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Assessing the Feasibility of Using Eye Tracking to Study Infants' Cognitive Functioning in Rural Malawi

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September 2015

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This publication is based on research funded 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. Additional funding was provided by the Competitive State Research Financing of the Expert Responsibility area of Tampere University Hospital (Grant 9R001), Nutriset S.A.S, and the Tampere Association of Medical Doctors. The research team also received support in grants to one of the co-authors of this report (Leppänen) from the Academy of Finland (# 218284) and the European Research Council (# 283763).

Acknowledgements

The authors thank the study participants, the local communities, the health service staff, and the research personnel at the study sites as well as members of the trial's data safety and monitoring board.

Recommended Citation

Forssman, Linda; Ashorn, Per; Ashorn, Ulla; Maleta, Kenneth; Leppänen, Jukka; and the MiTrack Study Team. 2015. *Assessing the Feasibility of Using Eye Tracking to Study Infants' Cognitive Functioning in Rural Malawi*. Washington, DC: FHI 360/FANTA.

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Background

Children growing up in low-income countries are at an increased risk for exposure to adverse contextual factors that may affect their cognitive development early in life. Yet, the prevalence and specific nature of cognitive problems are still poorly understood given a lack of objective, non-invasive, and field-friendly techniques for assessing early cognitive functioning in low-resource settings. In an effort to help address this gap, we carried out a study to evaluate the feasibility of using eye tracking to assess infants' cognitive functioning in a low-income setting.

Methods

A battery of eye tracking tests were used to assess basic cognitive functions, such as anticipatory looking, sequence learning, and perception of facial expressions, of 39 Finnish and 37 Malawian infants 9 months of age. To evaluate the feasibility of using the eye tracking method in Malawi, we measured and compared the acceptability of the eye tracking method (the participants' mothers' appreciation of the method) and quality of the eye tracking data collected from the Malawian site to that of data collected from the Finnish site. The following conditions needed to be met in order for the method to be defined as feasible: (1) a proportion of Malawian participants similar to that of Finnish participants had to be able to complete the whole assessment, (2) a proportion of participating Malawian mothers similar to that of Finnish mothers had to report acceptance of the method, and (3) the eye tracking data quality in terms of attrition rate and proportion of valid trials had to be similar at the two sites (Malawi and Finland) and in parity with previous infancy eye tracking studies (i.e., attrition rate around 20–35% or lower, based on Ambrosini et al. 2013, Oakes and Ellis 2013, and Watanabe et al. 2012, and proportion of valid trials in each eye tracking task at greater than 70%, based on Forssman, Wass, and Leppänen 2014 and Leppänen et al. 2014).

Results

The majority of Finnish (95%) and Malawian (92%) infants were able to complete the whole assessment. At both sites, 95% or more of the participating mothers reported acceptability of the method. Examination of eye tracking data quality between the Finnish and Malawian testing sites showed similar patterns, although the overall completion rate (Finland: 94.9%; Malawi: 91.9%) and the overall proportion of valid trials (Finland: 79.5%; Malawi: 71%) were slightly in favor of the Finnish sample. There were however no significant differences in task-specific data attrition rates between the two samples (p = .141–.946) and the attrition rates at both sites was equivalent to or better than the attrition rates reported in previous eye tracking studies with infants of similar age.

Conclusions

The consistency of data retention and test acceptance rate between the Finnish and Malawian samples demonstrates the feasibility of eye tracking-based assessments of infants' cognition in low-resource settings. Based on the results from this pilot test, we believe that eye tracking is a promising tool for assessing early cognitive functions in Malawi and other low-income countries. However, further research is still needed to establish the validity of early-emerging cognitive markers as predictors of long-term health outcomes in childhood.

Introduction

Poverty, malnutrition, and lack of adequate stimulation are common risk factors affecting children's development in Malawi and other low-income countries (Walker et al. 2011). These contextual risk factors have been shown to compromise the brain's growth process in postnatal life and may consequently have a negative impact on cognitive functioning and academic/work achievement throughout life (Hackman et al. 2010; Knudsen et al. 2006). There is currently a scarcity of objective non-invasive, field-friendly tools to measure infants' cognitive functioning in low-income countries where these risk factors are the most prevalent in the world (Walker et al. 2011). In the present study we set out to explore the feasibility of using a novel and highly automatized eye tracking method to study infants' cognitive functioning in a low-income setting in rural Malawi. If successful, eye tracking-based tools could potentially assist in overcoming a gap in global health research on early cognitive development. Further, since the first years of life is the time in development when the brain and neural circuitry are the most vulnerable to adverse experiences, which may result in the development of faulty brain circuitry that is difficult to restore later in life because of decreasing plasticity of the brain (Cusick and Georgieff 2012; Mendez and Adair 1999; Fox et al. 2010; Hensch 2005), it is critical to develop methods that can identify children at risk for cognitive deficits early in their development.

Visual attention is an important means for infants to learn about their environment, and oculomotor control, including the detecting and shifting of a child's gaze to visual stimuli, is one of the earliest developing skills in life (Butcher et al. 2002). Within the field of developmental psychology, there has been a long tradition of using observations of infants' eye movements as a method to draw conclusions about early developing cognitive functions (e.g., Aslin and McMurray 2004). As traditional observational assessment (e.g., manual coding of video records) of infant eye movement is very cumbersome and limited in its spatiotemporal resolution, there is growing interest in using corneal reflection eye tracking techniques to measure gaze behavior (Wass et al. 2014). Such eye tracking-based methods have been extensively used with easily accessible infant populations in high-resource settings (e.g., in Europe and North America), but no such data has been collected with infants in low-income countries. This, in turn, has limited the understanding of how environmental risk factors, such as poverty and malnutrition, affect infant cognitive development in low-income countries.

