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Research article

Estimation of the degree of autism spectrum disorder by the slow phase of optokinetic nystagmus in typical adults

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ABSTRACT

Atypical eye movement patterns demonstrated by individuals with autism spectrum disorder (ASD) have the potential to serve as biomarkers for ASD diagnosis. However, instead of estimating individual differences in the degree of ASD from those patterns, many researchers have compared ASD groups with typical development groups. This study investigates the relationship between the Autism-spectrum Quotient (AQ) scores in typical adults, which can evaluate the degree of the traits associated with ASD, as well as the properties of optokinetic nystagmus (OKN), including the gain of the slow phase, the peak velocity and duration of the fast phase, the frequency, and the mean eye position of OKN. A random dot pattern that moved in one direction was presented on the display, and the participants' eye movements were measured. The results showed a negative correlation between subjects' AQ scores and the gain of slow-phase OKN. In addition, the correlations between subjects' AQ scores and the properties of OKN fast phase were not significant. These results indicate that the gain of slow-phase OKN could be a biomarker that estimates individual differences in the degree of ASD, reflected in our findings which considered AQ scores in typical adults.

1. Introduction

Autism spectrum disorder (ASD) is a developmental disorder characterized by impairments in social communication and restricted and repetitive patterns of behavior (American Psychiatric Association, 2013). The literature suggests that the impairments in social communication observed in ASD may be related not only to social defects such as empathy and "theory of mind" (Baron-Cohen et al., 1985; Baron-Cohen, 1997), joint attention, and imitation but also to deficits in visual processing (Simmons et al., 2009). For example, the decrement in face-processing ability, such as face recognition and perceptual discrimination of faces, is associated with the enhancement of processing focused on details or features and inferior processing of overall/global structure (Behrmann et al., 2006). Therefore, to understand the cause of disorders regarding high-level processing, such as social communication, it is important to clarify the difference between typical development and ASD in visual processing at a low level, as well as eye movements and attention to objects.

To receive visual input appropriately in context, our eyes attempt to maintain the image of an object in the retina's view using voluntary and involuntary eye movements. For voluntary eye movements, researchers have demonstrated that individuals with ASD have the disorders of smooth-pursuit eye movements (SPEMs) and saccades. Takarae et al. (2004) investigated SPEMs (1) when the target is presented at the center, steps 3° to the left or right, and then moves at a constant speed (a step-ramp task), (2) when the target is presented at the center and then moves at a constant speed (pure ramp task), and (3) when the target oscillates back and forth at a constant speed (oscillating ramp task). The results suggest that individuals with autism have normal pursuit latency but reduced pursuit gain (i.e., eye velocity/stimulus velocity) in both ramp and oscillating tasks. Similarly, Schmitt et al. (2014) studied saccadic eye movements with targets presented at the center and the peripheral target displayed 200 ms after the disappearance of the central target (gap trials), as well as with a target presented at the center, remaining for 200 ms, with the peripheral target presented simultaneously (overlap trials). The results indicate that individuals with ASD have reduced accuracy and peak velocity of saccade, as well as prolonged duration of saccade. These findings suggest that disturbances exist in frontal eye fields, the cerebellum, and brainstem function.

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Optokinetic nystagmus (OKN) is an involuntary eye movement comprising a slow (pursuit movements in the direction of the stimulus motion) and fast (saccadic return movements in the opposite direction to the stimulus motion) phases (Purkinje, 1825). Although it is reported that children with autism have atypical OKN responses, the properties of OKN in ASD remain unclear. For example, 82% (28/34) of the ASD group exhibited atypical OKN (Scharre and Creedon, 1992), which is defined as having a "latency or response greater than 2 s, duration of the response less than 5 s, gaze avoidance, and/or stereotypic behavior" when looking at a hand-held rotary drum with stripes. Similarly, Milne et al. (2009) investigated OKN using the same stimulus as Scharre and Creedon (1992). However, only 4.9% (2/41) of the participants with ASD demonstrated reduced OKN, and the data analysis method was only based on the clinical experience of the examiner, leaving the results unclear. Other researchers have shown that the slow phase of OKN and SPEMs are controlled by the same mechanism (Ilg et al., 1993). Furthermore, OKN has been classified into two types, look-OKN and stare-OKN, which depend on the instructions provided to the observer (Ter Braak, 1936). The slow phase of stare-OKN is an involuntary response controlled by the subcortical area, and that of look-OKN is a voluntary response controlled by the cortical area (Konen et al., 2005; Kashou et al., 2010). These findings suggest that involuntary eye movement disorders in ASD can be clarified by examining the properties of the slow and fast phases of OKN in detail.

