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Discriminative Analysis of Autistic Tendencies at 18 Months of Age Using Eye Gaze Characteristics in 4-, 10-, and 18-month-old Infants

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***Abstract*— Anomalies in motor function and social communication skills constitute early signs of autism spectrum disorder (ASD). In recent years, researchers have paid attention to the possibility of the quantitatively evaluating infants' social communication skills based on their eye movement. In this paper, we attempt to evaluate ASD risk using infants' eye movement data by examining the relationship between eye movement patterns at 4, 10, and 18 months of age and ASD risk as assessed by caregivers using a checklist at 18 months of age. A total of 18 eye movement indices were calculated from eye movement data measured by an optical eye tracker. The results revealed an association between ASD risk and eye movement indices. The indices included those related to a preference for social information at 4 months of age, those related to visual exploration of images at 10 months of age, and those indices related to both preference and visual exploration at 18 months of age. These results indicate that eye movement analysis may potentially serve as a means for early screening of ASD risk.**

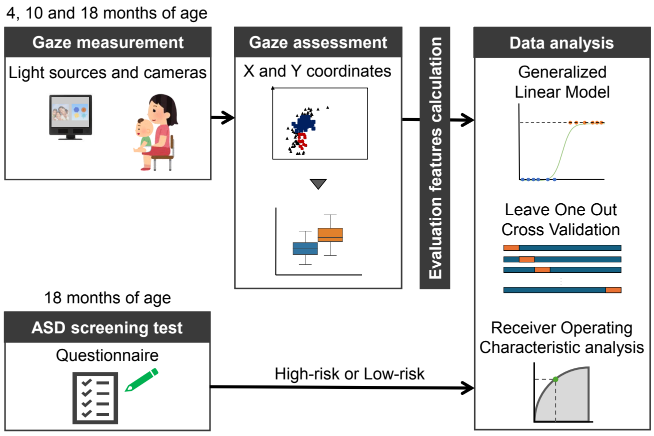

Fig. 1: Overview of the proposed analysis.

I. Introduction

Autism spectrum disorder (ASD) is a developmental disorder characterized by difficulties in social communication and restricted or repetitive behavior, interests, and activities [1]. No effective treatment has been established; however, early detection of ASD is important since early intervention and treatment can improve infants' development [2].

In current clinical practice, screening tests are recommended for early detection of infants' risk for ASD [3]. Parent-completed questionnaires such as the Modified Checklist for Autism in Toddlers (M-CHAT) for 14- to 18-month-old infants are often used for screening, and these questionnaires can assess ASD risk in terms of the infants' behavior and interest in others [4]. However, quantitative evaluation is difficult because it depends on parents' subjective reports. In addition, M-CHAT is not suitable for capturing early signs of ASD that appear before 12 months old [5].

Therefore, numerous studies have been conducted to quantitatively assess early signs of ASD [6], [7]. For example, Doi et al. evaluated the association between motor characteristics in the first few days of life and ASD risk, and showed the possibility that ASD risk at 18 months can be assessed based on the analysis of motor activity during the first few days of life [7]. These techniques allow for earlier screening of infants with ASD risk by making it possible to quantitatively assess infants' movements that are hard to detect by the human eye.

However, early signs of ASD are reported to appear not only in motor function but in social communication as well. Thus, assessing motor function alone is not sufficient. In recent years, researchers have succeeded in quantitative evaluation of the social communication skills of infants based on eye movement data [8], [9]. For example, Chawarska et al. evaluated the differences in eye gaze features at 6 months of age between infants later diagnosed with ASD and typically developing infants [9]. Thus, quantitative evaluation of eye gaze features can assess social communication skills and may allow earlier screening of infants with ASD risk.

In this paper, we analyze the relationship between eye movement patterns and ASD risk (Fig. 1). Eye movement data were collected at 4, 10, and 18 months of age, and ASD risk was determined at 18 months using M-CHAT. Eye movement indices were calculated from the eye movement data, and the relationship between these indices and ASD risk was analyzed. By analyzing the data at 4, 10, and 18 months of age, we explored developmental changes in the characteristics of the infants' eye movement patterns. We also attempted to determine which eye movement indices are useful in classifying infants with high and low ASD risk.

