Eye-tracker-based Evaluation of Saccadic Deficits in Young Children with Developmental Disorders

Yumie ONO,*, **, # Takahiro NIIDA, *** Yuma SHINOMIYA, *** Kenji SUZUKI, *** Naoto HARA, *** Yasuhiko AZEGAMI, † Taeko SATO, † Chigusa MIMORI, † Hideo SHIMOIZUMI††

Abstract Visually guided saccadic eye movement has been considered a promising screening tool for cognitive function because of its simple and objective nature. However, its application to young children, especially those with developmental disorders, is limited due to the lack of sustained attention required to complete the measurement using the traditional electrophysiological protocol. We have previously reported that saccades can be reliably evaluated in typically developing young children using an eye tracker, which allows non-contact measurement of eye movement with a sufficiently short preparation time. Using the eye tracker system combined with an in-house developed analysis software, we investigated the changes in saccadic behavior between typically developing children (n = 30) and children with developmental disorders (attention-deficit/hyperactivity disorder [ADHD] and autism spectrum disorder [ASD], n = 27) at ages ranging from 4.8 to 13.2 years. Four saccade responses were measured, consisting of eye movement to the instantaneously shifted visual target either to the right or left (step condition), to the visual target that appeared 200 ms after turning off the fixation point (gap condition), to the visual target while the fixation point remained (overlap condition), and in the direction opposite to the visual target (anti-saccade condition). Statistically significant deficits were found in children with developmental disorders compared to typically developing children, with decreased number of correct saccades in the step condition in children with ASD and reduced peak saccadic velocity in the overlap condition in children with ADHD. Interestingly, when saccadic parameters were further evaluated with regard to the direction of eye movement (rightward and leftward), a significant decrease in peak velocity in children with developmental disorders compared to typically developing children was only confirmed in saccades to the right side in the overlap condition. In addition, right-lateralized deficits in peak velocity and initial accuracy were also found in the step, overlap, and anti-saccade conditions in children with developmental disorders. These lateralized oculomotor responses may represent the affected cortical function in children with developmental disorders, suggesting a possible role of non-contact saccadic examination as an assessment tool for visual cognitive function, especially in young children.

Keywords: saccadic eye movement, children, developmental disorders, eye tracker, laterality.

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1. Introduction

Saccades are voluntary eye movements that rapidly redirect gaze for detailed visual analysis of the environment. Since the circuitry controlling eye movements are sufficiently understood [1], saccadic paradigms have been recognized as an excellent strategy to characterize mutational abnormalities in brain systems associated with neurodevelopmental disorders [2]. Another advantage of adopting saccade paradigms in people with neurodevelopmental disorders is that the characteristics of saccades rely solely on the oculomotor function. The cognitive ability of attention, inhibition, and executive control can be precisely evaluated with saccades [3], independent of other somatic neuromuscular functions that may be affected in people with developmental disorders [4]. However, conventional measurement of saccadic eye movement requires preparation, including attaching and calibrating electro-oculogram electrodes or infrared-light devices on the face. The use of saccade paradigms is
therefore difficult for individuals with limited attention spans and/or atypical somatosensation, such as young children and children with developmental disorders. Consequently, previous saccadic studies in children with developmental disorders mostly recruited preteens and early teens (aged 10–13 years; Fig. 1) [1, 2, 5–17].

Recent advances in non-contact eye camera systems have allowed faster preparation and less restriction, providing a potential to expand the age for evaluation of oculomotor function. Utilizing such a modern eye camera system, we have previously reported that saccadic performance can be reliably evaluated in typically developing young children at preschool and school ages [18]. A detailed investigation of oculomotor function in younger children with developmental disorders would further contribute to the understanding of the neuronal mechanisms of the pathology, since complex cognitive paradigms cannot be used in this population. The current study therefore investigated saccadic eye movements in preschool- and school-age children with developmental disorders (aged 4.8–13.2 years; Fig. 1) and age-matched typically developing children to characterize their visual cognitive function. Specifically, we collected data from children with attention-deficit/hyperactivity disorder (ADHD) and autism spectrum disorder (ASD) as major developmental disorders. From this population of participants, we aimed to extract alterations that appeared in the saccadic responses of young children with developmental disorders. Another purpose of the current study was to investigate in detail the characteristics of saccadic responses depending on the direction of eye movement. Research evidence indicating atypicalities in structural, behavioral, and functional lateralization in people with ASD/ADHD [19, 20] motivated us to investigate whether such atypical lateralization may also be detected in the visual cognitive behavior at an earlier age.

