccades-to-targets analysis, because these children did not perform enough saccades. This may have created a bias in our sample toward children with ASD who were able to complete this task. Note that this is likely to be a common bias in most eye-tracking studies. Second, we did not assess the cognitive abilities of participating control children. Third, we did not directly compare measures of social gaze behavior with measures of oculomotor function. Further development of eye-tracking protocols that contain clever child-friendly stimuli is likely to enable simultaneous assessment of basic oculomotor function simultaneously with high level aspects of social preference.

CONCLUSIONS

The main contribution of this study is in demonstrating that basic oculomotor function is similar in young 1–10-year-old children with ASD and controls. These findings help clarify the interpretation of results from numerous studies that have reported abnormal gaze behavior in young children with ASD during free viewing of movies. Our results suggest that these previously reported differences were not likely to be due to oculomotor deficiencies.

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