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Assessing the Validity of Using Eye Tracking to Study Infants' Cognitive Function in Rural Malawi

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April 2017

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This publication was made possible by the generous support of the American people through the support of the Office of Health, Infectious Diseases, and Nutrition, Bureau for Global Health, U.S. Agency for International Development (USAID) under terms of Cooperative Agreement No. AID-OAA-A-12-00005, through the Food and Nutrition Technical Assistance III Project (FANTA), managed by FHI 360.

April 2017

Recommended Citation

Pyykkö, Juha et al. 2017. *Assessing the Validity of Using Eye Tracking to Study Infants' Cognitive Function in Rural Malawi.* Washington, DC: Food and Nutrition Technical Assistance Project/FHI 360.

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Contents

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background. The current study examined whether known risk factors for early child development in low-resource settings, including preterm birth, child nutritional status, and aspects of early rearing environment, are linked with measurable variations in eye tracking measures of visual and cognitive function at 7 and 9 months of age.

Methods. Infants with ultrasound confirmed gestational age (GA) were enrolled in the study before the age of 4 weeks in Mangochi District, Malawi (targeted N = 425). A stratified sampling approach was used to recruit a predetermined ratio (1:2:2, later changed to 1:5:5) of infants born between 32.0 and 36.9 completed gestation weeks (preterm), between 37.0 and 38.9 gestation weeks (early term), and between 39.0 and 41.9 gestation weeks (full term). Data on child anthropometric measures (weight, length, mid-upper arm circumference, and head circumference) were collected at enrollment. Data on early rearing environment (maternal cognition and education, socioeconomic status, mood, and stress) were collected in home visits at 15 and 29 weeks after birth. All children participated in clinic visits at the age of 7 and 9 months for follow-up assessment of anthropometric measures and for eye tracking based testing of visual attention, anticipatory learning, and face perception.

Results. A total of 444 out of the 1,509 infants approached were enrolled in the study. Main reasons for non-enrollment were non-eligibility (52%, mostly due to obstetric ultrasound being carried out too late) and non-interest (37%). Seventy (16%) of the participants were preterm, 145 (33%) early term, and 229 (51%) full term. The mean length-for-age z-score (LAZ), weight-for-age z-score (WAZ), and head-circumference-for-age z-score (HCZ) of the participants were −1.34, −0.86, and −0.07 at enrollment, and −1.45, −0.72, and −0.52 at 9 months of age. At enrollment, 23.7% of infants were stunted (LAZ < −2) and 9.7% were underweight (WAZ < −2). At 9 months, the prevalence of stunting and underweight was 27.5% and 11.1%, respectively. Mean (standard deviation [SD]) maternal age in years and years in school for the mothers of enrolled children were 24 (7) and 3.2 (3.2), respectively. Between enrollment and the 9-month visit, 34 (7.7%) participants were lost to follow-up, or died.

GA was not associated with measures of visual processing speed (VPS) or percentage of correct anticipation (pre- or post-switch) at 9 months. An association between GA and face perception was found with preterm infants showing relatively shorter attention dwell time on faces as compared to early-term and full-term infants. Underweight at enrollment (WAZ < −2) was associated with slower VPS, but no other associations between nutritional status and eye tracking measures were found. Maternal literacy was positively associated with infant eye tracking test scores, with infants of literate mothers (1/3 of the sample) having faster VPS (mean saccadic reaction times), a higher percentage of successful visual search responses, and more anticipatory behavior than infants of illiterate mothers. There were no other associations between rearing environment and measures of visual-cognitive function.

None of the observed associations between GA, nutritional status, and rearing environment with infant eye tracking test scores were found in a sensitivity analyses using 7- instead of 9-month eye tracking test scores as dependent variables.

Conclusion. The results showed no consistent association between non-specific risk markers for early child development and eye tracking-based assessment of visual and cognitive function at 9 months of age, except circumscribed effects of preterm birth, low weight-for-age at enrollment, and maternal literacy on certain aspects of visual attention. Further research and follow-up assessments are needed to examine the implications of these findings (i.e., whether the results reflect a true lack of association of the studied factors in low-resource settings or a failure to detect an existing association) and of the functional significance and predictive importance of the found associations between risk factors and measures of visual attention/face perception.

Introduction

Poverty, preterm birth, and nutritional deficiencies, among other factors, are serious risk factors for child development, affecting not only children's physical growth but also their cognitive, emotional, and social development. A recent review in the *Lancet* estimated that approximately 200 million children are not attaining their developmental potential in low- and middle-income countries (Walker et al. 2011). The concern is pressing, as there is a growing consensus among pediatricians and developmental psychologists that neurocognitive development during the first years of life is critical for children's long-term psychological functioning, educational attainment, and socioeconomic success. In essence, child development is a hierarchical process where even a minor deterioration in an early phase may result in significant adverse carryover effects in terms of later cognitive outcome (Hertzman and Boyce 2010).

The high prevalence of risk factors for impaired child development in low-resource countries calls for innovative new methods to identify developmental problems and functional deficits in individual infants. Although some problems are reflected in global proxies of child developmental outcomes, such as weight and height gain, these measures do not capture all critical aspects of healthy growth. Assessment of motor development is often suggested as an alternative, but the existing methods are typically interview and observation-based techniques that are quite cumbersome, crude, and prone to measurement errors. Most importantly, there have been no good methods to objectively assess cognitive and social development in infants and very young children in low-resource settings.

The lack of progress in assessing infants' cognitive development is not due to a total lack of adequate methods. In fact, developmental psychologists have a tradition of assessing various cognitive processes in infants based on their looking behavior (e.g., information processing speed, novelty preferences, and memory), and there is evidence to support the sensitivity of these tests for infants' cognitive status and long-term development (Rose et al. 2005). It has been difficult, however, to implement these methods in routine clinical practice even in the developed world because the tests are laborious to administer and rely heavily on the manual control and interpretation skills of the clinician. In low-resource settings, their application has thus far been practically impossible.

Nevertheless, in recent years, there have been rapid developments in semi- or fully automated eye tracking systems that measure looking behavior (e.g., look duration, fixation patterns, and shifting of gaze) based on infrared reflections from the infant's cornea relative to the center of the pupil (Ahtola et al. 2014, Gredebäck et al. 2009). Eye tracking has offered the possibility of developing more-objective tests of cognitive development in infants but, so far, the use of this method has been mostly limited to application in industrialized countries. Our present work is motivated by the possibility of also using these new technologies in the assessment of infants' cognitive development in low-resource settings.

The eye tracking method offers the benefit of implementing many of the established cognitive tests (e.g., tests of processing speed, attention, and learning) in a more automatic, efficient, and objective way in populations with limited motor and linguistic skills, such as preverbal infants. In addition, eye tracking tests focusing on elementary perceptual and cognitive functions have now been extended by including tests that assess facial perception and other early-developing capacities that provide a basis for social interactions, learning, and attachment (Trevarthen and Aitken 2001). We believe that these tests may be used for early identification of altered developmental trajectories. For example, in a previous study, we showed that the transition to the second half of the first year is accompanied by a clear change in attention to facial expressions, possibly because attention to these cues are so important for learning, emotion regulation, and behavior (Leppänen and Nelson 2009). Failure to demonstrate this type of developmental shift may provide a robust test for identifying problems in infant cognitive and social development.

This current study is aimed at assessing the validity of eye tracking-based tests of cognitive and social development among young infants in rural Africa. In the first phase of the study, we established the technical feasibility of implementing eye tracking-based tests in a low-resource setting in rural Malawi (Forssman et al. 2015). The study also showed that, compared to Finnish 9-month-old infants, Malawian 9-month-old infants have slower visual processing speed (VPS) (i.e., saccadic reaction times) and relatively heightened attention to faces displaying happy or fearful emotions. In the current study, our goal was to expand on these findings to examine whether known risk factors for early child development, including preterm birth, poor growth and nutritional status, and selected parameters of the rearing environment (i.e., socioeconomic status, maternal cognition, maternal depression, stress, and social support), are associated with eye tracking test scores at the infant ages of 7 and 9 months.

Preterm birth in itself may not delay early cognitive development, as preterm infants without concomitant neurological problems perform similarly to full-term infants, matched in chronological age, in tests of visual-cognitive function (Peña et al. 2014). There are, however, several indications that, in practice, preterm birth is associated with higher incidence of deficits in brain development and function, with subsequent effects on early cognitive development (Linsell et al. 2015). Studies in high-resource settings have shown that preterm birth is associated with relatively slower visual orientation (Landry et al. 1985, Pel et al. 2016, Shah et al. 2006; however, see also Hunnius et al. 2008, Rose et al. 2002, Foreman et al. 1991), relatively slower attention shifts between two competing objects (Butcher et al. 2002, de Jong et al. 2015, Atkinson et al. 2008), and reduced attention to faces and other social stimuli (Telford et al. 2016). These problems in the early development of visual and cognitive processes (i.e., in visual orientation speed and attention to faces) may provide a precursor for later deficits in cognitive, academic, and social function (Hitzert et al. 2015, Rose et al. 2011).

Prior research has also shown that children's growth and nutritional status and their early rearing environment (i.e., socioeconomic status, maternal cognition, maternal mood, and maternal education) are associated with early cognitive development. Intrauterine growth restriction, for example, has been associated with lower scores in conventional tests of cognitive and behavioral competencies at school age (Chen et al. 2016). Studies examining the association between malnutrition and cognitive outcomes have shown large differences between growth-stunted (length-for-age z-score [LAZ] < -2) and control infants/toddlers in observation-based developmental tests (Thompson et al. 2015). Early childhood malnutrition has also been shown to have large effects on cognitive status at age 9–11 (Champakam et al. 1968) and moderate effects on adult executive function or personality traits (Galler et al. 2013). Finally, lower socioeconomic status and parental cognition and education have been associated with poorer attentional and cognitive outcomes (Hackman et al. 2015) and higher levels of parental stress and depression with increased attention to affectively salient stimuli (Forssman et al. 2014). None of these previous studies used eye tracking as an outcome measure (except Forssman et al. 2014), but the demonstrated association between growth, nutritional status markers, and socioeconomic factors with global cognitive function support the possibility that these factors explain variability in eye tracking test scores. The results (Forssman et al. 2014) also suggest the specific hypothesis that higher levels of parental depression and stress are associated with increased attention to faces displaying emotional expressions (especially fear).

Methods

Study Design and Participants

The trial was a prospective cohort study. The target population included newborn infants without a congenital malformation, severe illness, or known visual impairment who lived in the Lungwena and Malindi areas, Mangochi District, Malawi. For the study sample, we enrolled under 4-week-old healthy babies who were born between 32.0 and 41.9 gestation weeks and whose parents gave consent for the child's participation. The study included five visits: three at the clinic (the enrollment after the birth and visits at 7 and 9 months) and two home visits. The enrollment was done either at the Lungwena health center or the Malindi hospital. Post-enrollment clinic visits were conducted at the Lungwena health center.

Prior to the enrollment, a study nurse performed an obstetric ultrasound assessment of all women who started antenatal care at either of the two health facilities. The nurse measured fetal biparietal diameter, femur length, and abdominal circumference and determined the duration of pregnancy based on these measurements and Hadlock tables. The results and the estimated date of delivery were recorded in a log book and the woman's health passport, so that the information could later be retrieved to calculate gestational age (GA) at birth for those individuals who were later enrolled in the study.

The recruitment was stratified based on infants' GA. The target was to enroll 425 infants who were born between 32.0 and 36.9 completed gestation weeks (preterm), between 37.0 and 38.9 gestation weeks (early term), and between 39.0 and 41.9 gestation weeks (full term) at a ratio of 1:2:2. These categories were selected based on a recent redefinition of a term pregnancy, which was made to reflect new information about differential outcome expectations for the offspring after early-term and full-term births (American College of Obstetricians and Gynecologists Committee on Obstetric Practice, Society for Maternal-Fetal Medicine 2013). To achieve the aimed participant number in each stratum, we offered enrollment to every mother whose child was born preterm but to only some of the mothers whose infant was born early or full term. In practice, after the enrollment of a new preterm participant, we recruited the next two eligible infants from the same recruitment site to the 37.0–38.9 gestation weeks stratum and another two infants to the 39.0–41.9 stratum. The ratio of enrollment was changed to 1:5:5 after we had enrolled 251 participants. The change was due to a slower-than-expected recruitment pace for preterm infants.

The target sample size provided the study with 80% power and 95% confidence to document a statistically significant difference in the eye tracking scores between the preterm and the full-term infants, for an effect size in the target population of 0.45 SD or larger. For the comparison between early-term and full-term infants, the study had 80% power (and 95% confidence) to detect an effect size of 0.35 or larger. For the description of single proportions, the sample size provided a precision of approximately ±3 percentage points.

We conducted the study in accordance with the ethical standards of the Helsinki declaration. The study protocol was approved by the College of Medicine Research and Ethics Committee, Malawi; the Ethical Committee of Pirkanmaa Hospital District, Finland; and the Ethics Committee of the Tampere Region, Finland. Written informed consent was obtained from the participating infants' mothers before the start of the study. Mothers signed (48%) or thumb printed (52%) the consent form, on behalf of themselves and their infants, and received compensation for their travel costs and incentives on every visit (first visit, reusable napkins; second visit, soap; third visit, 1 kg of rice; fourth visit, 1 kg of sugar; and fifth visit, a piece of fabric).

General Procedure

Data for the study were collected in Malawi between November 2014 and July 2016. The enrollment visit at the clinic was done after the child's birth, before the child was 28 days old. During the enrollment, we took anthropometric measures (weight, length, mid-upper arm circumference [MUAC], and head circumference for the child; weight and height for the mother) and administered questions related to the delivery of the child and the child's living environment. The home location for the mother and child was also collected soon after consent for participation in the study was given.

Participants were visited at their home 15 weeks after the birth to collect information on possible home location changes and to conduct a maternal cognition assessment. Another home visit took place 29 weeks after birth to collect information on possible home location changes and on the social and demographic environment, food security, and maternal social support and to make a home observation.

During the clinic visits at 7 and 9 months (30 and 39 weeks after birth, ±14 days, respectively), we assessed the infants' cognitive functioning (via eye tracking) and social communication skills (via structured observation), took anthropometric measures of the child, and measured the mother's weight. We also made a medical examination of the child and observed the child's motor milestones. The eye tracking test battery administered consisted of two separate sessions (approximately 15–20 minutes in total). In between the two eye tracking sessions, a structured observation was administered to assess social communication skills (approximately 10 minutes). At 7 months, we also interviewed the mother to assess maternal depression and the strength of the mother's bond with her infant. At 9 months, we interviewed the mother again to assess maternal stress and the impact of life events.

Analyses in this report focus on the eye tracking data at 9 months of age. The 7-month eye tracking data serve as a sensitivity analysis. At the time of this report, manual coding of data from the structured observation tests was completed for 170 infants. These data are presented as preliminary results in the current report.

Eye Tracking Assessment

During the eye tracking assessment, the infants were positioned in a baby carrier, sitting on their mother's lap (or directly on the mother's lap if they refused to be placed in the baby carrier) at an approximately 60 cm viewing distance in front of a 22-inch monitor that was connected to a corneal-reflection eye tracker with a sampling rate of 60 hertz (Tobii TX-60, Tobii Technology, Stockholm, Sweden).

For the eye tracking assessment, three different tasks were presented in rotation: (1) a **visual search task** (modeled on Kaldy et al. 2011), (2) a **switch-task** (modeled on Kovács and Mehler 2009), and (3) an **attention disengagement task** (modeled on Forssman et al. 2014). As a composite measure of the infants' **VPS**, a combined reaction time score was created based on averaged reaction times from these three eye tracking tasks.

The **visual search task** assessed the ability of the infant to search for a target (a red apple) presented by itself (referred to as a single-search, one-object condition), among distractors of one kind (e.g., "same shape, but different color," referred to as a single-search, multiple-objects condition), or among distractors of two kinds ("same shape, but different color" and "different shape, but same color," referred to as a conjunction condition) (total number of trials = 24; 8 single-search, one-object conditions, 8 single-search, multiple-objects conditions, and 8 conjunction conditions). For this task, the proportion of successful searches for each condition was calculated.

The **switch-task** assessed the infant's ability to learn to anticipate the side (left or right) where a target would appear (pre-switch phase) and then be able to inhibit this initial rule in favor of a new rule when the appearance of the target switched sides (post-switch phase). For this task, the target appeared on one side for the first 8 trials, and then appeared on the other side for the last 8 trials (two sets; total number of trials = 32: 16 pre-switch and 16 post-switch). The outcome measure for this task was the proportion of correct anticipatory looks on the pre- and post-switch trials.

The **attention disengagement task** assessed the ability of the infant to disengage from a centrally presented stimulus (e.g., an emotional face, happy or fearful, or a control stimulus [randomized pixels]) to a lateral stimulus (an animated movie) (total number of trials = 32: 8 happy, 8 fearful, and 16 control). The outcome measure for this task was the proportion of missed attention shifts toward the lateral stimulus in each of the three conditions (happy, fearful, control). The difference in the proportion of occurred attention shifts for the control stimulus (a non-face pattern) and facial expressions (happy and fearful) in this task gives an indication of the infant's attentional bias for emotional faces.

In short, the eye tracking data was analyzed in following ways:

- **VPS**: the mean of the three variables defined below (two required), which were also analyzed separately:
  - **Visual search – single search condition without distractors, reaction time**: Time point when gaze enters the area of interest (AOI). Mean of reaction times observed between 150 and 1,000 ms.
  - **Switch-task – all anticipatory saccades to the correct location, reaction time:** Time point the gaze enters the AOI when the child anticipates the correct side of the stimulus. Mean of reaction times observed between 150 and 1,000 ms.
  - **Attention disengagement – control stimulus, reaction time**: Time point the gaze enters the lateral AOI after leaving the central AOI. Mean of reaction times observed between 150 and 1,000 ms.
- **Visual search – proportion of followed searches by condition**: Successful search is registered if the gaze hits the AOI within the predefined time limit (150–2,000 ms). Proportions were calculated as the number of successful searches for each condition divided by the total number of valid trials for that condition.
- **Switch-task – correct anticipations, by pre- and post-switch**: Proportions were calculated as the number of successful anticipations divided by the total number of valid trials for pre-switch and for post-switch, excluding first trials (pre- and post-switch) as they do not represent anticipatory.
- **Attention disengagement – occurred shifts and dwell times on faces**: An occurred shift was defined as a shift of gaze from the central to the lateral stimulus occurring within the predefined time limit (150–4,000 ms after the appearance of the lateral stimulus). Proportions of occurred shifts were calculated by dividing the number of occurred shifts by the total number of valid trials. Dwell time on faces was calculated as the average millisecond value for occurred shifts for trials with a non-control (i.e., emotional face) centrally presented stimulus.