In the current study we tested the feasibility of using an eye tracking-based method to assess infant cognitive functioning in a low-income setting. The eye tracking test battery consisted of tasks assessing early developing core cognitive functions (e.g., anticipatory eye movements and sequence learning) believed to underlie the development of more complex social and cognitive skills. To address the study aim, we collected eye tracking data from a sample of infants 9 months of age in rural Malawi and compared these data with eye tracking data collected from infants of the same age in Finland at an experienced infant eye tracking lab. We used three criteria to define the method as demonstrating feasibility: (1) a proportion of the Malawian participants similar to the Finnish participants had to be able to complete the whole eye tracking assessment, (2) a proportion of participating Malawian mothers similar to the Finnish mothers had to report acceptance of the method, and (3) the Malawian site eye tracking data quality in terms of attrition rate (i.e., percentage of participants meeting the eye tracking inclusion criteria) and proportion of valid trials (i.e., proportion of trials meeting the data quality cut-off) had to be comparable with data collected from the Finnish site and previous infant eye tracking studies (i.e., attrition rate around 20–35% or lower, based on Ambrosini et al. 2013, Oakes and Ellis 2013, and Watanabe et al. 2012, and proportion of valid trials in each eye tracking task greater than 70%, based on Forssman, Wass, and Leppänen 2014 and Leppänen et al. 2014). For exploratory purposes, we also compared the performance of the Malawian infants to that of the Finnish infants on the eye tracking tests.

Any observed difference in performance between the Malawian and Finnish samples could be related, in part, to growing up in very different rearing environments, and may provide useful information for helping to inform future research hypotheses.

Methods

Study Design and Participants

The target population for the feasibility study was 9-month-old Finnish and Malawian infants, with a target sample size of 30–40 infants per site. This sample size was convenience based due to limited time and resources, but believed to be sufficient for the purpose of determining the feasibility of the eye tracking method in rural Malawi. To be included in the study the child's biological mother had to be able to come to the study site and speak the local language fluently. Exclusion criteria included preterm birth (less than 37 gestational weeks), low birth weight (less than 2,500 grams), and known visual impairments, neurological disorders, or congenital malformations.

The recruitment of the Finnish sample was based on families living in the area of a University town in central Finland. Initially, letters with an invitation to participate in the study were sent to families living in the area who had an infant younger than 9 months of age. When an infant approached the targeted age, families who had indicated an interest to participate in the study were contacted by phone and screened for inclusion and exclusion criteria (see above). If the family met the inclusion criteria and none of the exclusion criteria applied, the biological mother and her 9-month-old infant were eligible for enrollment in the study.

The recruitment of the sample in Malawi was based on families living in the area of a health center in southern rural Malawi. To recruit study participants, verbal information about the study was provided to village chiefs, community advisors, and residents in the surrounding area of the health center (furthest distance was approximately 12–15 kilometers)—a catchment area with a population of approximately 35,000. If a mother indicated interest in participating in the study, her child was screened for appropriate age and an appointment was made for a visit to the health center. At the health center, the infant was further screened for inclusion and exclusion criteria (see above). If the infant met the inclusion criteria and none of the exclusion criteria applied, the biological mother and her 9-month-old infant were eligible for enrollment in the study.

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 participants' biological mother before the start of the study. All Finnish mothers signed the consent form, whereas Malawian mothers signed (35%) or thumb printed (65%) the consent form. The Finnish participants received a small token (a t-shirt worth about €5) for participating in the study and the Malawian participants received compensation for their travel cost and 1 kilogram of rice (about €0.75).

General Procedure

Data for the study were collected in Finland during the last 2 weeks of May and the last 2 weeks of June 2014 and in Malawi during the first 2 weeks of September 2014. During the study visit we assessed the infants' cognitive functioning (via eye tracking) and social communication skills (via structured observation), and took anthropometric measures (weight, length, and head circumference). We also interviewed the mothers to obtain information about their child's living environment, the strength of the mother's bond with her infant, and maternal life stress. The eye tracking test battery administered consisted of two separate sessions (approximately 15–20 minutes in total). In between the two eye tracking sessions, the structured observation assessment of social communication skills (approximately 10 minutes) was administrated. In total, the participants spent approximately 1–1.5 hours in the study clinic.

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-centimeter 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) (see Figure 1).