Atypical eye movement patterns demonstrated by individuals with ASD can serve as biomarkers for ASD diagnosis. However, many studies investigating eye movements and pupil response compared ASD with typical individuals. The autism spectrum hypothesis holds that developmental characteristics observed in individuals with ASD appear continuously even in typical individuals (Baron-Cohen, 1997; Frith and Mira, 1992; Wing, 1981). The degree of the traits associated with ASD in typical adults can be evaluated by the Autism-spectrum Quotient (AQ) (Baron-Cohen et al., 2001). A systematic search of computerized databases confirms that AQ can identify autistic traits within an adult non-clinical population (Ruzich et al., 2015). Scholars have shown that AQ scores in typical adults are related to pupillary changes when reporting the perceived direction of rotation of a bistable stimulus (Turi et al., 2018). These changes are associated with the characteristic that autistic people focus on local detail, as opposed to globally attending to the whole stimulus (Spencer et al., 2000; Atkinson, 2017). Thus, AQ may be associated with involuntary eye movement disorders in ASD as it can measure the degree of autistic traits in typical adults. Therefore, for the present study, we examined whether the degree of ASD tendency could be easily and objectively estimated by the properties of OKN when observing a short-term stimulus with a simple instruction.

In this study, we aimed to investigate the relationship between the properties of OKN, which is an involuntary eye movement, and the degrees of ASD in typical adults. In this experiment, a random dot pattern moving in one direction (leftward, rightward, upward, or downward) was presented on the display. The participants' eye movements were measured while they observed the stimuli. To generate stare-OKN—an involuntary response—the participants in the present study were instructed to stare at the motion stimulus in the center of the display but not to follow any individual element. The gain of the slow phase, the peak velocity, as well as the duration of the fast phase, the frequency, and the mean eye position of OKN were analyzed as OKN properties. The degree of the participants' ASD was assessed by the AQ scores.

2. Methods

2.1. Participants

Twenty-four naïve Japanese volunteers (24 females; age range: 18–24 years; mean age: 19.5) participated in this experiment. All self-reported normal or corrected-to-normal visual acuity (20/20), with two participants wearing spectacles, and none reported diagnosed neurological conditions. They were verified to have a stereo-acuity of at least 40 s of disparity using a stereotest (Stereo Fly test, Stereo Optical Co., Inc.) because researchers have shown that OKN is linked to the stereoscopic system (Howard and Simpson, 1989). All the participants completed validated the Japanese version of the AQ, which is a self-administered questionnaire (Baron-Cohen et al., 2001; Wakabayashi et al., 2004) and is created on Google Forms (Google LLC). They had no personal history of psychiatric or neurological disorders, no family history of autism, and no first-degree relatives with neuropsychiatric disorders with a genetic component. They had no history of developmental delay, no significant problems with school performance, or any sign of learning disabilities. All the participants provided written informed consent before participating. The study was approved by the Tokyo Institute of Technology Epidemiological Research Ethics Committee and was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Apparatus

The stimuli were presented on a 21-inch cathode ray tube monitor (SONY GDM F500R, 1400 × 1056 pixels, 35.1 × 28.9°, 36 × 29.4 cm) with a refresh rate of 60 Hz. The participants sat in a dark room and observed the stimulus with their head fixed on a chin rest. The viewing distance was 57 cm. Stimuli were produced and presented using a MacBook Pro (macOS Sierra 10.12.6, Apple) and MATLAB (MathWorks, Inc.) with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and the EyeLink Toolbox (Cornelissen et al., 2002).

2.3. Stimuli

The motion stimuli consisted of randomly positioned dots (Figure 1, right panel). The size and luminance of each individual dot was 0.77° and 0.01 cd/m^2, respectively. Dot density in the stimulus was 1.97 dot/deg^2. The velocity of the dots' motion was 15.4, 30.9, or 46.4 deg/s (10, 20, or 30 pixels/frame). The stimulus motion had a one-way direction over the whole display. The motion direction was leftward, rightward, upward, or downward. The motion stimulus was sized 35.1 ° × 28.9 °. The background luminance was 10.44 cd/m^2. The time course of the stimuli presentation in each trial is shown in Figure 1.

2.4. Procedure

Each trial began with the participant pressing a button. Immediately afterward, a fixation point (0.13°) at the center of the display was presented for 2.5–3.0 s. During this time, the participant was given instructions to look at the fixation point. Then, the fixation point disappeared, and the random dots began to move and continued to do so for 4 s. During the motion stimulus presentation, the instruction was to look at the motion stimulus in the center of the display but not to follow any individual element (stare-OKN). The participants were allowed to take a break of any length between trials, but they could not press the button again to launch the next trial for 5 s after the motion stimulus ended.

In each block, 12 trials with three different stimulus velocities (15.4, 30.9, or 46.4 deg/s) and four different motion directions (leftward, rightward, upward, or downward) were presented in a random order. Each participant performed three blocks as a whole, for a total of 36 trials. The experiment lasted for approximately 6 min (10 s × 36 trials).