The eye tracking data were stored on a laptop computer, pre-processed, and analyzed offline using *gazeAnalysisLib* (Leppänen et al. 2014). The pre-processing of the data was automated and included median filtering of the data with a moving window of 7 samples (equaling 117 ms in time), removal of abrupt spikes (technical artifacts), and interpolation of data gaps (maximum of 200 ms). In each task, trials that failed to meet predetermined data quality criteria (e.g., violated upper limit of interpolation) or specific task criteria (e.g., violation of lower limit fixation time on central stimulus in the attention disengagement task) were excluded. For a participant to be included in the statistical analyses of a particular task, the infant needed to provide at least 3 valid trials for each condition (e.g., for visual search: at least 3 valid trials out of 8 in the single-search, one-object condition, 3 out of 8 in the single-search, multiple-objects condition, and 3 out of 8 in the conjunction condition). Thus, the final sample size varies between different eye tracking outcome measures according to specific inclusion criteria for the eye tracking tasks. More details on the eye tracking procedures used in this study are provided in **Appendix 1**.

Structured Observation

The infants' ability to initiate and respond to social communication cues was assessed during a structured observation based on two tasks from the Early Social Communication Scale: **alternating gaze** and **gaze following** (Mundy et al. 2003). During the assessment, the child was seated on his/her mother's lap in front of a table where the mother was seated, facing the experiment leader. The experiment leader presented these two tasks in a rotating order to keep the infant interested and engaged, always in the following order: alternating gaze (3 trials, an airplane), gaze following (4 trials, the balls on the walls), alternating gaze (3 trials, a rattle), gaze following (4 trials, the balls on the walls), and alternating gaze (3 trials, a dog). The infants' behavior during the assessment was recorded with two video cameras placed so that the infants were always recorded face-on from two different angles. A trained coder coded the data offline.

Initiation of social communication was assessed with the alternating gaze task where the experiment leader presented a moving toy (e.g., spinning a propeller of a wooden airplane, shaking a rattle, wagging a tail of a wooden dog) on the table in front of the infant, but out of his or her reach for 6 seconds. After 6 seconds had elapsed, the infant was allowed to manipulate the toy briefly. The infant was presented with the same toy three times in a row. A total of three toys were presented at different times during the assessment (9 trials total). Initiating social communication was coded as the number of times the infant alternated his or her gaze (during each trial) between the activated toy and the experiment leader's line of gaze during the 6-second time period from the start of the activation of the toy. The total number of alternated gazes across the 9 trials were summed as the **alternating gaze score**.

Response to social communication was assessed with the gaze following task in which the experiment leader looked and pointed for 6 seconds (the experiment leader looked and pointed to the target for 3 seconds and then looked at the child followed by looking at the target again for 3 seconds) in turn to four objects (colorful soccer balls, located 90 and 45 visual degrees to the left and right of the infant) always in the same order (from the experiment leader's viewpoint: near left, far left, near right, and far right). Each object was considered as one trial. Two sets of four trials were presented during the assessment (8 trials total). Responding to social communication was coded as the total number of trials in which the infant looked to the correct object (i.e., the object the experiment leader pointed to) after the experiment leader's point had ended, but before that object was labeled or the next object was pointed to, resulting in the **gaze following score** (maximum score of 8).

Anthropometric Assessment

Infant length was assessed using a length board (Harpenden Infantometer, Holtain Limited, Crosswell, Crymych, UK) and recorded to the nearest 1 mm. Infant weight was assessed using an electronic infant weighing scale (SECA 735, Seca GmbH & Co., Hamburg, Germany) with reading increments of 10 g. MUAC and head circumference were measured with non-stretchable plastic insertion tapes (ShorrTape, Weigh and Measure, LLC, Olney, MD, USA) and the results recorded to the nearest 1 mm. All anthropometric measurements were done in triplicate by trained personnel. We used the mean of the first two readings if they did not differ by more than a prespecified tolerance limit (5 mm or 100 g). If the difference was above the limit, the third measurement was compared with the first and second measurements, and the pair of measurements that had the smallest difference was used to calculate the mean. If there were only one or two measurements, the mean of those was used for the analyses.

Age- and sex-standardized anthropometric indices (length-for-age, weight-for-age, weight-for-length, head circumference-for-age, and MUAC-for-age z-scores) were calculated using World Health Organization (WHO) Child Growth Standards (WHO 2006). WHO MUAC-for-age z-scores are available only for children older than 3 months of age; other z-scores are available for all ages. Thus, for the analysis, MUAC was used instead of MUAC-for-age z-score.

To estimate infant measurements (length, weight, and head circumference) at birth (0 days of age), we back-calculated birth measurements using enrollment measurements. Back-calculated birth measurements are equivalent to z-scores (WHO 2006) measured at enrollment, except for weight measurements done 1–5 days after birth, when weight was multiplied by 100/98, 100/96, 100/96, 100/98, and 100/99, respectively, due to a change in hydration status after the birth (Cheung 2013; Greenwood et al. 1992). Newborn size at birth z-scores based on GA were calculated using the INTERGROWTH-21st Newborn Size at Birth Chart (Villar et al. 2014) and back-calculated birth measurements. These measures were used for descriptive analysis of the sample.

Maternal Reports of Rearing Environment

Mothers provided information about their life situation and their children's living environment through interviews that took place during visits at the health center and participant's home. Interviews consisted of 10 questionnaires, each of which is described below.

1. In the **social and demographic environment** questionnaire, the mother was asked to respond to questions regarding her child's socio-demographic background. This questionnaire included questions about the age, literacy, and education level of the child's parents and questions about the child's family structure, such as the total number of children and people living in the household. A parent had to be able to write or read fluently in any language to be considered literate (all cases were Chewa or Yao). If a mother's reading and writing skills were not obvious, she was asked to read a piece of text and to write a piece of text. The child's father's literacy was assessed by asking the child's mother. The social and demographic environment questionnaire included an assessment of **subjective social status**, specifically, nine questions about the well-being of the mother in the past month. The first three questions were:

    - "How often did you eat three meals every day?"
    - "How often did your children eat three meals every day?"
    - "How often did you have enough money for everyday needs?"

    These questions had response options of "Never" (0), "Rarely" (1/3), "Sometimes" (2/3), and "Often" (1).

    The last six questions asked whether the mother had been able to buy food, clothes, and soap for laundry or washing for her or her children, and if she's been working in the past month, and the questions had response options of "Yes" (1) or "No" (0).

    Scores (indicated in parentheses) from the nine questions were summed to form a subjective social status score for the mother.

2. **Maternal cognition** was assessed with a digit span forward and backward test, a verbal fluency test (listing foods and girls' names), and a mental rotation test.
   - On the digit span forward and backward test, the mother was asked to repeat sequences of digits, increasing in length from two to nine digits. There were two sequences for each length and direction of digits. First, in the digit span forward test, the mothers were asked to repeat each digit in the sequence in the same order until the mother failed both sequences with a given number of digits. Second, in the digit span backward test the mothers were asked to repeat each digit in the sequence in backward order, and the test was terminated when the mother failed both sequences with a given number of digits. The total number of correct responses was calculated for each test (digit span forward score and digit span backward score).
   - On the verbal fluency test, the mother was first asked to name as many foods as possible in 60 seconds and then as many girls' names as possible in 60 seconds. For both conditions, each unique word in the category was counted as one point and a total number of unique words was calculated for each category.
   - The mental rotation test consisted of five rows of figures. For each row, the first figure was the original figure and the next eight figures were either rotated or flipped versions of the original figure. The mother was asked to point out the rotated figures (total of 4–6 rotated figures in a row). The number of rotated figures correctly identified and the number of flipped figures correctly not identified as rotated were summed to obtain a total test score (for a maximum of 40).

   For the maternal cognition score all five scores (digit span forward, digit span backward, food names, girl's names, and mental rotation) were standardized (mean 0, SD 1) and then summed.

3. The **maternal social support** questionnaire consisted of 12 questions about various aspects of practical and emotional support experienced by the mother. The questions were related to the mother's perceptions of the availability of a special person or friends to help, talk with, or share emotions with. Each question was answered from a choice of five responses using a response card with visual depictions of "Strongly disagree," "Mildly disagree," "Neutral," "Mildly agree," and "Strongly agree," scored 0, 1, 2, 3, or 4, respectively. Answers were summed to a create a total social support score (for a maximum of 48).

4. The **maternal self-reporting questionnaire** (SRQ) on depression consisted of 20 questions that asked about various symptoms, thoughts, or feelings that the mother may have experienced over the last 4 weeks. These questions referred to such items as appetite and happiness. Answer options were "No" and "Yes," where each "Yes" indicated a problem. The number of "Yes" responses was summed to create a total depression score.

5. The **maternal perceived stress** questionnaire focused on maternal stress during the last month, asking such questions as "How often have you felt that you were unable to control the important things in your life?" and "How often have you felt that things were going your way?" For each question, the respondent was asked if she had felt like that "Never," "Almost never," "Sometimes," "Fairly often," or "Very often," scored 0, 1, 2, 3, and 4, respectively. Scores were redefined so that a higher score reflected a positive outcome. Scores across all 10 items were summed to give a total score for maternal perceived stress.

6. The **maternal life events** questionnaire documented different life events and their potential impact on the mother's life. For this component, we adapted 17 questions from the Recent Life Events questionnaire (modeled on Brugha et al. 1985). The mothers were asked if the event (e.g., "Have any of your immediate family members died?" and "Have you separated from your partner") had occurred

during the past 12 months. A "Yes" (counted as 1) box was ticked if the event had occurred and a "Still affects me" (counted as 2) box was ticked if the event had occurred and was reported as still having an effect on her life, resulting in a maximum score of 34.

7. The **living environment** questionnaire included six questions about the building material of the house and the roof, the main source for drinking water, the sanitary facilities, the light source, and the main source for cooking oil. For each question, response options were ranked, with a higher score indicating more-developed construction. Based on the collected answers, each question was standardized (mean 0, SD 1) to represent the variety of housing conditions. Responses to the questions were then summed as a living environment score.

8. The **food security** questionnaire focused on the household's access to food. The household food insecurity access scale (HFIAS) questionnaire was used. The questionnaire includes a total of nine questions that ask about the household's ability to access food, the variety and amount of food consumed, and the hunger experienced by household members. For each question, the respondent was asked if the event occurred "Never," "Rarely," "Sometimes," or "Often" in the last 30 days. Items experienced rarely, sometimes, and often receive a score of 1, 2, and 3, respectively. Scores across all nine items are summed to give a total score for household food insecurity. Thus, the possible range of scores on the questionnaire is 0 to 27 (Coates et al. 2007). From the HFIAS data, the Household Hunger Scale (HHS) was also derived (Deitchler et al. 2010).

9. The **Home Observation for the Measurement of the Environment (HOME) inventory** (Caldwell and Radley 2003) was done at the child's home to assess infant care practices. The purpose of the assessment was to record the amount and quality of interactions and toys in the child's environment that promote cognitive, motor, and socio-emotional development. Specifically, the interview and observations focused on the mother's actions toward and responses to her child (e.g., mother caresses or kisses child at least once during the visit, mother neither slaps nor spanks the child during the visit, mother is asked whether the child gets out of the family living area at least four times a week). The form consisted of 36 questions or observations with response options of "No" and "Yes," where "Yes" was indicative of a positive outcome. The total number of "Yes" responses was summed to represent an infant care practices score.

10. The **mother-infant bond** questionnaire assessed the mother's bond to her infant. The Mother-to-Infant Bonding Scale (Taylor et al. 2005) was administered, which consisted of eight questions that ask about the mother's feelings for her child in the first few weeks after birth. The mother was asked to state the extent ("Very much," "A lot," "A little," "Not at all") that best described how she felt when presented with eight different adjectives, for example, "joyful," "resentful," "protective," and "aggressive." Each response was rated on a scale from 0 to 3 (range of 0–24), where a higher score indicated that the mother had more problems with creating a positive bond with her child (e.g., reporting "Very much" for "joyful" was scored 0, whereas "Very much" for "resentful" was scored 3).

For statistical analysis, the rearing environment variables from the above 10 questionnaires were redefined so that in all cases a higher score reflected a positive outcome. The responses to each scale were then standardized (mean 0, SD 1) (i.e., maternal cognition score and living environment score were standardized in two phases, and other sum variables were standardized once). Redefinition and standardization of variables were not undertaken for parents' ages, literacy, and schooling; maternal anthropometrics; maternal parity; number of people in the household; and number of children in the household.

Statistical Analysis and Definitions for Eye Tracking and Other Variables

Summary statistics of the sample characteristics were calculated as means and SD or median and interquartile range (IQR) for continuous measurements and as percentages for dichotomous measures. The primary outcome measures of interest were the VPS and other task-specific attributes compared to child's GA and anthropometrics. We performed tests to describe the association between the participants' eye tracking scores at 9 months of age and their GA. The participants' eye tracking scores at 9 months of age were also compared to head circumference-for-age z-score (HCZ), and nutritional status (LAZ, weight-for-age z-score [WAZ], and weight-for-length z-scores [WLZ]) at enrollment and at the time of eye tracking testing, and the change in HCZ and nutritional status between enrollment and the 9-month assessment. We also performed tests to describe the association between the participants' eye tracking scores at 9 months of age and their rearing environment variables. We analyzed correlations between eye tracking scores and structured observation scores.

We compared the infants' scores on the eye tracking tasks across gestation age groups using analysis of variance (ANOVA) or Kruskal-Wallis tests. We used *t* tests (with equal or unequal variances) or Mann-Whitney *U* tests for two-group comparisons. For continuous predictor variables, graphical and simple regression analysis was performed to assess linear or nonlinear associations with eye tracking scores. Pearson's correlations (for normally distributed variables) and Spearman's rank correlations (for skewed variables) were used to provide an estimate of the strength of the linear or monotonic association.

For two-group comparisons, the predicting variable was stratified at the 50th percentile value. The exceptions were LAZ and WAZ, which we stratified at the value of −2 (the cutoff for stunting and underweight, respectively).

A P value of < 0.05 was used to determine statistical significance. With $P < 0.05$, the hypothesis of no difference between groups was rejected. Each eye tracking test was considered conceptually distinct from every other eye tracking test, and each task had a distinct family of hypotheses so no adjustment was deemed necessary for multiple hypothesis testing. For correlation coefficients, P values were not evaluated; absolute values above 0.40 were considered as meaningful associations.

Sensitivity analysis was performed with the 7-month eye tracking and structured observations data for the variables with statistical significance in the 9-month data.

Results

Characteristics of the Study Sample and Success of Follow-up

Between November 2014 and October 2015, the MiTrack team approached 1,509 mothers after the birth of their children for participation in the study. A total of 444 children born to 444 mothers were enrolled. All children were under 4 weeks old at the time of enrollment, except one child who was 30 days old at the enrollment. The main reasons for non-enrollment in the study were non-eligibility (52%, mostly due to obstetric ultrasound being carried out too late) and non-interest (37%).

Seventy (16%) of the participants were preterm (born before 37 completed gestation weeks), 145 (33%) were early term (37.0–38.9 gestation weeks), and 229 (52%) were full term (39.0–41.9 gestation weeks). Mean (SD) GA was 38.7 (1.8) weeks. Mean (SD) maternal age in years and years of schooling completed were 24 (7) and 3.2 (3.2), respectively. The proportion of primiparous women was higher in the preterm group than in the early-term and full-term groups (44%, 34%, and 29%, respectively, $P < 0.001$). Other rearing environment variables of maternal and family characteristics are shown in **Table 1**. Women who were approached but whose infants were not included in the study had the same mean age (24 vs. 24, $P = 0.90$) and number of children currently living as women whose infants formed the study cohort (2.9 vs. 2.8, $P = 0.22$) (data not shown).

Between enrollment and the 9-month visit, 34 (7.7%) participants were lost to follow-up, or died (**Figure 1**). Infants who were lost to follow-up had smaller head size at enrollment than infants continuing in the study at 9 months (difference in HCZ: −0.51, $P = 0.007$), whereas there was no statistically significant difference in LAZ or WAZ. There were no differences between the infants lost to follow-up and the analyzed participants in terms of mean maternal age (24 vs. 24, $P = 0.89$) or number of children (alive) in the family (2.9 vs. 2.9, $P = 0.99$).

Distribution of Outcome Variables

The mean LAZ, WAZ, and HCZ of the participants were −1.34, −0.86, and −0.07 at enrollment and −1.45, −0.72, and −0.52 at 9 months of age, respectively (**Table 2**). Nearly a quarter (23.7%) of infants were stunted (LAZ < −2) and 9.7% underweight (WAZ < −2) at enrollment and 27.5% and 11.1% were stunted and underweight at 9 months, respectively. Further details of the anthropometric measurements are shown in Table 2. Distributions of rearing environment variables are shown in **Table 3**.

The mean (SD) VPS across all participants was 454 (50) ms. For the individual tasks, the mean (SD) reaction times were 437 (71) ms for visual search (single search, one object), 552 (90) ms for switch-task (correct anticipatory), and 361 (70) ms for attention disengagement (control stimulus). Pairwise correlations between three reaction times were 0.16 (attention disengagement/visual search), 0.06 (visual search/switch-task), and 0.06 (switch-task/attention disengagement).

The mean (SD) proportion of successful visual search tasks was 0.92 (0.16) for one object, 0.62 (0.22) for multiple objects, and 0.45 (0.20) for conjunction. The mean (SD) proportion of successful anticipation in the switch-task was 0.72 (0.27) for pre-switch and 0.54 (0.28) for post-switch. The mean (SD) proportion of occurred shifts for attention disengagement was 0.71 (0.26) with a central happy face, 0.67 (0.26) with a central fearful face, and 0.997 (0.018) with a central control stimulus. The mean (SD) dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) was 1,261 (513) ms.

For the structured observation at 9 months of age, 170 participants (43% of recorded data) were analyzed by the time of reporting. The mean (SD) number of alternating gaze and followed gaze were 3.53 (1.36) and 3.00 (1.04), respectively. The Spearman's correlation between alternating gaze and followed gaze was 0.08.

Comparison of Eye Tracking Results, Gestational Age, and Growth

Visual Processing Speed

The VPS and the task-specific reaction times were not associated with GA at birth (**Table 4a**, **Figure 2**), category of pregnancy duration at birth (Table 4a), LAZ at enrollment (**Table 4b**), or stunting (LAZ < -2) at enrollment (Table 4b). The VPS and the task-specific reaction times were also not associated with WAZ at enrollment, with the exception that underweight infants (WAZ < −2) had slower VPS compared to other infants (478 ms vs. 452 ms, $P = 0.001$) (**Table 4c**, **Figure 3**). The VPS and the task-specific reaction times were not associated with WLZ at enrollment (**Table 4d**); HCZ at enrollment (**Table 4e**); MUAC at enrollment (**Table 4f**); LAZ, WAZ, WLZ, HCZ, and MUAC at 9 months (**Tables 4g–4k**); or the change in LAZ, WAZ, WLZ, HCZ, and MUAC between enrollment and 9 months of age (**Tables 4l–4p**), with the exceptions of slower reaction time on the visual search for infants at 9 months with WLZ equal to or above the median (Table 4i) and infants at 9 months with HCZ equal to or above the median who had slower reaction time on visual search but faster reaction time on switch-task (Table 4j).