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II. Methods

A. Dataset information

1) Participants: Participants included 64 infants aged 4 months, 60 infants aged 10 months, and 63 infants aged 18 months. Eye movement data were collected at each age point in the presence of caregivers. At 18 months of age, ASD screening was conducted using the M-CHAT. The M-CHAT was sent to the mothers about a week before their infant turned 18 months of age, and the mothers were asked to return it after answering the questions. This research protocol underwent review and received approval from two institutional ethics committees: the Graduate School of Biomedical Sciences at Nagasaki University (Registration Numbers 14050205-2 and 10093099) and the Graduate School of Engineering at Hiroshima University (Registration Number: E-1150-1). The study's methodology strictly adhered to all applicable guidelines and regulations.

2) Gazing point measurement method: To prevent the infant's attention from being distracted, the examination was conducted in a private room, with curtains over the windows and lights on. The infant sat on the parent's lap and watched the movie at a distance of approximately 40–50 cm from the monitor. Only three people (the infant, their parent, and an operator) were allowed in the room. The operator sat behind the infant and the parent. We used Gazefinder (JVC KENWOOD Corporation, Kanagawa, Japan) [10] for the eye movement measurement. The device includes a 19-inch monitor (1280×1024 pixels) with infrared light sources and a stereo camera attached to the bottom of the monitor. Using corneal reflection techniques, it records the x and y coordinates of each infant's eye position at a frequency of 50 Hz. Before measurement, the eye position was calibrated using the 5-point method.

A total of 23 movie clips were used for the eye movement measurements, which were classified into nine categories: preference, blink, mouth movement, mouth stillness, pointing, window picture, point picture, stillness, and talking. Movie clips were presented as experimental stimuli in a fixed order. Between the movie clips, we inserted short attention-grabbing movie clips (2–5 seconds) nine times to set the fixation position at the center of the monitor before the next stimulus was presented. The total duration of the movie sequence was 107 seconds, including the time for short attention-grabbing movie clips.

In this paper, only the eight movie clips in the preference category (hereafter referred to as "Pref.") were used in the analysis to evaluate infants' eye movement patterns in simple preferences in detail. It has been previously confirmed that ASD children tend to pay more attention to geometric patterns than to people [11], suggesting that measuring responses to these stimuli may allow us to determine the degree of attention to social information. We evaluated infants' preferences by presenting two targets: a person as a social target and a geometric pattern as a nonsocial target. Two movie sets, Pref. 1 and Pref. 2, were used, and the placement of the geometric patterns and the person was swapped in each set to control for infants' spatial preferences. Each set contains four movie clips (Pref. 1-1 to 1-4 and Pref. 2-1 to 2-4) with different images (Fig. 2).

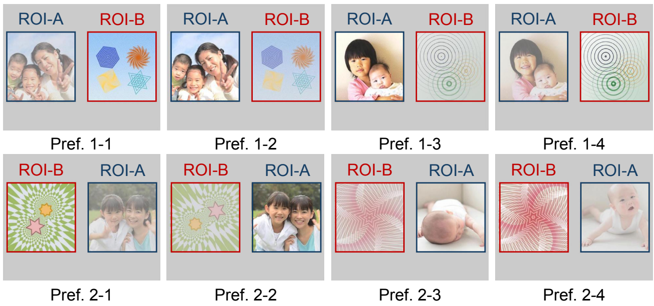


Fig. 2: Movie clips of preference tasks and definition of ROI.

- **Pref. 1**: After 5 seconds of an attention-grabbing movie clip, Pref. 1-1 with a highlighted geometric pattern was shown for 1 second, followed by Pref. 1-2 with a highlighted person for 4 seconds. Then, using a different image, Pref. 1-3, which highlighted a person, was shown for 1 second, followed by Pref. 1-4, which highlighted a geometric pattern, for 4 seconds.
- **Pref. 2**: After 2 seconds of an attention-grabbing movie clip, Pref. 2-1, which highlighted a geometric pattern, was shown for 1 second, and Pref. 2-2, which highlighted a person, was shown for 4 seconds. Then, using a different image, Pref. 2-3 with the person highlighted was shown for 1 second, and Pref. 2-4 with the geometric pattern highlighted was shown for 4 seconds.

