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BRIEF REPORT

From Focus to Function: Longitudinal Insights Into Infant Attention and Emerging Executive Functions via Remote Webcam Eye Tracking

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Growing evidence suggests that infant attention may predict subsequent cognitive outcomes. However, prior studies have predominantly tested small samples of infants in tightly controlled laboratory settings that differ from the complex, visually rich environments that infants experience in their day-to-day lives. The present study addresses this gap by measuring infant sustained attention in the home using novel remote webcam eye tracking methodology. A large, demographically diverse sample of 3- to 12-month-old infants ($N = 160$; 49% = female; 65% from low- to extremely low-income households; 48% White, 18% Black, 16% Hispanic/Latine, 9% more than one race, 5% Asian, and 4% other) were recruited across the United States. Infants were remotely administered a free-viewing video task previously validated in lab-based studies, and infant look durations and gaze shifts were measured using remote webcam eye tracking. Our results revealed expected age-related changes in infant look durations and no effects of family demographics on variations in infant attention. Notably, we also found that variation in infant attention predicted emerging executive functions in a subset of infants ($N = 78$) who participated in a subsequent longitudinal assessment using the Early Executive Functions Questionnaire. This research adds to a growing literature validating the use of at-home remote assessments for objective measurement of infant cognition. This is a notable step toward advancing ecological validity and accessibility of developmental psychology studies in diverse samples. Ultimately, these findings may have important implications for characterizing normative developmental trajectories and for understanding how early sociocultural contexts shape these trajectories.

Public Significance Statement

This study assessed infant attention using remote webcam eye tracking in a large, demographically diverse sample of infants tested across the United States. Results revealed age-related increases in sustained attention capacity. Moreover, individual differences in infant attention were longitudinally linked to emerging executive functions in toddlerhood. This study advances ecological validity and accessibility of developmental psychology studies and may have important implications for characterizing normative developmental trajectories.

Keywords: infant attention, executive functions, webcam eye tracking, home environment

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Executive functions, which include skills such as working memory, inhibitory control, and cognitive flexibility, are essential for flexible and goal-directed behavior (Blair, 2002; Blair & Razza, 2007). Executive functions develop rapidly over the first 3 years of life and are shaped by early experience (Blair et al., 2011; Raver et al., 2013; Werchan & Amso, 2017). Accumulating evidence indicates that infant attention is a reliable predictor of later executive functions (Brandes-Aitken et al., 2019; Cuevas & Bell, 2014; Werchan, Brandes-Aitken, et al., 2024). However, prior studies have largely tested predominately affluent and White samples, which may contribute to biased conceptualizations of normative development (Nketia et al., 2021). Moreover, the majority of studies examining infant attention have been conducted in artificial laboratory environments. Assessing representative samples of infants in more naturalistic settings is vital for understanding normative trajectories of cognition and, importantly, for targeting potential biases arising from mismatches between experimental settings and population experiences. The present study addresses this gap by examining longitudinal associations between sustained attention and executive functions in a sociodemographically diverse sample of infants tested in the home.

Sustained attention, or the ability to maintain attention over time, is observable from early in infancy and provides a foundation for more complex learning and executive functions (Colombo, 2001; Hendry et al., 2019; Ribner & Holmboe, 2024). This ability is particularly important during the first year of postnatal life, a time in which infants have substantially limited abilities to verbally communicate, manipulate objects, and physically explore the world around them. Attention is commonly indexed in infancy by the duration of time spent looking at a specific stimulus or task, with steady increases observed across the first postnatal year (Colombo, 2001; Oakes & Amso, 2018). Moreover, within-age variations in infant look durations are thought to reflect differences in the efficiency of infants' attentional processing abilities (Colombo et al., 1991). Indeed, prior studies indicate that infants classified as "short lookers" (e.g., infants with shorter look durations relative to similar-age peers) tend to score higher on subsequent measures of executive functions (Blankenship et al., 2019; Cuevas & Bell, 2014; Kraybill et al., 2019; Rose et al., 2012). In addition to look durations, gaze shifts have also been used as a measure of attentional flexibility, with prior studies demonstrating positive associations between infants' gaze shift rates and subsequent executive functions (Blankenship et al., 2019; Cuevas & Bell, 2014; Kraybill et al., 2019; Rose et al., 2012).

