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REPORT

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Caregiver executive functions are associated with infant visual working memory

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Abstract

Caregiver executive functions (EFs) play an integral role in shaping cognitive development. Here, we investigated how caregiver EF abilities (86 caregivers; *mean age* = 33.4 years, SD = 4.5) was associated with visual working memory (VWM) in infants (86 infants females; mean age = 250.6 days, SD = 35.8). The BRIEF-A was used to assess caregiver EFs, and a preferential looking task along with fNIRS was used to assess VWM function in infants. Our findings revealed that better caregiver behavioral regulation was associated with better VWM performance, greater right-lateralized parietal activation, and left-lateralized frontal suppression, while better caregiver metacognition and emotional control was associated with greater right-lateralized temporal suppression in infants. Taken together, these associations suggest that better caregiver EF abilities might shape visuo-spatial attention and memory, guide fixation on task-relevant goals, and suppress distractions in children from as early as the first year of life.

Highlights

- The study investigated the association between caregiver executive functions (EF) and visual working memory (VWM) function in infants.

Figures based on previous work have been recreated and not copied.

- Caregiver EFs were assessed using the BRIEF-A questionnaire, and infant VWM function was assessed using the preferential-looking task and brain imaging.
- Better caregiver EF abilities were associated with better VWM behavior and fronto-temporo-parietal engagement in infants.

KEYWORDS
caregivers, executive functions, fNIRS, infants, visual working memory

1 | INTRODUCTION

Caregivers play a pivotal role in guiding cognitive development in children. They are required to set and follow goals, appropriately shift attention, inhibit, and regulate behaviors, and exercise effortful control—collectively referred to as executive functions (EFs). Given the repetitive and profound nature of these interactions, it is vital to understand how child EFs are linked to caregiver EFs. Previous work has shown that harsh caregiving behaviors are associated with child conduct problems in caregivers with poor EFs (Deater-Deckard et al., 2012). Further, at 24 months of age, caregiver EFs are associated with child EFs, and by 36 months, caregiver EFs and negative caregiving behaviors predict child EFs (Cuevas et al., n.d.). Similarly, caregiver EFs predict emergent EFs in toddlerhood with caregiver EFs being related to shifting and working memory abilities in 12–24 month-old children (Ribner et al., 2022). These findings suggest that there is a link between individual differences in caregiver EFs and child EFs, but it is not clear whether such links are present and observable as early as infancy. Exploring alignment between infant EFs and caregiver EFs is challenging because it is unclear when and how different sub-functions emerge and develop in the first year of life, and there are limited tasks that can be used to study EF development very early on and be adopted to use with neuroimaging techniques.

One critical EF sub-function that is observable and measurable during infancy is visual working memory (VWM). This system emerges around 4 months of age, when infants begin to track and process visual stimuli within their surroundings (Buss et al., 2018; Isbell et al., 2015; Simmering, 2012). From there on, VWM capacity and accuracy steadily increases across childhood (Buss et al., 2018; Eschman & Ross-Sheehy, 2017; Eschman & Ross-Sheehy, 2023; Oakes et al., 2011; Oakes et al., 2017; Ross-Sheehy et al., 2003). Critically, this function is a reliable predictor of individual differences in later EFs, academic abilities, intelligence, socio-emotional development (Conway et al., 2003; Cowan, 2014; Davidson, Shing, et al., 2023; Gathercole et al., 2004). Using a preferential-looking paradigm, previous studies have shown that VWM changes as a function of load (Delgado Reyes et al., 2020; Ross-Sheehy et al., 2003), age (Delgado Reyes et al., 2020), fronto-parietal activation (Davidson et al., 2024; Delgado Reyes et al., 2020; Wijeakumar et al., 2019; Wijeakumar et al., 2023), socioeconomic status (Wijeakumar et al., 2019), health (Spencer et al., 2023), and physical status (Wijeakumar et al., 2023)—making it an excellent candidate system to probe in relation to caregiver involvement. Our recent work has shown that while caregiver efficiency of inhibitory control does not directly predict VWM behavior in 6-to-9-month-old infants, there is an *indirect* association through left parietal activation in infants, a region involving visuospatial attention and VWM maintenance (Davidson et al., 2024). In another study, we found that caregiver VWM function was directly linked to infant VWM function, both at the level of behavior and brain function (Theyer et al., 2024). Both studies used experimental paradigms to measure caregiver EF sub-functions and infant VWM function, enabling direct comparisons of behavioral performance and brain measures.