Visual Search

The proportion of successful searches was not associated with GA at birth (**Table 5a**), category of pregnancy duration at birth (Table 5a), LAZ at enrollment (**Table 5b**), or stunting (LAZ < −2) at enrollment (Table 5b). The proportion of successful searches was also not associated with WAZ at enrollment (**Table 5c**), WLZ at enrollment (**Table 5d**), HCZ at enrollment (**Table 5e**), MUAC at enrollment (**Table 5f**), LAZ, WAZ, WLZ, HCZ, and MUAC at 9 months (**Tables 5g–5k**), or the change in LAZ, WAZ, WLZ, HCZ, and MUAC between enrollment and 9 months of age (**Tables 5l-5p**), except that infants with MUAC below the median at enrollment had a lower proportion of successful searches on the conjunction condition (43% vs. 50%, $P = 0.041$) (Table 5f), and the same was observed for infants with MUAC below the median at 9 months (43% vs. 50%, $P = 0.009$) (Table 5k). Also, underweight infants (WAZ < −2) at 9 months had a lower proportion of successful searches on the conjunction condition compared to other infants (38% vs. 43%, $P = 0.024$) (Table 5h).

Switch-Task

The proportion of correct anticipatory looks was not associated with GA at birth (**Table 6a**), with proportion of correct anticipations by trial presented in **Figure 4**, category of pregnancy duration at birth (Table 6a), LAZ at enrollment (**Table 6b**), or stunting (LAZ < −2) at enrollment (Table 6b). The proportion of successful switch-task was also not associated with WAZ at enrollment (**Table 6c**), WLZ at enrollment (**Table 6d**), HCZ at enrollment (**Table 6e**), MUAC at enrollment (**Table 6f**); LAZ, WAZ, WLZ, HCZ, and MUAC at 9 months (**Tables 6g–6k**); or the change in LAZ, WAZ, WLZ, HCZ, and MUAC between enrollment and 9 months of age (**Tables 6l–6p**), with the exceptions of lower post-switch anticipations for infants at enrollment with MUAC below the median (50% vs. 60%, $P = 0.010$) (Table 6f), lower pre-switch anticipations for infants at 9 months with HCZ below the median (75% vs. 85%, $P = 0.003$) (**Table 6j**), better post-switch anticipation for infants with ΔWAZ below median (64% vs. 50%, $P < 0.001$) (**Table 6m**), and better post-switch anticipation for infants with ΔMUAC below the median (62% vs. 50%, $P = 0.008$) (**Table 6p**).

Attention Disengagement

The mean (SD) dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) was shorter for infants who were born preterm than those born early term or full term (1,107 ms, 1,348 ms, and 1,249 ms, respectively, $P = 0.022$) (**Table 7a**). Pearson's correlation between continuous GA and dwell time of gaze on faces was 0.06 (**Figure 5**). The proportion of successful shifts on attention disengagement task was not associated with LAZ, WAZ, WLZ, HCZ, or MUAC at enrollment (**Tables 7b–7f**) or at 9 months of age (**Tables 7g–7k**) or with the change in LAZ, WAZ, WLZ, HCZ, and MUAC between enrollment and 9 months of age (**Tables 7l–7p**), with exceptions of infants at enrollment with HCZ at or above the median having less occurred shifts on fearful stimulus (Table 7e), infants at 9 months with WLZ at or above the median having more occurred shifts on happy stimulus (Table 7i), and infants with ΔWAZ at or above the median having more occurred shifts on fearful stimulus (Table 7m).

Comparison of Eye Tracking Scores and Rearing Environment

The correlation coefficients did not show associations between VPS and rearing environment variables, such as maternal age, parity, completed years of maternal education (**Table 8**), maternal perceived stress, or life events (**Table 9**). There was no association between eye tracking scores and parents' ages, maternal characteristics (parity, schooling, height, and body mass index [BMI]), or household size (Table 8). There was no association between eye tracking scores and individual rearing environment variable scores (Table 9). Spearman's rank correlation coefficients between eye tracking variables, family characteristics, or rearing environment were between −0.23 and 0.16 for those variables (Tables 8–9). Maternal literacy was associated with faster VPS, a higher proportion of successful searches on the conjunction task, and a higher proportion of correct pre-switch anticipations (**Table 10**), whereas paternal literacy and the HHS had no association with eye tracking scores (data not shown).

Comparison of Structured Observation and Other Variables

The mean (SD) number of alternating gazes for infants who were born preterm, early term, and full term was 3.4 (1.5), 3.4 (1.5), and 3.7 (1.2), respectively ($P = 0.31$). The mean (SD) number of gaze followings for infants who were born preterm, early term, and full term was 2.9 (1.0), 2.9 (1.2), and 3.1 (0.9), respectively ($P = 0.40$). Alternating gazes or gaze followings were not associated with maternal and family characteristics or individual rearing environment scores (**Table 11**), GA or infant anthropometric measures (**Table 12**), or eye tracking scores (**Table 13**), as correlation coefficients ranged between −0.18 and 0.18.

Sensitivity Analysis

Generally, at 7 months of age, reaction times were slower and proportions for successful tasks were lower compared to the eye tracking results at 9 months of age. The correlations reported in Tables 4–9 for the eye tracking data collected at 9 months were carried out again using the 7-month eye tracking data, and the correlation coefficients for the 7-month data were compared to the 9-month correlation coefficients by Pearson's correlation (n = 455). The correlation between the 7-month and 9-month correlation results was 0.18 (**Appendix 2 Figure 1**). The same statistical tests carried out with the 9-month eye tracking data were also carried out with the eye tracking data collected at 7 months. Only one statistically significant difference found at 9 months of age was visible at the age of 7 months. A higher proportion of correct post-switch anticipation on the switch-task was observed at 7 and 9 months of age for infants with a lower change in MUAC from enrollment to 9 months (**Appendix 2 Table 10**). Statistically significant results for the eye tracking data collected at 9 months of age are shown with results for the eye tracking data collected at 7 months of age in **Appendix 2 (Tables 1–16)**.

Discussion

The present study examined whether preterm birth, different indicators of early nutritional status and growth, and early rearing environment are associated with cognitive development, as assessed by eye tracking-based tests. The current report documents the first results of a study aimed at validating new eye tracking-based tests as a technique for assessing early cognitive development in children in low-resource settings.

Preterm Birth and Eye Tracking Test Scores

Contrary to our hypotheses, GA was not associated with global measures of infant cognitive function, including the speed of visual orientation to the appearance of visual objects, attention shifts between two locations or two competing objects, or measures of anticipatory learning. As a negative result, the lack of association should be interpreted with caution. There are several reasons to believe that, instead of a failure to capture an existing difference, the current result may reflect a true lack of association between GA and visual-cognitive function in the target population. First, our pilot study, using the same eye tracking setup as that used in the current study, showed that the test success rates in Malawi were comparable to those found in previous studies in industrialized settings, suggesting that the lack of association is not simply attributed to difficulties in the technical administration of the tests at the Malawian sites (Forssman et al. 2015). Second, the current study had adequate (≥ 80%) power to document a statistically significant difference of a medium effect size in the eye tracking scores (i.e., a difference that was 0.45 SD or larger; see the *Study Design and Participants* section for further details of the power calculation). Finally, previous studies using highly similar measures as those used in the current study demonstrated that these measures have adequate psychometric properties (i.e., split-half correlations or test-retest correlations between 0.60 and 0.80; Ahtola et al. 2014, Leppänen et al. 2014, Rose et al. 2012) and are sensitive for deviations in early cognitive development (Dougherty and Haith 1997, Elison et al. 2013, Kaldy et al. 2011, Kovacs and Mehler 2009, Rose, 1994). Further, an association of eye tracking-based tests of cognitive development at 6–12 months of age and later cognitive development has been demonstrated in studies in industrialized settings (Rose et al., 2012).

In light of these considerations, the current results may provide a valid demonstration of the sparing of basic attention orienting and anticipatory learning skills in preterm infants in low-resource settings. This interpretation is in line with previous studies showing that preterm infants had no deficits in simple saccadic reaction times (i.e., a measure equivalent to the VPS in the current study), whereas they had lower score in oculomotor processes that can be studied at older ages and are sensitive to active cognitive control processes (i.e., saccade inhibition; Newsham et al. 2007). The possibility remains, however, that more "high-risk" preterm infants who were not included (or were possibly underrepresented) in the current sample, such as infants with extreme preterm birth (i.e., < 32 weeks) or infants with neurological deficits, are at higher risk for deficits in basic visual processes (e.g., Atkinson et al. 2008).

While there was no association of preterm birth with measures of "purely" cognitive abilities in infants, the current results showed an association of GA with attention dwell time on faces. Specifically, preterm infants tended to fixate on faces for a shorter period of time than early-term and full-term infants. This result replicates a recent study in an industrialized setting in Scotland, which showed that very preterm infants (< 33 weeks) fixate on faces for a shorter period of time than full-term infants (Telford et al. 2016). It is noteworthy, however, that while preterm infants in the current study fixated on faces for a shorter time than full-term infants, this effect was not accompanied by a decrease in "no-shift" trials (i.e., prolonged fixation without gaze shift from the face to the lateral stimulus) relative to the level found in early-term and full-term infants. There is no clear interpretation for this finding; it may indicate an inconsistency in the current results or, alternatively, point to partial independence of the two measures of attention. Overall, the current pattern of results, showing no association of preterm birth with visual cognitive abilities (i.e., visuospatial orienting, visual search, and anticipatory learning) and reduced scores in other tasks (e.g., attention dwell time for faces), is theoretically meaningful as the neural mechanisms underlying purely cognitive abilities (e.g., attention orienting), and those underlying face perception are likely to be partially distinct (Leppänen and Nelson 2009). Detection of infants with reduced attention to faces may be important in early screening of infants at risk, especially as there are both theoretical and empirical arguments to suggest that infants' attention bias for faces is an important adaptive trait that helps initiate vital interactions with caregivers during sensitive periods of development and promotes infants' social learning (Leppänen 2016).

Growth Markers and Eye Tracking Test Scores

Infants with low WAZ at birth (< -2) showed slower VPS relative to other infants. However, other indicators of early nutritional status were not associated with eye tracking-based indices of cognitive function in the predicted way. Also, changes in these measures of nutritional status between birth and 9 months and of nutritional status at 9 months were generally not associated with measures of VPS or attention in the predicted direction.

If the association between low newborn WAZ and relatively slower VPS holds in further follow-up studies, it may point to a critical contribution of pre- and perinatal weight gain on early cognitive development. This possibility is also supported by studies showing that very low birth weight children with lesions in occipital areas show saccadic abnormalities at 2 years of age (Shah et al. 2006). There are also indications that growth between birth and 4 months of age, but not between 4 and 12 months, is associated with cognitive performance later at 4 years of age (Varella and Moss 2015). Early-emerging problems in visual orientation in low birth weight infants may provide a precursor for lower scores in conventional tests of cognitive and behavioral competencies later in development, including relatively slower behavioral response times (Chen et al. 2016). It is noteworthy, however, that the association between birth weight and VPS in the current analysis was limited to children with WAZ < -2 of age-related growth standards. While this finding may point to the unique predictive value of WAZ in early development, the possibility that it reflects a false positive cannot be ruled on the basis of our current results. Analyses using continuous WAZ values and analyses using other markers of nutritional status at birth (e.g., LAZ, LAZ < -2) showed no association with eye tracking outcomes. A further limitation of our current analyses that may contribute to the associations observed between growth markers and cognitive development is that the predictors' values were not adjusted for correlated factors (e.g., GA) and were, therefore, not directly reflecting children's growth or not controlled for possible confounding effects of preterm birth. Finally, the possibility remains that nutritional status and growth markers have widespread effects on cognitive development, but that these effects are primarily seen in the more complex functions that emerge downstream in early development (i.e., construct assessed by traditional cognitive and behavioral tests) instead of the early functions evaluated by our eye tracking tests.

Rearing Environment

Maternal literacy was positively associated with infant eye tracking test scores in multiple subtests. Infants of literate mothers (approximately 1/3 of the sample) had faster VPS (i.e., saccadic reaction time), a higher percentage of successful visual search responses, and more anticipatory behavior than infants of illiterate mothers. These results are consistent with other studies showing that maternal literacy is positively associated with infant survival and development (e.g., Smith-Greenaway 2013). Maternal literacy may serve as a measurable proxy for multiple aspects of the mother and her infant's life (e.g., shared genetic predispositions, socioeconomic status and access to education, structuring of mother-infant interaction), each of which may contribute positively to the infant's development.

None of the other variables reflecting the infants' rearing environment were systematically associated with the eye tracking test results. This result stands in contrast to previous studies in industrialized settings showing that socioeconomic status, maternal education, and parental stress are associated with early childhood cognitive development and to results suggesting that some of these factors are associated with early eye tracking-based assessment of attention in infants (e.g., Forssman et al. 2014; Hackman et al. 2015). There are several possible explanations for the discrepancy in results between the previous studies in industrialized setting and those in the current study. First, as discussed above, the possibility that the lack of association is attributable to a failure to capture an existing effect with current measures of rearing environment and infant cognition cannot be ruled out, although it appears unlikely given the previous result demonstrating an association using highly similar methods (e.g., Forssman et al. 2014). Second, it is possible that a restricted range of variability in the measures of rearing environment reduced the associations of these variables with eye tracking outcomes. Most of the variables used to reflect the infant's rearing environment (e.g., socioeconomic status, maternal education, and possibly maternal care) are likely to have more variability in industrialized settings than in the current study context in Malawi. Restricted range of variability may have especially strong effects if the effects of the rearing environment (e.g., maternal education) start to be associated with child development only after a certain "threshold" level has been reached. Finally, we note that while rearing environment has been associated with cognitive development, most studies studying these factors have focused on cognitive processes that develop later in childhood (such as language or inhibitory skills). Thus, it remains possible that rearing environment does not impinge on early acquisition of basic cognitive and social processes as much as higher-order cognitive processes that emerge later in childhood.

Summary

In summary, the current study shows little difference between preterm and full-term infants in eye tracking-based assessment of cognitive function at 9 months of age, except a circumscribed effect of preterm birth on attentional dwell time on faces. Similarly, infant nutritional status and rearing environment were not consistently associated with eye tracking outcomes, with the exception of the observed associations between low WAZ at enrollment and maternal literacy with infant eye tracking test scores at 9 months of age. The functional significance of these potentially important early markers of infant cognitive development should be further studied in follow-up assessments carried out in mid- and late childhood, when more-complex cognitive and social abilities begin to emerge and can be reliably studied in children (e.g., executive function, inhibitory control, and prosocial behavior/empathy). Finally, it is important to note that whereas some subtle effects of risk factors were seen in eye tracking measures in the current study, our preliminary analyses (based on a sample of 170) showed no association between eye tracking and structured observation of infant cognitive skills and social behavior, and no associations between the studied risk factors and observational tests of cognitive development in infants. If these results hold in further analyses with the full sample, it would be consistent with our earlier results in this population (Forssman et al. 2015) and with the suggestion that eye tracking captures different aspects of cognitive function than traditional observational tasks and that eye tracking may be sensitive to subtle differences in cognitive development in young children prior to the appearance of overt behavioral symptoms or deficits.