2.5. Analysis

During the trials, the right eye position and pupil size were measured with an infrared eye-tracker camera (EyeLink 1000 Desktop Mount, SR Research Ltd.) with a sampling rate of 1,000 Hz. Spectacles and contact lenses can increase error by approximately 0.01° in EyeLink. A nine-point eye-tracker calibration was performed at the beginning of the

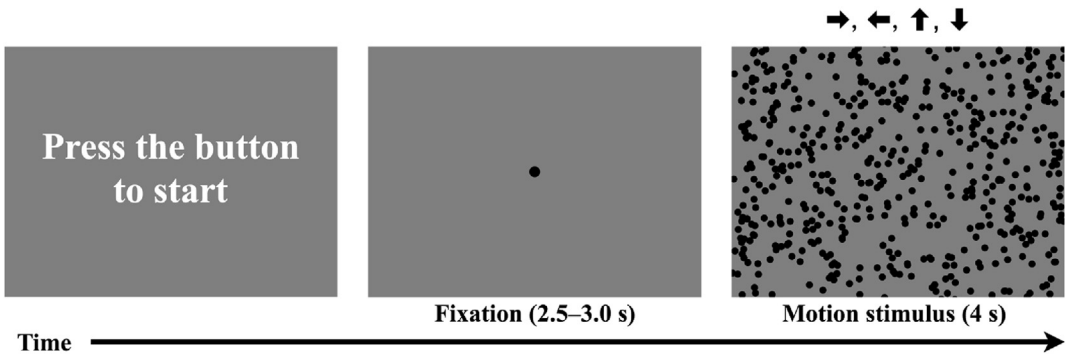

Figure 1. Time course of stimulus presentation in a trial. A fixation point was presented (middle panel), followed by the motion stimulus (right panel). To make it easier to see the stimulus, the fixation point's size in the middle panel is different from that of the actual stimulus.

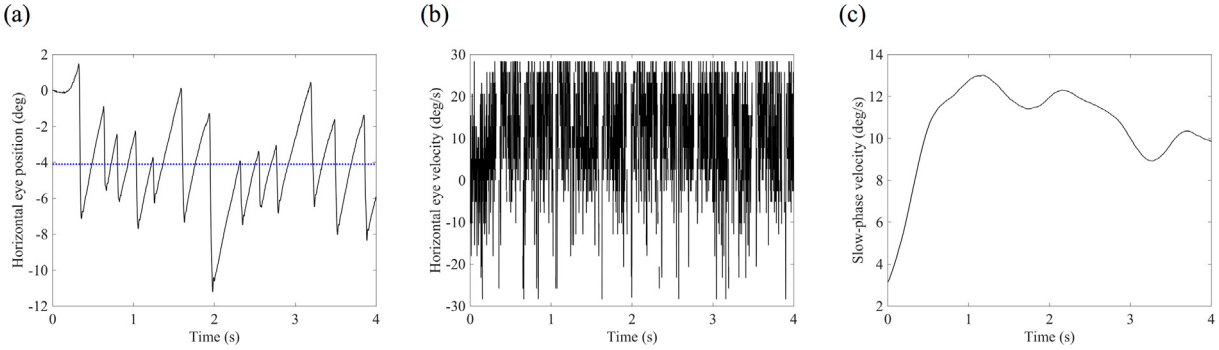

Figure 2. Time course of horizontal eye position (a), the horizontal eye velocity (b), and the slow phase velocity of the OKN (c) in one trial for one participant. A positive value on the ordinate in Figure 2a indicates that the eye position is on the right side of the display, and 0 indicates that an eye position is at the center of the display. The blue dotted line in Figure 2a indicates the mean eye position.

experiment. Periods of blinking were detected using the manufacturer's standard algorithms with the default settings. The blink data were treated as missing data. In addition, trials missing more than 20% of the data were excluded. Otherwise, missing data were interpolated with a cubic spline fit.

The gain of OKN, the mean eye position, the peak velocity of the fast phase, the duration of the fast phase, and the frequency of OKN were analyzed. The gain was calculated by the following method. The study identified the slow and fast phases of OKN with reference to previous studies (Naber et al., 2011; Frässle et al., 2014; Kanari and Kaneko, 2021). First, eye velocity as a function of time was calculated by the derivative of the eye's position (Figure 2a). To obtain the slow phase of OKN, the fast phase of OKN and saccade components were excluded from the eye velocity trace based on a velocity criterion (>stimulus velocity × 2 deg/s) (Figure 2b). After exclusion, the data were smoothed using a Gaussian-weighted moving average filter with a time window of 1,000 ms using the "smoothdata" function in MATLAB (Figure 2c). The moving window was overlapped because it was centered on the current element and contained window-1 neighboring elements. Slow-phase velocity was averaged in each trial. The gain was calculated by dividing the mean slow-phase velocity by the stimulus velocity. Figure 2 depicts a schematic illustration of the analysis. The panels in Figure 2 present the horizontal eye position (a), the horizontal eye velocity (b), and the slow phase velocity of the OKN (c) in one trial of one observer. The ordinate of Figure 2a–c displays the horizontal eye position (deg), the horizontal eye velocity (deg/s), and the slow-phase velocity of OKN (deg/s), respectively. A positive value on the ordinate in Figure 2a indicates an eye position on the right side of the display, and 0 indicates an eye position at the center of the display. The abscissa represents the time (in seconds) from stimulus onset. The mean eye position was calculated by averaging the eye position for 4 s relative to exposure to the stimulus (Figure 2, blue dotted line).