2. Methods

The participants in this study consisted of 30 typically developing children (TD; aged 8.2 ± 2.2 years) and 27 children with developmental disorders (DD; 8.7 ± 1.9 years old; Table 1). The diagnosis was made by pediatric

![Fig. 1 Distribution of participant age in studies of saccadic responses in children with developmental disorders. Circle shows the mean age of the participants (only the range is shown if mean age was not reported). Mean age ± 3 standard deviation is shown if the range was not provided. LD: learning disability; CP: cerebral palsy; ADHD: attention-deficit/hyperactivity disorder; ASD: autism spectrum disorder if the range was not provided. LD: learning disability; CP: cerebral palsy; ADHD: attention-deficit/hyperactivity disorder; ASD: autism spectrum disorder.](image)

| Table 1 | Characteristics of the participants. |
|---------|-------------------------------------|
| Typically developing | Development disorder | ADHD subgroup | ASD subgroup |
| Age at testing, years: | 8.2 (2.2) | 8.7 (1.9) | 9.1 (2.1) | 8.4 (1.8) |
| mean (Std.) [range] | [5.1–12.4] | [4.8–13.2] | [4.8–13.2] | [4.8–11.7] |
| Sex: boy/girl | 8/22 | 18/9 | 15/4 | 11/8 |
| WISC/WPPSI (intelligence scale for children): | | | | |
| Full scale IQ | 95.2 (16.1) | 96.4 (18.1) | 98.4 (16.6) |
| Verbal comprehension index | 101.2 (19.5) | 102.7 (22.0) | 101.5 (21.5) |
| Perceptual reasoning index | 95.6 (16.5) | 95.8 (18.3) | 101.7 (15.2) |
| Working memory index | 91.7 (15.1) | 92.1 (17.3) | 92.3 (16.6) |
| Processing speed index | 93.3 (13.3) | 95.2 (13.6) | 96.2 (13.6) |

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participants had any neurological, psychiatric or psycho-}

voluntary participation in the TD group. None of the TD
groups were matched with respect to age, the sex ratio
among the eye movement data collected from both
eyes, data from the left eye were analyzed in line with
standard procedures used in eye-tracking studies [23,
24]. Four saccade parameters were analyzed; namely, the
number of successful saccades, saccade reaction time

| A Step condition | B Gap condition |
|------------------|-----------------|
| ![Step condition diagram](image1) | ![Gap condition diagram](image2) |

Fig. 2 Saccade conditions. F: fixation point; T: target; Eye: eye position; SRT: saccadic reaction time.

(Fig. 2). In all cases, the fixation point was displayed
more than 1,000 ms before presenting the target, and the
target was presented at 500 ms or a longer duration after
continuous eye fixation to the center of the monitor was
confirmed. In the step condition (Fig. 2A), at the same
time when the fixation point disappeared, the target ap-
peared on either the left or right side. The participant was
instructed to look at the red filled circle for the entire
time. In the gap condition (Fig. 2B), the fixation point
disappeared, and, after a gap period of 200 ms, the target
appeared. The participant was instructed to look at the
red filled circle for the entire time while it was present.
In the overlap condition (Fig. 2C), the fixation point re-
mained illuminated while the target appeared. The par-
ticipant was instructed to look at the fixation point first
and gaze at the target immediately after it appeared. In
the anti-saccade condition (Fig. 2D), the presentation of
stimulus was identical to the step condition. The partici-
patent was instructed to look at the fixation point first, and
after appearance of the target, to shift his/her gaze to the
opposite side of the target for the same distance between
the fixation point and the target. The target location was
randomly assigned to either the right or left of the fixa-
tion point in all conditions, and the measurement contin-
ued until 30 saccade trials in both directions were mea-
sured. A practice session was given prior to each test
session for the participant to adapt to the conditions [22].
A break was given in the middle of the experiment when
the child’s attention to the task decreased, and the mea-

measurement was aborted when the child could not sustain
attention to the task or understand the task.