Between Pref. 1 and Pref. 2, and after Pref. 2, other movie clips were shown for 48 and 32 seconds, respectively. To include infants who watched movie clips for more than a certain amount of time, only infants who watched at least 1 second of each of Pref. 1 and Pref. 2 were included in the analysis. Under these conditions, 46 infants at 4 months of age, 55 infants at 10 months of age, and 57 infants at 18 months of age were evaluated.

In addition, a region of interest (ROI) was defined for each movie clip. Fig. 2 shows the ROIs defined in the movie clips. In this paper, to analyze the preference of infants, we defined ROI-A as the social region containing the person, ROI-B as the nonsocial region containing geometric patterns, and ROI-C as the other regions containing interest.

3) ASD screening test: The Japanese version of the M-CHAT was used for ASD screening at 18 months of age [4]. Parents of infants were asked to answer "yes/no" to 23 questions on the Japanese version of the M-CHAT. The infants were evaluated as ASD-high risk (HR) if they failed three or more of the 23 items, or failed one or more of the 10 critical items. All other infants were evaluated as ASD-low risk (LR). Based on the M-CHAT screening results, at 4 months of age, 35 infants were classified as LR and 11 as HR. At 10 months of age, 46 were classified as LR and 9 as HR. At 18 months of age, 48 were classified as LR and 9 as HR.

B. Gaze analysis

Let (x_t, y_t) denote the coordinates of the gazing point in the xy-plane at time t. For the time-series data of the gazing point, we calculate evaluation indices in terms of 1) fixation, 2) gaze dispersion, and 3) transitions within and between ROIs. The fixation and gaze dispersion are indices related to visual exploration, while the transitions within and between ROIs are indices related to preference.

1) Indices of fixation: Fixation is a phenomenon in which the gaze is focused on a single point and remains there. In this paper, we use a dispersion-based fixation detection algorithm, dispersion-threshold identification (I-DT) [12], to detect fixation. In this algorithm, a fixation is detected when the dispersion of the gazing point coordinate data is small for more than 50 ms.

$$F_t = \begin{cases} 1, & \text{if } \tau(t) \geq 50 \text{ ms}, \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where F_t denotes the presence or absence of fixation at time $t \in \{1, 2, ..., T\}$ (T represents the total number of time steps in the observation). $\tau(t)$ denotes the maximum time width for which the dispersion is less than or equal to the r pixel threshold and is calculated as follows:

$$\tau(t) = \max \{\tau \geq 0 \mid D(t, \tau') \leq r \text{ for all } \tau' \in [0, \tau]\}. \tag{2}$$

The threshold value is set to $r = 25$ pixels. Here, $D(t, \tau)$ is the dispersion of the gazing point coordinates within a period τ ending at time t.

$$\begin{aligned} D(t, \tau) = & \max_{t-\tau \leq t' \leq t} x_{t'} - \min_{t-\tau \leq t' \leq t} x_{t'} \\ & + \max_{t-\tau \leq t' \leq t} y_{t'} - \min_{t-\tau \leq t' \leq t} y_{t'}. \end{aligned} \tag{3}$$

The following four indices were calculated based on the above fixation detection results.

- Number of fixations (I_1):

$$I_1 = \frac{1}{2} \sum_{t=2}^{T} |F_t - F_{t-1}|. \tag{4}$$

- Total time of fixation (I_2):

$$I_2 = \sum_{t=1}^{T} F_t \Delta t, \tag{5}$$

  where Δt is the sampling interval.
- Maximum time of fixation (I_3):

$$I_3 = \max\{\tau(t) \mid F_t = 1\}. \tag{6}$$

- Duration time per fixation ($I_4 = I_2/I_1$)

2) Indices of gaze spread: To evaluate the spread of the gazing point, we calculated the standard deviation σ_i ($i \in \{x, y\}$) in the x and y axes, and defined each as the following indices:

- Gaze spread in x axis direction ($I_{5x} = \sigma_x$)
- Gaze spread in y axis direction ($I_{5y} = \sigma_y$)

