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学位論文

Developmental changes in visual-cognitive and attentional functions in infancy

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Developmental changes in visual–cognitive and attentional functions in infancy

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ABSTRACT

Background: Identifying developmental changes in visual-cognitive and attentional functions during infancy may lead to early diagnosis of neurodevelopmental disorders such as ASD and ADHD.
Aims: To clarify the developmental changes in visual–cognitive and attentional functions during infancy (3–36 months of age).
Study design: Cross-sectional study.
Subjects: We included 23, 24, 31, and 26 participants aged 3, 9, 18, and 36 months, respectively (full-term births). Fifteen children who cried intensely or whose data could not be accurately recorded were excluded.
Outcome measures: Three activities were given to each child while they were seated in front of a gaze-tracking device to evaluate re-gaze, motion transparency, and color–motion integration. We analyzed whether the child's attention shifted to the new stimulus in their peripheral vision in the re-gaze task. In the motion transparency and color–motion integration tasks, two images were presented simultaneously on the screen. In the motion transparency task, participants preferred random dots moving in opposite directions; in the color–motion task, they preferred subjective contours from apparent motion stimuli consisting of random red and green dots with different luminance.
Results: In the re-gaze task, fewer 3-month-olds gazed at the new target than other age groups participants. All ages showed preference for target stimuli in the motion transparency task, but 3-month-olds showed significantly lower preference in the color–motion integration task.
Conclusion: These tasks may be useful for measuring visual–cognitive and attentional functions in infants.

1. Introduction

The development of attentional function is important for a child's growing ability to cope with the social, physical, and educational demands of everyday life. Deficits in the ability to direct and maintain attention are found in children with early brain injury, after very premature birth, and in children with genetic developmental disorders [1]. Barkley et al. suggested that impaired executive function underlies the core symptoms of ADHD [2]. The executive function selects necessary information from a variety of inputs and takes appropriate action to achieve a goal. The attentional function plays a major role in this process [3,4].

Researchers have suggested that impaired face perception underlies the characteristic behaviors of neurodevelopmental disorders in children with ASD. Impaired face perception can be detected even before the other characteristic behaviors of ASD, such as impaired verbal communication and addictive behaviors, become evident [5–9]. Pellicano et al. used the Children's Embedded Figures Test to demonstrate that children with ASD could find triangles hidden in a pillar clock diagram faster than typically developing children [10]. This finding suggests that ASD children are better at morphological vision than typically developing children [10].

In order to clarify the developmental changes in these functions during infancy, we examined the results of three tasks performed on

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Abbreviations: ADHD, attention deficit hyperactivity disorder; ASD, autism spectrum disorder; CFM, color from motion; RDP, random dot patterns; SCAM, subjective contours from apparent motion.

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typically developing children from 3 months to 3 years of age: “re-gaze,” “motor transparency,” and “color–motion integration” tasks.

The re-gaze task examines whether a child can shift fixation from a target in the center of the screen to a newly presented target in the periphery. Fixation shift is thought to involve attentional control, one of the functions of attention [11], and it has been reported that typically developing infants as young as 3 months of age can shift fixation from a central target to a peripheral target [12]. Braddick et al. reported that infants who underwent hemispherectomy for the treatment of intractable epilepsy were unable to perform fixational shifts under “competing” conditions in which a new target was presented peripherally in situations where the target remained visible in the center of the visual field [13].

The motor transparency task is a task using videos of randomly positioned dots moving left and right, and it has been reported that 5-month-old infants show preference in this task [14,15] and that ASD children have higher motor coherence thresholds in the motor transparency task than typically developing children [16].

The color–motion integration task is a task using stimuli in which a green area surrounded by a subjective contour appears to move over a red dot, and 5-month-olds have been reported to recognize the subjective contour [17].

Two major subcortical pathways, the paracellular pathway (parvo pathway) and the macrocellular pathway (magno pathway), are thought to be involved in this task [18], and it has been hypothesized that the motor vision deficits in ASD children may be due to the impairment of the macrocellular pathway [19].

In this study, three tasks—namely, the “re-gaze,” “motor transparency,” and “color–motion integration” tasks—were examined in infants aged 3, 9, 18, and 36 months. We aimed to clarify the developmental changes in visual cognition and attention during infancy by measuring and analyzing eye movements using an eye-tracking device.