Among the eye movement data collected from both
eyes, data from the left eye were analyzed in line with
standard procedures used in eye-tracking studies [23,
24]. Four saccade parameters were analyzed; namely, the
number of successful saccades, saccade reaction time

| C Overlap condition | D Anti condition |
|---------------------|------------------|
| ![Overlap condition diagram](image3) | ![Anti condition diagram](image4) |

neurologists and speech-language-hearing therapists of
the International University of Health and Welfare Hos-
pital, International University of Health and Welfare Re-
habilitation Center, or International University of Health
and Welfare Clinic, based on the Diagnostic and Statisti-
cal Manual of Mental Disorders, fifth edition (DSM-5).
Children diagnosed with ADHD and/or ASD were in-
cluded in the DD group. The DD group was further di-
vided into two subgroups, ADHD and ASD, depending
on their diagnosis. There was an overlap of participants
in these subgroups since children with comorbid ADHD
and ASD (n = 11; boys/girls = 8/3) were included in
both groups. Detailed clinical information for partici-
pants in the DD group is provided in Supplemental ma-
terial 1. Three children were treated with methylpheni-
date, which has been reported to ameliorate saccadic
responses in children with ADHD [21]. However, they
were included in the current study because their saccadic
responses were comparable to those of other children in
the DD group not treated with medication. Participants
in the TD group were recruited from a broader commu-

nity via local advertising. Although the TD and DD
groups were matched with respect to age, the sex ratio
was significantly different (p < 0.01) due to the nature of
voluntary participation in the TD group. None of the TD
participants had any neurological, psychiatric or psycho-
diagnosis; history of acquired brain injury; or a
first-degree relative with any developmental disorders
determined through parent interviews. The TD partici-
pants included those who were recruited in our pilot
study [18]. The Institutional Review Board (IRB) of the
International University of Health and Welfare approved
this study. The children’s parents provided written in-
formed consent, and they assented to participate in the
study.

The horizontal displacement of the eye was recorded
using an Eyelink 1000 Plus system (SR Research Ltd.) at
a sampling rate of 500 Hz. Visual stimuli were presented
on a 27” LCD monitor (Apple Thunderbolt display; re-

fresh rate: 59.95 Hz; response time: 12 ms). Participants
were seated 650 mm directly in front of the monitor,
with their heads stabilized using a chin rest. Stimuli were
presented on a white background: the target was a red
filled circle with the size of visual angle 0.5° and lasted
for 2 s. The target was presented at 5 degrees either to
the right or left of a centrally positioned fixation point, which
had the same visual property as the target (a red filled
circle). This environment was developed in our previous
study targeting typically developing young children [18],
in which the acquired saccade parameters were con-

firmed to be appropriate through comparisons with those
measured using electrophysiological protocols.

All participants performed four types of saccades

![Advanced Biomedical Engineering. Vol. 10, 2021.](image5)
(SRT), peak velocity, and initial accuracy. A successful saccade was defined as the eye movement to the target direction with a velocity faster than 100°/s during 2,100 ms after the target was displayed. For clarity, the number of successful saccades was converted to the rate of successful trials over total trials and referred to as successful trials (Eq. 1) hereinafter.

\[
\text{Successful trials} = \frac{\text{Number of successful saccades}}{\text{Number of total trials}} \times 100 \% \tag{1}
\]

The SRT was defined as the time from target onset until the velocity of the saccadic eye movement exceeded 20°/s. Trials with SRT less than 80 ms and/or peak velocity more than 1,000 degree/s were excluded as anticipatory responses [25] and technical errors exceeding the physiological range of eye movement [26], respectively. The initial accuracy of saccades was defined as the ratio of saccade displacement to target displacement (Eq. 2). The saccade displacement was defined as the horizontal distance from the fixation point at which the saccade velocity first decelerated to 0°/s after it reached the maximum velocity.

\[
\text{Initial accuracy} = \frac{\text{Saccade displacement}}{\text{Target displacement}} \times 100 \% \tag{2}
\]

Initial accuracy was not determined in the anti-saccade condition because there was no target displayed in the direction of eye movement. An in-house developed MATLAB program automatically detected these parameters from the output log files of the EyeLink system. For each dataset, the program displayed the waveforms of saccadic eye movement and the histograms of SRT, which were manually checked by trained orthoptists (Y. S. and K. S.).