TABLE I: List of evaluation indices

Index		
Pref. 1	Pref. 2	Description
${}^1I_1$	${}^2I_1$	Number of fixations
${}^1I_2$	${}^2I_2$	Total time of fixation
${}^1I_3$	${}^2I_3$	Maximum time of fixation
${}^1I_4$	${}^2I_4$	Duration time per fixation
${}^1I_{5x}$	${}^2I_{5x}$	Gaze spread in x axis direction
${}^1I_{5y}$	${}^2I_{5y}$	Gaze spread in y axis direction
${}^1I_{6\mathrm{A}}$	${}^2I_{6A}$	Time to see ROI-A for the first time
${}^1I_{6\mathrm{B}}$	${}^2I_{6B}$	Time to see ROI-B for the first time
${}^1I_{6\mathrm{C}}$	${}^2I_{6\mathrm{C}}$	Time to see ROI-C for the first time
${}^1I_{7\mathrm{A}}$	${}^2I_{7\mathrm{A}}$	Total dwell time of ROI-A
${}^1I_{7\mathrm{B}}$	${}^2I_{7\mathrm{B}}$	Total dwell time of ROI-B
${}^1I_{7\mathrm{C}}$	${}^2I_{7\mathrm{C}}$	Total dwell time of ROI-C
${}^1I_{8\mathrm{AB}}$	${}^2I_{8\mathrm{AB}}$	Number of transitions from ROI-A to ROI-B
${}^1I_{8\mathrm{AC}}$	${}^2I_{8\mathrm{AC}}$	Number of transitions from ROI-A to ROI-C
${}^1I_{8\mathrm{BA}}$	${}^2I_{8\mathrm{BA}}$	Number of transitions from ROI-B to ROI-A
${}^1I_{8\mathrm{BC}}$	${}^2I_{8\mathrm{BC}}$	Number of transitions from ROI-B to ROI-C
${}^1I_{8\mathrm{CA}}$	${}^2I_{8\mathrm{CA}}$	Number of transitions from ROI-C to ROI-A
${}^1I_{8\mathrm{CB}}$	${}^2I_{8\mathrm{CB}}$	Number of transitions from ROI-C to ROI-B

3) Indices of transitions within and between ROIs: The following indices were calculated from the ROI defined in Fig. 2.

- Time to see ROI for the first time (I_6)
- Total dwell time in ROI (I_7)
- Number of transitions between ROIs (I_8)

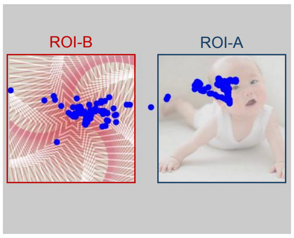
The time to see the ROI for the first time and the number of transitions between ROIs were calculated based on the presence or absence of gaze within the ROI, regardless of the duration of gaze. Indices I_6 and I_7 were calculated for each of the three ROIs, and I_8 was calculated for each of the six transition patterns between ROIs.

Using these, a total of 18 eye movement indices were calculated for Pref. 1 and Pref. 2, respectively (Table I). Note that the subscripts (1, 2) in the upper left corner of the indices indicate the distinction between Pref. 1 and Pref. 2.

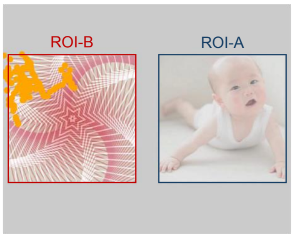
C. ASD risk group classification

To investigate the possibility of classifying ASD risk using calculated eye movement indices, logistic regression models were used to analyze data at 4, 10, and 18 months of age, respectively. All indices were standardized to have a mean of 0 and a standard deviation of 1 to account for their different scales and units. In this analysis, variable selection based on the Bayesian information criterion (BIC) was conducted to find the best combination of indices to describe the relationship between ASD risk and these indices. BIC is a selection criterion that evaluates model complexity and fit, and models with smaller BIC values show better fit with fewer parameters. In this paper, we used the forward-backward stepwise selection method to search for the combination of indices that minimized the BIC.

To evaluate the discriminative ability of the models selected based on BIC, an analysis based on leave-one-out cross-validation (LOOCV) was performed. Note that this



(a) LR (sub:1025).