In the current study, we build upon our afore-mentioned research by first measuring caregiver EF sub-functions embedded in real-world daily life cognition, and then relating them to infant VWM function. To this end, we measured caregiver EFs using the Behavior Rating Inventory of Executive Function–Adult Version (BRIEF-A) and we measured VWM behavior and brain function in 6-to-10-month-old infants as they engaged with a preferential looking visual cognition task. The study posed two research questions. The first research question inquired whether caregiver EFs measured using the BRIEF-A would be categorized into a three-factor model as reported in previous related literature in young adults (Roth et al., 2013)—a behavioral regulation index (made up of self-monitor and inhibit), a metacognition index (made up of initiate, working memory, plan/organize, task monitor, and organization of materials) and an emotional regulation index (made up of shift and emotional control). We predicted that the same factor structure would emerge from the caregiver dataset in the current study. The second research question inquired whether caregiver EFs would be associated with infant VWM behavioral performance and VWM-related brain function. Given that our caregiver EF factors reflected daily life cognition (and not experimental measures as in recent work (Davidson et al., 2024; Theyer et al., 2024)) and previous caregiver-child associations in infancy (Theyer et al., 2024) and toddlerhood (Cuevas et al., n.d.; Ribner et al., 2022), we predicted that caregiver EF factors would be linked to infant VWM performance. In relation to brain function, previous work has shown that VWM performance is associated with greater activation in the parietal cortex important for better visuo-spatial attention and VWM maintenance (Davidson et al., 2024; Davidson, Caes, et al., 2023; Davidson, Shing, et al., 2023; Delgado Reyes et al., 2020; McKay et al., 2021; Theyer et al., 2024; Todd & Marois, 2004; Todd & Marois, 2005; Wijeakumar et al., 2023), reduced/suppressed activation in the temporal cortex important for suppressing re-orienting attention to irrelevant items/goals (Todd et al., 2005; Wijeakumar et al., 2023), and reduced/suppressed activation in the frontal cortex suggesting reduced need to attend to distracting events (Davidson, Caes, et al., 2023; Wijeakumar et al., 2019; Wijeakumar et al., 2023). Thus, we predicted that better caregiver EFs would be associated with increased parietal activation, reduced/supressed temporal activation, and reduced/suppressed frontal activation in infants. For both behavioral performance and brain function, we expected to observe stronger associations with the metacognition factor compared with the other two factors as it was composed of WM and goal initiation and planning abilities.

2 | MATERIALS AND METHODS

2.1 | Participants

Families with infants aged between 6 and 10 months were recruited for this study through communication with relevant organisations and public engagement events. Interested families were screened to ensure they met the inclusion criteria: infants were born to full term and had caregivers with no history of illicit drug use or severe alcohol usage during pregnancy, neither caregivers nor infants had been diagnosed with neurological or major psychiatric illnesses, all infants had a normal or corrected-to-normal vision, and infants came from households where English was one of the primary languages spoken. After screening, families were invited to visit the research facility. Caregivers gave consent for themselves and their infants. Ethical approval was granted by the School of Psychology Ethics Committee (Approval Reference: F1415). Power calculations were performed before the project began, with an effect size of 0.15 based on results from a one-factor ANOVA examining the effect of load on looking measures in Delgado Reyes et al. (2020) ($\alpha = 0.05$ and power $= 0.80$). It was determined that 85 families would need to participate in the study based on the calculations.

A total of 111 families expressed interest in the study. Out of this sample, 17 families withdrew from the study and a further 4 families were not included due to infants being outside the age range of interest. A total of 90 families were recruited into the study. Data from 3 families were excluded from analyses due to a family history of color blindness. Further, data from two infants were excluded due to an inconsistent number of runs on the infant VWM task. Questionnaire data from 1 caregiver was excluded due to investigator error. Consequently, the final sample consisted of 86 caregivers (85 females and 1-non-binary; $M_{age} = 33.4$ years, SD = 4.5) and 86 infants, including one pair of twins (44 females; $M_{age} = 250.6$ days, SD = 35.8). A breakdown of sample size for each aspect of the study are presented in the Data Analyses section below. Table 1 shows demographic and socioeconomic status information from the families. Figure 1b shows a histogram of infant age in days. Note that we have previously published the infant VWM behavior and brain data (Davidson et al., 2024).