For statistical analysis, median values of the parameters were determined for each condition of each participant because of the non-Gaussian nature of the distribution of saccadic eye responses [27, 28]. Group differences in parameters between typically developing group and developmental disorder group were analyzed using Mann-Whitney U test. Within-group differences in parameters between the target directions (left and right) were analyzed using Wilcoxon signed-rank test. Statistical significance was set at \( P < 0.05 \).

3. Results

Table 2 summarizes the saccade responses of typically developing children (TD) and children with developmental disorders (DD).

| Step condition | Successful trials (%) | SRT (ms) | Peak velocity (°/s) | Initial accuracy (%) |
|----------------|-----------------------|----------|---------------------|----------------------|
| TD             | 91.7 (15.0)           | 178.0 (30.0) | 327.1 (46.4)       | 106.2 (21.3)        |
| DD             | 86.7 (14.6)           | 191.0 (42.5) | 306.1 (78.7)       | 107.5 (8.0)         |
| ADHD           | 86.7 (10.4)           | 184.0 (35.8) | 306.1 (46.9)       | 106.9 (7.0)         |
| ASD            | 85.0 (12.5)           | 184.0 (42.5) | 295.8 (60.5)       | 107.4 (7.4)         |
| Gap condition  |                       |          |                     |                      |
| TD             | 80.8 (18.3)           | 156.5 (24.0) | 309.6 (58.0)       | 99.5 (17.4)         |
| DD             | 79.2 (20.0)           | 155.0 (17.0) | 298.8 (88.2)       | 101.1 (10.0)        |
| ADHD           | 79.2 (25.8)           | 154.0 (27.5) | 282.7 (49.9)       | 96.1 (12.5)         |
| ASD            | 76.7 (15.4)           | 154.0 (15.8) | 288.8 (86.3)       | 99.1 (12.7)         |
| Overlap condition |                   |          |                     |                      |
| TD             | 88.3 (13.3)           | 181.0 (55.5) | 292.7 (70.2)       | 96.3 (24.8)         |
| DD             | 90.0 (15.4)           | 200.0 (66.0) | 272.5 (73.0)       | 92.0 (18.5)         |
| ADHD           | 90.8 (15.0)           | 199.0 (61.0) | *257.2 (61.2)      | 91.4 (18.6)         |
| ASD            | 88.3 (13.3)           | 186.5 (76.0) | 270.4 (82.7)       | 90.5 (21.1)         |
| Anti condition |                       |          |                     |                      |
| TD             | 38.3 (33.3)           | 299.5 (76.0) | 391.9 (135.5)      |                     |
| DD             | 20.0 (27.9)           | 309.0 (112.0) | 355.1 (117.5)     |                     |
| ADHD           | 26.7 (33.3)           | 298.5 (70.0) | 362.7 (98.4)       |                     |
| ASD            | 16.7 (21.7)           | 327.5 (140.5) | 341.7 (128.9)      |                     |

Group DD is subdivided into ADHD and ASD groups. Data are expressed as median (interquartile range). Asterisks indicate statistically significant differences compared to TD group.
developing children and children with developmental disorders. Typically developing children showed saccadic responses to the correct direction in more than 80% of the trials in the step, gap, and overlap conditions, but the ratio of successful saccadic responses decreased to approximately 40% in the anti-saccade condition. These values agree with the previously reported saccade eye responses in typically developing children measured with EOG [29]. Although statistically insignificant, saccadic responses of children with developmental disorders were characterized by (i) decreased successful trials in the step and anti-saccade conditions, (ii) longer reaction time in step, overlap, and anti-saccade conditions, and (iii) slower peak velocity in all conditions. Subgroup analysis showed a statistically significant decrease in successful trials (step condition) in the ASD group, and in peak velocity (overlap condition) in the ADHD group, compared to the TD group.

The saccadic responses were further analyzed with respect to the target direction to investigate atypical functional lateralization in oculomotor responses (Table 3). Children with developmental disorders showed slower peak velocity for the right saccades, but not for the left saccades, in the overlap condition, compared to typically developing children. Subgroup analysis confirmed significantly slower peak velocity in the overlap condition in children with ADHD, but not in children with ASD, compared to typically developing children.