(b) HR (sub:1008).

Fig. 3: Examples of gazing points (4 months of age, Pref. 2-4).

TABLE II: Results of statistical evaluation of resultant model.

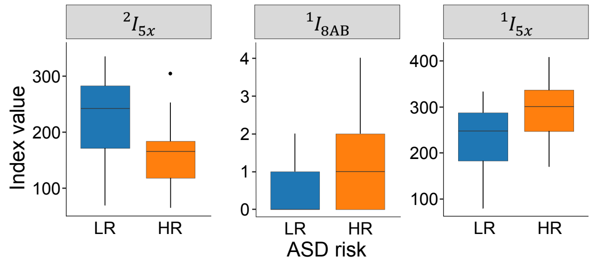
Age	Variable	β-estimate	Std. err.	Z-value	p-value
4 months	Intercept	-2.0914	0.6476	-3.230	0.0012
	${}^2I_{5x}$	-1.3423	0.5499	-2.441	0.0147
	${}^1I_{8\mathrm{AB}}$	1.2938	0.4739	2.730	0.0063
	${}^1I_{5x}$	1.3695	0.6827	2.006	0.0448
10 months	Intercept	-2.3976	0.6433	-3.727	0.0002
	${}^2I_1$	1.2289	0.5724	2.147	0.0318
	${}^1I_4$	-1.5726	0.8501	-1.850	0.0643
18 months	Intercept	-3.8483	1.0889	-3.534	0.0004
	${}^1I_4$	-3.2352	1.1037	-2.931	0.0034
	${}^2I_2$	3.1272	1.2005	2.605	0.0092
	${}^2I_{8\mathrm{CB}}$	1.1166	0.6068	1.840	0.0658

cross-validation process was applied after variable selection had been made across the entire data set; therefore, it was not intended to evaluate the generalization performance of the model, but rather to evaluate the consistency of the results of a specific model with respect to variations in the data. Receiver operating characteristic (ROC) analysis was performed on the risk probability of ASD for each infant obtained from the LOOCV, and the area under the curve (AUC) was calculated. The AUC values range from 0 to 1, with 0.5–0.7, 0.7–0.9, and 0.9–1.0 indicating low, medium, and high discrimination accuracy, respectively [13]. The cutoff value θ_{th} was set as the threshold value at which the Youden index was maximized for the ROC analysis results, and the sensitivity, specificity, and F-measure were calculated.

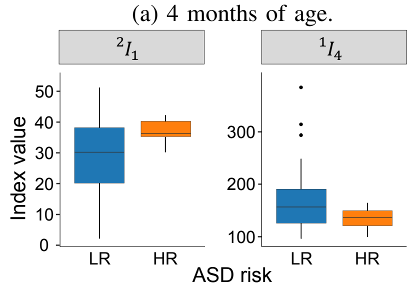
III. Results

Fig. 3 shows an example of the gaze points in the movie clip for one HR infant and one LR infant in Pref. 2-4 at 4 months of age. From Fig. 3, it can be seen that the LR infant explores extensively across ROI-A and ROI-B, whereas the HR infant keeps their gaze on the nonsocial region of ROI-B.

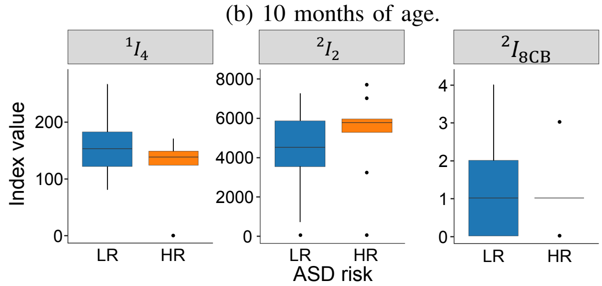
The models with the lowest BIC at 4, 10, and 18 months of age are shown in Table II. The BIC of the obtained models was 45.6637 at 4 months of age, 51.3889 at 10 months of age, and 46.2033 at 18 months of age. As can be seen from Table II, three indices were selected for infants at 4 months of age: the spread of gaze in the x-axis direction in Pref. 1 and Pref. 2, respectively, and the number of transitions from ROI-A to ROI-B in Pref. 1. At 10 months of age, two indices were selected: the number of fixations in Pref. 2 and the duration time per fixation in Pref. 1. At 18 months of age, three indices were selected: the duration time per fixation in Pref. 1, the total time of fixation in Pref. 2, and the number of transitions from ROI-C to ROI-B. Fig. 4 shows a boxplot of the selected indices for each age group. The blue and orange boxplots represent the LR and HR groups, respectively.