Figure 1. Eye Tracking Testing at the Finnish and Malawian Sites

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

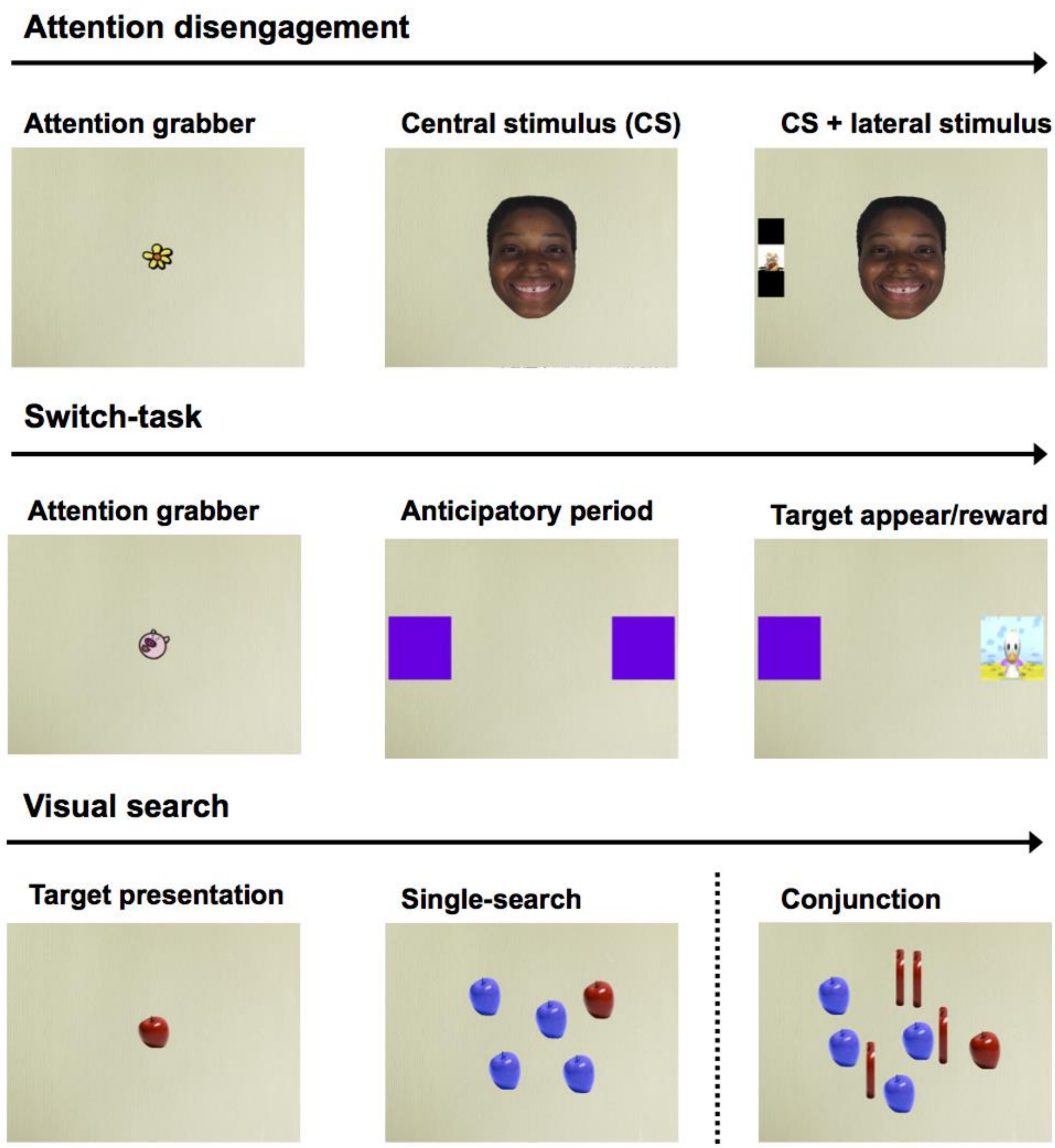
The **attention disengagement task** assessed the ability of the infant to disengage from a centrally presented stimulus (e.g., an emotional face, happy or fearful, or a control stimulus) to a lateral stimulus (total number of trials = 32; 8 happy, 8 fearful, and 16 control trials). The outcome measure 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 missed 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.

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 (total number of trials =

32; 16 pre-switch, and 16 post-switch trials). The outcome measure for this task was the proportion of correct anticipatory looks on the pre- and post-switch trials.

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

Figure 2. Screenshots from Malawi of the Three Eye Tracking Tasks: Attention Disengagement, Switch-Task, and Visual Search



After ending the eye tracking assessment, the experiment leader asked the mother of the infant if she enjoyed participating with her child in the eye tracking assessment and if she would recommend a friend to participate in the eye tracking assessment with her child. The responses were marked as "yes" or "no." The mothers' responses were used to help inform whether the eye tracking method was acceptable to the participating mothers.

The eye tracking data were stored on a laptop computer, pre-processed, and analyzed offline using gazeAnalysisLib (Leppänen et al. 2014). The pre-processing was automated and included median filtering of the data with a moving window of 7 samples (equaling 117 milliseconds in time), removal of abrupt spikes (technical artifacts), and interpolation of data gaps (maximum of 200 milliseconds). 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.[1]

Structured Observation of Social Communication Skills

The infants' ability to initiate and respond to social communication cues was assessed during a structured observation and based on two tasks, **alternating gaze** and **gaze following**, from the Early Social Communication Scale (Mundy et al. 2003). During this assessment, the child was seated on a marked spot on the floor in front of his/her caregiver, facing the experiment leader (see left side of Figure 3). The experiment leader presented these two tasks in a rotating order to keep the infant interested and engaged: alternating gaze (3 trials), gaze following (4 trials), alternating gaze (3 trials), gaze following (4 trials), alternating gaze (3 trials).

Initiating social communication was assessed with the alternating gaze task where the experiment leader presented a moving toy (e.g., a shaking rattle) on the floor (or just above the floor) in front of the infant, but out of his or her reach (i.e., from a 105 centimeter distance) for 6 seconds. After 6 seconds had elapsed the infant was then 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 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 a 6-second time period from the start of the activation of the toy.

Responding to social communication was assessed with the gaze following task in which the experiment leader looked and pointed for 6 seconds in turn to four objects (located 90 and 45 visual degrees to the left and right of the infant). Two sets of four trials were presented during the assessment (8 trials total). Responding to social communication was coded as the proportion of trials in which the infants looked to the correct object (i.e., the object the experiment leader pointed to).

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 all dependent variables offline. A second trained coder coded the dependent variables from 22% of the assessments.

[1] For additional information, refer to Appendix 1, which includes a detailed description of the methods used for pre-processing of the eye tracking data and the specific inclusion criteria for each eye tracking task.

Inter-rater reliability was calculated using Spearman's rho and showed .98 and .73 for proportion of alternating gaze and proportion of gaze following, respectively.

Four participants (Malawian) were excluded from the analysis of the structured observation assessment because of technical error (in one case) or error in the administration of the tasks (in three cases).

Anthropometric Assessment

Infant length was assessed using a length board (Harpenden Infantometer, Holtain Limited, Crosswell, United Kingdom) and recorded to the nearest 1 millimeter. Infant weight was assessed using an electronic infant weighing scale (SECA 735) with reading increments of 10 grams. Mid-upper arm circumference (MUAC) and head circumference was measured with non-stretchable plastic insertion tapes and the results recorded to the nearest 1 millimeter. All anthropometric measurements were done in triplicate by trained personnel (see right side of Figure 3), and the mean of the triplicate measurements was used in the analyses. Age- and sex-standardized anthropometric indices (weight-for-age, length-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).