2.2 | Caregiver EFs

The BRIEF-A (Roth et al., 2005) is a 72-item questionnaire assessing adults' self-reported daily executive functioning and self-regulation. Caregivers were asked to answer the following question for each item: 'During the past month how often has each of the following behaviors been a problem?'. Caregivers responded with never (given a value of 1), sometimes (given a value of 2), or often (given a value of 3). The listed items were categorized into nine EF subscales: inhibition, self-monitor, plan/organise, shift, initiate, task monitoring, emotional control, working memory, and organisation of material. Raw scores were calculated by summing responses across relevant items for each scale. Raw scores were converted to T-scores to provide information relative to the scores of adults in the standardized sample. Here, T-scores <59 are considered within the typical range, T-scores of 60–64 are within the mildly elevated range, and T-scores ≥65 are significantly high scores. A higher score on any scale is indicative of dysfunction.

2.3 | Infant VWM task

The preferential-looking task was used to assess VWM in infants (Figure 1a) (Davidson et al., 2024; Theyer et al., 2024). The task was created using Psychopy v2021.2.3 and presented on a TV screen. Each trial began with an attentional dynamic cue presented at the centre of the screen. This cue was a rotating animated star with a smiley face accompanied with music. The attentional cue remained on the screen until the infant looked at the TV. Once

TABLE 1 Demographic and socioeconomic status information from families.

Measure	*N*	Mean	SD
Infant age (days)	86	250.6	35.8
Primary caregiver age (years)	86	33.4	4.5
Primary caregiver education (years)	78	16.2	2.2
Secondary caregiver education (years)	76	13.8	4.3
Primary caregiver income (£)	69	£28,125	£13,402
Secondary caregiver income (£)	49	£31,452	£11,552
Primary caregiver's ethnicity	***N***		**%**
Arab	1		1.1
Asian	5		5.8
Mixed	4		4.6
White British	65		75.5
Other White	2		2.3
Did not answer	9		10.4

Note: This information was not available for all families (as reflected in the differences in *N*).

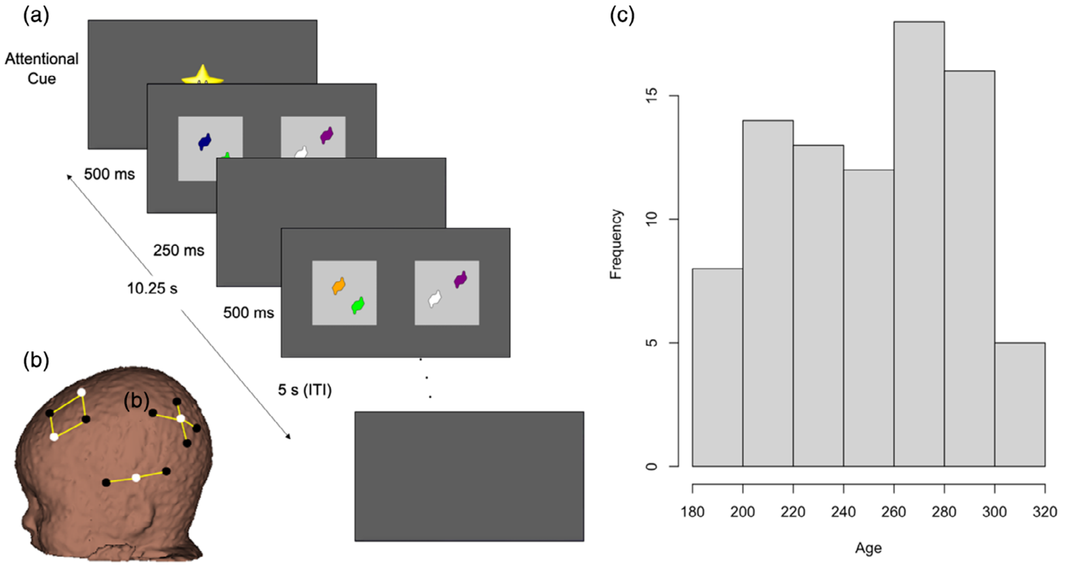

FIGURE 1 (a) Preferential-looking task with changing side shown on the left for medium load. (b) Infant fNIRS probe geometry. White dots indicate sources, black dots indicate detectors and yellow connections indicate channels. (b) Histogram of infant's age in days.