However, prior studies examining infant attention have primarily been conducted in constrained laboratory settings, which drastically differ from infants' familiar day-to-day environments. Moreover, existing data have largely been skewed toward predominantly White and high-socioeconomic status (SES) families (Singh et al., 2023; Singh & Rajendra, 2024). These constraints may lead to biased conceptualizations of development, in part due to mismatches between testing contexts and the naturalistic environments in which development unfolds (Werchan & Amso, 2017). These issues are increasingly acknowledged (Ellis et al., 2017; Garcini et al., 2025; Nketia et al., 2021) but have been difficult to tackle in part due to limitations in the tools available for testing infants in more naturalistic settings.

Recent progress in remote webcam eye tracking has the potential to address issues with ecological validity and sociodemographic diversity by taking the laboratory into the home. Prior studies have shown that OWLET—a novel methodology for analyzing infant eye

tracking data using prerecorded webcam videos—shows high reliability with time-intensive manual annotation of infant looking behaviors (Werchan et al., 2023). Importantly, this platform is compatible with videos obtained using smartphones, in contrast to other webcam-based eye trackers that are only compatible with computer webcams (e.g., iCatcher+; Erel et al., 2022). This is an important consideration given socioeconomic divides in access to computers relative to mobile devices in the United States (Vogels, 2021). Indeed, aligning with these known digital divides, prior work has also shown that giving families the option to participate in remote studies using their smartphones was associated with greater sample sociodemographic diversity (Werchan et al., 2023). Thus, webcam eye tracking offers a feasible opportunity for assessing more representative samples of infants in naturalistic environments.

In the present study, we use webcam eye tracking to conduct rigorous remote assessments of infant attention in the home using a validated behavioral task. Using data from a sociodemographically diverse sample of 3- to 12-month-old infants tested across the United States, we examine age-related changes in infant attention as well as correlations between infant attention and indicators of family SES. Importantly, we also evaluate longitudinal associations between infant attention and subsequent emerging executive functions using the Early Executive Functions Questionnaire (EEFQ)—a parent-report measure validated for 8- to 30-month-old infants (Hendry & Holmboe, 2021). In line with prior findings, we hypothesize that (a) the duration of time spent in sustained visual attention during the video-based attention task will increase with age, (b) individual differences in attention will be a reliable predictor of subsequent emerging executive functions, and (c) associations between family SES and infant attention will be reduced when testing a representative sample of infants in the home.