Figure 3. Structured Observation and Anthropometric Assessment from the Malawian Site

Maternal Report of Child's Living Environment, Mother-to-Infant Bond, and Stressful Life Events

Mothers provided information about her child's living environment through an interview that took place during the visit to the lab in Finland or at the health center in Malawi. The interview consisted of three questionnaires. In the first questionnaire, the mother was asked to respond to questions regarding her child's socio-demographic background. This questionnaire included questions about the age 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.

The second questionnaire assessed the mother's bond to her infant by administering the Mother-to-Infant Bonding Scale (Taylor et al. 2005). This questionnaire consists of eight questions that ask about the mother's feelings for her child in the first few weeks after birth. The mothers were asked to state the extent ("Very Much"; "A Lot"; "A Little"; "Not at All") that best described how they felt when presented with eight different adjectives, for example, "Joyful," "Resentful," "Protective," or "Aggressive." Each response was rated on a scale from 0–3 (total minimum-maximum: 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 as 0, whereas "Very Much" for "Resentful" was scored as 3).

The third questionnaire focused on maternal event-related stress in the past 12 months. 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," "Have you separated from your partner") had occurred during the past 12 months. A "no" or "yes" box was ticked if the event had occurred, and a "still affects me" box was ticked if the event was reported as still having an effect on her life. The sum of all "yes" responses and "still affects me" responses were calculated separately (total minimum-maximum: 0–17). A higher value on each of these variables indicates more event-related stress in the participating mothers' lives.

Statistical Analysis

Summary statistics of the sample characteristics were calculated as means and standard deviation (SD) for continuous measurements and as n (%) for dichotomous measures. Chi-square tests, Fisher's exact test, or *t*-tests were used to compare sample characteristics, anthropometric data, and eye tracking data quality across samples. The primary outcome measures of interest were feasibility of the eye tracking method, as measured by percent of participants completing the whole eye tracking assessment, mothers' report on acceptability of the method, and data quality (attrition rate and proportion of valid trials/task).

As an exploratory analysis, we compared the infants' scores on the eye tracking tasks and the structured observation measures across samples using *t*-tests or non-parametric tests (Mann-Whitney U test) if the variable was not normally distributed. As mentioned previously, the final sample size varies between different eye tracking outcome measures according to specific inclusion criteria for the eye tracking tasks as explained in Appendix 1.

Results

Characteristics of the Study Sample

Initially, 79 infants 9 months of age enrolled in the study (39 Finnish infants and 40 Malawian infants). However, three infants from the Malawian site were excluded—one mother opted out of the study after giving consent but before the start of the assessment, another mother opted out during the first few minutes of assessment, and in one case the assessment could not take place because the infant was too upset and could not be soothed. Thus, the final study sample consisted of 76 infants (39 Finnish and 37 Malawian).

The Finnish and Malawian samples did not differ in the distribution of sex or in age, and there was not a significant difference in the Finnish and Malawian mothers' rating of mother-to-infant bond (see Table 1). As expected, there were, however, several significant differences between the two samples: the Finnish parents had more years of education, Finnish mothers were older, and the number of children in the household was smaller in Finland. Significant differences were also found for maternal reports of life events. Whereas Malawian mothers reported a higher frequency of recent stressful life events taking place (i.e., "Life Event - not affecting"), Finnish mothers rated themselves as being more affected by recent stressful life events (i.e., "Life Event - still affecting"). In addition, Finnish infants showed higher weight-for-age, length-for-age, head circumference-for-age, and MUAC-for-age z-scores in comparison to the Malawian infants (see Table 2). No significant difference was found for weight-for-length z-scores between the two samples.

Table 1. Description of Malawian and Finnish Infants' Characteristics

	Malawian infants (n = 37)	Finnish infants (n = 39)	P-value[a]
Sex			
Females	48.6%	51.3%	0.818
Age in months	9.1 (.21)[b]	9.1 (.13)	0.942
Socio-demographics			
Mothers' years of education	3.4 (3.9)	16.1 (2.6)	< 0.001
Fathers' years of education	5.1 (4.4)	15.4 (2.6)	< 0.001
Mothers' age, years	24.3 (5.4)	32.2 (4.5)	< 0.001
Number of children in the household	2.4 (1.2)	1.7 (1.2)	0.030
Number of people in the household	4.8 (1.9)	3.8 (1.2)	0.055
Maternal characteristics			
Mother-to-Infant Bond[c]	1.8 (2.0)	1.4 (2.0)	0.325
Life Events (not affecting)[d]	4.1 (2.3)	1.0 (0.9)	< 0.001
Life Events (still affecting)[d]	0.2 (0.6)	1.4 (1.1)	< 0.001

[a] Means were compared with *t*-tests; percentages and nominal data were compared with chi-square tests
[b] Mean (SD) for all such values
[c] Higher score indicates more difficulties in bonding
[d] Higher score indicates higher number of reported stressful life events

Table 2. Anthropometric Data for the Malawian and Finnish Infants

	Malawian infants (n = 37)	Finnish infants (n = 39)	P-value[a]
Anthropometrics			
Weight at birth (kilogram)[b]	3.11 (0.35)[c]	3.70 (0.55)	< 0.001
Weight (kilogram)	7.95 (0.98)	9.09 (1.03)	< 0.001
Length (centimeter)	67.0 (2.1)	73.3 (2.5)	< 0.001
Mid-upper arm circumference (centimeter)	14.5 (1.2)	15.5 (1.2)	0.001
Head circumference (centimeter)	44.0 (1.3)	45.3 (1.2)	< 0.001
Anthropometric z-scores			
Weight-for-age	-0.71 (1.01)	0.48 (0.98)	< 0.001
Weight-for-length	0.39 (1.10)	0.08 (0.87)	0.178
Length-for-age	-1.76 (0.80)	0.98 (1.07)	< 0.001
Head circumference-for-age	-0.55 (0.93)	0.71 (0.84)	< 0.001
Mid-upper arm circumference-for-age	0.11 (1.04)	0.95 (1.02)	0.001

[a] Means were compared with *t*-tests
[b] Based on health passports
[c] Mean (SD) for all such values

Feasibility of the Eye Tracking Method

All but 5 (2 Finnish and 3 Malawian) of the 76 participating infants were able to complete the whole eye tracking assessment. The reasons for early termination of the assessment were: the infant became tired/inattentive during the testing (2 Finnish, 1 Malawian), a discontinuation in electricity supply (1 Malawian), or the infant reacted negatively to the stimuli in one task (1 Malawian). These 5 infants were still able to provide a sufficient number of valid trials on most of the eye tracking tasks. Overall, no significant difference in completion rate was found between the two sites (p = .600) (see Table 3).