the experimenter noted that infants were attending to the cue, they continued to the trial. During each trial, two side-by-side flashing displays of colored shapes are presented. On one side ('changing side'), the color of one of the shapes randomly changed to another color. On the other side ('unchanging side'), the colors of the shapes (Drucker & Aguirre, 2009) remained the same. The displays had a solid grey background. The colors of the shapes presented on each display were selected from a set of 16 colors: (RGB values: 0 0 0; 255,255,255; 255 0 0; 0255 0; 0 0255; 255,255 0; 0255 255; 255 0255; 128 0 0; 128,128 0; 0128 0; 128 0128; 0128128; 0 0128; 255,165 0; 222,184,135). The positions of the shapes on each display were randomly selected from a 3-×-3 grid of possible positions in a trial, the colors of the shapes differed from each other, but colors could be repeated between the displays (i.e., the same color could appear on both displays). There was an inter-trial interval of 5 s between each trial. Infants were presented with either 1 (low load), 2 (medium load) or 3 (high load) shapes on each side. Each run consisted of 18 trials (6 trials at each load) with each load randomly presented 6 times (3 trials where the changing side was on the left of the screen and 3 trials where the changing side was on the right side of the screen). We presented between 1 and 6 runs of the task depending on infants' engagement (mean: 3.17 ± 1.29). One run of 18 trials took around 5 min (without cartoons or breaks).

One video camera recorded the TV display using the Movavi program (https://www.movavi.com/mac/) while another video camera used the BandiCam program (https://www.bandicam.com) to record the infant's face during the task. Live feed from the video cameras were presented to the experimenters so that they could use infant engagement to introduce the cue, advance to the next trial, or put on a cartoon.

2.4 | fNIRS data collection

fNIRS data was collected using the NIRScout System (wavelengths 760 nm and 850 nm). Infant probe geometry consisted of 16 sources and 8 detectors creating 20 channels (Figure 1b). The probe geometry covered frontal, temporal, and parietal regions. Multiple cap sizes were used to accommodate for the varying head sizes (42, 44, 46, and 48 cm). Source-detector separation was scaled according to cap size (e.g., 48 cm: 2.4 cm).

2.5 | Procedure

Recruited families visited the University research facility. Two researchers were always present at each of the sessions; one researcher was responsible for presenting the task to the infants and the other researcher monitored the fNIRS signals. One of the researchers also administered the questionnaires. After obtaining informed consent from the caregiver, infants were seated either in a high chair or on the caregiver's lap, approximately 100 cm away from the TV screen. A cartoon was played for the infant to keep them engaged while the researchers set up the task and placed the fNIRS cap on the infant's head. Once the infant was comfortable and their attention was drawn towards the screen, the experimenters began the task and monitored the infant through the real-time video recordings of the session. If the infant showed signs of disengagement or distress, the attentional cue or cartoon clips were displayed on the screen. Breaks were given if the infant needed to be fed, fell asleep, or could not be calmed even after using the cartoon clips. The caregiver also filled in the BRIEF-A questionnaire and carried out other aspects of the project. Participants received an inconvenience allowance for each visit.

3 | DATA ANALYSES

3.1 | Caregiver EF analyses

We conducted an exploratory factor analysis (EFA) on the raw BRIEF-A data using RStudio (RStudio Team, 2020) to identify underlying EF factors. BRIEF-A data from 86 caregivers were used in the analysis. Prior to conducting the EFA, we validated the psychometric properties of the data. Specifically, we checked whether any item was highly correlated with any other item (>0.8). Next, data suitability for factor analysis was assessed using the Kaiser-Meyer-Olkin test and a Bartlett's Test of Sphericity. Kaiser-Meyer-Olkin measures the adequacy of data for factor analysis and Bartlett's Test of Sphericity needs to be significant at $p < 0.05$ level to be considered suitable for EFA. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.83 (values ranging between 0.5 and 1.0 are indicative of appropriateness of the data). The Bartlett's Test of Sphericity was significant at the <0.00001 level (X^2 (36) $=306.8$, $p = 1.06 \times 10^{-44}$). The overall Cronbach's alpha was 0.79, which is considered reliable.

Once we ensured that the data met the above requirements, we conducted an EFA with principal axis factoring and varimax rotation technique with maximum iterations for convergence at 25 to extract our factors. We also suppressed small coefficients using an absolute value below 0.32 (item loadings <0.32 are viewed as undesirable for an EFA). Two EF factors were identified from the data—caregiver behavioral regulation and caregiver metacognition and emotional regulation. We discuss these factors in the Results section. T-scores of relevant items were averaged to create a caregiver behavioral regulation score and a caregiver metacognition and emotional regulation score. Data was considered an outlier if it fell outside of $\pm$ 3 SDs from the mean. There were no outliers in any of the caregiver factors.