Figures

Figure 1. Flowchart

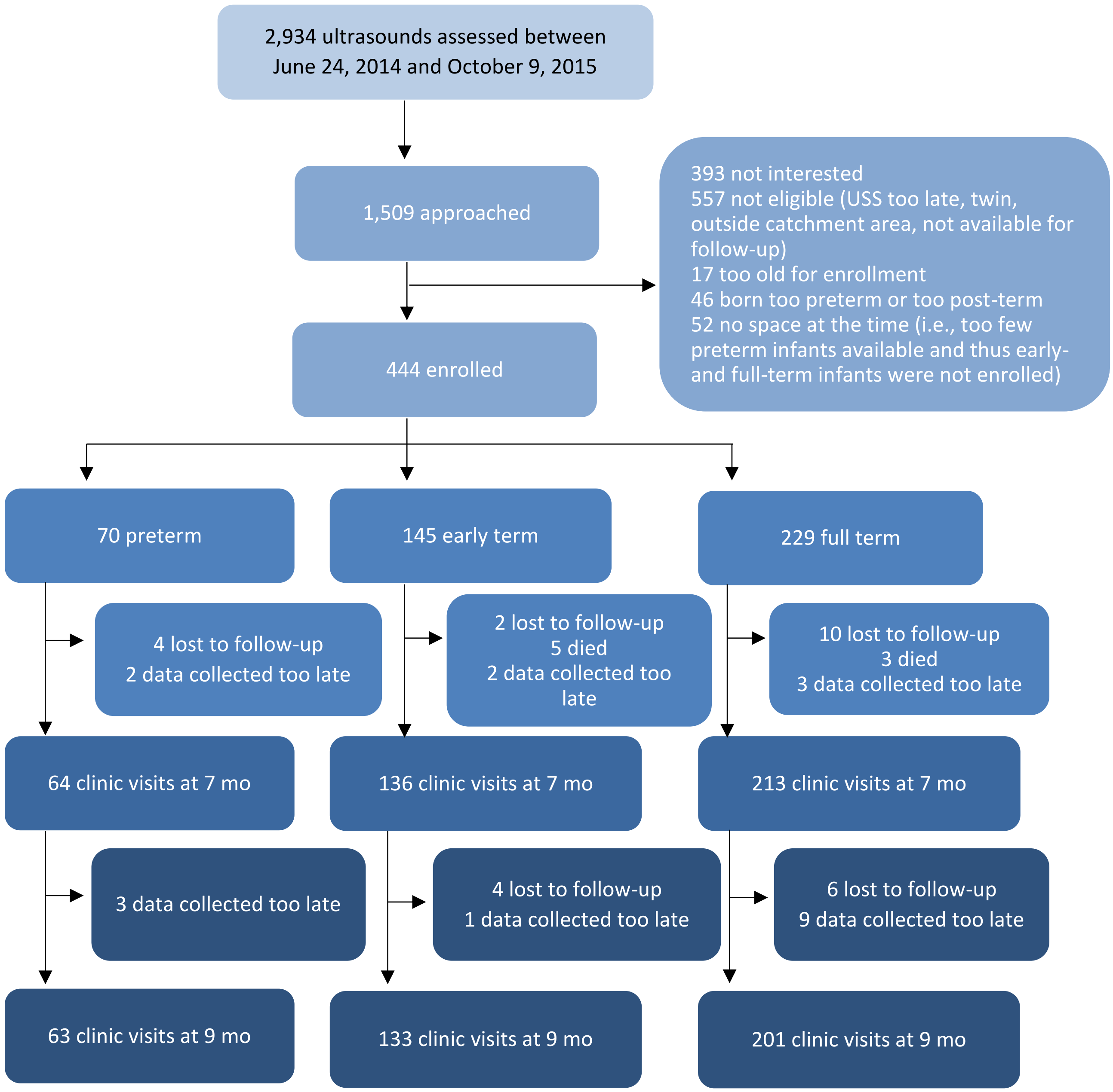
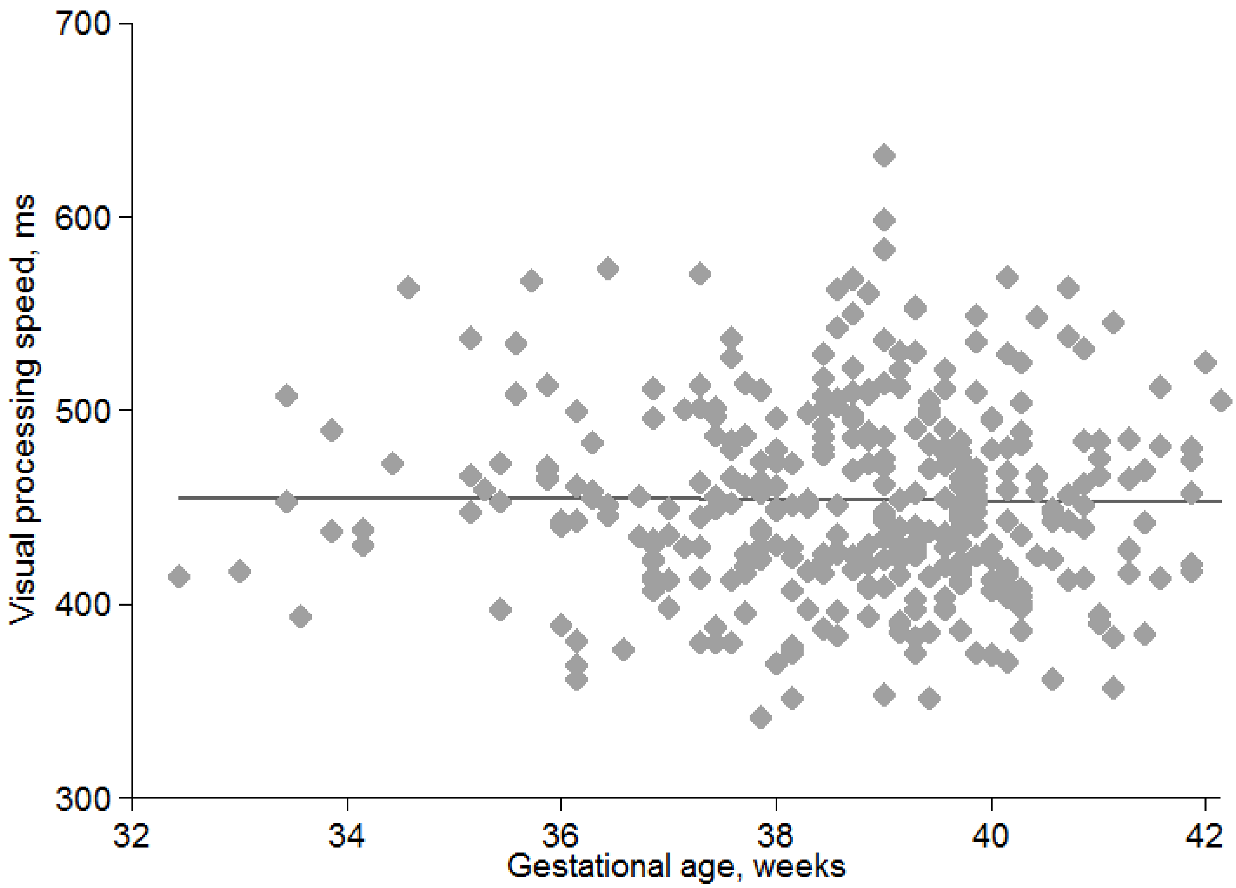
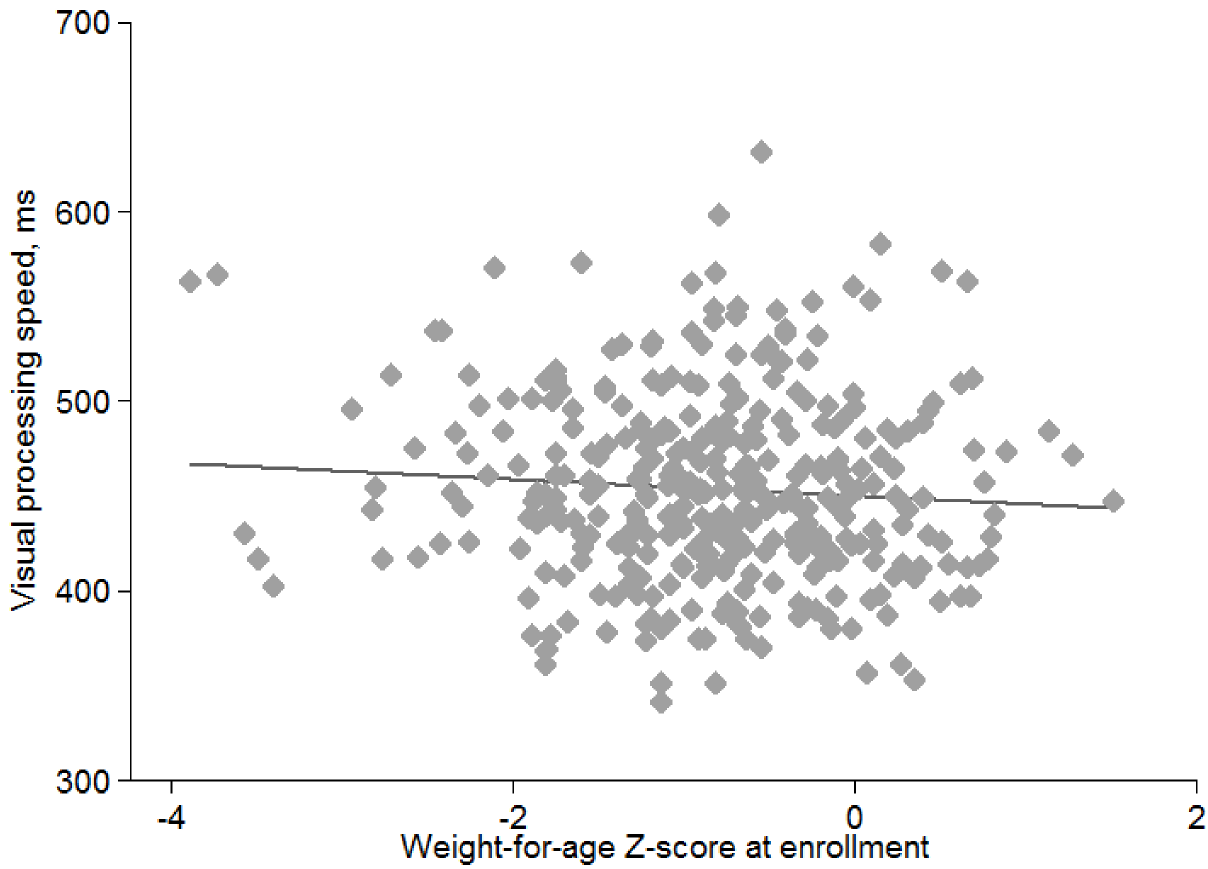


Figure 2. VPS compared to GA



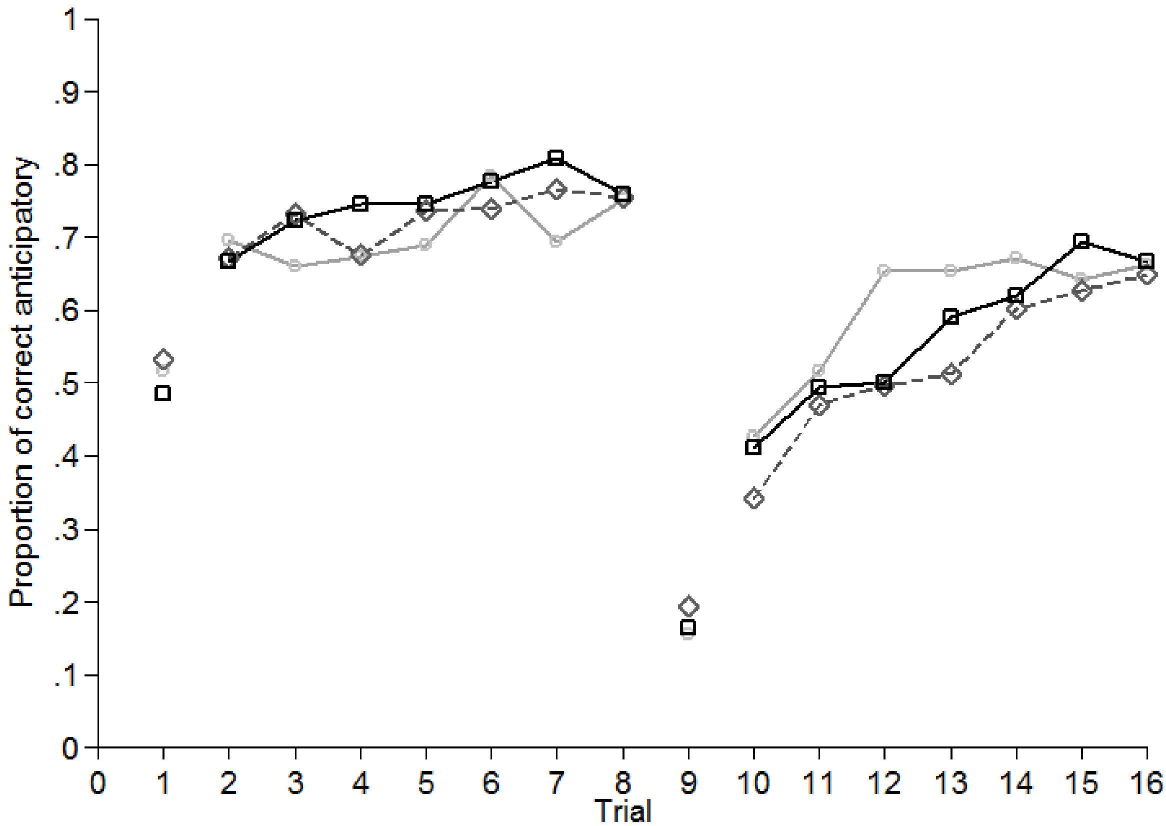
Pearson's r = −0.01 (n = 348). Observations as points. Linear fit as a line.

Figure 3. VPS compared to WAZ at enrollment



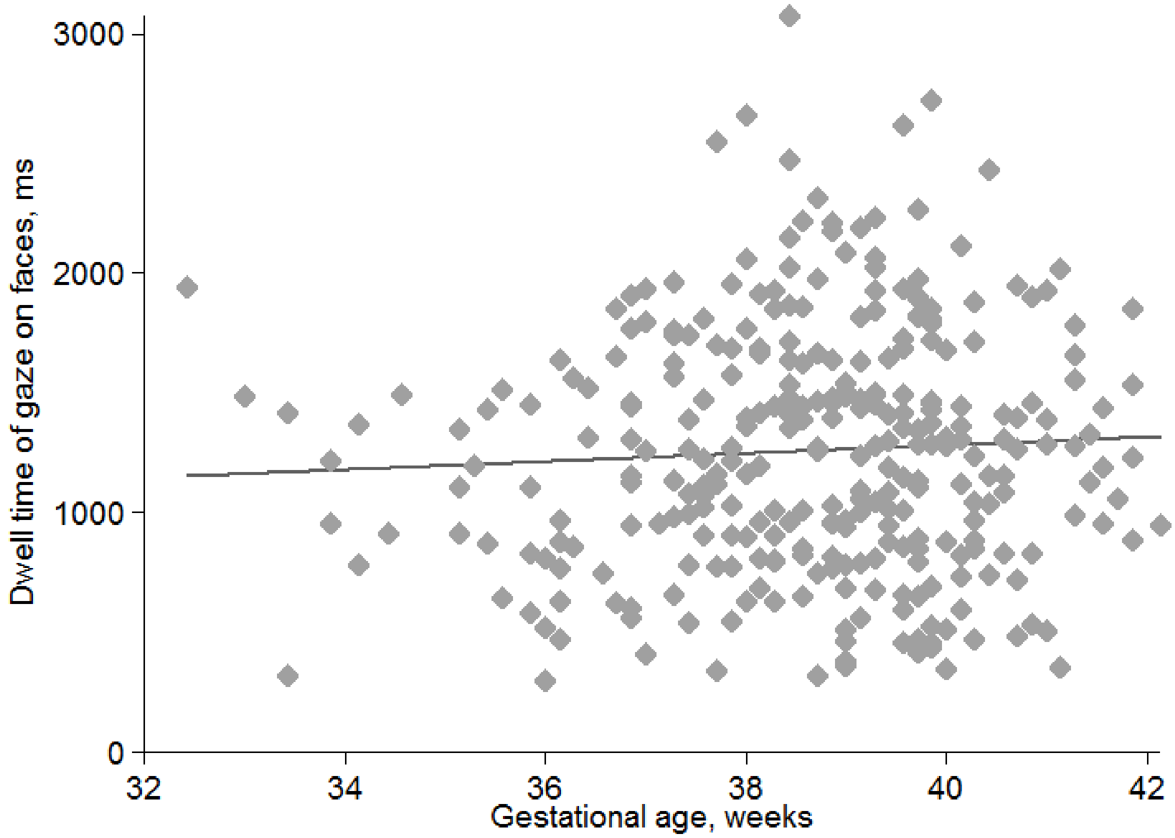
Pearson’s r = −0.07 (n = 348). Observations as points. Linear fit as a line.

Figure 4. Proportion of correct anticipation in the switch-task across trials



Switch at trial number 9. Preterm as solid gray line, early term as dashed dark gray line, and full term as solid black line.

Figure 5. Dwell time of gaze on faces before gaze transition to a new object (reaction time to lateral stimulus using a central stimulus of a face) compared to GA



Pearson's r = 0.06. Observations as points (n = 310). Linear fit as a regression line.

Tables

Table 1. Rearing environment variables: Maternal and family characteristics

Characteristic	N	Mean (SD) or %	Median (IQR)	*P* value between GA (at birth) groups[a]
Mother's age, years	444	24 (7)	23 (10)	**0.005**[b]
Father's age, years	422	31 (9)	30 (13)	**0.001**[c]
Mother's years in school	424	3.2 (3.2)	3 (5)	0.38
Father's years in school	410	4.8 (3.9)	5 (8)	0.63
Mother's literacy, %	424	35.4	N/A	0.60
Father's literacy, %	423	61.0	N/A	0.79
Primiparous women, %	444	29.1	N/A	< **0.001**[d]
Children alive (born to mother)	444	2.9 (1.8)	3 (3)	**0.002**[e]
Children under-5 living in the household	424	1.7 (0.7)	2 (1)	0.79
People living in the household	424	5.2 (1.9)	5 (2)	0.89
Maternal height	444	155.8 (5.6)	155.4 (7.5)	0.38
Maternal BMI at enrollment	444	22.4 (2.7)	22.0 (3.3)	**0.018**[f]
Maternal BMI change from enrollment to 9 months	409	−1.1 (1.6)	−1.0 (2.0)	**0.023**[g]
Moderate or severe household hunger (HHS), %	424	26.2	N/A	0.30

[a] *P* value from ANOVA for continuous variables and Fisher's exact test for proportions. **Bold** indicates statistically significant. GA groups: preterm, early term, and full term.
[b] Mother's age, years, mean; preterm: 23, early term: 24, full term: 25.
[c] Father's age, years, mean; preterm: 29, early term: 30, full term: 31.
[d] Primiparous women, %, mean; preterm: 44, early term: 34, full term: 29.
[e] Alive children by mother, mean; preterm: 2.5, early term: 2.7, full term: 3.2.
[f] Maternal BMI at enrollment, mean; preterm: 21.8, early term: 22.2, full term: 22.7.
[g] Maternal BMI change from enrollment to 9 months, mean; preterm: −0.8, early term: −0.9, full term: −1.3.

Table 2. Characteristics at clinic visits

Characteristic	Enrollment N = 443	7 months N = 413	9 months N = 397
Birth length, cm (back-calculated)[a]	47.0 (2.4)		
Birth weight, g (back-calculated)[a]	2954 (413)		
Birth head circumference, cm (back-calculated)[a]	34.1 (1.4)		
Newborn LAZ based on GA (n = 440)[b]	−0.96 (1.26)		
Newborn WAZ based on GA (n = 440)[b]	−0.43 (1.01)		
Newborn HCZ based on GA (n = 440)[b]	0.47 (1.03)		
Age at measurement, d	7 (8)	210 (3)	275 (4)
Length, cm	48.1 (2.8)	65.0 (2.3)	67.8 (2.4)
Weight, g	3089 (504)	7468 (923)	7939 (958)
MUAC, cm	10.3 (0.8)	14.2 (1.1)	14.3 (1.1)
Head circumference, cm	34.8 (1.5)	42.9 (1.3)	43.7 (1.3)
LAZ	−1.34 (1.24)	−1.39 (0.97)	−1.45 (0.98)
WAZ	−0.86 (0.95)	−0.58 (1.02)	−0.72 (1.01)
WLZ	0.03 (1.05) (n = 393)[c]	0.43 (0.98)	0.16 (0.96)
MUAC-for-age z-score	N/A	0.04 (0.94)	−0.04 (0.93)
HCZ	−0.07 (1.07)	−0.35 (0.97)	−0.52 (0.94)
Percentage of children with LAZ < −2	23.7	27.4	27.5
Percentage of children with WAZ < −2	9.7	8.7	11.1
Percentage of children with WLZ < −2	4.1 (n = 393)	0.7	1.3
Percentage of children with MUAC-for-age z-score < −2	N/A	1.5	1.8
Percentage of children with HCZ < −2	3.2	3.9	6.3

Note: Values are mean (SD) unless otherwise mentioned. N for enrollment 0–28 days of age and for 7 and 9 months ±14 days of the target date.

[a] Birth measurements (back-calculated for 0 days of life) are based on the Z-score at the measurement taken at enrollment, except for when weight at enrollment was measured 1-5 days after birth when birth weight was multiplied by 100/98, 100/96, 100/96, 100/98, and 100/99, respectively.

[b] INTERGROWTH-21st Newborn Size at Birth Chart Z-score not available for children under 232 gestational days at birth. Uses back-calculated birth measurements.

[c] 50 measurements out of reference chart for weight-for-length Z-score (length < 45 cm).