Of the 76 participating mothers, a large majority at both sites reported acceptability of the method. In the Malawian sample, 97% reported that they enjoyed participating in the eye tracking assessment with their child and 100% of the mothers stated that they would recommend a friend to participate. The corresponding percentages for Finnish mothers were 95% for participating in the assessment and 100% for recommending the assessment to a friend.

To clarify any differences in eye tracking data quality between the Finnish and Malawian testing sites we compared the within-task attrition rate (i.e., percentage of participants not meeting the eye tracking inclusion criteria: less than 3 valid trials for each condition in each task) and within-task proportion of valid trials (i.e., proportion of trials meeting the data quality criteria) across sites for the three eye tracking tasks. The within-task attrition rates vary between the eye tracking tasks, as the participants may have met the eye tracking inclusion criteria for one task, but not for another task. Although the within-task attrition rate was slightly lower for the Finnish sample in all the tasks, there was not a significant difference in attrition rate between the 2 sites for any task (p = .141–.946). The Finnish sample did, however, have a significantly higher proportion of valid trials for the switch-task (p = .020) and the visual search task ($p <$ 0.001) (see Table 3).

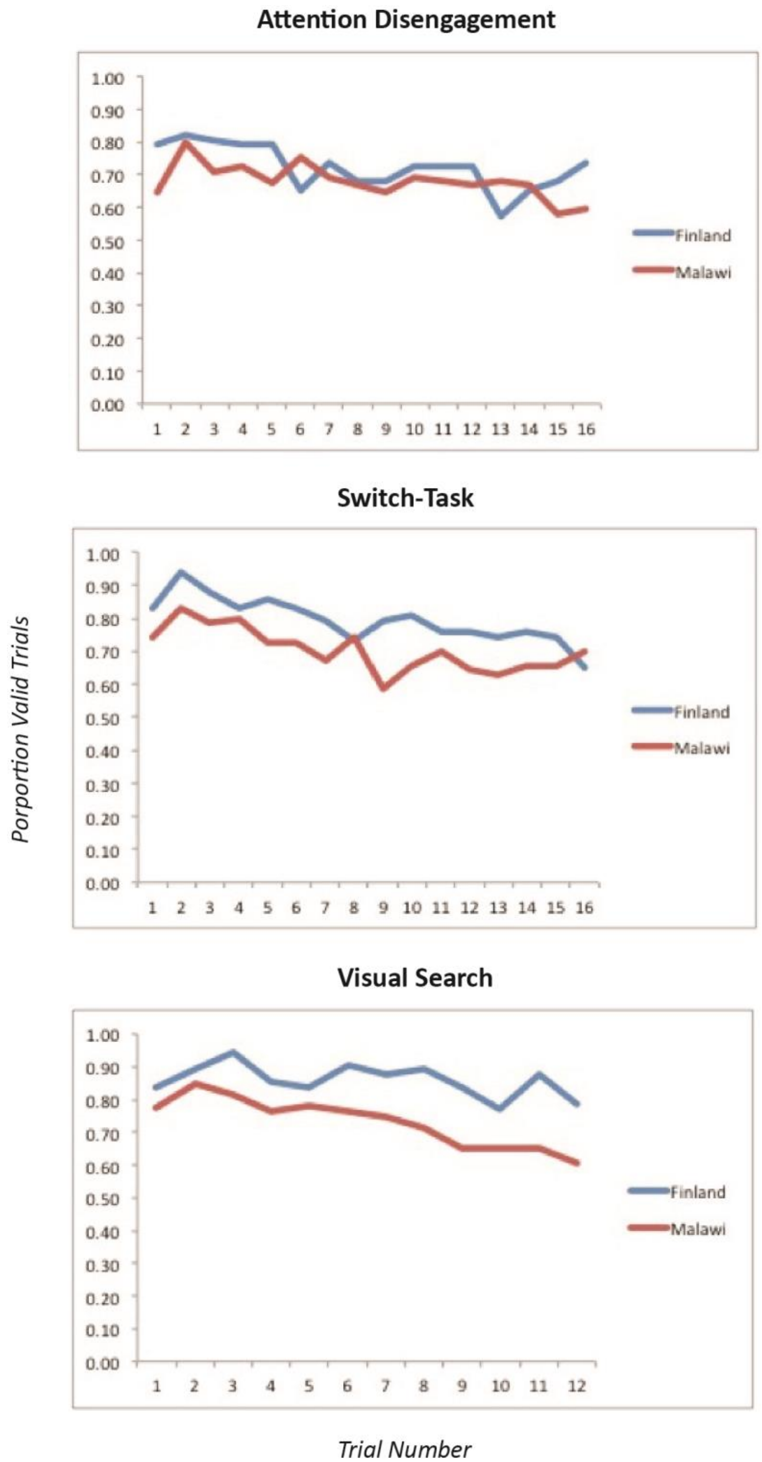
For both samples, the proportion of valid trials for a given task tended to decrease over time, but there was no apparent difference in the proportion of valid trials over time between the two samples (i.e., the differences that exist seems to be equally spread across the trials over time), possibly with the exception of the visual search task for which the proportion of valid trials in the Malawian sample decreased slightly more over time (see Figure 4).