The peak velocity of the fast phase of OKN was calculated by averaging the peak of the eye velocity trace for 4 s (Figure 3a, blue circles). The peak velocities were extracted from the eye velocity trace without a smoothing filter based on a velocity criterion (>stimulus velocity × 2 deg/s). The duration of the fast phase was calculated by averaging the time intervals at which the fast phase velocity became 0 before and after each the peak velocity of the fast phase for 4s (Figure 3b, blue arrow). The frequency of the OKN was defined as one time when the slow phase and the fast phase occurred continuously and was calculated by dividing the number of times in one trial by the duration of the stimulus presentation (4 s) (Figure 3c, blue circles). The gain, the mean eye position, the peak velocity of the fast phase, the duration of the fast phase, and the frequency were averaged over three repetitive trials under each condition for each participant.

3. Results

The mean (SD) of the AQ scores was 22.375 (6.405). The minimum and maximum of AQ scores were 9 and 33, respectively. The scores were normally distributed as measured by the Shapiro–Wilk normality test ($SW = 0.959$, $p = 0.423$). Figure 4 depicts a histogram of the AQ scores. The study measured the correlation coefficients using the Bayesian estimation method via the open-source software JASP (JASP Team, 2019; Ly et al., 2016; Ly et al., 2018). Figure 5 presents the relationship between the gain (slow-phase velocity/stimulus velocity) of OKN and the participants' AQ scores (a), between the mean horizontal eye position (deg) and the participants' AQ scores (b), between the peak velocity of the fast phase of OKN (deg/s) and the participants' AQ scores (c), between the

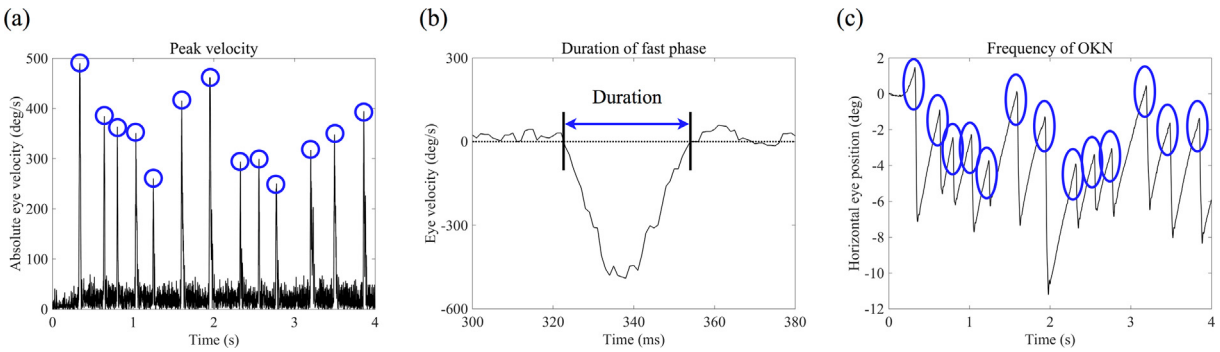

Figure 3. Time course of absolute eye velocity (a), the eye velocity (b), and the horizontal eye position (c) in one trial for one participant. The blue circles in Figure 3a indicate the peak velocities of the fast phase of OKN. The range of the blue arrow in Figure 3b indicates the duration of the fast phase. The blue circles in Figure 3c indicate the continuous occurrence of the slow phase and fast phase.

duration of the fast phase of OKN (ms) and the participants' AQ scores (d), and between the frequency of OKN (Hz) and the participants' AQ scores (e) in the rightward motion at 15.4 deg/s. Figure 5f presents the relationship between the mean gain at each stimulation rate and AQ scores. The text insets in Figure 5 indicate the Pearson's correlation coefficients (r), 95% credible intervals for the correlation coefficients, and the Bayes factor (BF). The study tested for the null hypothesis that the population correlation between pairs of variables equals 0. The BF provides evidence for the alternative hypothesis relative to the null hypothesis. At a BF of more than 10, the data are at least 10 times more likely under the selected hypothesis (Jeffreys, 1961). The correlation between the gain of OKN and AQ scores was found in the rightward motion at 15.4 deg/s. In contrast, the study found no correlations between the other indicators and AQ scores.

Tables 1, 2, 3, 4, and 5 display the mean OKN properties and Pearson's correlation coefficients under all conditions. At a stimulus velocity of 15.4 deg/s, negative correlations were observed between the gain and AQ scores, except for the upward motion (Table 1). In contrast, no correlations were found between the other properties of OKN and AQ scores (Tables 2, 3, 4, and 5).

Gain was decreased as the stimulus velocity increased, regardless of the direction of the stimulus motion. This result is consistent with those in previous studies (van den Berg and Collewijn, 1988). The mean gain in the upward direction was higher than that in the downward direction under all velocity conditions (BF_{10} = 27.433, median effect size (δ) = 0.674, 95% CI [0.238, 1.140]). This result is consistent with those of previous studies (van den Berg and Collewijn, 1988; Murasugi and Howard, 1989). A positive value for the eye's horizontal (vertical) position indicates an eye position on the right (upper) side of the display, and 0 indicates an eye position in the center of the display. The mean eye position clearly shifted in the direction of the fast phase (the opposite direction to the motion stimulus), regardless of the direction of stimulus motion. For example, the mean eye position shifted to the left when the direction of the motion stimulus was rightward (leftward). This result is consistent with those in previous studies (Jung and Mittermaier, 1939; Dubois and Collewijn, 1979; Abadi et al., 1999).