Table 3. Rearing environment variables: Maternal life situation and cognition

	N	Mean (SD)	Median (IQR)
Maternal life situation variables			
Subjective social status score (collected at 27 weeks) [range 0–9]	424	5.1 (1.6)	5 (2.3)
Maternal social support score (collected at 27 weeks) [0–48]	424	34.0 (7.5)	34 (12)
Maternal SRQ depression score (collected at 7 months) [0–20]	419	14.2 (4.1)	15 (5)
Maternal perceived stress score (collected at 9 months) [0–40]	408	21.9 (4.1)	22 (4)
Maternal life events score (collected at 9 months) [0–34]	409	29.4 (2.9)	30 (4)
Living environment score (collected at enrollment) [0–22]	444	13.1 (1.9)	13 (2)
Household food security score (collected at 27 weeks) [0–27]	424	18.5 (5.4)	19 (8)
HOME score (collected at 27 weeks) [0–36]	424	23.8 (2.4)	24 (3)
Mother-infant bond score (collected at 7 months) [0–24]	419	18.9 (2.4)	19 (4)
Maternal cognition variables (collected at 15 weeks)			
Digit span forward, successful subsets	429	5.2 (1.5)	5 (2)
Digit span backward, successful subsets	429	2.4 (1.5)	2 (1)
Food names in 60 seconds	429	15.3 (4.7)	15 (6)
Girls' names in 60 seconds	429	16.3 (5.2)	16 (7)
Mental rotation figures, correct answers [0–40]	429	23.9 (3.9)	24 (5)

Note: Non-standardized scores, where a higher score reflects a more positive outcome.

Table 4a. Association between VPS at 9 months of age and the duration of pregnancy at birth

Test variable	N	Pearson's correlation coefficient between the indicated test variable and GA at birth (continuous)	Mean (SD) value for the indicated test variable in participant subgroups			
			Infants born preterm	Infants born early term	Infants born full term	*P*[a]
VPS, ms	348	−0.01	454 (49)	455 (50)	453 (50)	0.89
Visual search, mean reaction time (single search, one object)	334	−0.01	440 (64)	437 (68)	434 (59)	0.81
Switch-task, mean reaction time (correct anticipatory)	365	−0.04	555 (105)	551 (79)	545 (78)	0.67
Attention disengagement, mean reaction time (control stimulus)	312	−0.01	350 (53)	366 (65)	357 (59)	0.26

[a] *P* value from ANOVA.

Table 4b. Association between VPS at 9 months of age and LAZ at enrollment

Test variable	Pearson's correlation coefficient between the indicated test variable and LAZ at enrollment (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with LAZ < −2 at enrollment	Infants with LAZ ≥ −2 at enrollment		
VPS, ms	−0.04	455 (45)	453 (51)	2 (−11, 14)	0.80
Visual search, reaction time (single search, one object), ms	0.04	430 (59)	438 (64)	−8 (−23, 9)	0.37
Switch-task, reaction time (correct anticipatory), ms	−0.09	561 (92)	545 (80)	16 (−5, 36)	0.13
Attention disengagement, reaction time (control stimulus), ms	−0.01	359 (62)	359 (60)	0 (−16, 16)	0.98

[a] *P* value from *t* test.

Table 4c. Association between VPS at 9 months of age and WAZ at enrollment

Test variable	Pearson's correlation coefficient between the indicated test variable and WAZ at enrollment (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with WAZ < −2 at enrollment	Infants with WAZ ≥ −2 at enrollment		
VPS, ms	−0.07	478 (49)	452 (49)	26 (6, 45)	**0.009**
Visual search, reaction time (single search one object), ms	−0.00	454 (50)	435 (64)	19 (−5, 43)	0.13
Switch-task, reaction time (correct anticipatory), ms	−0.10	573 (106)	546 (80)	27 (−16, 70)	0.21
Attention disengagement, reaction time (control stimulus), ms	−0.03	380 (75)	357 (59)	23 (−4, 49)	0.09

[a] *P* value from *t* test. **Bold** indicates statistically significant.

Table 4d. Association between VPS at 9 months of age and WLZ at enrollment

Test variable	Pearson's correlation coefficient between the indicated test variable and WLZ at enrollment (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with WLZ < 50th percentile at enrollment	Infants with WLZ ≥ 50th percentile at enrollment		
VPS, ms	0.04	453 (51)	455 (48)	−3 (−14, 8)	0.63
Visual search, reaction time (single search, one object), ms	0.03	435 (64)	441 (61)	−6 (−21, 8)	0.40
Switch-task, reaction time (correct anticipatory), ms	0.00	544 (81)	548 (76)	−3 (−21, 14)	0.69
Attention disengagement, reaction time (control stimulus), ms	0.02	360 (59)	361 (61)	−1 (−15, 14)	0.92

[a] *P* value from *t* test.

Table 4e. Association between VPS at 9 months of age and HCZ at enrollment

Test variable	Pearson's correlation coefficient between the indicated test variable and HCZ at enrollment (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with HCZ < 50th percentile at enrollment	Infants with HCZ ≥ 50th percentile at enrollment		
VPS, ms	−0.02	454 (46)	454 (53)	0 (−11, 10)	0.98
Visual search, reaction time (single search, one object), ms	0.07	432 (64)	440 (62)	−8 (−23, 5)	0.20
Switch-task, reaction time (correct anticipatory), ms	−0.10	552 (83)	545 (83)	7 (−10, 24)	0.42
Attention disengagement, reaction time (control stimulus), ms	−0.02	360 (61)	358 (60)	2 (−12, 15)	0.82

[a] *P* value from *t* test.

Table 4f. Association between VPS at 9 months of age and MUAC at enrollment

Test variable	Pearson's correlation coefficient between the indicated test variable and MUAC at enrollment (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with MUAC < 50th percentile at enrollment	Infants with MUAC ≥ 50th percentile at enrollment		
VPS, ms	−0.09	456 (49)	452 (50)	4 (−7, 14)	0.46
Visual search, reaction time (single search, one object), ms	0.01	434 (57)	439 (68)	−5 (−18, 9)	0.48
Switch-task, reaction time (correct anticipatory), ms	−0.11	554 (89)	543 (77)	11 (−6, 28)	0.22
Attention disengagement, reaction time (control stimulus), ms	−0.06	362 (63)	356 (59)	6 (−8, 19)	0.41

[a] *P* value from *t* test.

Table 4g. Association between VPS at 9 months of age and LAZ at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and LAZ at 9 months (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with LAZ < −2 at 9 months	Infants with LAZ ≥ −2 at 9 months		
VPS, ms	−0.02	456 (47)	453 (53)	4 (−8, 15)	0.55
Visual search, reaction time (single search, one object), ms	0.01	433 (58)	437 (65)	−4 (−19, 11)	0.63
Switch-task, reaction time (correct anticipatory), ms	−0.02	557 (84)	545 (82)	12 (−7, 31)	0.23
Attention disengagement, reaction time (control stimulus), ms	−0.02	358 (62)	359 (60)	−1 (−16, 14)	0.88

[a] *P* value from *t* test.

Table 4h. Association between VPS at 9 months of age and WAZ at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and WAZ at 9 months (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with WAZ < −2 at 9 months	Infants with WAZ ≥ −2 at 9 months		
VPS, ms	0.04	451 (48)	454 (50)	-3 (-19, 12)	0.70
Visual search, reaction time (single search, one object), ms	0.08	434 (69)	436 (62)	-2 (-23, 19)	0.83
Switch-task, reaction time (correct anticipatory), ms	−0.02	544 (69)	549 (84)	-5 (-31, 21)	0.73
Attention disengagement, reaction time (control stimulus), ms	0.02	355 (69)	360 (60)	-5 (-26, 16)	0.65

[a] *P* value from *t* test.

Table 4i. Association between VPS at 9 months of age and WLZ at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and WLZ at 9 months (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with WLZ < 50th percentile at 9 months	Infants with WLZ ≥ 50th percentile at 9 months		
VPS, ms	0.06	451 (47)	457 (52)	−6 (−17, 4)	0.23
Visual search, reaction time (single search, one object), ms	0.09	429 (62)	444 (63)	−15 (−28, −1)	**0.035**
Switch-task, reaction time (correct anticipatory), ms	−0.02	549 (80)	548 (85)	2 (−15, 19)	0.84
Attention disengagement, reaction time (control stimulus), ms	0.04	358 (61)	360 (61)	−2 (−15, 12)	0.83

[a] *P* value from *t* test. **Bold** indicates statistically significant.

Table 4j. Association between VPS at 9 months of age and HCZ at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and HCZ at 9 months (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with HCZ < 50th percentile at 9 months	Infants with HCZ ≥ 50th percentile at 9 months		
VPS, ms	−0.01	453 (46)	455 (54)	−2 (−12, 9)	0.75
Visual search, reaction time (single search one object), ms	0.15	429 (61)	444 (64)	−16 (−29, -2)	**0.024**
Switch-task, reaction time (correct anticipatory), ms	−0.15	558 (83)	539 (82)	18 (1, 35)	**0.034**
Attention disengagement, reaction time (control stimulus), ms	−0.02	360 (60)	358 (61)	2 (−11, 16)	0.72

[a] *P* value from *t* test. **Bold** indicates statistically significant.

Table 4k. Association between VPS at 9 months of age and MUAC at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and MUAC at 9 months (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with MUAC < 50th percentile at 9 months	Infants with MUAC ≥ 50th percentile at 9 months		
VPS, ms	0.04	453 (48)	455 (51)	−2 (−13, 8)	0.65
Visual search, reaction time (single search, one object), ms	0.08	432 (60)	441 (65)	−9 (−23, 4)	0.17
Switch-task, reaction time (correct anticipatory), ms	−0.04	552 (80)	545 (86)	7 (−10, 24)	0.44
Attention disengagement, reaction time (control stimulus), ms	0.05	358 (59)	360 (62)	−2 (−16, 11)	0.74

[a] *P* value from *t* test.

Table 4l. Association between VPS at 9 months of age and the change in LAZ (ΔLAZ) from enrollment to 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and ΔLAZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	*P*[a]
		Infants with ΔLAZ < 50th percentile	Infants with ΔLAZ ≥ 50th percentile		
VPS, ms	0.02	452 (50)	456 (50)	−3 (−14, 7)	0.51
Visual search, reaction time (single search, one object), ms	−0.03	436 (43)	436 (63)	1 (−13, 14)	0.94
Switch-task, reaction time (correct anticipatory), ms	0.08	544 (77)	553 (88)	−9 (−26, 8)	0.30
Attention disengagement, reaction time (control stimulus), ms	−0.01	357 (60)	361 (62)	−5 (−18, 9)	0.50

[a] *P* value from *t* test.

Table 4m. Association between VPS at 9 months of age and the change in WAZ (ΔWAZ) from enrollment to 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and ΔWAZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	*P*[a]
		Infants with ΔWAZ < 50th percentile	Infants with ΔWAZ ≥ 50th percentile		
VPS, ms	0.10	450 (47)	458 (52)	−8 (−19, 2)	0.11
Visual search, reaction time (single search, one object), ms	0.08	434 (62)	438 (64)	−4 (−18, 9)	0.54
Switch-task, reaction time (correct anticipatory), ms	0.06	544 (78)	553 (88)	−10 (−27, 7)	0.26
Attention disengagement, reaction time (control stimulus), ms	0.05	357 (52)	361 (59)	−4 (−17, 10)	0.58

[a] *P* value from *t* test.

Table 4n. Association between VPS at 9 months of age and the change in WLZ (ΔWLZ) from enrollment to 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and ΔWLZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	*P*[a]
		Infants with ΔWLZ < 50th percentile	Infants with ΔWLZ ≥ 50th percentile		
VPS, ms	0.00	452 (47)	457 (51)	−5 (−16, 6)	0.41
Visual search, reaction time (single search, one object), ms	0.03	433 (61)	443 (63)	−10 (−24, 4)	0.17
Switch-task, reaction time (correct anticipatory), ms	−0.03	545 (72)	547 (85)	−3 (−20, 15)	0.76
Attention disengagement, reaction time (control stimulus), ms	0.01	360 (59)	362 (61)	−2 (−16, 12)	0.77

[a] *P* value from *t* test.

Table 4o. Association between VPS at 9 months of age and the change in HCZ (ΔHCZ) from enrollment to 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and ΔHCZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	*P*[a]
		Infants with ΔHCZ < 50th percentile	Infants with ΔHCZ ≥ 50th percentile		
VPS, ms	0.02	454 (47)	454 (52)	0 (−10, 11)	0.93
Visual search, reaction time (single search, one object), ms	0.07	435 (65)	437 (61)	−2 (−15, 12)	0.82
Switch-task, reaction time (correct anticipatory), ms	−0.03	551 (78)	546 (87)	4 (−12, 22)	0.61
Attention disengagement, reaction time (control stimulus), ms	0.00	359 (61)	359 (61)	0 (−14, 14)	0.99

[a] *P* value from *t* test.

Table 4p. Association between VPS at 9 months of age and the change in MUAC (ΔMUAC) from enrollment to 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and ΔMUAC (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P[a]
		Infants with ΔMUAC < 50th percentile	Infants with ΔMUAC ≥ 50th percentile		
VPS, ms	0.10	451 (49)	456 (51)	−5 (−15, 6)	0.36
Visual search, reaction time (single search, one object), ms	0.07	431 (63)	441 (63)	−10 (−24, 4)	0.15
Switch-task, reaction time (correct anticipatory), ms	0.04	549 (77)	548 (88)	1 (−17, 18)	0.96
Attention disengagement, reaction time (control stimulus), ms	0.10	356 (62)	363 (59)	−7 (−20, 7)	0.32

[a] *P* value from *t* test.

Table 5a. Successful searches on the visual search task by GA groups

Test variable	Spearman's rank correlation coefficient between the indicated test variable and GA (continuous)	Median (IQR) value for the indicated test variable in participant subgroups			P[a]
		Infants born preterm	Infants born early term	Infants born full term	
Visual search, % of successful search, one object	−0.06	100 (14)	100 (13)	100 (14)	0.92
Visual search, % of successful search, multiple objects	0.05	63 (33)	62 (25)	63 (25)	0.48
Visual search, % of successful search, conjunction	0.00	46 (25)	0.43 (35)	42 (27)	0.53

[a] *P* value from Kruskal-Wallis test.

Table 5b. Successful searches on the visual search task by LAZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and LAZ at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		*P*[a]
		Infants with LAZ < −2 at enrollment	Infants with LAZ ≥ −2 at enrollment	
Visual search, % of successful search, one object	−0.04	100 (7)	100 (14)	0.43
Visual search, % of successful search, multiple objects	0.01	67 (28)	63 (25)	0.57
Visual search, % of successful search, conjunction	0.03	50 (31)	43 (31)	0.38

[a] *P* value from Mann-Whitney *U* test.

Table 5c. Successful searches on the visual search task by WAZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WAZ at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with WAZ < −2 at enrollment	Infants with WAZ ≥ −2 at enrollment	
Visual search, % of successful search, one object	0.01	100 (17)	100 (13)	0.84
Visual search, % of successful search, multiple objects	0.06	67 (32)	63 (25)	0.60
Visual search, % of successful search, conjunction	0.07	43 (25)	43 (27)	0.23

[a] *P* value from Mann-Whitney *U* test.

Table 5d. Successful searches on the visual search task by WLZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WLZ at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with WLZ < 50th percentile at enrollment	Infants with WLZ ≥ 50th percentile at enrollment	
Visual search, % of successful search, one object	0.04	100 (17)	100 (13)	0.08
Visual search, % of successful search, multiple objects	0.01	63 (32)	63 (25)	0.40
Visual search, % of successful search, conjunction	0.08	43 (29)	50 (34)	0.30

[a] *P* value from Mann-Whitney *U* test.

Table 5e. Successful searches on the visual search task by HCZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and HCZ at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		*P*[a]
		Infants with HCZ < 50th percentile at enrollment	Infants with HCZ ≥ 50th percentile at enrollment	
Visual search, % of successful search, one object	0.06	100 (17)	100 (13)	0.41
Visual search, % of successful search, multiple objects	−0.02	63 (25)	63 (25)	0.42
Visual search, % of successful search, conjunction	0.05	43 (29)	46 (28)	0.23

[a] *P* value from Mann-Whitney *U* test.

Table 5f. Successful searches on the visual search task by MUAC at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and MUAC at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with MUAC < 50th percentile at enrollment	Infants with MUAC ≥ 50th percentile at enrollment	
Visual search, % of successful search, one object	0.02	100 (14)	100 (13)	0.84
Visual search, % of successful search, multiple objects	0.10	63 (25)	63 (25)	0.61
Visual search, % of successful search, conjunction	0.14	43 (32)	50 (29)	**0.041**

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table 5g. Successful searches on the visual search task by LAZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and LAZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with LAZ < −2 at 9 months	Infants with LAZ ≥ −2 at 9 months	
Visual search, % of successful search, one object	0.01	100 (14)	1.00 (13)	0.53
Visual search, % of successful search, multiple objects	0.03	63 (25)	63 (25)	0.56
Visual search, % of successful search, conjunction	0.13	40 (32)	50 (27)	0.06

[a] *P* value from Mann-Whitney *U* test.

Table 5h. Successful searches on the visual search task by WAZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WAZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		*P*[a]
		Infants with WAZ < −2 at 9 months	Infants with WAZ ≥ −2 at 9 months	
Visual search, % of successful search, one object	0.01	100 (13)	100 (14)	0.50
Visual search, % of successful search, multiple objects	0.02	67 (25)	63 (25)	0.47
Visual search, % of successful search, conjunction	0.16	38 (25)	43 (27)	**0.024**

[a] *P* value from Mann-Whitney *U* test. Bold indicates statistically significant.

Table 5i. Successful searches on the visual search task by WLZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WLZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with WLZ < 50th percentile at 9 months	Infants with WLZ ≥ 50th percentile at 9 months	
Visual search, % of successful search, one object	0.01	100 (13)	100 (14)	0.12
Visual search, % of successful search, multiple objects	0.01	63 (25)	63 (25)	0.65
Visual search, % of successful search, conjunction	0.01	43 (29)	50 (29)	0.08

[a] *P* value from Mann-Whitney *U* test.

Table 5j. Successful searches on the visual search task by HCZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and HCZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups: Infants with HCZ < 50th percentile at 9 months	Median (IQR) value for the indicated test variable in participant subgroups: Infants with HCZ ≥ 50th percentile at 9 months	P[a]
Visual search, % of successful search, one object	0.02	100 (17)	100 (13)	0.16
Visual search, % of successful search, multiple objects	−0.04	63 (25)	63 (25)	0.68
Visual search, % of successful search, conjunction	0.05	43 (27)	50 (31)	0.57

[a] *P* value from Mann-Whitney *U* test.

Table 5k. Successful searches on the visual search task by MUAC at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and MUAC at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups: Infants with MUAC < 50th percentile at 9 months	Median (IQR) value for the indicated test variable in participant subgroups: Infants with MUAC ≥ 50th percentile at 9 months	*P*[a]
Visual search, % of successful search, one object	0.74	100 (14)	100 (13)	0.80
Visual search, % of successful search, multiple objects	0.12	63 (25)	63 (25)	0.75
Visual search, % of successful search, conjunction	0.03	43 (25)	50 (29)	**0.009**

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table 5l. Successful searches on the visual search task by the change in LAZ (ΔLAZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔLAZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups: Infants with ΔLAZ < 50th percentile at 9 months	Median (IQR) value for the indicated test variable in participant subgroups: Infants with ΔLAZ ≥ 50th percentile at 9 months	*P*[a]
Visual search, % of successful search, one object	0.01	100 (14)	100 (14)	0.97
Visual search, % of successful search, multiple objects	0.02	63 (25)	67 (25)	0.63
Visual search, % of successful search, conjunction	0.06	43 (27)	43 (31)	0.61

[a] *P* value from Mann-Whitney *U* test.