Table 3. Description of Eye Tracking Data Quality

	Malawian infants (n = 37)	Finnish infants (n = 39)	P-value[a]
Overall completion rate	34/37 (91.9%)	37/39 (94.9%)	0.600
Mothers' acceptability of the eye tracking method			
Enjoyed participating	36/37 (97.3%)	37/39 (94.9%)	0.587
Would recommend to a friend	37/37 (100%)	38/38 (100%)[b]	
Attention disengagement			
Attrition	3/37 (8.1%)	3/39 (7.7%)	1.00
Number of valid trials	823/1,184 (70.0%)	911/1,248 (73.1%)	0.439
Switch-task			
Attrition	2/37 (5.4%)	0/39 (0.0%)	0.234
Number of valid trials	625/1,184 (70.4%)	992/1,248 (79.5%)	0.020
Visual search			
Attrition	5/37 (13.5%)	2/39 (5.1%)	0.256
Number of valid trials	646/888 (72.7%)	804/936 (85.9%)	< 0.001

[a] Categorical variables were compared with chi-square or Fisher's exact test; continuous variables with t-tests
[b] One Finnish mother was never asked whether she would recommend the method to a friend, therefore n = 38 for the Finnish sample for this question

Figure 4. Proportion of Valid Trials over Time in the Switch-Task, Visual Search Task, and Attention Disengagement Task



Comparison of Finnish and Malawian Infants' Cognitive Functioning

Overall, infants at both sites showed a generally expected performance pattern on the three eye tracking tasks (see Table 4 and Figure 5). In the attention disengagement task both Finnish and Malawian infants had a higher proportion of missing saccades in the emotion conditions compared to in the control condition. For the switch-task, both groups showed increased learning over time in the pre- and post-switch phase and also the expected perseveration (i.e., initial poorer performance) on the post-switch trials (starting at trial number 9; see Figure 6). Finally, in the visual search task both the Finnish and Malawian infants had more missed searches in the conjunction condition with two types of distractors compared to the condition with one type of distractor (single-search multiple-objects), and few failed searches in the condition without distractors (single-search one-object).

There was a significant difference in the Finnish and Malawian infants' processing speed. The Finnish infants had faster reaction times than the Malawian infants, with the Malawian infants taking on average 40 milliseconds longer than Finnish infants to respond. Significant differences between the two samples were also found in the attention disengagement task. Malawian infants were more likely to miss attention shifts in the happy and fearful conditions compared to the Finnish infants, whereas no significant difference was found between the two samples in the proportion of missing attention shifts in the control condition. No significant differences were found in performance on the switch-task and the visual search task. There were also no significant differences in performance between the two samples on the structured observation assessments of ability to respond to joint attention cues (i.e., correctly following gaze/pointing cue to target) or ability to initiate joint attention (i.e., average frequency of alternating looks between a target and experiment leader's point of gaze).

Table 4. Performance on the Eye Tracking and Structured Observation Assessment by Site

Eye Tracking Tasks	Malawian infants Mean (SD)	Finnish infants Mean (SD)	P-value
Attention disengagement: proportion missing shifts			
Control	.06 (.10)	.06 (.11)	0.626[b]
Happy	.57 (.24)	.36 (.27)	< 0.001[b]
Fear	.69 (.27)	.29 (.31)	< 0.001[b]
Switch-task: proportion correct anticipation			
Pre-switch	.70 (.04)	.70 (.04)	0.917[a]
Post-switch	.52 (.04)	.47 (.04)	0.371[a]
Visual search: proportion missing search			
Single-search one-object	.05 (.13)	.03 (.12)	0.130[b]
Single-search multiple-objects	.32 (.22)	.26 (.23)	0.198[b]
Conjunction	.49 (.25)	.40 (.25)	0.086[b]
Processing speed			
Reaction times (milliseconds)	428.82 (54.09)	388.40 (67.70)	0.006[a]

Eye Tracking Tasks	Malawian infants Mean (SD)	Finnish infants Mean (SD)	P-value
Structured observation			
Proportion correct gaze following Responding to joint attention	.43 (.20)	.47 (.22)	0.573[a]
Average number of alternating gazes Initiating joint attention	.47 (.34)	.47 (.27)	0.993[a]

[a] Mean values were compared with *t*-test
[b] Mean values were compared with Mann-Whitney U test

Figure 5. Finnish and Malawian Infants' Performance on the Eye Tracking Outcome Measures