4. Discussion

This study revealed a negative correlation between participants' AQ scores and the gain of OKN. In other words, the higher the autism spectrum tendency, the slower the slow-phase velocity of OKN. In addition, correlations between participants' AQ scores and the properties of fast phase OKN (i.e., mean eye position, peak velocity, and duration) were not found. Look-OKN and stare-OKN are characterized by low frequencies (<1 Hz) and high frequencies (1–5 Hz), respectively (Leguire et al., 1991). It is presumed that stare-OKN occurred as we intended because the frequency of OKN in the present study was 1.5–2.3 Hz. These results indicate that the decrease in the gain of the slow-phase OKN observed in high AQ participants is associated with an involuntary mechanism disorder.

Unlike the previous study on this topic (Scharre and Creedon, 1992), no atypical OKN response was observed in this research. Presumably, this is because the characteristics "gaze avoidance, and/or stereotypic behavior" of the atypical OKN that Scharre and Creedon defined are associated with the ASD phenotype and are not characteristics found exclusively in OKN. In addition, although a useful cutoff for diagnosing ASD at a clinically significant level is an AQ score of 32+ (Baron-Cohen et al., 2001), only one participant (AQ score 33) exceeded 32 in the present study. This finding suggests that few participants in the present study are more likely to be diagnosed with ASD. Notably, however, the results of the current study and those of Scharre and Creedon cannot be compared directly because they undertook not an in-depth investigation of OKN but only a clinical measure as part of their vision assessment.

The gain of the slow phase of OKN decreased as participants' AQ scores increased. This result is consistent with those of other studies, where individuals with ASD displayed lower pursuit gain than healthy individuals (Takarae et al., 2004). In addition, Johnson et al. (2016) conducted the meta-analyses and found that the gain of SPEMs is significantly lower in individuals with ASD. Although the authors examined SPEMs, others demonstrated that the same mechanism controls the slow phase of OKN and SPEMs (Ilg et al., 1993). In addition, scholars have found that stare-OKN, in contrast with look-OKN, is nearly independent of higher-level cortical areas (Konen et al., 2005; Kashou et al., 2010). Therefore, the decrease in the gain of OKN observed in the present study is presumed to be related to lower-level areas, such as the

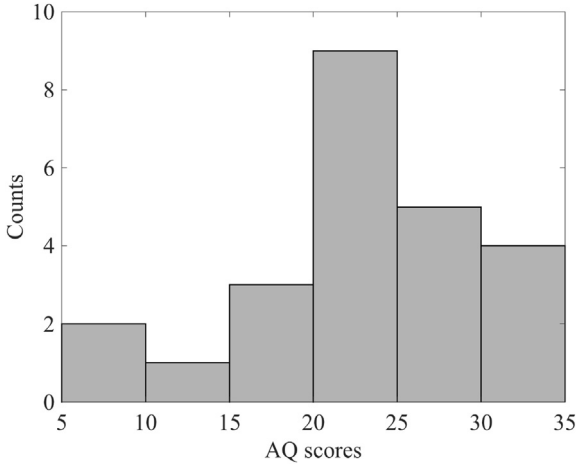

Figure 4. Distribution of participants' AQ.