2. Methods

2.1. Participants

The participants were infants aged 3–36 months who received regular health examinations in Kagawa Prefecture, Japan, between December 2013 and November 2018. They were examined by a pediatrician, and confirmed to have no developmental abnormalities. Children with significant developmental delays and those with underlying diseases such as chromosomal abnormalities were excluded. This study was approved by the Ethics Committee of the Kagawa University School of Medicine (approval number: Heisei 30-025). Written informed consent was obtained from the parents before any measurements were performed.

2.2. Equipment and procedures

Eye movements were recorded using a Tobii 1750 eye tracker (Tobii Inc., Stockholm, Sweden), which records eye position every 20 ms (50 Hz). The accuracy of this eye tracker is 0.5°. Stimulus images were projected on a 17″ TFT monitor integrated with the eye tracker. Signals from the eye tracker were converted to eye positions using ClearView software (ClearView version 2.5.1; Tobii Technology).

Each participant was seated in front of the monitor at a distance of approximately 60 cm. The child was held in the lap of a parent or guardian and shown images presented on a screen. The presented visual stimulus was 10-cm-wide and 15-cm-high and had a viewing angle of 95°. Children who did not look directly at the screen during the task were excluded from the study. A five-point calibration was performed before presenting the assignment and repeated until all five calibration points were measured. Once the infant's eyes were detected by the infrared camera (shown as two moving dots on the interface dialogue box), the five-location (center, top left, top right, bottom left, and bottom right) calibration procedure began. Once the five-point calibration was completed with sufficient quality (within the default range of spatial precision), the eye tracker system was able to determine the precise direction of the infant's gaze during the examination.

After the calibration phase, the tasks were presented in the following order: 1) re-gaze, 2) motion transparency, and 3) color–motion integration. Each infant's gaze duration for each stimulus was measured. In all tasks, the focal point for gazing was first presented with a sound, and stimuli were presented only after the infant was confirmed to have gazed at the center of the screen. Parents were instructed not to look at the screen during the test.

2.3. Stimuli

I. The re-gaze task: a picture of a strawberry was initially presented in the center of the screen. After 2 s, a picture with the same shape was presented at 23° to the right or left of the center for 2 s (Fig. 1). Next, the position of the target (left or right) was switched and the picture was presented twice.

II. The motion transparency task: motion transparency is a phenomenon in which participants presented with a stimulus consisting of superimposed random dot patterns (RDP) moving in different directions on the same plane perceive transparent dot patterns moving in different depth planes. Two sheets represented transparent motion, consisting of 90 small square dots moving horizontally opposite to each other on a white background. These were presented on a monitor simultaneously with two sheets representing coherent motion, consisting of 90 small square dots moving in the same direction. Each stimulus was presented twice for 16 s, and the left and right sides were switched between rounds (Fig. 2a). The transparent motion was used as the target, and the coherent motion was used as the non-target. Gaze time to the stimulus and preference for the target were measured.

III. The color–motion integration task: in this task, subjective

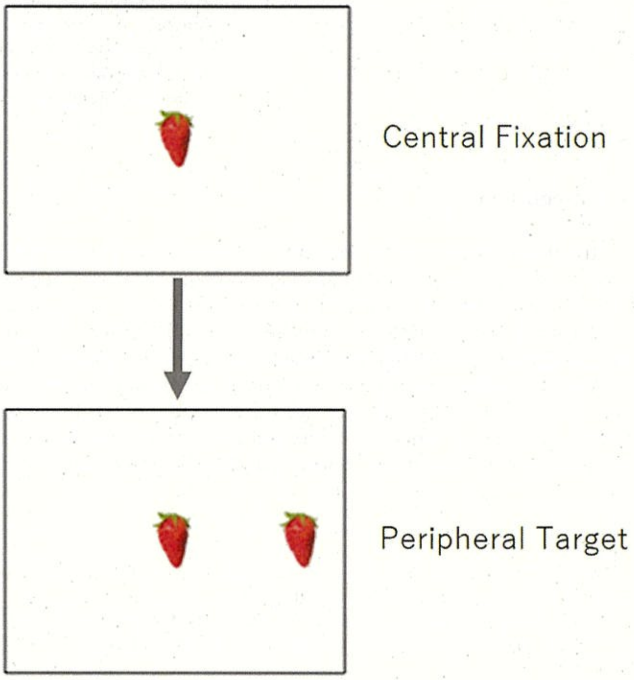

Fig. 1. Re-gaze task.
Fixation shifts under competition. In this stimulus, a picture of a strawberry is presented in the center of the screen, followed by another strawberry on either side (left or right).