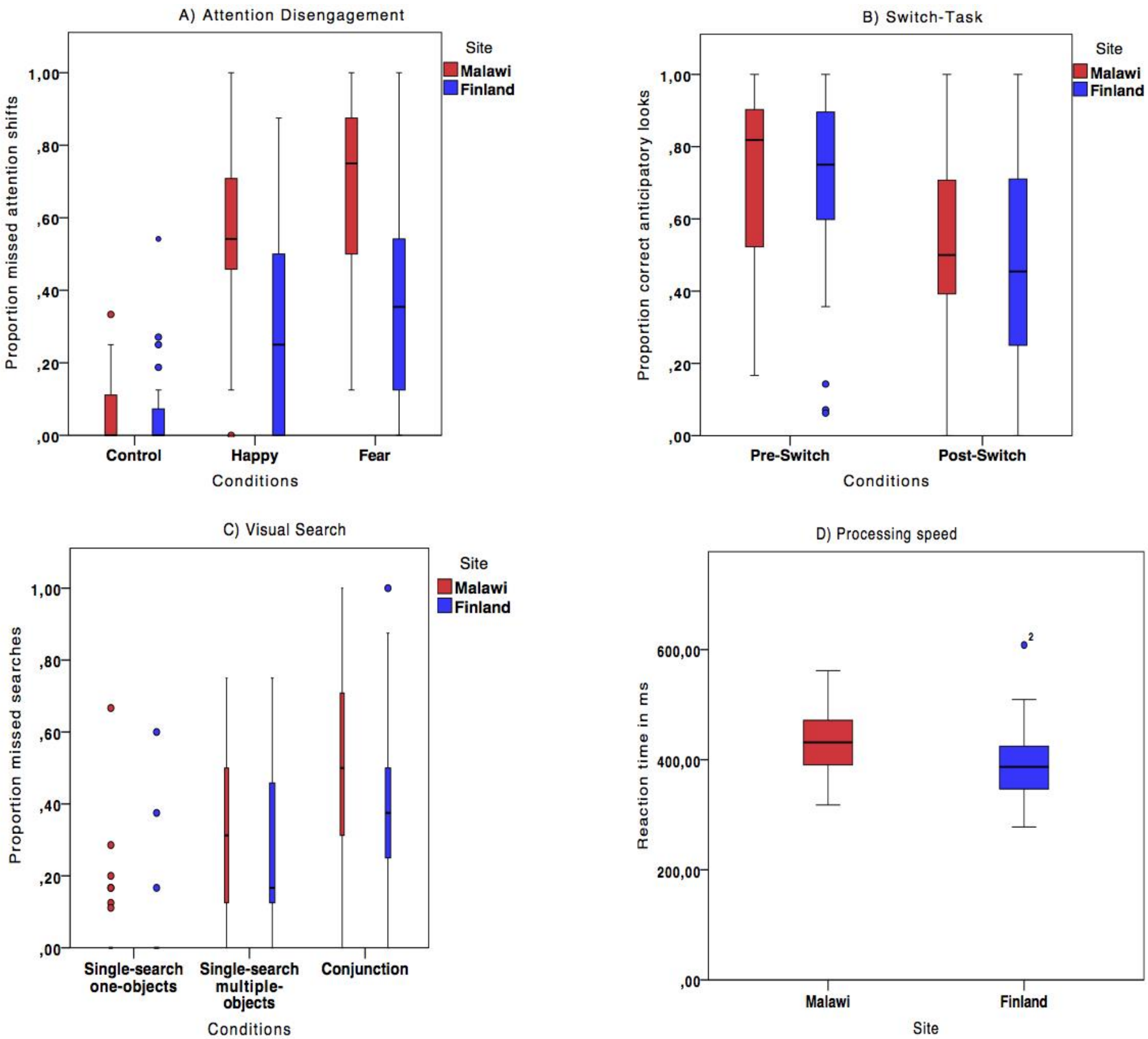
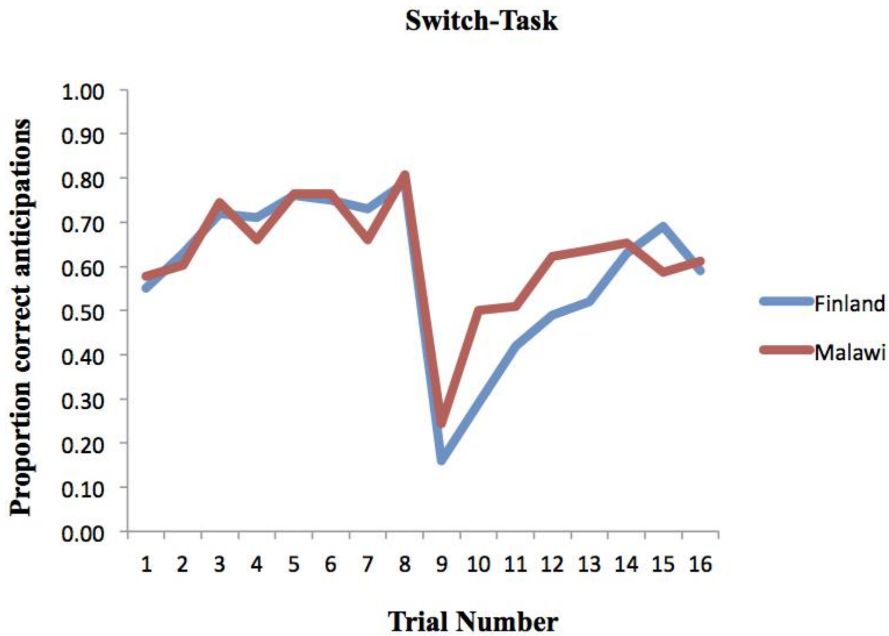


Figure 6. Proportion of Correct Anticipatory Looks in the Switch-Task across Trials



Discussion

This study supports the feasibility of using eye tracking to assess infants' cognitive functioning in low-income settings. Most Malawian participants (91.9%) were able to complete the whole eye tracking assessment, which is comparable to the percentage of Finnish participants that completed the whole eye tracking assessment (94.9%). Further, the large majority of Malawian mothers reported the assessment as a positive experience, similar to the Finnish mothers. The attrition rate of the eye tracking assessment, approximately 5–14% for the Malawian participants and approximately 0–8% for the Finnish participants, compares favorably with attrition rates reported in previous eye tracking studies in high-resource settings with infants of similar age (e.g., 20–35% in Ambrosini et al. 2013, Oakes and Ellis 2013, and Watanabe et al. 2012) and was therefore judged as acceptable.

Further, as an indicator of data quality, in both samples the percentage of valid trials for the attention disengagement task was in parity with previous studies (e.g., over 70% in Leppänen et al. 2014). For the other two eye tracking tasks—the switch-task and the visual search task for which there have been no previous studies with which to make comparisons—a higher percentage of valid trials were acquired from the Finnish sample. This did not, however, lead to a higher attrition rate in the Malawian sample (e.g., even with a lower number of valid trials in a particular task the participants can still meet the specific inclusion criteria) and therefore did not cause any meaningful problem with demonstrating the feasibility of the eye tracking method.

The results from this feasibility study along with the personal experiences of the study team suggest that the procedure, test paradigms, and the length of the testing sessions were well suited for infants in the studied age range and robust against variations in research settings and sample characteristics (e.g., differences in socioeconomic status). The eye tracking assessment was conducted with an experienced research team from Finland together with a local team in Malawi. With further training, the Malawian team is expected to acquire the skills necessary to run these assessments independently at the Malawian site.