Table 5m. Successful searches on the visual search task by the change in WAZ (ΔWAZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔWAZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups: Infants with ΔWAZ < 50th percentile at 9 months	Median (IQR) value for the indicated test variable in participant subgroups: Infants with ΔWAZ ≥ 50th percentile at 9 months	*P*[a]
Visual search, % of successful search, one object	0.09	100 (14)	100 (14)	0.79
Visual search, % of successful search, multiple objects	0.01	63 (25)	67 (30)	0.25
Visual search, % of successful search, conjunction	0.07	43 (29)	50 (29)	0.09

[a] *P* value from Mann-Whitney *U* test.

Table 5n. Successful searches on the visual search task by the change in WLZ (ΔWLZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔWLZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔWLZ < 50th percentile at 9 months	Infants with ΔWLZ ≥ 50th percentile at 9 months	
Visual search, % of successful search, one object	−0.02	100 (13)	100 (14)	0.84
Visual search, % of successful search, multiple objects	0.00	63 (25)	63 (25)	0.95
Visual search, % of successful search, conjunction	0.03	43 (31)	43 (24)	0.86

[a] *P* value from Mann-Whitney *U* test.

Table 5o. Successful searches on the visual search task by the change in HCZ (ΔHCZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔHCZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔHCZ < 50th percentile at 9 months	Infants with ΔHCZ ≥ 50th percentile at 9 months	
Visual search, % of successful search, one object	−0.03	100 (13)	100 (14)	0.70
Visual search, % of successful search, multiple objects	0.00	63 (25)	63 (25)	0.89
Visual search, % of successful search, conjunction	0.01	43 (31)	50 (27)	0.31

[a] *P* value from Mann-Whitney *U* test.

Table 5p. Successful searches on the visual search task by the change in MUAC (ΔMUAC) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔMUAC at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with ΔMUAC < 50th percentile at 9 months	Infants with ΔMUAC ≥ 50th percentile at 9 months	
Visual search, % of successful search, one object	−0.03	100 (13)	100 (14)	0.78
Visual search, % of successful search, multiple objects	−0.04	63 (25)	63 (25)	0.36
Visual search, % of successful search, conjunction	0.02	43 (24)	43 (29)	0.88

[a] *P* value from Mann-Whitney *U* test.

Table 6a. Proportion of correct anticipation on switch-task by GA at birth

Test variable	Spearman's rank correlation coefficient between the indicated test variable and GA (continuous)	Median (IQR) value for the indicated test variable in participant subgroups			P[a]
		Infants born preterm	Infants born early term	Infants born full term	
Switch-task, % of correct anticipation, pre-switch	0.05	78 (39)	79 (43)	80 (36)	0.75
Switch-task, % of correct anticipation, post-switch	−0.02	67 (41)	55 (45)	58 (42)	0.32

[a] *P* value from Kruskal-Wallis test.

Table 6b. Proportion of correct anticipation on switch-task by LAZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable LAZ at enrollment	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with LAZ < −2 at enrollment	Infants with LAZ ≥ −2 at enrollment	
Switch-task, % of correct anticipation, pre-switch	0.04	71 (42)	80 (37)	0.11
Switch-task, % of correct anticipation, post-switch	0.11	50 (38)	58 (44)	0.13

[a] *P* value from Mann-Whitney *U* test.

Table 6c. Proportion of correct anticipation on switch-task by WAZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable WAZ at enrollment	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with WAZ < −2 at enrollment	Infants with WAZ ≥ −2 at enrollment	
Switch-task, % of correct anticipation, pre-switch	−0.02	90 (42)	79 (39)	0.42
Switch-task, % of correct anticipation, post-switch	0.09	62 (44)	56 (44)	0.59

[a] *P* value from Mann-Whitney *U* test.

Table 6d. Proportion of correct anticipation on switch-task by WLZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable WLZ at enrollment	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with WLZ < 50th percentile at enrollment	Infants with WLZ ≥ 50th percentile at enrollment	
Switch-task, % of correct anticipation, pre-switch	−0.03	79 (36)	80 (38)	0.82
Switch-task, % of correct anticipation, post-switch	0.03	56 (44)	58 (44)	0.47

[a] *P* value from Mann-Whitney *U* test.

Table 6e. Proportion of correct anticipation on switch-task by HCZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable HCZ at enrollment	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with HCZ < 50th percentile at enrollment	Infants with HCZ ≥ 50th percentile at enrollment	
Switch-task, % of correct anticipation, pre-switch	0.07	79 (39)	80 (39)	0.35
Switch-task, % of correct anticipation, post-switch	0.07	55 (39)	58 (46)	0.32

[a] *P* value from Mann-Whitney *U* test.

Table 6f. Proportion of correct anticipation on switch-task by MUAC at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable MUAC at enrollment	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with MUAC < 50th percentile at enrollment	Infants with MUAC ≥ 50th percentile at enrollment	
Switch-task, % of correct anticipation, pre-switch	0.02	80 (39)	79 (44)	0.94
Switch-task, % of correct anticipation, post-switch	0.13	50 (44)	60 (43	**0.01**

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table 6g. Proportion of correct anticipation on switch-task by LAZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable LAZ at 9 months	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with LAZ < −2 at 9 months	Infants with LAZ ≥ −2 at 9 months	
Switch-task, % of correct anticipation, pre-switch	−0.04	86 (50)	77 (38)	0.39
Switch-task, % of correct anticipation, post-switch	−0.04	55 (44)	57 (44)	0.86

[a] *P* value from Mann-Whitney *U* test.

Table 6h. Proportion of correct anticipation on switch-task by WAZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable WAZ at 9 months	Median (IQR) value for the indicated test variable in participant subgroups		*P*[a]
		Infants with WAZ < −2 at 9 months	Infants with WAZ ≥ −2 at 9 months	
Switch-task, % of correct anticipation, pre-switch	0.02	90 (36)	77 (39)	0.05
Switch-task, % of correct anticipation, post-switch	0.03	60 (42)	55 (42)	0.10

[a] *P* value from Mann-Whitney *U* test.

Table 6i. Proportion of correct anticipation on switch-task by WLZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable WLZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with WLZ < 50th percentile at 9 months	Infants with WLZ ≥ 50th percentile at 9 months	
Switch-task, % of correct anticipation, pre-switch	0.05	79 (43)	80 (36)	0.43
Switch-task, % of correct anticipation, post-switch	−0.10	58 (44)	54 (48)	0.15

[a] *P* value from Mann-Whitney *U* test.

Table 6j. Proportion of correct anticipation on switch-task by HCZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable HCZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with HCZ < 50th percentile at 9 months	Infants with HCZ ≥ 50th percentile at 9 months	
Switch-task, % of correct anticipation, pre-switch	0.14	75 (42)	85 (42)	**0.003**
Switch-task, % of correct anticipation, post-switch	0.04	55 (47)	59 (43)	0.46

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table 6k. Proportion of correct anticipation on switch-task by MUAC at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable MUAC at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with MUAC < 50th percentile at 9 months	Infants with MUAC ≥ 50th percentile at 9 months	
Switch-task, % of correct anticipation, pre-switch	0.03	79 (39)	79 (44)	0.70
Switch-task, % of correct anticipation, post-switch	−0.09	58 (42)	55 (50)	0.34

[a] *P* value from Mann-Whitney *U* test.

Table 6l. Proportion of correct anticipation on switch-task by change in LAZ (ΔLAZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔLAZ (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔLAZ < 50th percentile	Infants with ΔLAZ ≥ 50th percentile	
Switch-task, % of correct anticipation, pre-switch	−0.06	81 (37)	77 (39)	0.40
Switch-task, % of correct anticipation, post-switch	−0.14	58 (48)	56 (38)	0.19

[a] *P* value from Mann-Whitney *U* test.

Table 6m. Proportion of correct anticipation on switch-task by change in WAZ (ΔWAZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔWAZ (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔWAZ < 50th percentile	Infants with ΔWAZ ≥ 50th percentile	
Switch-task, % of correct anticipation, pre-switch	0.03	79 (43)	82 (41)	0.49
Switch-task, % of correct anticipation, post-switch	−0.16	64 (43)	50 (45)	**< 0.001**

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table 6n. Proportion of correct anticipation on switch-task by the change in WLZ (ΔWLZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔWLZ (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔWLZ < 50th percentile	Infants with ΔWLZ ≥ 50th percentile	
Switch-task, % of correct anticipation, pre-switch	0.06	80 (37)	79 (37)	0.80
Switch-task, % of correct anticipation, post-switch	−0.11	58 (45)	55 (50)	0.26

[a] *P* value from Mann-Whitney *U* test.

Table 6o. Proportion of correct anticipation on switch-task by the change in HCZ (ΔHCZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔHCZ (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔHCZ < 50th percentile	Infants with ΔHCZ ≥ 50th percentile	
Switch-task, % of correct anticipation, pre-switch	0.10	77 (42)	82 (43)	0.17
Switch-task, % of correct anticipation, post-switch	−0.06	57 (44)	56 (42)	0.30

[a] *P* value from Mann-Whitney *U* test.

Table 6p. Proportion of correct anticipation on switch-task by the change in MUAC (ΔMUAC) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔMUAC (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔWAZ < 50th percentile	Infants with ΔWAZ ≥ 50th percentile	
Switch-task, % of correct anticipation, pre-switch	0.00	80 (38)	77 (43)	0.99
Switch-task, % of correct anticipation, post-switch	−0.18	62 (44)	50 (45)	**0.008**

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table 7a. Occurred shift and dwell time on faces on attention disengagement task by GA

Test variable	Correlation coefficient between the indicated test variable and GA (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]			P^c
		Infants born preterm	Infants born early term	Infants born full term	
Attention disengagement, happy stimulus, % of occurred shifts	0.05	75 (50)	75 (30)	75 (43)	0.68
Attention disengagement, fearful stimulus, % of occurred shifts	−0.03	80 (57)	67 (33)	71 (38)	0.47
Attention disengagement, control stimulus, % of occurred shifts	0.07	100 (0)	100 (0)	100 (0)	0.17
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.06	1,107 (430)	1,348 (533)	1,249 (513)	0.022

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Kruskal-Wallis test for occurred shifts and from ANOVA for dwell times.

Table 7b. Occurred shift and dwell time on faces on attention disengagement task by LAZ at enrollment

Test variable	Correlation coefficient between the indicated test variable and LAZ at enrollment (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with LAZ < −2 at enrollment	Infants with LAZ ≥ −2 at enrollment	
Attention disengagement, happy stimulus, % of occurred shifts	−0.00	80 (28)	75 (50)	0.50
Attention disengagement, fearful stimulus, % of occurred shifts	−0.04	75 (38)	71 (38)	0.42
Attention disengagement, control stimulus, % of occurred shifts	0.04	100 (0)	100 (0)	0.22
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.05	1,254 (476)	1,264 (525)	0.88

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[a] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7c. Occurred shift and dwell time on faces on attention disengagement task by WAZ at enrollment

Test variable	Correlation coefficient between the indicated test variable and WAZ at enrollment (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with WAZ < −2 at enrollment	Infants with WAZ ≥ −2 at enrollment	
Attention disengagement, happy stimulus, % of occurred shifts	0.03	86 (50)	75 (42)	0.66
Attention disengagement, fearful stimulus, % of occurred shifts	−0.05	73 (45)	71 (38)	0.94
Attention disengagement, control stimulus, % of occurred shifts	0.03	100 (0)	100 (0)	**0.025**[d]
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	−0.03	1,376 (451)	1,253 (517)	0.28

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times. **Bold** indicates statistically significant.
[d] Infants with WAZ < −2 at enrollment had a higher proportion of events where all shifts did not occur compared to infants with WAZ ≥ 2 at enrollment (9.1% [2/22] and 1.7% [5/290], respectively, *P* = 0.08, Fisher's exact test).

Table 7d. Occurred shift and dwell time on faces on attention disengagement task by WLZ at enrollment

Test variable	Correlation coefficient between the indicated test variable and WLZ at enrollment (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with WLZ < 50th percentile at enrollment	Infants with WLZ ≥ 50th percentile at enrollment	
Attention disengagement, happy stimulus, % of occurred shifts	−0.01	75 (28)	71 (50)	0.19
Attention disengagement, fearful stimulus, % of occurred shifts	0.01	71 (38)	67 (45)	0.40
Attention disengagement, control stimulus, % of occurred shifts	−0.03	100 (0)	100 (0)	0.46
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	−0.05	1,264 (515)	1,283 (533)	0.77

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7e. Occurred shift and dwell time on faces on attention disengagement task by HCZ at enrollment

Test variable	Correlation coefficient between the indicated test variable and HCZ at enrollment (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with HCZ < 50th percentile at enrollment	Infants with HCZ ≥ 50th percentile at enrollment	
Attention disengagement, happy stimulus, % of occurred shifts	−0.05	75 (43)	75 (38)	0.41
Attention disengagement, fearful stimulus, % of occurred shifts	−0.10	75 (38)	68 (40)	**0.046**
Attention disengagement, control stimulus, % of occurred shifts	−0.01	100 (0)	100 (0)	0.74
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	−0.02	1,279 (515)	1,244 (512)	0.55

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times. **Bold** indicates statistically significant.

Table 7f. Occurred shift and dwell time on faces on attention disengagement task by MUAC at enrollment

Test variable	Correlation coefficient between the indicated test variable and MUAC at enrollment (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with MUAC < 50th percentile at enrollment	Infants with MUAC ≥ 50th percentile at enrollment	
Attention disengagement, happy stimulus, % of occurred shifts	0.08	75 (38)	75 (43)	0.55
Attention disengagement, fearful stimulus, % of occurred shifts	0.08	71 (36)	71 (38)	0.65
Attention disengagement, control stimulus, % of occurred shifts	0.04	100 (0)	100 (0)	0.20
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.07	1,235 (40)	1,286 (42)	0.38

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7g. Occurred shift and dwell time on faces on attention disengagement task by LAZ at 9 months

Test variable	Correlation coefficient between the indicated test variable and LAZ at 9 months (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P[c]
		Infants with LAZ < −2 at 9 months	Infants with LAZ ≥ −2 at 9 months	
Attention disengagement, happy stimulus, % of occurred shifts	−0.02	75 (50)	75 (31)	0.43
Attention disengagement, fearful stimulus, % of occurred shifts	−0.04	71 (50)	67 (38)	0.33
Attention disengagement, control stimulus, % of occurred shifts	−0.03	100 (0)	100 (0)	0.45
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.02	1,207 (453)	1,281 (532)	0.27

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7h. Occurred shift and dwell time on faces on attention disengagement task by WAZ at 9 months

Test variable	Correlation coefficient between the indicated test variable and WAZ at 9 months (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		*P*[c]
		Infants with WAZ < −2 at 9 months	Infants with WAZ ≥ −2 at 9 months	
Attention disengagement, happy stimulus, % of occurred shifts	0.06	75 (38)	75 (50)	0.73
Attention disengagement, fearful stimulus, % of occurred shifts	0.04	75 (38)	71 (38)	0.91
Attention disengagement, control stimulus, % of occurred shifts	0.02	100 (0)	100 (0)	0.80
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.05	1,167 (516)	1,273 (491)	0.25

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7i. Occurred shift and dwell time on faces on attention disengagement task by WLZ at 9 months

Test variable	Correlation coefficient between the indicated test variable and WLZ at 9 months (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with WLZ < 50th percentile at 9 months	Infants with WLZ ≥ 50th percentile at 9 months	
Attention disengagement, happy stimulus, % of occurred shifts	0.10	75 (38)	83 (40)	**0.029**
Attention disengagement, fearful stimulus, % of occurred shifts	0.11	68 (42)	75 (38)	0.08
Attention disengagement, control stimulus, % of occurred shifts	0.06	100 (0)	100 (0)	0.07
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.04	1,233 (501)	1,292 (526)	0.31

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times. **Bold** indicates statistically significant.

Table 7j. Occurred shift and dwell time on faces on attention disengagement task by HCZ at 9 months

Test variable	Correlation coefficient between the indicated test variable and HCZ at 9 months (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with HCZ < 50th percentile at 9 months	Infants with HCZ ≥ 50th percentile at 9 months	
Attention disengagement, happy stimulus, % of occurred shifts	−0.04	75 (30)	75 (50	0.77
Attention disengagement, fearful stimulus, % of occurred shifts	−0.06	75 (38)	68 (33)	0.17
Attention disengagement, control stimulus, % of occurred shifts	−0.07	100 (0)	100 (0)	0.21
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	−0.02	1,255 (501)	1,268 (528)	0.83

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7k. Occurred shift and dwell time on faces on attention disengagement task by MUAC at 9 months

Test variable	Correlation coefficient between the indicated test variable and MUAC at 9 months (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P[c]
		Infants with MUAC < 50th percentile at 9 months	Infants with MUAC ≥ 50th percentile at 9 months	
Attention disengagement, happy stimulus, % of occurred shifts	0.08	75 (38)	75 (43)	0.55
Attention disengagement, fearful stimulus, % of occurred shifts	0.08	71 (36)	71 (38)	0.65
Attention disengagement, control stimulus, % of occurred shifts	0.04	100 (0)	100 (0)	0.20
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.07	1,235 (40)	1,286 (43)	0.38

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7l. Occurred shift and dwell time on faces on attention disengagement task by change in LAZ (ΔLAZ) from enrollment to 9 months

Test variable	Correlation coefficient between the indicated test variable and ΔLAZ (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		*P*[c]
		Infants with ΔLAZ < 50th percentile	Infants with ΔLAZ ≥ 50th percentile	
Attention disengagement, happy stimulus, % of occurred shifts	0.01	75 (50)	75 (43)	0.58
Attention disengagement, fearful stimulus, % of occurred shifts	0.02	71 (40)	71 (38)	0.49
Attention disengagement, control stimulus, % of occurred shifts	−0.09	100 (0)	100 (0)	0.26
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	−0.03	1,265 (42)	1,258 (40)	0.91

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7m. Occurred shift and dwell time on faces on attention disengagement task by change in WAZ (ΔWAZ) from enrollment to 9 months

Test variable	Correlation coefficient between the indicated test variable and ΔWAZ (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with ΔWAZ < 50th percentile	Infants with ΔWAZ ≥ 50th percentile	
Attention disengagement, happy stimulus, % of occurred shifts	0.04	73 (38)	80 (43)	0.17
Attention disengagement, fearful stimulus, % of occurred shifts	0.09	67 (41)	75 (38)	**0.02**
Attention disengagement, control stimulus, % of occurred shifts	−0.02	100 (0)	100 (0)	0.68
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.07	1,240 (41)	1,283 (41)	0.46

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times. **Bold** indicates statistically significant.