3.2 | Infant behavioral analyses

DataVyu (https://datavyu.org/) was used to code the data. Three coders (GA, AT, CD) with high reliability independently coded the video recordings. First, they coded the video recording of the TV display, assigning load (low, medium, or high) and changing side (left or right) for each trial. This information was then hidden from the coders' view and the recording of the infant's face was coded. Looks were manually coded and assigned to the category of either ‘left’ or ‘right’ based on whether the infant looked to the left or right of the screen. We computed reliability using Cohen's Kappa, a statistic that looks at the percent agreement across categories normed by the base rate of each category. Kappa values from 0.81 to 0.99 indicate near-perfect agreement, while 23% of all data were double coded for checking reliability, with a mean Kappa value of 0.94. For each trial, a change preference score (CP) was calculated as the looking time to the changing side divided by the total time spent looking at the left and right displays on the screen. Greater CP scores were indicative of better VWM. CP scores were calculated for each trial and for each infant. Then, a weighted average CP score was calculated to account for differing number of trials across infants for each load. Data was considered an outlier if it fell outside of $\pm$ 3 SDs from the mean. Looking behavior data at the medium load from three infants were identified as outliers and removed from the dataset. Thus, a total of 86 infants contributed to CP scores at the low load, 83 infants contributed to CP scores at the medium load, and 86 infants contributed to CP scores at the high load.

Statistical analyses were run using RStudio (RStudio Team, 2020). A one-factor ANCOVA was run to examine the impact of load on CP scores, after controlling for infant age. Regression models were run to examine the impact of caregiver EF factors on infant CP scores, after controlling for infant age.

4 | INFANT BRAIN ANALYSES

4.1 | fNIRS pre-processing

All fNIRS data was pre-processed in *EasyNIRS* using Homer2. Raw data was pruned to remove noisy channels (dRange = 0.03–2.0; SNRthresh = 2; SDrange = 2.5–4.5 and SDrange = 2–3). 3.15% of the channels were pruned. Raw intensity values were converted to optical density units. Targeted principal component analyses were used to detect and remove motion artifacts (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5, nSV = 0.97, maxIter = 5). The data were then scanned again for remaining motion artifacts (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5). The StimRejection fuction was used to reject uncorrected motion artifacts (tRange = −1–18). The data were then band-pass filtered (hpf = 0.016, lpf = 0.5). Following pre-processing, the percentage of trials lost in the infant dataset was 7.55% for low load, 7.83% for medium load, and 6.96% for high load. This pre-processed optical density time-series data were then used for image reconstruction described below.

4.2 | fNIRS image reconstruction

To account for age-specific differences in head size and head shape, age-specific atlases (infants: at 6, 7.5, and 9 months) were obtained from the Neurodevelopmental MRI database (Richards et al., 2016). Each atlas was segmented into four tissue types (scalp, cerebrospinal fluid, grey matter, and white matter). Scalp landmarks and probe geometry were digitized on a single child wearing a 48 cm cap using a Polhemus Patriot Digitizer. The digitized scalp landmarks and probe geometry were projected onto each age-specific atlas using *AtlasViewerGUI* in Homer2. Monte Carlo simulations with 1 million photons were run to create sensitivity profiles for each channel and for each infant. The sensitivity profiles were converted to NIFTI format. Image reconstruction techniques were used to integrate pre-processed optical density time-series data with the sensitivity profiles to generate voxel-wise time-series data for each chromophore and infant (Forbes et al., 2021).

A general linear model with three regressors (low, medium, and high loads) was separately run for each chromophore and each infant. Each trial was modeled with a 10 s boxcar using a hemodynamic response function derived from diffuse optical imaging (Eggebrecht et al., 2014). These analyses generated beta coefficient images for each load, chromophore, and infant. Additionally, to control for the variability in the number of trials per load across infants, weighted averages were computed for each load, chromophore, and infant. Resulting beta coefficient maps were registered to the MNI space and used in group analyses described below.

4.3 | fNIRS group analyses

A group mask was calculated for infants by masking and summing beta maps representative of each age-specific atlas and extracting voxels that contained data from 70% of the data. Only data from these voxels were used for linear mixed effects modeling.