Lateralized oculomotor responses were found mostly in children with developmental disorders when saccadic responses were compared between the eye movement directions. Children with developmental disorders exhibited significantly slower peak velocity in the rightward relative to the leftward direction in the step and anti-conditions. They also showed a larger displacement error for the right target (15.9%) relative to the left target (3.2%) in the step condition, resulting in a significant difference in the initial accuracy. Subgroup analysis also confirmed the slower peak velocity and lower initial accuracy for the rightward saccades than for the leftward saccades in the ADHD and ASD subgroups in the step condition. Decreased peak velocity to the right side was additionally found in the ASD subgroup in the overlap condition. In the anti-saccade condition, a statistically significant decrease in peak velocity in the rightward relative to the leftward direction was confirmed in the ADHD subgroup but not in the ASD group, possibly due to the larger variation in data in this subgroup.

Typically developing children performed saccadic responses to the correct direction significantly better for the left than the right side in the overlap condition, whereas there was no change in the rate of successful trials between saccadic directions in children with developmental disorders. Children with developmental disorders showed an approximately 10% smaller median rate of successful trials to the right than to the left in the gap condition, but only the ADHD subgroup reached statistical significance.

We also investigated the effects of sex (boy/girl) and comorbidity status (sole diagnosis of ADHD, sole diagnosis of ASD, or comorbid ADHD and ASD) on the saccadic responses of the selected conditions in which we found statistically significant differences in the above group-level comparisons. Although the number of participants in each subgroup was small, no statistically significant differences in saccadic responses between sexes and among comorbidity status were found in the selected conditions. Therefore, we focused on the differences in saccadic responses found in the TD and DD groups (and ADHD and ASD subgroups in the DD group) with mixed sexes and mixed comorbidity status in the following discussion. Please see Supplemental materials 2 and 3 for detailed results of the sex- and comorbidity-based analyses.

4. Discussion

Utilizing non-contact eye-tracking technology, we investigated the oculomotor function in preschool- and school-age children with typically developing children and children with developmental disorders. Some deficits in saccadic responses were confirmed in children with developmental disorders compared to typically developing children, suggesting that the oculomotor dysfunction previously found in older children with developmental disorders could emerge from a younger age.

When saccadic responses were summarized regardless of the direction of eye movement, children with ASD made significantly more errors than typically developing children in the step condition. Previous studies reported a tendency (with no significant difference) of higher rate of pro-saccade error in adults with ASD [30, 31]. These results suggest that simple pro-saccade function is impaired in young children with ASD, but can be ameliorated along with development. Although children with ADHD showed comparable rates of successful trials compared with typically developing children, as reported by Rothlin et al. [2], they demonstrated significantly slower saccadic velocity in the overlap condition. Analysis of peak velocity with regard to direction of saccades further supports that this reduction in saccadic velocity mainly arises from deficits in rightward eye movement. However, when we incorporated children with ASD and ADHD in the DD group, we found no significant difference in any of the saccadic parameters despite previous reports of common deficits in saccade trials and SRT in children with ADHD [2, 6] and ASD [10, 11].
One possible explanation is that there were large variations in these parameters when testing the current population of younger children. Further studies on a larger sample size is required to determine the heterogeneity of saccadic responses in children with ADHD and ASD.

A novel finding of this study is an imbalance of ocu-

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**Table 3** Saccade parameters of typically developing children (TD) and children with developmental disorders (DD) with respect to the saccade direction (L: leftward; R: rightward).