(a) 4 months of age.



(b) 10 months of age.



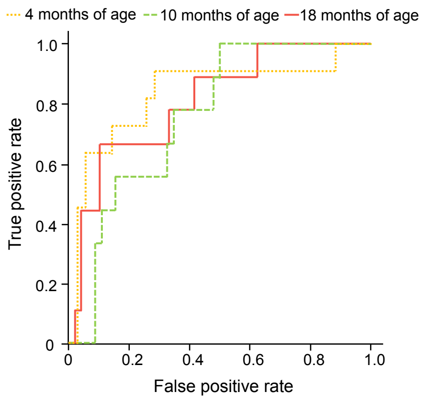
(c) 18 months of age.

Fig. 4: Boxplots of selected evaluation indices.

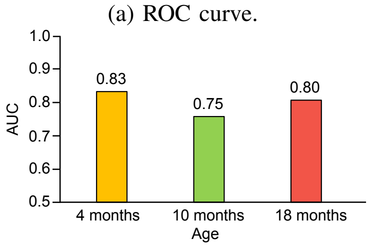
Fig. 5 shows the results of the ROC analysis based on the LOOCV. The AUC values were 0.83 at 4 months of age, 0.75 at 10 months of age, and 0.80 at 18 months of age. Fig. 6(a) shows the sensitivity, specificity, and F-measure obtained using the cutoff value at which the Youden index was maximized for each iteration of LOOCV, and Fig. 6(b) shows the confusion matrix. At 4 months of age, the sensitivity and specificity were greater than 70%. At 10 months of age, the sensitivity was greater than 85%, while specificity was relatively low. At 18 months of age, sensitivity and specificity were both around 65%. Table III shows the mean and standard deviation of the cutoff value θ_{th} calculated by ROC analysis.

IV. Discussion

Model selection based on logistic regression and BIC resulted in the selection of three indices for the 4 months model. Table II shows that in Pref. 1, infants with a higher

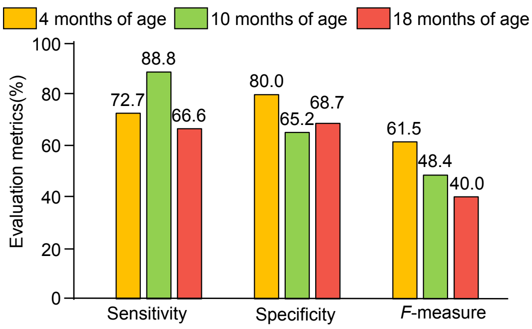


(a) ROC curve.

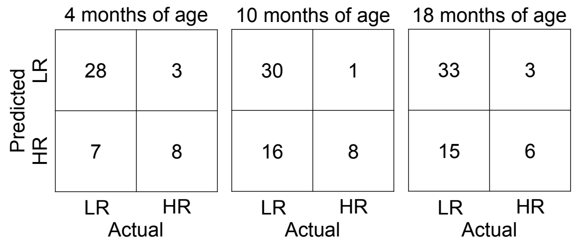


(b) AUC value.

Fig. 5: Results of ROC analysis.



(a) Evaluation metrics.



(b) Confusion matrix.

Fig. 6: Results of performance indicators.

TABLE III: Optimal cutoff values obtained by ROC analysis.