Two separate linear mixed-effects models were run to investigate the impact of (1) caregiver behavioral regulation, and (2) caregiver metacognition and emotional regulation on the infant brain (in AFNI using *3dLME*). Each model consisted of load (low, medium, and high), and chromophore (HbO and HbR) as multi-level factors and infant CP score, and caregiver factor score as quantitative variables. Here, we only examined effects that included chromophore and caregiver factors. We included chromophore as a variable because we expected increased HbO concentration and decreased HbR concentration to represent 'activation', and decreased HbO concentration and increased HbR concentration to represent 'suppression'. Resultant F-statistic interaction images were thresholded at a cluster-wise threshold of upto 247 voxels and a voxel-wise *p*-value of <0.01 (using *3dClustSim* and *3dClusterize*). *3dROIstats* was used to extract average HbO and HbR concentration from significant clusters. Averaged HbO and HbR concentration were used in regression models to run follow-up tests, after controlling for infant age.

5 | RESULTS

5.1 | Factor structure of caregiver EFs

Basing on the examination of the scree plot and prioritizing eigen values of >1, the EFA showed that a two-factor model best fit for our data and accounted for 50% of the variance. The first factor was composed of six subscales (plan/organize, initiate, working memory, task-monitor and shift and emotional control) and conceptualized as 'metacognition and emotional regulation'. The second factor was composed of two subscales (self-monitor and inhibit) and conceptualized as 'behavioral regulation'. Organization of materials showed weak loading onto both factors (<0.32) and therefore was excluded from further analyses. For both factors, higher scores were indicative of poorer abilities.

5.2 | Infant VWM performance

After controlling for age, the main effect of load was significant (F [2,251] $= 13.683$, $p = 0.00002$, $\eta^2 = 0.098$; low load $= 0.59 \pm 0.08$; medium load $= 0.55 \pm 0.07$; high load $= 0.54 \pm 0.07$). Pairwise comparisons revealed that CP score at the low load was higher than CP scores at the medium ($p = 0.0003$) and high loads ($p = 0.00005$).

5.3 | Association between caregiver EFs and infant VWM behavior

We ran two linear effects models to examine the association between caregiver EFs and infant VWM behavior. In the first model, infant CP score was the outcome variable, load and caregiver metacognition and emotional regulation were predictors and infant age was a covariate. There was no significant interaction between caregiver metacognition and emotional control and load.

In the second model, infant CP score was the outcome variable, load and caregiver behavioral regulation were predictors, and infant age was a covariate. There was a significant interaction between caregiver behavioral regulation and load ($F_{(2,246)} = 5$, $p = 0.006$, $\eta^2 = 0.04$). Follow-up tests were run to examine whether caregiver behavioral regulation predicted infant CP score at specific loads. Only at the medium load, caregiver behavioral regulation predicted infant CP score ($p = 0.03$, $\eta p^2 = 0.06$) (see Figure 2).

5.4 | Impact of caregiver EFs on infant VWM-related brain function

In the first model, there was an interaction between chromophore and caregiver metacognition and emotional regulation in the right superior temporal gyrus (rSTG), left middle temporal gyrus (lMTG) and right superior parietal lobule (rSPL)—see Figure 3a and Table 2. Separate follow-up tests were run for each chromophore and for each region, after controlling for infant age. There was a significant effect for rSTG HbO concentration only. Specifically, better caregiver metacognition and emotional regulation (indicated by lower scores) was associated with reduced/supressed rSTG HbO concentration ($p = 0.0006$, $\eta p^2 = 0.14$; Figure 3b).

In the second model, there was a two-way interaction between chromophore and caregiver behavioral regulation, a three-way interaction between chromophore, caregiver behavioral regulation, and infant CP scores, and a four-way interaction between chromophore, caregiver behavioral regulation, load, and infant CP scores (see Table 2). We ran follow-up tests to examine whether concentration averaged across voxels of each cluster yielded significant effects for each chromophore, load, and/or median-split group. We describe these below.

The two-way interaction between chromophore and caregiver behavioral regulation was observed in rSPL cluster (Figure 4a). Separate follow-up tests were run for each chromophore, after controlling for infant age. Better caregiver behavioral regulation (indicated by lower scores) was associated with increased rSPL HbO concentration ($p = 0.029$, $\eta p^2 = 0.06$; Figure 4b).

The three-way interaction between chromophore, caregiver behavioral regulation, and infant CP scores was observed in the left inferior parietal lobule (lIPL) and left middle frontal gyrus (lMFG). Follow-up tests conducted for each chromophore did not reveal significant interactions in any of the regions.