|                       | Successful trials (%) | SRT (ms) |
|-----------------------|-----------------------|----------|
|                       | L         | R         | L         | R         |
| **Step condition**    |           |           |           |           |
| TD                    | 90.0 (13.3) | 91.7 (16.7) | 181.5 (30.0) | 182.5 (34.0) |
| DD                    | 86.7 (17.7) | 83.3 (16.0) | 190.0 (45.5) | 197.0 (34.5) |
| ADHD                  | 93.3 (9.3)  | 86.7 (16.0) | 184.0 (37.8) | 197.0 (31.8) |
| ASD                   | 86.7 (19.3) | 83.3 (12.7) | 190.0 (47.8) | 182.0 (45.8) |
| **Gap condition**     |           |           |           |           |
| TD                    | 78.3 (16.7) | 80.0 (18.3) | 157.0 (30.0) | 152.0 (18.0) |
| DD                    | 83.3 (23.3) | 73.3 (27.7) | 155.0 (23.5) | 152.0 (14.5) |
| ADHD                  | 83.3 (25.0) | 73.3 (28.3) | 159.5 (34.5) | 151.5 (17.5) |
| ASD                   | 80.0 (18.3) | 73.3 (26.7) | 155.0 (19.8) | 152.0 (11.8) |
| **Overlap condition** |           |           |           |           |
| TD                    | 90.0 (8.3)  | 86.7 (16.7) | 196.0 (69.0) | 185.5 (59.0) |
| DD                    | 90.0 (15.0) | 88.3 (13.3) | 203.0 (84.0) | 182.5 (65.0) |
| ADHD                  | 90.0 (13.3) | 88.3 (16.7) | 203.0 (64.0) | 186.0 (65.5) |
| ASD                   | 86.7 (16.7) | 86.7 (16.7) | 193.0 (96.0) | 178.0 (93.0) |
| **Anti condition**    |           |           |           |           |
| TD                    | 30.0 (43.3) | 40.0 (43.3) | 296.0 (75.5) | 323.0 (80.0) |
| DD                    | 16.7 (24.3) | 23.3 (37.7) | 302.0 (131.5) | 320.0 (103.8) |
| ADHD                  | 26.7 (20.0) | 28.3 (40.0) | 292.0 (74.0) | 303.0 (99.8) |
| ASD                   | 13.3 (21.7) | 23.3 (32.7) | 296.0 (163.8) | 322.0 (115.5) |

|                       | Peak velocity (°/s) | Initial accuracy (%) |
|-----------------------|---------------------|----------------------|
|                       | L       | R       | L       | R       |
| **Step condition**    |           |           |           |           |
| TD                    | 327.8 (71.8) | 314.4 (68.8) | 105.4 (17.0) | 108.8 (32.1) |
| DD                    | 315.5 (79.2) | 298.4 (41.5) | 103.2 (18.1) | 115.9 (20.6) |
| ADHD                  | 317.3 (68.6) | 288.8 (35.8) | 99.4 (15.3)  | 117.7 (19.0) |
| ASD                   | 302.7 (79.2) | 296.3 (39.8) | 98.4 (18.7)  | 117.4 (23.8) |
| **Gap condition**     |           |           |           |           |
| TD                    | 315.1 (86.5) | 301.9 (50.4) | 95.2 (33.1)  | 104.0 (37.9) |
| DD                    | 295.1 (93.2) | 286.5 (67.5) | 99.2 (20.9)  | 107.7 (18.9) |
| ADHD                  | 290.8 (78.5) | 280.0 (56.0) | 96.2 (15.0)  | 106.9 (28.0) |
| ASD                   | 295.1 (99.1) | 282.7 (72.9) | 99.6 (27.1)  | 108.2 (15.6) |
| **Overlap condition** |           |           |           |           |
| TD                    | 303.4 (98.9) | 277.9 (60.0) | 90.8 (26.4)  | 105.7 (45.2) |
| DD                    | 286.4 (91.0) | 260.7 (62.1) | 96.6 (33.0)  | 90.7 (25.2)  |
| ADHD                  | 269.6 (88.8) | 254.9 (28.8) | 95.1 (33.0)  | 90.7 (25.6)  |
| ASD                   | 297.0 (91.5) | 257.7 (91.0) | 96.5 (35.4)  | 93.8 (26.7)  |
| **Anti condition**    |           |           |           |           |
| TD                    | 385.2 (124.5) | 369.8 (161.7) |           |           |
| DD                    | 401.3 (141.1) | 345.1 (132.1) |           |           |
| ADHD                  | 407.7 (127.4) | 367.9 (114.9) |           |           |
| ASD                   | 401.3 (198.2) | 311.4 (138.1) |           |           |

Group DD is subdivided into groups ADHD and ASD. Data are expressed as median (interquartile range). Asterisks and daggers indicate statistically significant differences compared to TD group and between target directions within the group, respectively.
lomotor responses depending on the direction of eye movement in children with developmental disorders. The peak velocity for the rightward saccade, but not for the leftward saccade, was significantly slower in children with developmental disorders than in typically developing children in the overlap condition. Furthermore, impaired peak velocity and initial accuracy for the rightward compared to the leftward saccade were found in children with developmental disorders in the step condition, and impaired rightward peak velocity was also confirmed in the anti-saccade condition. These results suggest that atypical lateralization of oculomotor function is a common characteristic of oculomotor function in children with developmental disorders.