	Cut-off value	
Age	Mean	SD
4 months	0.2288	0.0193
10 months	0.1290	0.0061
18 months	0.2522	0.1106

number of transitions from ROI-A to ROI-B ($^1I_{8\mathrm{AB}}$) and larger gaze spread in the x-axis direction ($^1I_{5x}$) are at higher risk of ASD. In Pref. 1, the person (ROI-A) is placed on the left side and the geometric pattern (ROI-B) on the right side. Since it is known that targets in the left visual field are detected earlier than those in the right visual field [14], we can assume that the infant saw the person in ROI-A at the beginning of the Pref. 1. At this time, HR infants are considered to have looked at ROI-A, which is a social region, and then searched in the movie clip and looked at ROI-B, which is a nonsocial region. In contrast, in Pref. 2, infants with a smaller gaze spread in the x-axis direction ($^2I_{5x}$) are at higher risk of ASD. In Pref. 2, contrary to Pref. 1, the geometric pattern (ROI-B) is placed on the left and the person (ROI-A) on the right, suggesting that the infant saw the geometric pattern of ROI-B at the beginning of Pref. 2. At this time, the HR infant stayed in ROI-B after looking at the nonsocial region of ROI-B and did not search in the movie clip. These results suggest that HR infants at 4 months of age tend to show avoidance behavior toward the social region and a preference for the nonsocial region. It is reported that HR infants avoid the gaze of persons [15] and prefer nonsocial images to social images [16], and signs of this behavior may already be present in 4 months of age infants.

Two indices were selected for the model at 10 months of age. Table II shows that infants with q higher number of fixations in Pref. 2 ($^2I_1$) and shorter duration time per fixation in Pref. 1 ($^1I_4$) are at higher risk for ASD. Thus, HR infants are likely to search multiple times with shorter fixations than LR infants. ASD infants are reported to fixate longer and more frequently on search images because they are fixated and detail-oriented [17], and these signs may already be apparent at the age of 10 months.

Three indices were selected for the model at 18 months of age. Table II shows that infants with shorter duration time per fixation in Pref. 1 ($^1I_4$) are at higher risk for ASD. Therefore, it can be assumed that HR infants perform multiple searches in a shorter fixation time than LR infants. Furthermore, in Pref. 2, infants with a longer total time of fixation ($^2I_2$) and a higher number of transitions from ROI-C to ROI-B ($^2I_{8\mathrm{CB}}$) are at higher risk of ASD. Thus, it is considered that HR infants may spend more time looking at ROI-B, a nonsocial region, than LR infants. These trends are consistent with those observed at 4 months of age and 10 months of age and are considered to capture the characteristics of ASD.

In addition, we evaluated the consistency of the results with the selected indices by using the LOOCV. The results of the ROC analysis showed that the gazing point evaluation indices could discriminate ASD risk with medium accuracy since AUC values of 0.75 or higher were obtained at 4 months of age, 10 months of age, and 18 months of age. Furthermore, the F-measure calculated using the cutoff value of θ_{th}, the threshold at which the Youden index is maximized, indicates that the lower the age, the better the overall discrimination performance. However, this difference in discrimination accuracy results for each age group may be due to the small overall sample size and the imbalance between the LR and HR groups. Table III also shows that the mean of the cutoff value θ_{th} is close to zero, indicating that the sample size bias may have a large impact. Further study is needed to increase the number of participants.

V. Conclusions

In this paper, we evaluated the relationship between eye movement patterns and ASD risk by analyzing eye movement data at 4, 10, and 18 months of age. The analysis results suggested that at 4 months of age, preference-related indices were associated with ASD risk. At 10 months, indices related to visual exploration of images were associated with ASD risk. At 18 months, both preference-related indices and visual exploration indices were found to be associated with ASD risk. Furthermore, ROC analysis based on LOOCV using the selected indices showed the possibility of identifying ASD risk with medium accuracy. These results indicate that early signs of ASD are expressed in eye movement features and that the risk of ASD at 18 months of age can be assessed by extracting these features.

However, due to the large penalty term in the BIC-based indices selection, there is a possibility that effective indices were excluded. In the future, we aim to optimize the variable selection method and further improve the identification accuracy.

References

[1] American Psychiatric Association, *Diagnostic and Statistical Manual of Mental Disorders*, 5th ed. American Psychiatric Publishing, 2013.

[2] G. Dawson, "Early behavioral intervention, brain plasticity, and the prevention of autism spectrum disorder," *Development and Psychopathology*, vol. 20, no. 3, p. 775–803, 2008.

[3] F. Thabtah and D. Peebles, "Early autism screening: a comprehensive review," *International Journal of Environmental Research and Public Health*, vol. 16, no. 18, p. 3502, 2019.