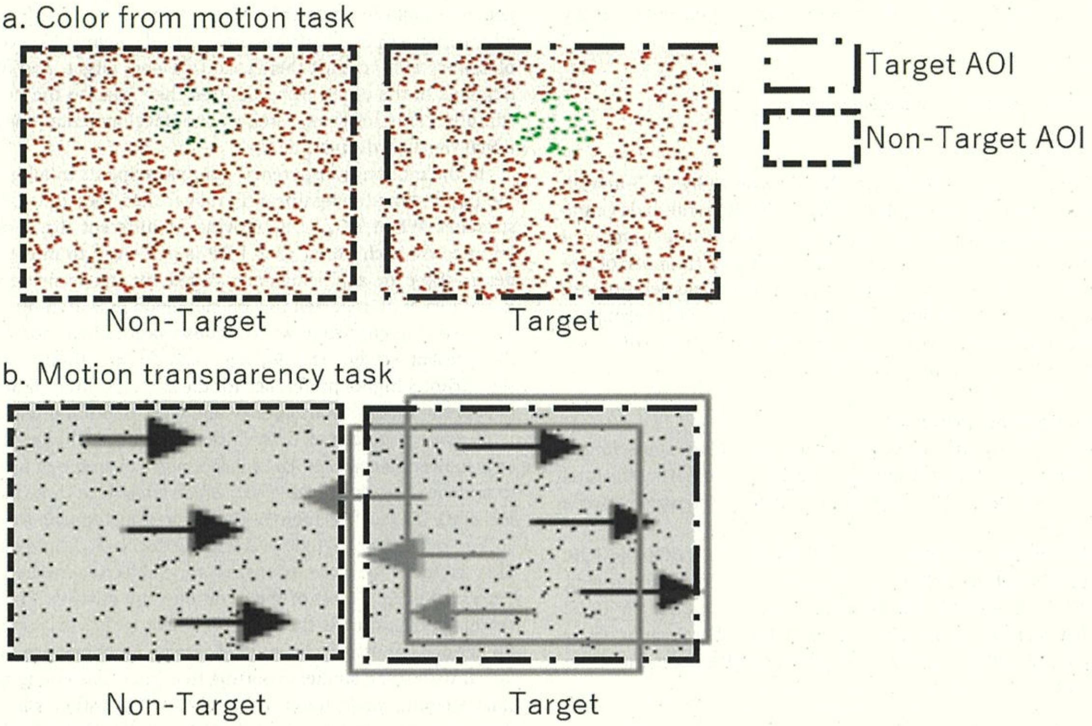

Fig. 2. (a) Motion transparency task. In this task, two transparent sheets with dots move horizontally in opposite directions to each other on the right (transparent motion), and two sheets move in the same direction on the left (coherent motion). (b) Color–motion integration task. In this task, the subjective contours from apparent motion (SCAM) stimulus consists of a circle composed of green dots (higher luminance) and red dots (lower luminance) on the right. The non-SCAM stimulus (green and red dots with the same luminance) is on the left.

contours from apparent motion (SCAM) stimuli consisting of random red and green dots of different luminance were presented simultaneously with non-SCAM stimuli of identical luminance. Two types of stimuli were used: SCAM stimuli with red dots of different luminance in the area surrounding the green circular region and non-SCAM stimuli with dots of the same luminance around the circular region. Each stimulus consisted of a circular area moving up and down in a square composed of 900 randomly placed dots (Fig. 2b). Stimuli were presented twice for 10 s, with the left and right sides being switched between rounds.

2.4. Items for evaluation

I. The re-gaze task (fixation shifts under competition): the participants were shown the stimuli twice, and we recorded whether they noticed the newly appearing target each time. The evaluator played a video recorded in the eye tracker and assessed whether the child fixated on the strawberry presented in the center and then shifted his/her gaze to the newly appeared strawberry picture. Fixation was defined as follows; minimum fixation duration is 100 ms, fixation radius is 35°.

We defined a child as having passed the task if he or she showed a fixation shift to the new strawberry on at least one of the two trials, and the number of children who passed the task was examined. The number of participants who passed the task and the number of eye movements between the two stimuli (while the new stimulus was being presented) were examined.