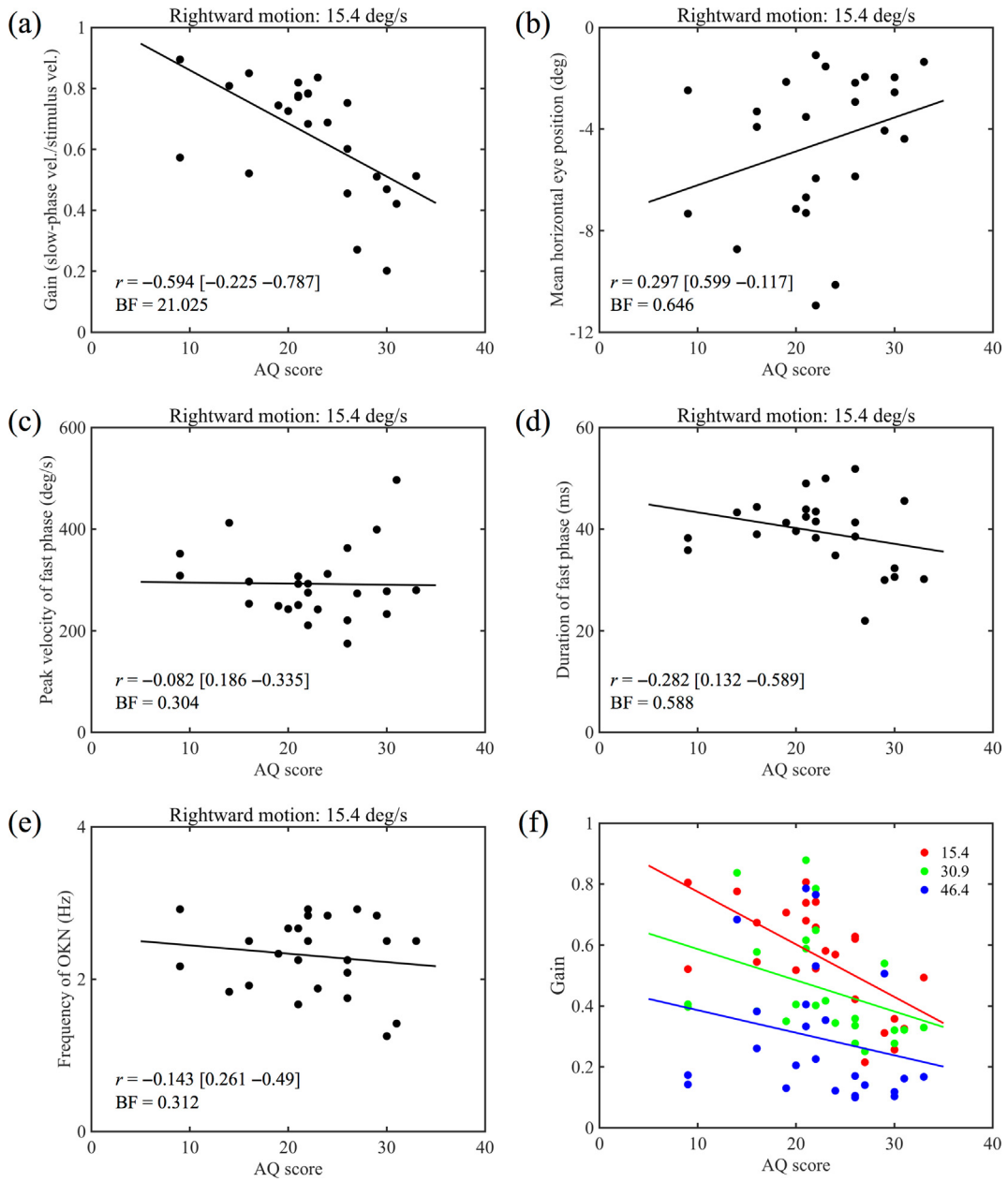

Figure 5. Relationship between the gain of OKN and the participants' AQ scores (a), between the mean horizontal eye position and the participants' AQ scores (b), between the peak velocity of the fast phase of OKN and the participants' AQ scores (c), between the duration of the fast phase of OKN and the participants' AQ scores (d), between the frequency of OKN and the participants' AQ scores (e), and between the mean gain at each stimulus velocity and the participants' AQ scores (f). Text insets pertain to Pearson's correlation coefficient (*r*), the 95% confidence interval, and the Bayes factor (BF).

cerebellum and the pretectum (Bauman, 1991; Hashimoto et al., 1993; Courchesne, 1997; Stoodley, 2014).

Gain decreased with the increase in stimulus velocity (Van Die and Collewijn, 1986; van den Berg and Collewijn, 1988). The decrease in gain among individuals with high AQ was small when the stimulus velocity was high as they originally exhibited a low gain at a low stimulus velocity (Figure 5f). In contrast, the decrease in gain among individuals with low AQ was large at a high stimulus velocity as they originally displayed a high gain at a low stimulus velocity. Therefore, the current study presumed that the correlation between AQ and gain diminishes with the increase in stimulus velocity. Thus, future studies are required to examine at velocities less than 15.4 deg/s. The reason for the absence and presence of correlation between gain and AQ in the upward and downward directions, respectively, may be that the downward OKN system is more functionally related to the horizontal system than the upward OKN system (Knapp et al., 2009). During forward motion, objects in the inferior visual field move in a downward direction, whereas objects in the horizontal plane produce movements of a similar magnitude in the right and left visual fields (Knapp et al., 2013). In addition, the mean eye position in the upward direction, which was the lowest, may be related to the difference in the OKN system.

Furthermore, the study found no correlation between the properties of the fast phase of OKN (peak velocity and duration) with AQ scores. This finding is consistent with that of Johnson et al. (2016) who argued that the saccade dynamics (i.e., latency, peak velocity, gain, and variable error) are comparable between ASD and control groups. A reduced peak

Table 1. Mean (SD) for OKN gain and the correlation coefficients between the OKN gain and the participants' AQ scores; SD = Standard deviation, BF = Bayes factor, CI = Credible intervals, * $BF_{10} > 10$.

Stimulus velocity (deg/s)		Gain			
		Rightward	Leftward	Upward	Downward
15.4	Mean (SD)	0.64 (0.18)	0.60 (0.19)	0.51 (0.18)	0.49 (0.20)
	Pearson's r	−0.594*	−0.567*	−0.543	−0.596*
	BF_{10}	21.025	13.044	8.718	21.55
	Upper 95% CI	−0.225	−0.189	−0.157	−0.227
	Lower 95% CI	−0.787	−0.771	−0.756	−0.788
30.9	Mean (SD)	0.50 (0.22)	0.51 (0.23)	0.46 (0.17)	0.37 (0.18)
	Pearson's r	−0.294	−0.195	−0.453	−0.378
	BF_{10}	0.637	0.376	2.617	1.211
	Upper 95% CI	0.119	0.214	−0.05	0.034
	Lower 95% CI	−0.597	−0.528	−0.701	−0.653
46.4	Mean (SD)	0.34 (0.29)	0.33 (0.25)	0.29 (0.20)	0.22 (0.16)
	Pearson's r	−0.151	−0.205	−0.354	−0.124
	BF_{10}	0.32	0.392	0.988	0.297
	Upper 95% CI	0.254	0.205	0.059	0.277
	Lower 95% CI	−0.496	−0.535	−0.637	−0.477

Table 2. Mean (SD) for mean eye position and the correlation coefficients between the mean eye position and the participants' AQ scores. The abbreviation is the same as Table 1.