The four-way interaction between chromophore, caregiver behavioral regulation, load, and infant CP scores was observed in the left middle frontal gyrus (lMFG), right middle frontal gyrus (rMFG), and left inferior parietal lobule (lIPL). For each region, we first ran follow-up tests to check whether the interaction between caregiver behavioral

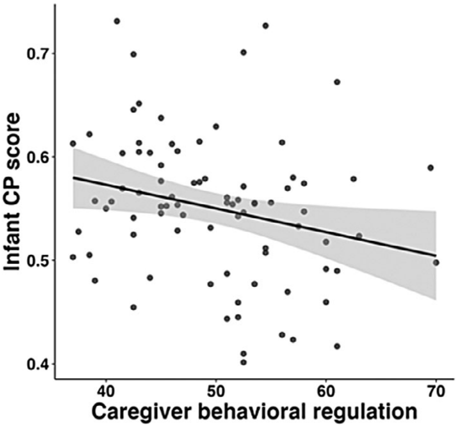

FIGURE 2 Caregiver behavioral regulation predicted infant CP score at the medium load. Note that better behavioral regulation is represented by lower scores.

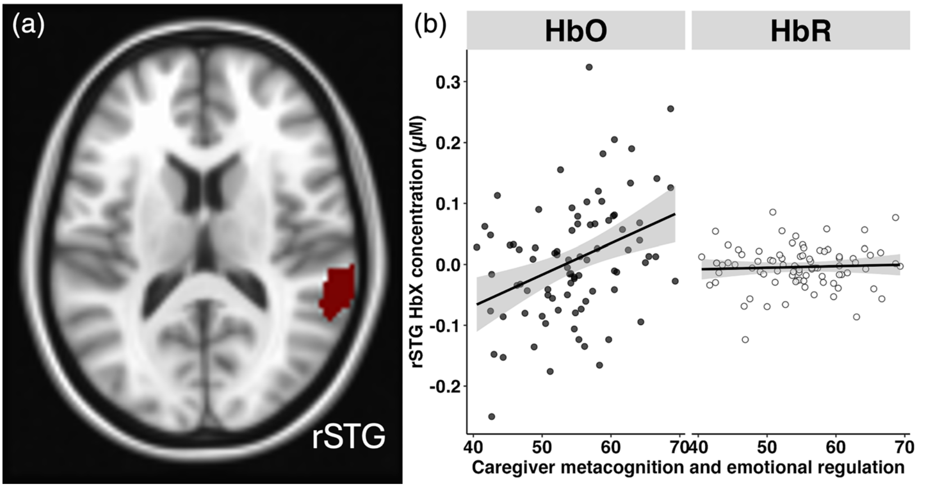

FIGURE 3 (a) Interaction between chromophore and caregiver metacognition and emotional regulation in right superior temporal gyrus (rSTG). (b) Better caregiver metacognition and emotional regulation was associated with reduced/suppressed rSTG HbO concentration. Note that better metacognition and emotional regulation is represented by lower scores.

regulation, infant CP scores and load were significant for each chromophore. For this step, and every following step, we controlled for infant age. Our findings revealed a significant interaction between caregiver behavioral regulation, infant CP score and load for lMFG HbO concentration ($p = 0.006$, $\eta p^2 = 0.03$) and lIPL HbO concentration ($p = 0.03$, $\eta p^2 = 0.02$). We then checked if the interaction between caregiver behavioral regulation and infant CP scores was significant for each load in both regions. We found that the interaction between caregiver behavioral regulation and infant CP scores was significant only at the high load for both lMFG HbO concentration ($p = 0.00004$, $\eta p^2 = 0.19$) and lIPL HbO concentration ($p = 0.01$, $\eta p^2 = 0.08$). To better understand these interactions between three *continuous* variables (caregiver behavioral regulation, infant CP scores and brain activation), infant CP scores were median-split into two groups—infants with high CP scores and infants with low CP scores. Follow-up tests run for each group separately revealed a borderline non-significant effect of caregiver behavioral regulation on lMFG HbO concentration only for infants with high CP scores ($p = 0.053$, $\eta p^2 = 0.09$; Figure 5). Specifically, in infants with high CP scores, greater caregiver behavioral regulation was associated with reduced lMFG HbO concentration.