Atypically lateralized oculomotor responses have also been demonstrated in previous studies in school-age children with developmental disorders. Children with ADHD showed slower peak velocity [6] and impaired initial accuracy [1] in rightward relative to leftward pro-saccade task. Takarae et al. [32] reported deficits in the foveofugal step-ramp task and pure-ramp task specific to the visual target on the right side. Increased variability in the accuracy of saccades to the right has also been reported even in the siblings and parents of children with ASD [33]. Our results revealed that atypical lateralized oculomotor responses emerge at an earlier stage of development.

Current results of rightward-lateralized deficits in saccadic responses, commonly found in various saccadic conditions, in children with developmental disorders suggest impaired function in the left frontal eye field, which controls saccadic movements in the rightward direction. The decreased velocity and accuracy of saccadic responses also raise the possibility of deficits in the parietal cortex and superior colliculus [1]. A statistically significant decrease in saccadic responses in children with developmental disorders compared to typically developing children was found only in the overlap condition, suggesting impaired function of the basal ganglia required to release visual attention to the original fixation. Although the current observational study did not estimate the origin of oculomotor deficits in children with developmental disorders, the collective results suggest the potential role of any one or a combination of the above regions in the central nervous system in the altered saccadic response pattern in children with developmental disorders.

Previous neuroimaging studies using MRI, fMRI, and EEG have revealed atypical laterality in brain structure, behavior, and cognitive functions in children and adults with developmental disorders [19, 20]. Regarding the functional aspect, children with ASD are characterized by atypical asymmetry in language, sensorimotor, visual, executive, and attention functions, with a shift toward the right hemisphere for all these domains [19, 34, 35]. Lateralization of attentional behavior and cortical electrophysiological activity has also been reported in children with ADHD [20]. In the current study, differences in saccadic parameters related to the direction of eye movement may be another aspect of atypical functional asymmetry in children with developmental disorders. Our results suggest that atypical functional asymmetry emerges from a younger age in children with developmental disorders. Eye movement examination could be an excellent strategy to investigate atypical functional asymmetry in younger children who have difficulty undergoing neuroimaging examinations such as fMRI and EEG.

There are limitations to the interpretation of the results of this study. First, 11 children had comorbid ASD and ADHD and were included in both the ASD and ADHD subgroups. Therefore, even though lateralized oculomotor response was detected in both subgroups, it could have originated from the altered oculomotor function associated with either disorder (see Supplemental material 3 for a detailed discussion regarding comorbidity). The current study contributes to the detection of altered oculomotor responses commonly found in young children with developmental disorders, rather than those specific to types of disorder or comorbidities. Second, the sex ratio was different between the groups of typically developing children and children with developmental disorders. Although our additional subgroup analysis showed limited contribution of sex imbalance to most of the differences in saccadic parameters between typically developing children and children with developmental disorders found in the current study (see Supplemental material 2 for details), further examination with a larger sample size is required to determine the interaction between sex and the presence of developmental disorders in oculomotor function in young children.

5. Conclusion
The non-contact eye-tracking technology revealed the existence of atypical asymmetry of oculomotor responses in preschool- and school-age children with developmental disorders. Rightward-lateralized deficits in saccadic velocity and accuracy may represent the early symptoms of atypical laterality in brain structure and function that have been confirmed in later stages of development in these children.

Conflicts of interest
The authors declare no conflicts of interest with any companies or commercial organizations in accordance with the definition of the Japanese Society for Medical
and Biological Engineering.

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Yumie Oso
Yumie Oso received her PhD in Electrical Engineering in 2004 from the Waseda University. After she worked as an Assistant and Associate Professor in Waseda University and Kanagawa Dental College, she is currently a Professor in the Department of Electronics and Bioinformatics, School of Science and Technology at Meiji University. Her work focuses on the application of noninvasive brain imaging and biomedical measurement techniques on medicine and rehabilitation. She is a member of Japanese Society for Medical and Biological Engineering and the Japan Neuroscience Society, and a councilor of Japan Society of Neurorehabilitation Research and Japanese Association of Noninvasive Brain Imaging and Bioelectromagnetics Society.