Method

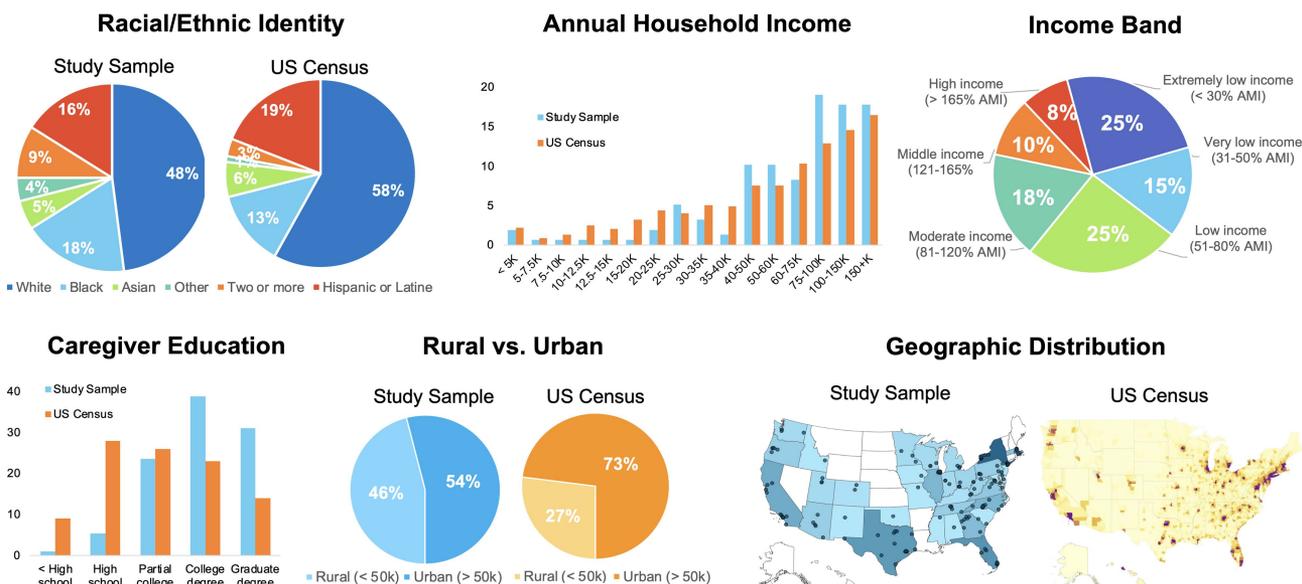
Participants

Data for the present study were drawn from the Online Remote Child Assessment project. The broader goal of the Online Remote Child Assessment project is to evaluate the feasibility of using novel remote assessments of early child development to increase the accessibility of research for families from traditionally underrepresented backgrounds in developmental psychology. Families with full-term (>36 weeks gestation) infants were recruited across the United States using social media advertisements. The total sample consisted of 160 infants (79 females, 81 males), ranging from 3 to 12 months of age ($M = 8.55$, $SD = 2.88$). Full demographic information is displayed in Figure 1. Chi-square tests indicated that there were no differences in the distributions of caregiver educational attainment, annual household income, racial/ethnic identity, or rurality status between the study sample and the U.S. population demographics based on 2020 Census Data, $ps > .22$. The New York University Institutional Review Board approved the study (Protocol No. FY2022-6371), and parental consent was obtained prior to testing. Families were compensated for their time.

Procedure

Data were collected remotely in the home at two time points. During the first assessment, the child's primary caregiver completed

Figure 1
Sample Demographic Characteristics



Note. AMI = area median income. See the online article for the color version of this figure.

online questionnaires assessing family demographics, and infant visual attention was evaluated synchronously over Zoom. Caregivers were asked to participate in a quiet area of their home and were instructed to have the infant sit on their lap. A total of 160 infants were tested, but 23 infants (14%) did not provide usable data due to poor video quality.

A subset of families ($N = 78$) participated in a follow-up assessment 1–9 months later when infants were 8–24 months of age ($M = 14.12$ months, $SD = 3.6$). Caregivers completed the EEFQ (Hendry & Holmboe, 2021) online via REDCap. We verified that there were no differences in attention or sociodemographic measures between infants who did and did not complete the second assessment, $p_s > .30$.

Measures

Infant Attention

Infant gaze behavior was measured remotely in the home during a moderated Zoom visit. Infants watched a short 80-s Sesame Street free-viewing video task that has been validated as a reliable measure of attention in both lab-based (Blankenship et al., 2019; Kraybill et al., 2019) and remote studies (Werchan, Hendrix, et al., 2024). Prior to beginning the video, experimenters guided caregivers through positioning their infants so that their eye movements to the left, right, bottom, and top of the screen could be clearly seen during a calibration procedure. Experimenters recorded the infants during calibration and the visual attention task for subsequent offline eye tracking analysis of infants' gaze behavior using OWLET (Werchan et al., 2023). OWLET was used to analyze (a) peak look duration, defined as infants' single longest consecutive fixation to the video, and (b) gaze shifts, defined as the total number of looks to the video.