II. Motion transparency task: as with the color and motion transparency task, we measured the time spent gazing at the target and non-target stimuli. Based on this, we examined the participants' preference for the target stimuli, differences in total gazing time, and preference rates by age. All data were analyzed using Eye Track Report (F System., Takamatsu, Kagawa, Japan) software. Eye tracking videos were analyzed frame by frame by a research assistant who did not know the group status of the participants. Gazing times for two areas of interest (AOI), target AOI and non-target AOI, were investigated (see Fig. 2a). The sum of both was used as the total gazing time, and comparisons were made for each month of age. The percentage of time spent gazing at the target stimulus out of the total gazing time was calculated as the preference ratio, and differences by age were examined.

III. Color from motion task: the time spent gazing at the target and non-target stimuli were measured to determine whether the participants preferred the target stimuli. We set the AOI as well as the motion transparency task and investigated gazing times and preferences for target and non-target AOIs.

2.5. Statistical analysis

A χ^2 test was performed to evaluate differences in the number of participants who saw the target in the re-gazing task. Paired *t*-tests were used to compare the time spent gazing at the target and non-target stimuli in the color–motion integration and motion transparency tasks. Other variables were compared using the Wilcoxon test. Variables that showed significant differences in the Wilcoxon test results were further compared with the Steel–Dwass test for multi-group comparisons. Statistical analyses were conducted in JMP14 (SAS Institute Inc., Cary, NC, USA). All hypotheses were tested with a significance level of 0.05.

3. Results

3.1. Participants

Fifteen children (3 at 3 months, 6 at 9 months, 4 at 18 months, and 2 at 36 months) were excluded due to intense crying or inability to accurately record data. In total, 23, 34, 31, and 26 3-month-olds (9 boys and 14 girls, mean age 106.9 ± 11.2 d), 9-month-olds (14 boys and 20 girls, mean age 303.2 ± 18.8 d), 18-month-olds (19 boys and 12 girls, mean age 559.1 ± 15.9 d) and 36-month-olds (15 boys and 11 girls, mean age 1291.4 ± 28.2 d), respectively, participated in the study (Table 1).

3.2. Measurement results and analysis findings

3.2.1. The re-gazing task

The first task was successfully completed (passed) by 18 3-month-olds (number of eye movements, 1.43 ± 0.92); all 9-month-olds (number of eye movements, 2.32 ± 0.83); 28 18-month-olds (mean number of eye movements, 2.16 ± 1.02); and all 36-month-olds (number of eye movements, 2.58 ± 0.74). The proportion of participants who passed was significantly lower in the 3-month-old group than in other groups ($p = 0.045$). The 3-month-olds also made significantly fewer eye movements than any other group ($p = 0.0002$).

3.2.2. The motion transparency task

In all groups, gazing time to target stimuli was significantly longer than gazing time to non-target stimuli ($p = 0.0044$). Comparing the total gazing time at each age, there were no significant differences between any of the groups.

The median preference rates for target stimuli were 69.0 % (IQR: 51.0–87.6) for 3-month-olds, 88.0 % (IQR: 82.6–95.7) for 9-month-olds, 88.6 % (IQR: 77.5–94.8.0) for 18-month-olds, and 82.4 % (IQR: 65.8–89.6) between the 3-month-olds and the other groups ($p = 0.0044$), but no significant differences were found among the other groups (Fig. 3a).

3.2.3. The color and motion integration task

The median attention time to target stimuli was 3143.0 ms (IQR: 1489.0–4456.5), and the median attention time to non-target stimuli was 2085.0 ms (IQR: 865.5–3363.0) for 3-month-olds, showing no significant differences between stimuli (Table 1). In the other groups, gazing time to target stimuli was significantly longer than the gazing time to non-target stimuli ($p = 0.1312$).

The median preference rates for target stimuli were 51.5 % (IQR: 38.3–72.0) for 3-month-olds, 80.6 % (IQR: 72.6–90.5) for 9-month-olds, 82.0 % (IQR: 71.9–86.8) for 18-month-olds, and 73.9 % (IQR: 62.8–83.0) for 36-month-olds. Significant differences were found between the 3-month-olds and the other groups ($p < 0.0001$) but not between the other groups (Fig. 3b).