The demonstrated cross-setting feasibility of the eye tracking assessment is an important step toward the goal of developing new tools to measure infants' cognitive functioning in a wide variety of settings. Compared to the existing (mostly manual) tools to measure early child development, the highly automatized recording and analyses of eye movements appears to have several advantages as it enables increased standardization (i.e., computer-controlled presentation of tasks) and objectivity (i.e., less human input is required for data analysis or recording). The portability of the eye tracking system used in the current study makes it possible to transport the same eye tracker between different testing sites, thus also making it a field-friendly tool. An important task for future work within eye tracking-based research on infant cognitive functioning is to develop standardized tasks and normative data sets, as this will allow for assessing whether an individual's performance score is in the average range or not for his/her age and will thus allow for a wider applicability of the method.

In addition to demonstrating the feasibility of the eye-tracking technology in a low-income setting, the results from this study show differences in cognitive function between Finnish and Malawian infants. Although these results are preliminary and based on a small sample size, some of the findings (e.g., slower processing speed among Malawian infants) are consistent with the cognitive effects that might be expected to be associated with poverty and malnutrition.

Animal research has shown that malnutrition can lead to a decrease in myelination, neurons, and brain volume (Georgieff 2007) and socioeconomic status has been associated with cortical thickness and cognitive functioning in preadolescents (Lawson et al. 2013). Further, slower processing speed in infancy has been found to predict poorer cognitive functioning in preschool (Cuevas and Bell 2014) and at 11 years of age (Rose et al. 2012). These findings point to the potential usefulness and sensitivity of the cognitive markers used in this study for assessing individual differences in infants' healthy growth, although future research with a larger and more diverse sample (i.e., in the current study the participants were all healthy and born full-term) is needed to establish their predictive validity in low-income settings. Additionally, the fact that some of the results from the comparisons across the two samples were not significant (e.g., correct anticipatory looks) suggests that the Finnish sample's likelihood of previous screen exposure compared to the Malawian sample may not play a large role in infants' performance on eye tracking tasks in the studied age span.

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Appendix 1. Eye Tracking Set-Up, Test Battery, and Processing of the Eye Tracking Data

Eye Tracking Set-Up

The eye tracking assessment took place in a quiet and dimly lit room at the Finnish and Malawian sites. To make similar testing environments for the Finnish and Malawian participants, particularly in terms of luminance, 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 meters from the floor and directed down. The study utilized a portable Tobii X2-60 eye tracker (Tobii Technology, Stockholm), which tracks the participant's point of gaze at 60 hertz with a spatial accuracy of 0.4 degrees. The eye tracker unit was connected to a laptop computer (MacBook Pro OS X, Apple Inc.) and a 22-inch monitor (Dell Inc.) 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. All the testing equipment (e.g., computer, eye tracker, monitor, speakers, fabric, and spotlight) used at the Finnish site was transported to Malawi for testing of the Malawian infants.

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. For the Finnish sample we used two "typically" Finnish-looking face models and for the Malawian sample we used two "typically" Malawian-looking face models. The validity of the Finnish face stimuli (two models of happy and fearful facial expressions) in terms of belonging to the intended emotional categories and equality of emotional intensity has been shown to be acceptable (Peltola et al. 2009). For the Malawian site, 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 Finnish fearful (M = 6.42, SD = .96) and happy (M = 6.11, SD = 1.47) facial expressions and the Malawian fearful (M = 6.31, SD = 1.07) and happy (M = 5.58, SD = 1.26) 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 > .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, the trial commenced following a short delay. In each trial the infant was first presented with the central stimuli (subtending 16 and 14 degree visual angle). After 1,000 milliseconds, 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 milliseconds had passed from the onset of the lateral stimulus, the movie played for 2,000 milliseconds.

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).

Similar 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 milliseconds 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 1,000 milliseconds 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 3 valid trials for each condition (3 in Finland and 4 in Malawi).

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. At the start of each trial two blank rectangles were presented to the left and right together with auditory stimulus for 1,000 milliseconds. When the infants made correct gaze anticipations to the location where the target would appear (or after 1,000 milliseconds had passed) an audiovisual reward appeared for 2,000 milliseconds. The reward appeared on one side (left or right) for the first 8 trials and then on the other side for the last 8 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 0–1,000 milliseconds 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 3 valid trials in both the pre- and post-switch phase (0 in Finland and 2 in Malawi).

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 their 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 the target, a search trial commenced after a short delay (500 milliseconds). 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-object 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 red sliced apples. If the participant fixated the target within 4 seconds from the start of the trail 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 0–2,000 milliseconds 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 100 to 2,000 milliseconds from the start of the search trial in the single-search one-object trials, single-search multiple-object trials, and conjunction trials was calculated. A 2,000 millisecond cut-off 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-object, and conjunction; 2 in Finland and 5 in Malawi).

Processing Speed

To measure the infants' processing speed, 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 processing speed. 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 from the single-search one-object trials were re-analyzed using a 1,000 millisecond cut-off (instead of a 2,000 millisecond cut-off), as it is equivalent to the cut-off score in the other two tasks. 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 indicates 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. One Malawian infant failed to meet this criterion and was therefore not included in this analysis. Therefore, 86% of the participants had valid reaction time data from all three eye tracking tasks; 90% in Finland and 81% in Malawi, and this result remained consistent both when including only infants with reaction time data from all three eye tracking tasks in the analysis, and when using the number of valid processing speed trials as a covariate.

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 milliseconds (i.e., trials with segments of missing data less than 200 milliseconds were rejected). Analyses of the participants' gaze was measured by fixation times inside pre-defined 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., processing speed) 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, and/or (2) the minimum required gaze fixation time inside one area of interest, prior to a saccade, was not met, and/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.