Stimulus velocity (deg/s)		Mean eye position (deg)			
		Rightward	Leftward	Upward	Downward
15.4	Mean (SD)	−4.56 (2.82)	3.81 (2.33)	−1.55 (2.05)	3.5 (3.32)
	Pearson's r	0.297	−0.175	−0.016	−0.068
	BF_{10}	0.646	0.347	0.254	0.265
	Upper 95% CI	0.599	0.232	0.368	0.326
	Lower 95% CI	−0.117	−0.514	−0.394	−0.434
30.9	Mean (SD)	−4.21 (2.59)	3.73 (3.11)	−1.21 (2.87)	3.26 (3.14)
	Pearson's r	0.137	0.061	0.009	0.13
	BF_{10}	0.307	0.263	0.253	0.301
	Upper 95% CI	0.486	0.429	0.388	0.481
	Lower 95% CI	−0.267	−0.331	−0.373	−0.272
46.4	Mean (SD)	−3.4 (2.54)	2.18 (1.95)	−0.44 (2.58)	2.58 (3.39)
	Pearson's r	−0.074	0.226	−0.107	0.35
	BF_{10}	0.268	0.432	0.285	0.956
	Upper 95% CI	0.32	0.55	0.292	0.635
	Lower 95% CI	−0.439	−0.185	−0.464	−0.063

velocity and a prolonged duration of saccade in ASD (Schmitt et al., 2014) may be related to the target amplitudes due to the dependence of saccade peak velocity on target amplitude. In addition, no correlation was observed between the properties of the fast phase of OKN and AQ scores, which may be due to the difference between involuntary and voluntary saccades. In previous studies, the participants' task was to voluntarily saccade from the fixation point to the target. Therefore, individuals with ASD could not control their eye movements well, which resulted in slow peak velocities and long durations of the saccade. In contrast, the fast phase of the involuntary saccade and that of OKN are controlled by the same mechanism (Garbutt et al., 2001; Leigh and Kennard, 2004) and could not be controlled by the participant. The meta-analysis of Johnson et al. (2016), who demonstrated the association between ASD impaired voluntary control of saccade inhibition, supported this assumption. Therefore, we can conclude that no difference existed in the peak velocity and the duration of the saccade according to the participants' AQ scores.

The mean eye position during OKN did not correlate with the participants' AQ scores, which indicates that attentional shifts induced by the motion stimulus were constant. The shift of the mean eye position during OKN in the direction of the fast phase is presumed to enable the visual system to more efficiently detect targets (Watanabe, 2001). In addition, this shift might reflect the utilization of global motion signals by the attention system. Individuals with ASD have been shown to have elevated global motion thresholds (Spencer et al., 2000; Pellicano and Gibson, 2008). All the elements in the stimulus used for the present study

Table 3. Mean (SD) for peak velocity of OKN fast-phase and the correlation coefficients between the peak velocity of OKN fast-phase and the participants' AQ scores. The abbreviation is the same as Table 1.

Stimulus velocity (deg/s)		Peak velocity (deg/s)			
		Rightward	Leftward	Upward	Downward
15.4	Mean (SD)	291.49 (71.3)	298.78 (79.85)	269.77 (55.33)	288.52 (95.75)
	Pearson's r	−0.019	−0.085	0.175	0.026
	BF_{10}	0.254	0.273	0.347	0.255
	Upper 95% CI	0.365	0.311	0.514	0.402
	Lower 95% CI	−0.396	−0.447	−0.232	−0.36
30.9	Mean (SD)	326.44 (85.01)	310.73 (69.36)	318.36 (84.11)	301.43 (122.34)
	Pearson's r	−0.115	−0.018	0.204	−0.074
	BF_{10}	0.29	0.254	0.39	0.268
	Upper 95% CI	0.286	0.366	0.535	0.321
	Lower 95% CI	−0.469	−0.395	−0.206	−0.438
46.4	Mean (SD)	335.90 (103.81)	326.70 (115.44)	305.48 (105.65)	320.57 (129.72)
	Pearson's r	−0.087	−0.037	0.125	−0.015
	BF_{10}	0.273	0.257	0.297	0.254
	Upper 95% CI	0.309	0.351	0.477	0.369
	Lower 95% CI	−0.448	−0.41	−0.276	−0.393

Table 4. Mean (SD) for duration of OKN fast-phase and the correlation coefficients between the duration of OKN fast-phase and the participants' AQ scores. The abbreviation is the same as Table 1.