Early Executive Functions Questionnaire (Hendry & Holmboe, 2021)

The EEFQ is a parent-report measure of emerging executive functions validated for ages 8–30 months. Only the parent-report questions of the EEFQ were administered, resulting in a total of 28 items. It includes four scales: (a) Inhibitory Control (IC; seven items), (b) Flexibility (FX; seven items), (c) Working Memory (WM; six items), and (d) Regulation (RG; eight items). For each item, parents reported on the frequency with which their child had exhibited various behaviors in the past 2 weeks (e.g., “repeat something they had just been shown how to do,” “hesitate for at least a second when you said no,” “try a different way to complete a tricky task without being shown,” “return to being calm within 3 min of a small frustration”) on a 7-point Likert scale (1 = *never*, 7 = *always*). Scores for each scale were computed by calculating the average of all items within each scale. Cronbach's α indicated acceptable to good reliability for all four scales (EEFQ-IC: $\alpha = .66$; EEFQ-FX: $\alpha = .63$; EEFQ-WM: $\alpha = .78$; and EEFQ-RG: $\alpha = .87$).

Sociodemographic Questionnaire

Caregivers provided demographic information including caregiver and infant age, primary caregiver educational attainment, annual household income, relationship status (partnered vs. single), number of children and adults in the household, and infant racial/ethnic identity. Caregiver educational attainment was calculated as the total number of years of education (10 = *high school*, 12 = *high school or equivalent*, 14 = *some college*, 16 = *college degree*, 18 = *graduate degree*). Family area median income (AMI) ratio was calculated as the total household income divided by the median income for the corresponding household size and zip code.

Analytic Plan

All analyses were performed using the *Lavaan* package in R Version 4.3.2. We first examined descriptive statistics and bivariate correlations. We then examined sociodemographic predictors of infant attention using multiple linear regressions. Finally, we examined longitudinal associations between infant attention and subsequent emerging executive functions in the subset of $N = 78$ infants who participated in the follow-up assessment. We used full-information maximum likelihood estimation to account for missing attention data (14% within the full sample; 8% within the $N = 78$ follow-up sample). Relative to other methods (e.g., listwise or pairwise deletion, mean imputation), full-information maximum likelihood generates unbiased estimates for data missing at random and is considered a superior method for handling missing data.

Transparency and Openness

All information about the sample, measures, and data collection processes relevant to this study were reported. The data from this study are unavailable to the public as the informed consent process did not explicitly authorize public sharing. This study design was not preregistered.

Results

Descriptive statistics and correlations among infant attention and sociodemographic variables are presented in Table 1. Of note, infant age at test was correlated with longer peak look durations, consistent with expected age-related increases in sustained attention. In addition, infant age was also correlated with fewer gaze shifts. To account for these age-related changes in subsequent analyses, we binned the data into 1-month age groups and then standardized scores within each bin. Thus, infant peak look duration and gaze shifts were standardized relative to their age in all subsequent analyses, with positive values reflecting longer peak look durations and increased gaze shifts relative to similar-age infants.

Next, we used multiple linear regressions to examine associations between measures of infant attention and family SES. Family AMI ratio, primary caregiver educational attainment, and marital status (partnered vs. single) were used as predictors of infant look durations and gaze shifts (standardized relative to age). Infant biological sex at birth was included as a covariate. Results revealed no effects of primary caregiver educational attainment, family AMI ratio, or caregiver relationship status on infant peak look durations, $\beta s < .16$, $ps > .09$. However, there was an effect of infant sex, with female

infants showing longer peak look durations on average relative to male infants, $\beta = .16$, $p = .04$. Neither caregiver education, relationship status, family AMI ratio, nor infant sex predicted variation in infant gaze shifts, $\beta s < .13$, $ps > .16$.

We then used multiple regression analyses to test hypothesized links between measures of infant attention (standardized relative to age) and subsequent emerging executive functions. All analyses controlled for infant biological sex and age at the second assessment. Full regression results are reported in Table 2. Of note, there were no associations between the regulation component of the EEFAQ and infant fixation durations or gaze shifts. However, higher cognitive flexibility scores were predicted by longer fixation durations and increased gaze shifts. Similarly, longer fixation durations also predicted higher working memory scores. The number of gaze shifts was not associated with working memory scores, and there were no associations between measures of infant attention and inhibitory control.