[4] D. Robins, D. Fein, M. Barton, and J. Green, "The modified checklist for autism in toddlers: An initial study investigating the early detection of autism and pervasive developmental disorders," *Journal of Autism and Developmental Disorders*, vol. 31, pp. 131–144, 2001.

[5] L. Zwaigenbaum, S. Bryson, and N. Garon, "Early identification of autism spectrum disorders," *Behavioural Brain Research*, vol. 251, pp. 133–146, 2013.

[6] A. Caruso, L. Gila, F. Fulceri, T. Salvitti, M. Micai, W. Baccinelli, M. Bulgheroni, and M. L. Scattoni, "Early motor development predicts clinical outcomes of siblings at high-risk for autism: Insight from an innovative motion-tracking technology," *Brain Sciences*, vol. 10, no. 6, 2020.

[7] H. Doi, A. Furui, R. Ueda, K. Shimatani, M. Yamamoto, K. Sakurai, C. Mori, and T. Tsuji, "Spatiotemporal patterns of spontaneous movement in neonates are significantly linked to risk of autism spectrum disorders at 18 months old," *Scientific Reports*, vol. 13, 2023.

[8] W. Jones, C. Klaiman, S. Richardson, M. Lambha, M. Reid, T. Hamner, C. Beacham, P. Lewis, J. Paredes, L. Edwards, N. Marrus, J. Constantino, S. Shultz, and A. Klin, "Development and replication of objective measurements of social visual engagement to aid in early diagnosis and assessment of autism," *JAMA Network Open*, vol. 6, p. e2330145, 2023.

[9] K. Chawarska, S. Macari, and F. Shic, "Decreased spontaneous attention to social scenes in 6-month-old infants later diagnosed with autism spectrum disorders," *Biological Psychiatry*, vol. 74, no. 3, pp. 195–203, 2013.

[10] T. Fujioka, K. Inohara, Y. Okamoto, Y. Masuya, M. Ishitobi, D. N. Saito, M. Jung, S. Arai, Y. Matsumura, T. X. Fujisawa *et al.*, "Gazefinder as a clinical supplementary tool for discriminating between autism spectrum disorder and typical development in male adolescents and adults," *Molecular Autism*, vol. 7, pp. 1–14, 2016.

[11] K. Pierce, D. Conant, R. Hazin, R. Stoner, and J. Desmond, "Preference for geometric patterns early in life as a risk factor for autism," *Archives of General Psychiatry*, vol. 68, no. 1, pp. 101–109, 01 2011.

[12] N. Al Madi, D. Guarnera, B. Sharif, and J. Maletic, "Emip toolkit: A python library for customized post-processing of the eye movements in programming dataset," in *ACM Symposium on Eye Tracking Research and Applications*. Association for Computing Machinery, 2021.

[13] J. A. Swets, "Measuring the accuracy of diagnostic systems," *Science*, vol. 240, no. 4857, pp. 1285–1293, 1988.

[14] J. A. Wainwright and S. E. Bryson, "Visual-spatial orienting in autism," *Journal of Autism and Developmental Disorders*, vol. 26, no. 4, pp. 423–438, 1996.

[15] D. Kliemann, I. Dziobek, A. Hatri, R. Steimke, and H. R. Heekeren, "Atypical reflexive gaze patterns on emotional faces in autism spectrum disorders," *Journal of Neuroscience*, vol. 30, no. 37, pp. 12 281–12 287, 2010.

[16] K. Pierce, S. Marinero, R. Hazin, B. McKenna, C. C. Barnes, and A. Malige, "Eye tracking reveals abnormal visual preference for geometric images as an early biomarker of an autism spectrum disorder subtype associated with increased symptom severity," *Biological Psychiatry*, vol. 79, no. 8, pp. 657–666, 2016.

[17] N. J. Sasson, L. M. Turner-Brown, T. N. Holtzclaw, K. S. Lam, and J. W. Bodfish, "Children with autism demonstrate circumscribed attention during passive viewing of complex social and nonsocial picture arrays," *Autism Research*, vol. 1, no. 1, pp. 31–42, 2008.