4. Discussion

The results of the present study allowed us to identify developmental changes in visual–cognitive and attentional functions during infancy (3–36 months of age).

Normally developing infants have been reported to shift their gaze to newly emergent targets at 3–4 months of age [20]. Neonates have very immature attentional functions, are reflexively attracted to salient features of the environment (areas of high contrast, the boundaries of stimuli, or movement), and exhibit inefficient visual scanning and information processing. At 3 months of age, infants can voluntarily control fixation. Accordingly, the time required to process information decreases, and more complex information processing becomes possible after 6 months [19,21]. In the present study, nearly 80 % of the 3-month-olds were able to shift their gaze to a new target, and almost all participants in the other groups shifted their gaze to the newly displayed stimulus. This result may reflect the developmental changes in attentional function during infancy.

Table 1
Characteristics of participants.

	3 months ($n = 23$)	9–10 months ($n = 34$)	18 months ($n = 31$)	36 months ($n = 26$)
Male, n (%)	9 (39.1)	14 (41.2)	19 (61.3)	15 (57.7)
Gestational age (weeks)	38.7 ± 1.1	39.7 ± 1.0	39.8 ± 1.2	39.5 ± 1.6
Birth weight (g)	3013.3 ± 333.1	3184.2 ± 389.5	3231.6 ± 315.5	2991.0 ± 590.3
Age (days)	106.9 ± 11.2	303.2 ± 18.8	559.1 ± 15.9	1291.4 ± 28.2

In the motion transparency task, participants in all groups gazed at the target stimulus significantly longer than they did at the non-target stimulus. When two RDPs moving in different directions are superimposed on each other, each RDP is perceived to move on a different depth plane in a phenomenon called motion transparency [22–25]. Kanazawa et al. reported this phenomenon in 3- to 5-month-old infants [14], which is consistent with our observations in 3-month-old infants in the present study. The 9-, 18-, and 36-month-old infants showed significantly higher preference for the target stimulus than the 3-month-olds in the motion transparency and color–motion integration tasks.

A contour perceived in the absence of physical boundaries is known as a subjective contour. The most popular example of a subjective contour is the Kanizsa triangle [26], which consists of three black disks with incisions (called "pacmen"). These incisions appear to constitute the corners of a larger triangle overlapping the black disks on a higher plane. This happens because triangles are subjective figures that can be perceived even if most of their contours are missing. The perception of subjective contours is thought to involve early visual cortices, such as the secondary visual cortex [27]. These functions are acquired in infancy, with some studies reporting that infants as young as four months can recognize subjective contours [28]. Other studies have shown that these functions are acquired at 7–8 months of age [29]. In addition, motion stimuli have been reported to enhance the recognition of subjective contours. For example, Otsuka et al. reported that infants could recognize subjective contours in static images at seven months and in dynamic stimuli at 3–4 months [30]. Cicerone et al. introduced the color from motion (CFM) effect, in which the perception of apparent motion is accompanied by the perception of subjective color spreading across the achromatic region of the stimulus [18]. In CFM stimuli, adults can perceive subjective color spread and subjective contours from the apparent motion produced by changes in dot luminance. Yamaguchi et al. used SCAM stimulation (a type of CFM stimulation) to show that 5-month-olds could recognize subjective contours. In the present study, we found that 3-month-olds showed no preference for target stimuli, whereas 9-month-olds did. This is consistent with the findings of Yamaguchi et al. [17]. Furthermore, the preference persisted in older infants, and the 36-month-olds gazed longer at the target stimuli. This may be because executive functions develop during this time (especially during 2–6 years of age) [31,32].

Infants aged 3, 9, 18, and 36 months were included in this study. These are all crucial periods in the development of infants. In Japan, infants in these age groups are included in group health examinations conducted by local governments. In the past, the development of the visual–cognitive function was assessed by observing infant behavior and through responses to questionnaires. For example, the infant health checkups include questions regarding whether the child smiles often when stimulated at 3–4 months of age; is shy at 9–10 months; points to animals or body parts in picture books at 18 months; can draw circles at 36 months, and so on. The checklist is not just limited to visual functions but also includes questions related to memory, language, and motor functions of the limbs.