Table 7n. Occurred shift and dwell time on faces on attention disengagement task by the change in WLZ (ΔWLZ) from enrollment to 9 months

Test variable	Correlation coefficient between the indicated test variable and ΔWLZ (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with ΔWLZ < 50th percentile	Infants with ΔWLZ ≥ 50th percentile	
Attention disengagement, happy stimulus, % of occurred shifts	0.08	71 (38)	75 (43)	0.14
Attention disengagement, fearful stimulus, % of occurred shifts	0.08	67 (38)	73 (38)	0.10
Attention disengagement, control stimulus, % of occurred shifts	0.08	100 (0)	100 (0)	0.44
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.09	1,264 (519)	1,283 (46)	0.77

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7o. Occurred shift and dwell time on faces on attention disengagement task by the change in HCZ (ΔHCZ) from enrollment to 9 months

Test variable	Correlation coefficient between the indicated test variable and ΔHCZ (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with ΔHCZ < 50th percentile	Infants with ΔHCZ ≥ 50th percentile	
Attention disengagement, happy stimulus, % of occurred shifts	0.02	75 (43)	75 (50)	0.81
Attention disengagement, fearful stimulus, % of occurred shifts	0.06	71 (45)	71 (38)	0.46
Attention disengagement, control stimulus, % of occurred shifts	−0.03	100 (0)	100 (0)	0.72
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.01	1,243 (42)	1,280 (41)	0.54

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 7p. Occurred shift and dwell time on faces on attention disengagement task by the change in MUAC (ΔMUAC) from enrollment to 9 months

Test variable	Correlation coefficient between the indicated test variable and ΔMUAC (continuous)[b]	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^c
		Infants with ΔMUAC < 50th percentile	Infants with ΔMUAC ≥ 50th percentile	
Attention disengagement, happy stimulus, % of occurred shifts	0.04	75 (50)	75 (38)	0.16
Attention disengagement, fearful stimulus, % of occurred shifts	0.09	71 (45)	71 (38)	0.25
Attention disengagement, control stimulus, % of occurred shifts	0.01	100 (0)	100 (0)	0.76
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	0.11	1,243 (42)	1,280 (41)	0.54

[a] Values are median (IQR) for occurred shifts and mean (SD) for dwell times.
[b] Spearman's rank correlation coefficient for occurred shifts and Pearson's correlation coefficient for dwell times.
[c] *P* value from Mann-Whitney *U* test for occurred shifts and from *t* test for dwell times.

Table 8. Association between eye tracking scores at 9 months and rearing environment variables (parental sociodemographic and anthropometric variables) by Spearman's rank correlation coefficient

Test variable	Maternal age	Paternal age (one missing)	Maternal parity	# people living in the household	# children under 5 years old living in household	Maternal height	Maternal BMI at enrollment	Maternal BMI change from enrollment to 9 months	Completed years of maternal education
VPS, ms (n = 348)	−0.03	−0.03	0.05	−0.01	−0.01	−0.04	−0.07	0.02	−0.05
Visual search, mean reaction time (single search) (n = 334)	0.03	0.06	−0.04	−0.03	0.03	−0.02	−0.09	0.10	0.02
Switch-task, mean reaction time (correct anticipatory) (n = 365)	−0.04	−0.00	0.10	0.04	0.00	−0.04	−0.02	0.02	−0.04
Attention disengagement, mean reaction time (control stimulus) (n = 312)	−0.01	−0.05	0.01	−0.02	−0.04	−0.02	−0.01	0.01	0.02
Visual search, % of successful search, single search (n = 340)	−0.07	−0.07	0.06	0.01	−0.06	−0.03	−0.02	0.00	0.00
Visual search, % of successful search, distractor (n = 340)	−0.06	−0.03	0.06	−0.04	−0.02	0.00	−0.01	−0.08	0.05
Visual search, % of successful search, conjunction (n = 340)	0.04	0.02	0.10	0.02	−0.04	0.04	0.04	0.03	0.16
Switch-task, % of correct anticipation, pre-switch (n = 365)	−0.02	−0.00	−0.00	−0.06	0.01	−0.08	0.01	0.03	0.05
Switch-task, % of correct anticipation, post-switch (n = 365)	0.02	0.03	−0.05	−0.07	0.05	−0.00	−0.01	−0.05	−0.01
Attention disengagement, happy stimulus, % of occurred shifts (n = 312)	0.01	−0.08	0.00	−0.07	−0.02	−0.04	0.14	−0.23	0.06
Attention disengagement, fearful stimulus, % of occurred shifts (n = 312)	0.00	−0.04	0.01	−0.04	0.02	−0.06	0.14	−0.18	0.04
Attention disengagement, control stimulus, % of occurred shifts (n = 312)	0.04	−0.02	0.00	0.06	0.01	−0.04	−0.04	0.06	0.10

Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) (n = 310)	0.05	0.00	0.06	0.03	−0.02	−0.08	−0.06	0.08	0.01

Table 9. Association between eye tracking scores and rearing environment variables (maternal life situation) by Spearman's rank correlation coefficient

Test variable	Maternal cognition score	Maternal social support score	Maternal SRQ depression score	Maternal perceived stress score	Maternal life events score	Living environment score	Subjective social status score	Food security score	HOME score	Mother-infant bond score
VPS, ms (n = 348)	−0.09	−0.05	−0.07	0.00	−0.01	0.01	0.04	0.02	0.00	−0.04
Visual search, mean reaction time (single search) (n = 334)	−0.03	−0.03	−0.01	0.07	0.03	0.06	0.08	−0.04	−0.06	0.05
Switch-task, mean reaction time (correct anticipatory) (n = 366)	−0.08	−0.01	−0.03	0.01	0.04	−0.04	−0.03	0.05	0.08	−0.04
Attention disengagement, mean reaction time (control stimulus) (n = 312)	−0.01	0.04	0.00	−0.02	0.03	0.05	0.05	0.07	−0.02	−0.10
Visual search, % of successful search, single search (n = 340)	0.03	0.03	−0.02	0.05	0.03	−0.14	0.06	−0.04	0.03	0.02
Visual search, % of successful search, distractor (n = 340)	0.03	0.03	0.11	0.06	0.07	−0.01	0.05	0.02	0.01	0.10
Visual search, % of successful search, conjunction (n = 340)	0.12	0.08	−0.04	0.01	0.05	0.07	0.06	0.05	0.10	0.12
Switch-task, % of correct anticipation, pre-switch (n = 365)	0.07	0.03	−0.04	−0.01	−0.03	−0.05	0.10	0.00	−0.03	0.05
Switch-task, % of correct anticipation, post-switch (n = 365)	0.05	−0.01	0.00	−0.02	−0.09	0.02	0.10	0.05	0.00	0.05

Attention disengagement, happy stimulus, % of occurred shifts (n = 312)	0.04	0.05	0.07	0.14	0.11	0.14	0.02	0.05	0.07	−0.01
Attention disengagement, fearful stimulus, % of occurred shifts (n = 312)	0.03	0.03	0.02	0.07	0.10	0.02	−0.01	0.04	0.07	0.02
Attention disengagement, control stimulus, % of occurred shifts (n = 312)	0.08	0.08	−0.02	0.03	−0.06	−0.03	0.09	0.00	0.08	−0.05
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) (n = 310)	−0.03	−0.01	−0.08	0.01	−0.04	−0.10	0.01	−0.04	0.02	0.02

Table 10. Association between eye tracking and structured observation scores and maternal literacy

Test variable	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups[a]		P^b
	Infants with illiterate mother	Infants with literate mother	
VPS, ms (n = 348)	459 (53)	445 (42)	**0.011**
Visual search, mean reaction time (single search) (n = 334)	437 (65)	434 (59)	0.65
Switch-task, mean reaction time (correct anticipatory) (n = 365)	554 (89)	538 (67)	0.07
Attention disengagement, mean reaction time (control stimulus) (n = 312)	361 (59)	355 (63)	0.37
Visual search, % of successful search, single search (n = 340)	100 (13)	100 (14)	0.45
Visual search, % of successful search, distractor (n = 340)	63 (25)	63 (25)	0.99
Visual search, % of successful search, conjunction (n = 340)	43 (29)	50 (29)	**0.040**
Switch-task, % of correct anticipation, pre-switch (n = 365)	75 (42)	86 (40)	**0.007**
Switch-task, % of correct anticipation, post-switch (n = 365)	55 (44)	58 (42)	0.71
Attention disengagement, happy stimulus, % of occurred shifts (n = 312)	75 (50)	75 (38)	0.21
Attention disengagement, fearful stimulus, % of occurred shifts (n = 312)	67 (45)	73 (31)	0.15
Attention disengagement, control stimulus, % of occurred shifts (n = 312)	100 (0)	100 (0)	**0.037**[c]
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) (n = 310)	1254 (516)	1273 (510)	0.76
Structured observation: Alternating gaze (n = 170)	3.6 (1.4)	3.4 (1.3)	0.58
Structured observation: Gaze following (n = 170)	2.9 (1.1)	3.1 (1.0)	0.37

[a] Values are median (IQR) for successful searches, correct anticipations, and occurred shifts; and mean (SD) for processing speed, reaction times, dwell time, alternating gaze and gaze following.
[b] *P* value from Mann-Whitney *U* test for successful searches, correct anticipations, and occurred shifts. *P* value from *t* test for processing speed, reaction times, dwell time, alternating gaze and gaze following. **Bold** indicates statistically significant.
[c] Infants with an illiterate mother had a higher proportion of events where all shifts did not occur compared to infants with a literate mother (3.2% [8/253] and 1.4% [2/140], respectively, $P = 0.25$, Fisher's exact test).

Table 11. Association between structured observation scores and rearing environment variables

Characteristic	Spearman's rank correlation coefficient between the indicated test variable and alternating gaze	Spearman's rank correlation coefficient between the indicated test variable and gaze following
Maternal age	0.12	0.10
Paternal age	0.12	0.03
Maternal parity	−0.16	−0.04
# people living in the household	0.07	0.06
# children under 5 years old living in household	0.12	−0.01
Maternal height	0.02	−0.01
Maternal BMI at enrollment	0.02	0.04
Maternal BMI change from enrollment to 9 months	0.01	0.08
Maternal years in school	−0.04	0.05
Maternal cognition score	−0.01	0.04
Maternal social support score	0.06	0.08
Maternal SRQ depression score	0.02	0.06
Maternal perceived stress score	0.09	−0.03
Maternal life events score	−0.05	0.05
Living environment score	0.03	−0.08
Subjective social status score	0.05	0.02
Food security score	−0.14	−0.06
HOME score	−0.12	0.10
Mother-infant bond score	0.00	−0.07

Table 12. Association between structured observation scores and infant anthropometrics

Characteristic	Spearman's rank correlation coefficient between the indicated test variable and alternating gaze	Spearman's rank correlation coefficient between the indicated test variable and gaze following
GA at birth	0.06	0.07
LAZ at enrollment	0.08	0.08
WAZ at enrollment	0.18	0.11
WLZ at enrollment	0.11	0.13
HCZ at enrollment	0.16	0.13
MUAC at enrollment	0.13	0.09
LAZ at 9 months	0.07	0.00
WAZ at 9 months	0.06	0.02
WLZ at 9 months	0.02	−0.01
HCZ at 9 months	0.14	0.03
MUAC at 9 months	0.01	−0.01
Change in LAZ from enrollment to 9 months	−0.02	−0.05
Change in WAZ from enrollment to 9 months	−0.18	−0.06
Change in WLZ from enrollment to 9 months	−0.07	−0.07
Change in HCZ from enrollment to 9 months	−0.05	−0.11
Change in MUAC from enrollment to 9 months	−0.07	−0.05

Table 13. Association between structured observation scores and eye tracking scores

Test variable	Spearman's rank correlation coefficient between the indicated test variable and alternating gaze	Spearman's rank correlation coefficient between the indicated test variable and gaze following
VPS, ms	−0.09	−0.09
Visual search, mean reaction time (single search)	0.02	−0.05
Switch-task, mean reaction time (correct anticipatory)	−0.13	0.06
Attention disengagement, mean reaction time (control stimulus)	−0.16	−0.01
Visual search, % of successful search, single search	0.05	0.03
Visual search, % of successful search, distractor	0.07	0.03
Visual search, % of successful search, conjunction	−0.03	0.01
Switch-task, % of correct anticipation, pre-switch	0.02	−0.02
Switch-task, % of correct anticipation, post-switch	−0.02	−0.07
Attention disengagement, happy stimulus, % of occurred shifts	0.10	0.01
Attention disengagement, fearful stimulus, % of occurred shifts	0.05	0.07
Attention disengagement, control stimulus, % of occurred shifts	0.10	0.03
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus)	−0.13	−0.02

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Appendix 1. Eye Tracking Setup, Test Battery, and Processing of the Eye Tracking Data

Methods described in this appendix have been reported in the appendix to *Assessing the Feasibility of Using Eye Tracking to Study Infants' Cognitive Functioning in Rural Malawi* (Forssman et al. 2015). The version included here has only relevant information for Malawian data collection. On the attention disengagement task, the upper limit was changed from 1,000 to 4,000 ms compared to the feasibility study.

Eye Tracking Setup

The eye tracking assessment took place in a quiet and dimly lit room. A room (approximately 2x2 meters) was created out of black fabric that surrounded the testing area, i.e., the area where the participants were placed in front of the eye tracker. During the testing, the only light source came from the monitor and a spotlight (E14 LED light bulb) that was placed slightly behind the participant, about 2 m from the floor and directed down. The study used a portable Tobii X2-60 eye tracker (Tobii Technology, Stockholm, Sweden), which tracks a participant's point of gaze at 60 Hz with a spatial accuracy of 0.4 degrees. The eye tracker unit was connected to a laptop computer (MacBook Pro OS X, Apple Inc., Cupertino, CA) and a 22-inch monitor (Dell Inc., Round Rock, TX) for stimuli presentation. The eye tracking testing package was run using Psychtoolbox (as a MATLAB interface) with the Tobii SDK plug-in and custom-written MATLAB scripts.

Test Battery

The eye tracking test battery was presented in two sessions and took between 15 to 20 minutes to administer, including breaks for the infant during the testing. In both eye tracking sessions, the same tasks were presented in the same order for each participant. The structured observation was administered between the two eye tracking sessions. The purpose of this design was to allow for a break from the eye tracking assessment, while still continuing with the testing, as infants are limited in their ability to sit still and stay focused on one task.

The eye tracking test battery consisted of three tasks: an attention disengagement task, a switch-task, and a visual search task. In addition, an aggregated measure of processing speed based on reaction times from the three eye tracking tasks was calculated. Each testing session started with presenting either the attention disengagement task or the switch-task, and this presentation order was balanced in an odd/even number fashion based on the participant number. The visual search task was always presented between the other two tasks, as it was more complex, involving more than the infant to shift his/her gaze vertically to the left and right of the center to find a target.

Before the start of each eye tracking session, an eye tracking calibration procedure was performed. This procedure is critical for obtaining valid and reliable gaze tracking of an individual. During the calibration, five small cartoon figures with accompanying sounds appeared, one at a time, in each corner and in the center of the screen. Any unsuccessful calibration was recalibrated at least two times to reach satisfactory calibration.

The eye tracking test battery was designed to be engaging for infants by using infant-friendly stimuli and gaze-contingent features. Besides making the tasks more engaging, the gaze-contingent features also allowed for a more automatic presentation of the tasks (e.g., a trial commenced after the infant fixated on an attention-grabber) and also had the function of rewarding correct performance during the tasks (e.g., in the visual search task, the target spun and made sound after a "gaze hit"), which is a particularly applicable feature when testing pre-verbal infants.

During the testing, the experimenter sat behind a curtain out of the infant's view. From that position, the infant's behavior was monitored through a "hidden" video camera and the infant's gaze tracked in real time on a computer. If the infant became fidgety or inattentive during the assessment, a short break was taken. If the infant's tracked gaze started to look flickery (i.e., lots of gaps in tracking), the infant's position was adjusted or the testing was paused and the infant's eyes were recalibrated**.**

Attention Disengagement

The attention disengagement task assessed the ability of the infant to disengage from a centrally presented stimulus, an emotional face or a control stimulus, to a lateral stimulus using an overlap design (e.g., Peltola et al. 2013, Forssman et al. 2014), i.e., the lateral stimulus was presented after the central stimulus while the latter stayed on the screen. The face stimuli consisted of color images of two different female faces presenting a happy or fearful facial expression. The control stimuli was created by randomizing the phase spectrum (i.e., the pixels' positions) of all the face images, controlling for low-level visual features (e.g., brightness and amplitude spectrum), thus creating four different control stimuli that corresponded to each face image. We used two "typically" Malawian-looking face models. A group of 18 Malawian adults rated all the face stimuli for happiness and fearfulness on a scale from 1 (very little) to 7 (very much). The study team determined from the ratings of the Malawian fearful (mean = 6.31, SD = 1.07) and happy (mean = 5.58, SD = 1.26) facial expressions that all facial expressions were acceptable to use in the study. Pairwise-comparison of the fearful and happy facial expressions across sites revealed no significant difference in ratings of intensity ($P > 0.05$).

Before the start of each trial, the participants were presented with a gaze-contingent attention grabber (a yellow cartoon flower, 5 degree visual angle). Once the participant fixated on the attention grabber, a short period of preparatory time was allowed to elapse (500 ms) and the trial began. In each trial, the infant was first presented with the central stimuli (subtending 16 and 14 degree visual angle). After 1,000 ms, the central stimulus was flanked by a gaze-contingent lateral stimulus (15 degree visual angle off-center), an audiovisual reward, on the left or right. The lateral stimulus consisted of a colorful animated movie on a white background embedded between two black squares. When the infant looked at the lateral stimulus, or if 3,000 ms passed from the onset of the lateral stimulus whether the infant looked at it or not, the movie played for 2,000 ms.

The trials were presented in a pseudo-randomized order in which neither the condition (fearful, happy, or control) nor the same target side (left or right) was repeated more than three times in a row. The facial expressions and the control stimuli from one model were presented in the first 8 trials in each session, after which the stimulus from the second model was used. The order of the two models was counterbalanced across participants. The participants were presented with two blocks of 16 trials (32 trials in total: 16 control condition trials, 8 fearful condition trials, and 8 happy condition trials).

imilar to previous studies (e.g., Leppänen et al. 2014), a trial was considered invalid if the infant did not look at the central stimulus for at least 70% of the time prior to saccade, if the infant made an anticipatory eye movement (i.e., eye movement commenced less than 150 ms after the onset of the lateral stimulus), or if the infant made an eye movement toward an incorrect location (i.e., the extremely rare cases when the participant's gaze did not move toward the lateral stimulus, which could be caused by a technical artifact). Of the valid trials (see subsequent section, Processing of the Eye Tracking Data, for pre-processing criteria), the proportion of missing saccades from the centrally presented emotional faces and control stimuli was calculated (i.e., absence of eye movement toward the lateral stimulus during a time window from 150 to 4,000 ms after the onset of the lateral stimulus). This outcome measure gives an index of the infants' attention to emotional cues by examining whether they show the age-typical preference of increased attention to emotional faces over the control stimuli. Data were excluded from infants who failed to provide at least three valid trials for each condition.