Discussion

Here, we measured associations between infant attention and emerging executive functions using data from a large, demographically diverse sample of 3- to 12-month-old infants tested in the home using remote webcam eye tracking. Our primary findings are threefold. First, we observed expected age-related changes in infant attention, replicating prior findings showing that remote eye tracking is a reliable method for assessing infant attention in the home (Werchan, Hendrix, et al., 2024; Werchan et al., 2023). Second, we found that variation in infant attention predicted emerging executive functions in a subset of infants who participated in a longitudinal assessment. Last, we found that indices of family SES were not associated with infant attention when testing a representative sample of infants in their homes.

The lack of an association between family SES and attention contrasts with some prior reports from lab-based studies (Clearfield & Jedd, 2013; Rosen et al., 2021; Werchan et al., 2019). Importantly, however, we recruited a large, demographically and geographically diverse sample of families. Indeed, the demographic distribution of our sample was representative of the broader U.S. population (Figure 1). In contrast, the majority of developmental psychology samples have consisted of predominantly White families from higher income households (Singh et al., 2023; Singh & Rajendra, 2024). Moreover, few studies have assessed infant attention in the home (although see Bradshaw et al., 2023; Brandes-Aitken et al., 2019; Werchan, Brandes-Aitken, et al., 2024; Werchan, Hendrix, et al., 2024). Testing infants in familiar environments may be more ecologically valid and reduce biases resulting from contextual

Table 1

Descriptive Statistics and Correlation Matrix

Variable	<i>M</i> or %	<i>SD</i>	1	2	3	4	5	6
1. Peak look duration (s)	32.8	25.9	—					
2. Gaze shifts	5.02	2.9	-.73***	—				
3. Infant age (months)	8.43	2.8	.24**	-.18*	—			
4. Family AMI ratio	0.77	0.52	.15	-.03	.14	—		
5. Education (years)	15.93	1.8	.21**	-.06	.03	.28***	—	
6. Marital status (partnered)	78%		.12	-.04	.11	.23**	.27***	—

Note. AMI = area median income.

* $p < .05$. ** $p < .01$. *** $p < .01$.

Table 2
Longitudinal Associations Between Infant Attention and Emerging Executive Functions

Predictor variable	Regression model			
	Beta coefficient	EEFQ-RG	EEFQ-FX	EEFQ-IC
Peak look duration	-.14	.35*	.15	.32*
Gaze shifts	-.20	.41**	.21	.15
Infant age	-.15	.08	-.10	.08
Infant biological sex	-.01	.08	-.12	.02

Note. EEFQ = Early Executive Functions Questionnaire; RG = Regulation; FX = Flexibility; IC = Inhibitory Control; WM = Working Memory.

* $p < .05$. ** $p < .01$.

mismatches between experimental designs and population experiences (Bronfenbrenner, 1974). Complementing research in laboratory settings with more ecologically valid assessments is likely to enrich our understanding of normative development and the experiential factors that shape individual variability.

Notably, we found that webcam eye tracking-based measures of infant attention were associated with subsequent parent reports of emerging executive functions measured using the EEFQ (Hendry & Holmboe, 2021). Specifically, longer peak look durations and increased gaze shifts predicted higher cognitive flexibility scores. Similarly, longer peak look durations also predicted higher working memory scores. These findings replicate prior lab-based reports demonstrating that increased gaze shifts predict better subsequent cognitive outcomes (Blankenship et al., 2019; Cuevas & Bell, 2014; Kraybill et al., 2019; Rose et al., 2001, 2012). However, several studies have also reported that *shorter* fixation durations are associated with better subsequent outcomes (Blankenship et al., 2019; Colombo et al., 1991; Cuevas & Bell, 2014; Kraybill et al., 2019; Rose et al., 2001, 2012), whereas we observed the opposite.