Takahiro Niida
Takahiro Niida graduated school of Medicine, Kitasato University and received degree of Doctor of Medicine in Graduate School of Medicine and Faculty of Medicine, Kitasato University in 1990. He is currently a Vice President of International University of Health and Welfare, Dean and Professor in the School of Health Sciences, and Head of Department of Orthoptics and Visual Science. His research interests cover the assessment of visual functions in patients with severe motor and intellectual disabilities and the binocular physiological interaction as related to ocular dominance and refractive correction under monovision. He is a member of Japanese Ophthalmological Society, and the editorial member of Tochigi Speech-Language-Hearing Therapists, the Japanese Society of Communication Disorders, He is currently a Professor in the Department of Orthoptics and Visual Science, School of Health Sciences, International University of Health and Welfare. His major research fields include Neuro-Ophthalmology and Autonomic Nervous System.

Yuma Shinomiya
Yuma Shinomiya received his PhD in Health Sciences from the International University of Health and Welfare in 2014. He is currently a Lecturer (full-time) in the Department of Orthoptics and Visual Sciences, School of Health Sciences, International University of Health and Welfare. His work focuses on the neural mechanism of eye movement. He is a member of Japanese Association for Strabismus and Amblyopia (JASA), Vision Society of Japan and Japanese Association of Certified Orthoptist.

Kenji Suzuki
Kenji Suzuki received his PhD in Health Sciences from the International University of Health and Welfare in 2015. He is currently a Lecturer (full-time) in the Department of Orthoptics and Visual Sciences, School of Health Sciences, International University of Health and Welfare. His work focuses on visual function test. He is a member of Japanese Ophthalmological Society, Japanese Association for Strabismus and Amblyopia (JASA), and Japanese Association of Certified Orthoptist.

Naoto Hara
Naoto Hara graduated from Kitasato University, School of Medicine in 1988. After completing his training as an Ophthalmology, he commenced research in brain research at Department of physiology, Niigata University. From 1995 to 1996, he was a postdoctoral fellow at the Department of Ophthalmology, Indiana University. From 1996 to 1997, he was a research fellow at the Department of Neurology, Johns Hopkins University, Baltimore, USA. He was appointed Associate professor, at the Kanagawa Dental College, Ophthalmology in 2002 and Professor in 2004 at the Department of Ophthalmology. Since 2014, he was a Professor at the Department of Orthoptics and Visual Sciences, School of Health Sciences, International University Health and Welfare. His major research fields include Neuro-Ophthalmology and Autonomic Nervous System.

Yasuhiko Azeami
Yasuhiko Azeami earned his MA in Education for Special Needs Children in 1984 from Tsukuba University in Japan. Upon the graduation, he worked at Saitama Rehabilitation Center as speech language therapist. He has been teaching child language development at International University of Health and Welfare ever since 2001, and currently a professor in the Department of Speech and Hearing Sciences as well as the Director of Speech Hearing Clinic of the University. His specialty is developmental disorders of children especially using INREAL Approach. He is a member of the Japanese Society of Speech-Language-Hearing Therapists, the Japanese Society of Communication Disorders, He’s the president of Tochigi Speech-Language-Hearing Therapists.

Taeko Sato
Taeko Sato earned her PhD in Speech, Language and Hearing Sciences in 2017 from International University of Health and Welfare. She works as a senior assistant professor in the Department of Speech and Hearing Sciences at International University of Health and Welfare. Her primary clinical research is focused on cognition and language, currently the children with developmental disabilities. She is a member of the Japanese Society of Communication Disorders, and the Japan Society of Higher Brain Dysfunction, and Neuropsychology Association of Japan.
Chigusa Mimori
Chigusa Mimori earned her master’s degree in Speech, language and Hearing Sciences in 2015 from the International University of Health and Welfare (IUHW). Upon graduation, she has joined faculty as an assistant professor of IUHW. She is currently in the doctoral program pursuing research on emotion and social cognition of children with autism spectrum disorder. She is a member of Japanese Association of Speech-Language-Hearing Therapists, The Japan Society of Logopedics and Phoniatrics and The Japan Society for Higher Brain Dysfunction.

Hideo Shimoizumi
Hideo Shimoizumi received his MD in 1982 from the Tokushima university and PhD in 1992 from the Jichi Medical University. He is currently director of rehabilitation center in the International university of health and welfare and a professor in the School of Health sciences at International university of health and welfare. His work focuses on neurodevelopmental disorders. He is a member of Japanese Society for pediatrics and pediatric neurology.