Stimulus velocity (deg/s)		Duration (ms)			
		Rightward	Leftward	Upward	Downward
15.4	Mean (SD)	39.46 (6.89)	40.47 (6.54)	45.44 (7.45)	43.28 (7.92)
	Pearson's r	−0.282	−0.177	−0.223	−0.237
	BF_{10}	0.588	0.35	0.425	0.455
	Upper 95% CI	0.132	0.231	0.188	0.175
	Lower 95% CI	−0.589	−0.515	−0.548	−0.558
30.9	Mean (SD)	43.13 (7.38)	43.00 (9.16)	52.86 (7.30)	45.48 (6.98)
	Pearson's r	−0.199	−0.061	−0.392	−0.226
	BF_{10}	0.382	0.263	1.385	0.431
	Upper 95% CI	0.211	0.331	0.018	0.186
	Lower 95% CI	−0.531	−0.429	−0.662	−0.55
46.4	Mean (SD)	43.57 (9.51)	43.55 (10.77)	49.76 (12.03)	47.32 (7.72)
	Pearson's r	−0.262	0.006	−0.36	−0.198
	BF_{10}	0.523	0.253	1.037	0.381
	Upper 95% CI	0.151	0.386	0.053	0.211
	Lower 95% CI	−0.575	−0.376	−0.641	−0.531

moved in the same direction, and the stimulus did not include coherent motion. Therefore, we can infer that there was no difference in the mean eye position of OKN because this stimulus does not cause a difference in global/local motion processing. Alternatively, the process of orienting attention to a new target and disengaging attention from an existing target is presumed intact in ASD (Johnson et al., 2016).

In this study, we only examined the relationship between participants' AQ scores and the properties of OKN. Therefore, it is possible that the effects of properties other than AQ have not been eliminated. Individuals with ASD are more likely than the general population to have comorbid psychiatric disorders, such as intellectual disability (ID) (Lotter, 1966; Bryson et al., 2008), attention deficit hyperactivity disorder (ADHD) (Leyfer et al., 2006; Ronald et al., 2008), anxiety disorders (White et al., 2009; Hallett et al., 2010), and developmental coordination disorder (DCD) (Lichtenstein et al., 2010). In particular, attention and saccade processes are tightly integrated at the neural level in physiological studies (Corbetta et al., 1998; Hoffman and Subramaniam, 1995; Moore and Fallah, 2001; Moore et al., 2003). Therefore, it is necessary to examine the relationship between the degree of ADHD and the properties of fast phase OKN. In addition, several studies reported sex differences in AQ scores (Baron-Cohen et al., 2001; Ruzich et al., 2015) and eye movements (Sargezeh et al., 2019; Mathew et al., 2020). Thus, given that this study only tested females, further studies are required to confirm if a similar relationship occurs in males. Finally, this study was conducted only on typical adults and used methods for measuring and analyzing OKN that differed from those of previous studies (Scharre and Creedon,

Table 5. Mean (SD) for frequency of OKN and the correlation coefficients between the frequency of OKN and the participants' AQ scores. The abbreviation is the same as Table 1.

Stimulus velocity (deg/s)		Frequency (Hz)			
		Rightward	Leftward	Upward	Downward
15.4	Mean (SD)	2.31 (0.48)	2.12 (0.54)	2.18 (0.59)	2.22 (0.47)
	Pearson's r	−0.143	0.029	−0.141	−0.145
	BF_{10}	0.312	0.255	0.31	0.314
	Upper 95% CI	0.261	0.404	0.263	0.259
	Lower 95% CI	−0.49	−0.357	−0.489	−0.492
30.9	Mean (SD)	2.24 (0.62)	2.14 (0.68)	2.02 (0.73)	1.92 (0.54)
	Pearson's r	−0.03	−0.045	−0.236	−0.066
	BF_{10}	0.256	0.258	0.454	0.265
	Upper 95% CI	0.356	0.344	0.176	0.327
	Lower 95% CI	−0.405	−0.416	−0.557	−0.433
46.4	Mean (SD)	1.89 (0.87)	1.90 (0.87)	1.83 (0.68)	1.55 (0.63)
	Pearson's r	0.021	0.041	−0.255	0.115
	BF_{10}	0.254	0.258	0.502	0.29
	Upper 95% CI	0.398	0.414	0.158	0.47
	Lower 95% CI	−0.364	−0.347	−0.571	−0.285

1992; Milne et al., 2009). Therefore, investigating whether the methods of this study can be applied to other studies on ASD is an interesting avenue for future research.

5. Conclusions

The present study has revealed a negative correlation between participants' AQ scores and the gain of slow-phase OKN, and no correlation was found between participants' AQ scores and the properties of fast phase OKN. These findings indicate that the OKN disorder reported in ASD is associated with the neural basis disorder of the involuntary movement of slow-phase OKN. Our findings contribute to the development of tools that facilitate the diagnosis of the degree of ASD than methods that require instructions, such as saccade tasks, simply by observing the visual stimuli that induce OKN.

Declarations

Author contribution statement

Kei Kanari: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Moe Kikuchi-Ito: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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