This discrepancy in the direction of observed associations between infant peak look durations and emerging executive functions may relate to the contextual effects of the task and experimental design. The majority of studies demonstrating the positive effects of shorter look durations have used static stimuli and/or habituation-based paradigms (Colombo et al., 1991; Cuevas & Bell, 2014; Rose et al., 2001, 2012). It is possible that look durations measured using dynamic, changing stimuli may reflect variation in sustained attention rather than the efficiency of information processing abilities. This difference could also result from mismatches between experimental designs and infants' daily life experiences. In contrast to visually sparse laboratory settings, naturalistic environments are rife with distractions, which may also vary substantially from home to home. Attending to target stimuli in these more "distracting" or visually rich contexts would necessitate the suppression of external distractors, consequently upping the gain of attended stimuli (Amso & Scerif, 2015). This suggests that longer look durations in more distracting environments may reflect enhanced attentional processing. Indeed, experimentally increasing distraction has been shown to improve attentional processing and subsequent learning and memory outcomes (Nussenbaum et al., 2017). Similarly, other findings have shown that infants spend increased time exploring complex objects relative to simpler ones (Oakes & Tellinghuisen, 1994). As such,

our findings are consistent with the idea that the measurement and development of infant behavior are intimately entwined with contextual features of the environment. In some contexts, this could lead to differences in observed behavior due to mismatches between testing environments and infants' daily life experiences (Werchan & Amso, 2017). Assessing infants in more naturalistic environments, such as their homes, may help ameliorate some of these issues arising from potential contextual mismatches. As such, this study highlights the importance of assessing representative samples of infants in more naturalistic settings to gain a more accurate and less-biased, understanding of developmental processes.

In contrast to the significant associations with working memory and cognitive flexibility scores, we did not observe a relationship between measures of infant attention and the emotional regulation or inhibitory control dimensions of the EEFQ. Previous longitudinal studies examining associations between infant attention and specific subdomains of executive functions largely report similar results as those found in the present study. Specifically, measures of infant-looking behavior have been found to predict variation in subsequent working memory and cognitive flexibility skills, but not inhibitory control skills in later childhood (Holmboe et al., 2018; Kraybill et al., 2019; Rose et al., 2012). Similar to our findings, a validation study of the EEFQ found that measures of infant attention were only weakly associated with the regulation subscale; moreover, this association was only observed in older toddlers and not in infants under 12 months of age (Hendry & Holmboe, 2021). As such, our findings are consistent with prior work and suggest that associations between infant attention and subsequent inhibitory control and emotional regulation skills may not be apparent at early ages of development.

There are several limitations to this study. First, our data come from infants spanning a large age range (3–12 months of age). This range was an intentional study design feature, as the broader goal of this research was to assess the feasibility of remote webcam eye tracking in the home across a range of ages and contexts. However, testing more constrained age groups in future work may be informative for identifying sensitive windows as well as individual variability within particular age groups. Second, we only measured infant attention at one time point; future work would benefit from repeat assessments of infant attention. This is particularly relevant given that prior studies have found that individual differences in the *change* in attention over time are a stronger predictor of subsequent outcomes than individual differences at a single point in time (Hendry et al., 2018, 2020; Werchan, Brandes-Aitken, et al., 2024). Third, we did not have a measure of infant screen time exposure, which may contribute to individual differences in how infants deploy attention, particularly during a video-based assessment. Assessing infant screen time exposure and other relevant prior experience may be helpful for reducing noise and better isolating the experiential factors that shape early trajectories of attention development. Last, even though we tested infants in a naturalistic environment, video-based tasks are relatively artificial compared to other contexts that elicit attention (e.g., social interactions) and may not be ecologically valid for many families within the United States and worldwide. For example, a recent meta-analysis of families across the globe indicates that nearly one quarter of infants under age 2 do not regularly watch television (McArthur et al., 2022). Using culturally sensitive tasks that better

mirror how infants engage attentional resources in their everyday lives is an important goal for future work.

In sum, the present study replicates prior findings showing associations between infant attention and emerging executive functions using a webcam eye tracking-based task administered fully remotely in the home. This research adds to growing evidence validating at-home remote assessments for objective measurement of infant behavior. This is a notable step toward increasing the accessibility of participating in developmental psychology studies for families from a variety of backgrounds. Importantly, this work also underscores the significance of the infancy period in shaping subsequent neurocognitive outcomes. Ultimately, these findings may have implications for characterizing normative developmental trajectories and for understanding how early sociocultural contexts shape individual variability in these trajectories.

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