Switch-Task

The switch-task assessed the infant's ability to anticipate where a target would appear and the infant's ability to inhibit an initial rule (pre-switch) in favor of a new rule (post-switch phase) (modeled on Kovács and Mehler 2009). After the participant fixated on an attention grabber (a cartoon image of a pink pig face, 5 degree visual angle), each trial started following a short delay/preparatory time (500 ms). At the start of each trial, two blank rectangles were presented to the left and right, together with auditory stimulus for 1,000 ms. When the infants made correct gaze anticipations to the location where the target would appear (or after 1,000 ms had passed), an audiovisual reward appeared for 2,000 ms. The reward appeared on one side (left or right) for the first eight trials and then on the other side for the last eight trials. Two blocks (i.e., eye tracking session 1 and 2) of 16 trials were presented during the assessment (a total of 16 pre-switch and 16 post-switch trials). A trial was considered valid if it met the pre-processing criteria for the analysis period (i.e., from 0 to 1,000 ms from the onset of the anticipatory period; see subsequent section, Processing of the Eye Tracking Data, for criteria). Of the valid trials, the proportion of correct anticipatory looks was calculated. Data were excluded for infants who failed to provide at least three valid trials in both the pre- and post-switch phases.

Visual Search

The visual search task assessed the infant's ability to search for a target with and without distractors (modeled on Kaldy et al. 2011). Before the start of each trial, the infants were presented with a familiarization trial where the target, a red apple (5 degree visual angle), was shown in the center of the screen accompanied with a "oh" sound. Similar to Kaldy et al.'s study (2011), a maximum presentation time of 4 seconds was used. In contrast to that study, the length of the presentation was gaze-contingent, but with a minimum presentation time of 2 seconds to ensure that the infant was given sufficient time to process the stimulus. If the infant fixated on the target, a search trial commenced after a short delay/preparatory time (500 ms). The search trials were presented in two blocks (eye tracking session 1 and 2) and in each block they consisted of 4 single-search, one-object trials (1 target and no distractors), 4 single-search, multiple-objects trials (2 trials: 1 target and 4 distractors; 2 trials: 1 target and 8 distractors), and 4 conjunction trials (2 trials: 1 target and 4 distractors; 2 trials: 1 target and 8 distractors).

In the single-search trials, the red apple target was presented with distractors consisting of either blue apples (same shape, but different color; 5 degree visual angle) or red elongated rectangle sliced apples (same color, but different shape). In the conjunction trials, half of the distractor objects were blue apples and the other half were red sliced apples. If the participant fixated the target within 4 seconds from the start of the trial, a reward sound (children voices cheering "yeah") was played while the target spun. The same audiovisual effect was presented to the participant if the target was not found within 4 seconds to make the task more engaging and to draw attention to the target. A trial was considered valid if it met the pre-processing criteria for the analysis period (i.e., from 0 to 2,000 ms from the onset of the anticipatory period; see subsequent section, Processing of the Eye Tracking Data, for pre-processing criteria). Of the valid data, the proportion of missed/unsuccessful searches between 150 to 2,000 ms from the start of the search trial in the single-search, one-object trials; single-search, multiple-objects trials; and conjunction trials was calculated. A 2,000 ms cutoff for missed/unsuccessful searches was used to avoid ceiling effects. Data were excluded from infants who failed to provide at least 3 valid trials for each condition (single-search, one object; single-search, multiple objects; and conjunction).

Visual Processing Speed

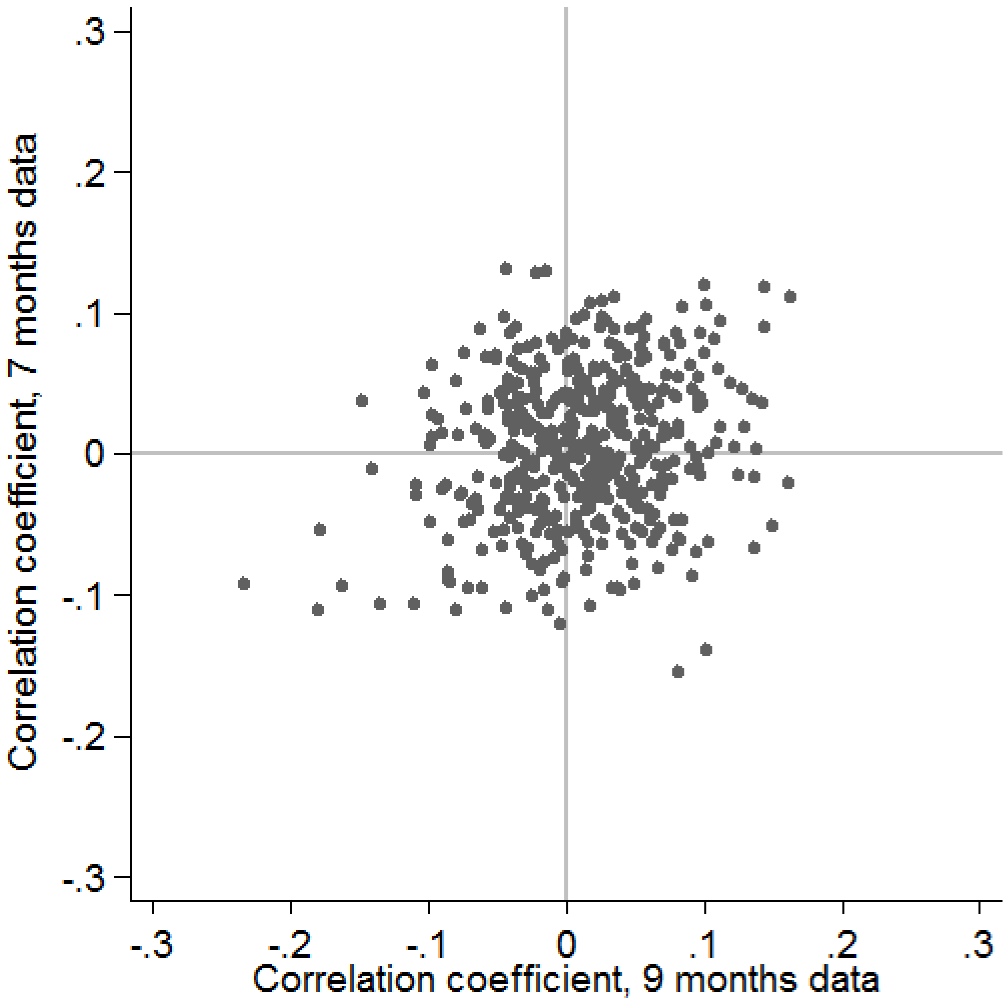
To measure the infants' VPS, a combined reaction time score averaged across the three eye tracking tasks was used. The purpose of constructing an aggregated measure of reaction time was to create a broader construct of VPS. Reaction times were taken from the control condition in the attention disengagement task, from correct anticipatory looks in the switch-task, and from the single-search, one-object trials in the visual search task. These tasks/conditions were selected to create a more "pure" measure of reaction time (i.e., the emotional conditions from the attention disengagement task and the distractor conditions from the visual search task were not included because these conditions include potential confounding factors). For this measure, reaction times were re-analyzed using a 1,000 ms cutoff. For an individual task score to be included in the combined reaction time measure, the participant had to meet the eye tracking inclusion criteria for that particular task, as failure to do so indicated that there was problem with the overall data quality for the task, e.g., because of inattentiveness or excessive head movements. Further, the participant had to contribute valid reaction time data from at least two of the eye tracking tasks.

Processing of the Eye Tracking Data

Data reduction, pre-processing, and analysis of the eye tracking data were conducted offline by using the gazeAnalysisLib, a library of MATLAB (Mathworks, Natick, MA) routines for automated offline analysis of raw gaze data (Leppänen et al. 2014) and custom-written MATLAB scripts for each specific eye tracking task. The MATLAB routines are open source and can be downloaded from http://www.uta.fi/med/icl/methods.html. In brief, the raw data were first pre-processed. This involved down-sampling the data by applying a 9-sample moving median filter to remove abrupt spikes in the gaze data that were attributable to technical artifacts. The pre-processing also included interpolating segments of missing data with an upper limit of 200 ms (i.e., trials with segments of missing data less than 200 ms were rejected). Analyses of the participants' gaze was measured by fixation times inside predefined areas of interest within the stimulus presentation screen, e.g., gaze fixation times inside areas that covered the face and lateral target stimuli in the attention disengagement task. The actual analyses of dependent variables (e.g., VPS) were further subjected to a number of predetermined and task-specific post-verification checks. A trial was excluded from the analysis if: (1) the upper limit of interpolation was violated or (2) the minimum required gaze fixation time inside one area of interest, prior to a saccade, was not met, or (3) a border violation took place during interpolation (i.e., data were missing for segments where the gaze shifted between two areas of interest). See Leppänen et al. (2014) for a more detailed description and rationale for the steps involved in the processing of the eye tracking data.

Appendix 2. Sensitivity Analysis Figures and Tables

Figure A2-1. The association between 7- and 9-month eye tracking correlation coefficients for variables presented in Tables 4–9 (n = 445)



Pearson's *rho* = 0.18.

Table A2-1 (referring to Table 4c). Association between VPS at 9 months of age and WAZ at enrollment

Test variable	Pearson's correlation coefficient between the indicated test variable and WAZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with WAZ < −2 at enrollment	Infants with WAZ ≥ −2 at enrollment		
VPS, ms [9 mo]	−0.07	478 (49)	452 (49)	26 (6, 45)	**0.009**
VPS, ms [7 mo]	−0.05	499 (57)	480 (57)	19 (−2, 40)	0.07

[a] *P* value from *t* test. **Bold** indicates statistically significant.

Table A2-2 (referring to Table 4i). Association between VPS at 9 months of age and WLZ at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and WLZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with WLZ < 50th percentile at 9 months	Infants with WLZ ≥ 50th percentile at 9 months		
Visual search, reaction time (single search, one object), ms [9 mo]	0.09	429 (62)	444 (63)	−15 (−28, −1)	**0.035**
Visual search, reaction time (single search, one object), ms [7 mo]	−0.09	452 (69)	445 (73)	7 (−8, 22)	0.36

[a] *P* value from *t* test. **Bold** indicates statistically significant.

Table A2-3 (referring to Table 4j). Association between VPS at 9 months of age and HCZ at 9 months

Test variable	Pearson's correlation coefficient between the indicated test variable and HCZ (continuous)	Mean (SD) value for the indicated test variable in participant subgroups		Difference (95% CI)	P^a
		Infants with HCZ < 50th percentile at 9 months	Infants with HCZ ≥ 50th percentile at 9 months		
Visual search, reaction time (single search, one object), ms [9 mo]	0.15	429 (61)	444 (64)	−16 (−29, −2)	**0.024**
Visual search, reaction time (single search, one object), ms [7 mo]	−0.05	451 (74)	446 (68)	4 (−11, 19)	0.58
Switch-task, reaction time (correct anticipatory), ms [9 mo]	−0.15	558 (83)	539 (82)	18 (1, 35)	**0.034**
Switch-task, reaction time (correct anticipatory), ms [7 mo]	0.04	598 (96)	602 (93)	−4 (−24, 16)	0.68

[a] *P* value from *t* test. **Bold** indicates statistically significant.

Table A2-4 (referring to Table 5f). Successful searches on the visual search task by MUAC at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and MUAC at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with MUAC < 50th percentile at enrollment	Infants with MUAC ≥ 50th percentile at enrollment	
Visual search, % of successful search, conjunction [9 mo]	0.14	43 (32)	50 (29)	**0.041**
Visual search, % of successful search, conjunction, [7 mo]	0.00	43 (24)	50 (27)	0.29

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-5 (referring to Table 5h). Successful searches on the visual search task by WAZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WAZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with WAZ < −2 at 9 months	Infants with WAZ ≥ −2 at 9 months	
Visual search, % of successful search, conjunction [9 mo]	0.16	38 (25)	43 (27)	**0.024**
Visual search, % of successful search, conjunction [7 mo]	−0.02	43 (21)	43 (24)	0.61

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-6 (referring to Table 5k). Successful searches on the visual search task by MUAC at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and MUAC at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with MUAC < 50th percentile at 9 months	Infants with MUAC ≥ 50th percentile at 9 months	
Visual search, % of successful search, conjunction [9 mo]	0.03	43 (25)	50 (29)	**0.009**
Visual search, % of successful search, conjunction [7 mo]	0.01	43 (29)	43 (27)	0.52

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-7 (referring to Table 6f). Proportion of correct anticipation on switch-task by MUAC at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and MUAC at enrollment (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with MUAC < 50th percentile at enrollment	Infants with MUAC ≥ 50th percentile at enrollment	
Switch-task, % of correct anticipation, post-switch [9 mo]	0.13	50 (44)	60 (43)	**0.010**
Switch-task, % of correct anticipation, post-switch [7 mo]	0.02	44 (50)	50 (45)	0.56

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-8 (referring to Table 6j). Proportion of correct anticipation on switch-task by HCZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and HCZ at 9 months (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with HCZ < 50th percentile at 9 months	Infants with HCZ ≥ 50th percentile at 9 months	
Switch-task, % of correct anticipation, pre-switch [9 mo]	0.14	75 (42)	85 (42)	**0.003**
Switch-task, % of correct anticipation, pre-switch [7 mo]	0.03	60 (47)	64 (47)	0.53

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-9 (referring to Table 6m). Proportion of correct anticipation on switch-task by change in WAZ (ΔWAZ) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔWAZ (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔWAZ < 50th percentile	Infants with ΔWAZ ≥ 50th percentile	
Switch-task, % of correct anticipation, post-switch [9 mo]	−0.16	64 (43)	50 (45)	**<0.001**
Switch-task, % of correct anticipation, post-switch [7 mo]	−0.09	46 (45)	43 (47)	0.53

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-10 (referring to Table 6p). Proportion of correct anticipation on switch-task by change in MUAC (ΔMUAC) from enrollment to 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔMUAC (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔMUAC < 50th percentile	Infants with ΔMUAC ≥ 50th percentile	
Switch-task, % of correct anticipation, post-switch [9 mo]	−0.18	62 (44)	50 (45)	**0.008**
Switch-task, % of correct anticipation, post-switch [7 mo]	−0.11	50 (48)	40 (47)	**0.039**

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-11 (referring to Table 7a). Occurred shift and dwell time on faces on attention disengagement task by GA at birth

Test variable	Pearson's correlation coefficient between the indicated test variable and GA (continuous)[b]	Mean (SD) value for the indicated test variable in participant subgroups			P[a]
		Infants born preterm	Infants born early term	Infants born full term	
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) [9 mo]	0.06	1,107 (430)	1,348 (533)	1,249 (513)	**0.022**
Dwell time of gaze on faces before gaze transition to a new object (lateral stimulus) [7 mo]	0.00	1,239 (494)	1,126 (497)	1,176 (586)	0.49

[a] *P* value from ANOVA. **Bold** indicates statistically significant.

Table A2-12 (referring to Table 7c). Occurred shift and dwell time on faces on attention disengagement task by WAZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WAZ at enrollment (continuous) [3]	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with WAZ < −2 at enrollment	Infants with WAZ ≥ −2 at enrollment	
Attention disengagement, control stimulus, % of occurred shifts [9 mo]	0.03	100 (0)	100 (0)	**0.025**
Attention disengagement, control stimulus, % of occurred shifts [7 mo]	−0.02	100 (0)	100 (0)	0.52

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-13 (referring to Table 7e). Occurred shift and dwell time on faces on attention disengagement task by HCZ at enrollment

Test variable	Spearman's rank correlation coefficient between the indicated test variable and ΔWAZ (continuous)	Median (IQR) value for the indicated test variable in participant subgroups		P[a]
		Infants with HCZ < 50th percentile at enrollment	Infants with HCZ ≥ 50th percentile at enrollment	
Attention disengagement, fearful stimulus, % of occurred shifts [9 mo]	−0.10	75 (38)	68 (40)	**0.046**
Attention disengagement, fearful stimulus, % of occurred shifts [7 mo]	0.03	61 (42)	67 (40)	0.19

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-14 (referring to Table 7i). Occurred shift and dwell time on faces on attention disengagement task by WLZ at 9 months

Test variable	Spearman's rank correlation coefficient between the indicated test variable and WLZ at 9 months (continuous)[b]	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with WLZ < 50th percentile at 9 months	Infants with WLZ ≥ 50th percentile at 9 months	
Attention disengagement, happy stimulus, % of occurred shifts [9 mo]	0.10	75 (38)	83 (40)	**0.029**
Attention disengagement, happy stimulus, % of occurred shifts [7 mo]	0.09	63 (46)	67 (40)	0.66

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-15 (referring to Table 7m). Occurred shift and dwell time on faces on attention disengagement task by change in WAZ (ΔWAZ) from enrollment to 9 months

Test variable	Correlation coefficient between the indicated test variable and ΔWAZ (continuous)[b]	Median (IQR) value for the indicated test variable in participant subgroups		P^a
		Infants with ΔWAZ < 50th percentile	Infants with ΔWAZ ≥ 50th percentile	
Attention disengagement, fearful stimulus, % of occurred shifts [9 mo]	0.09	67 (41)	75 (38)	**0.023**
Attention disengagement, fearful stimulus, % of occurred shifts [7 mo]	0.06	60 (40)	67 (46)	0.34

[a] *P* value from Mann-Whitney *U* test. **Bold** indicates statistically significant.

Table A2-16 (referring to Table 10). Association between maternal literacy and eye tracking scores

Table variable	Median or mean (IQR or SD) value for the indicated test variable in participant subgroups2		P^{a}
	Infants with illiterate mother	Infants with literate mother	
VPS, ms [9 mo]	459 (53)	445 (42)	**0.011**
VPS, ms [7 mo]	483 (53)	479 (64)	0.49
Visual search, % of successful search, conjunction [9 mo]	43 (29)	50 (29)	**0.040**
Visual search, % of successful search, conjunction [7 mo]	43 (21)	50 (27)	0.11
Switch-task, % of correct anticipation, pre-switch [9 mo]	75 (42)	86 (40)	**0.007**
Switch-task, % of correct anticipation, pre-switch [7 mo]	60 (46)	64 (52)	0.56
Attention disengagement, control stimulus, % of occurred shifts [9 mo]	100 (0)	100 (0)	**0.037**
Attention disengagement, control stimulus, % of occurred shifts [7 mo]	100 (0)	100 (0)	0.38

[a] *P* value from Mann-Whitney *U* test for successful searches, correct anticipations, and occurred shifts. *P* value from *t* test for processing speed. **Bold** indicates statistically significant.