The present study revealed developmental changes in visual–cognitive and attentional functions during infancy. The number of participants who gazed at a new target in the re-gaze task and the number of eye movements were significantly lower in the 3-month-old group than in the other age groups. In the motor transparency task, 3-month-olds showed preference at significantly lower rates than participants in the other age groups, although there was no difference in the duration of gazing. In the color–motion integration task, preference rates were lower in the 3-month-old group and significantly higher in

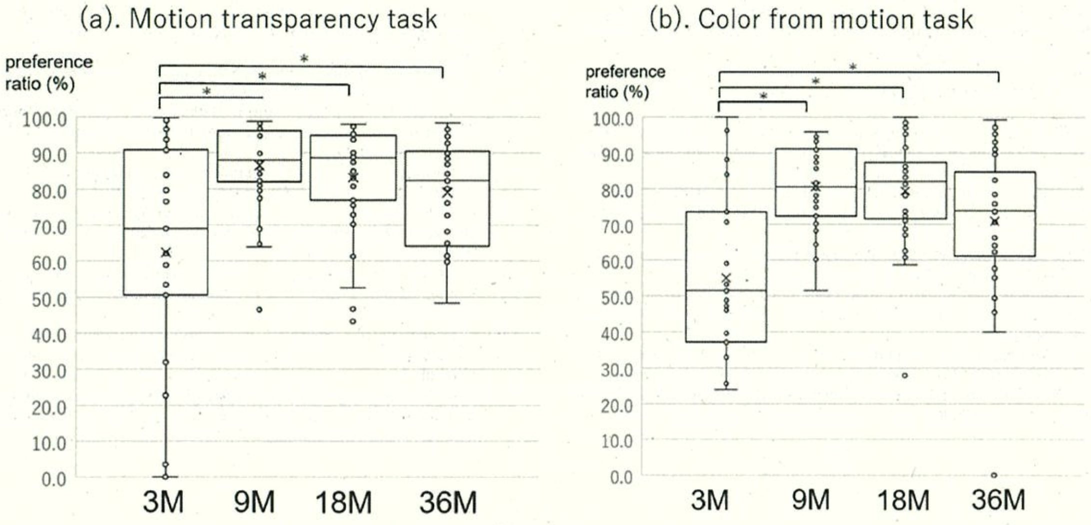

Fig. 3. Preference rates in the motion transparency and color–motion integration tasks.
(a) Preference rates for each age group in the motion transparency task.
(b) Preference rates for each age group in the color–motion integration task.

the 9-month-old group. Gazing time was also significantly longer at 36 months. Our results suggest that the tasks used in this study may be useful indicators of visual–cognitive and attentional functions in infants and young children.

In future studies, we will examine developmental changes in children with suspected ASD and pre-term infants at high risk for ASD and ADHD. These data can be collected by conducting tests during routine health examinations.

The present study has several limitations. The first is eye tracking accuracy. In this study, the results for 3-month-olds differed from the other groups, potentially due to low eye tracking accuracy caused by the narrowness of the eyelids of 3-month-olds. Since eye tracking accuracy was not assessed in this study, we cannot be certain of its impact, but future studies should consider the effect of age on eye tracking accuracy. Second, the sample size was small, and the results of this study may not reflect the visual–cognitive functioning of infants in general. Thus, studies with larger sample size are needed. Third, this was a cross-sectional study, and we did not perform a longitudinal assessment of the development of these functions in participants. As mentioned above, the results of these tasks are associated with neurodevelopmental disorders. To clarify the relevance of the results of this study to later developmental prognosis, it is necessary to evaluate longitudinally the developmental changes in visual–cognitive function at infancy obtained in this study and to examine how these changes are related to future developmental prognosis.

5. Conclusions

We investigated three visual–cognitive tasks in infancy and found that each task showed different developmental changes. In order to understand the pathogenesis of neurodevelopmental disorders, such as ASD and ADHD, and to construct measures for early diagnosis by objectively evaluating visual-cognitive function in infancy, we highlight the need for longitudinal studies with a larger sample size in the future.

CRediT authorship contribution statement

Kaori Koyano: Data curation, Formal analysis, Writing – original draft. **Yukihiko Konishi:** Data curation, Conceptualization, Methodology, Software, Writing – original draft, Project administration. **Kosuke Koyano:** Data curation, Investigation. **Shinji Nakamura:** Data curation, Investigation. **Ikuko Kato:** Visualization, Investigation. **Tomoko Nishida:** Supervision, Visualization. **Takashi Kusaka:** Funding acquisition, Writing – review & editing.

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