6 | DISCUSSION

The current study had two main findings. First, caregiver EFs were categorized into two factors – metacognition and emotional regulation, and behavioral regulation. Second, we found robust links between both caregiver EF factors and infant VWM function. Concretely, better caregiver behavioral regulation was associated with better infant VWM performance, greater activation in right-lateralized parietal cortex, and a trend for greater load and performance-dependent suppression in left-lateralized frontal cortex. Lastly, better caregiver metacognition and emotional regulation were linked to greater suppression in right-lateralized temporal cortex. We discuss these findings below.

We predicted that caregiver EFs would be organized into three factors—metacognition, emotional regulation, and behavioral regulation. Our finding only partially confirmed our prediction. Our caregiver data loaded on to two factors. In line with previous work (Roth et al., 2013) and our prediction, the behavioral regulation factor was composed of self-monitor and inhibit subscales. However, unlike previous findings (Roth et al., 2013), organization of

TABLE 2 Significant clusters showing effects of caregiver EFs in both infant brain models.

Model	Interaction effect	Cluster	Size (mm^3)	MNI coordinates x	y	z
Caregiver metacognition and emotional regulation	Chromophore × metacognition and emotional regulation	Right superior temporal gyrus (rSTG)[a]	633	−62	40.5	16.5
		Left middle temporal gyrus (lMTG)	553	62.4	38.2	6.4
		Right superior parietal lobule (rSPL)	405	−23.4	67	57.6
Caregiver behavioral regulation	Chromophore × caregiver behavioral regulation	Right superior parietal lobule (rSPL)[a]	356	−25.9	67.7	54.6
	Chromophore × caregiver behavioral regulation × infant CP scores	Left inferior parietal lobule (lIPL)	1030	41.6	52.6	54.7
		Left middle frontal gyrus (lMFG)	730	41.3	−32.7	29.2
	Chromophore × caregiver behavioral regulation × load × infant CP scores	Left middle frontal gyrus (lMFG)[a]	584	−40.3	−36.1	27
		Right middle frontal gyrus (rIFG)	575	−46.9	−24	36.4
		Left inferior parietal lobule (lIPL)[a]	474	44.7	54.0	51.8

[a]Indicates effects that yielded significant results after follow-up and after controlling for infant age.

materials did not load on to caregiver metacognition. This subscale measures organization in adults' everyday environment, compared with other related subscales such as plan/organize which refers to cognitive processing associated with organization. We speculate that items in the organization of materials subscale (e.g., I lose things or I leave my room or home in a mess) might not directly apply to caregivers with young infants who might generally be more conscientious about organization in their homes. More research is necessary to evaluate whether future caregiver-related research with this questionnaire should include items from this subscale. We also found that emotional control and shift subscales loaded on to the metacognition factor, instead of on to a third separate factor, emotional regulation (Roth et al., 2013). The shift subscale refers to adults' ability to move freely from one situation, activity, or aspect of a problem to another as the circumstances demand, and the emotional control subscale measures adults' ability to modulate emotional responses. Particularly within the context of caregiving, it is possible that both these factors are more aligned with metacognition-related factors. Concretely, caregivers might have responded to items in the questionnaire through the lens of tasks and practices associated with caregiving even though they were not explicitly instructed to do so. There are limited findings in this direction (Rutherford et al., 2015); more research is required to closely examine whether there are differences in factor loadings between context-dependent and context-general responses from caregivers.

Next, we predicted that better caregiver EF abilities would be associated with better VWM performance and fronto-temporo-parietal engagement in infants and that these associations would be stronger for the metacognition factor. Again, our findings only partially confirmed our predictions. Only better caregiver behavioral regulation, and not metacognition and emotional control, was linked to better infant VWM behavior. We also found that caregiver behavioral regulation had more links to infant VWM brain function compared with caregiver metacognition and emotional control – however, both EF factors complementarily impacted parieto-temporal engagement. Specifically, better caregiver behavioral regulation was associated with greater right-lateralized parietal activation, and better caregiver metacognition and emotional control was associated with greater right-lateralized temporal suppression. In adults and children, right parietal activation is involved in visuo-spatial WM (Ambrose et al., 2016; Delgado Reyes et al., 2020; Malhotra et al., 2009; McKay et al., 2021; Reuter-Lorenz et al., 2000; Wijeakumar et al., 2015) and spatial processing during verbal WM tasks (Hazeltine et al., 2003), sustained (Corbetta et al., 2002; Coull & Frith, 1998) and selective attention (Bunge et al., 2002) and task-switching (Behrmann et al., 2004). Interestingly, in adults,

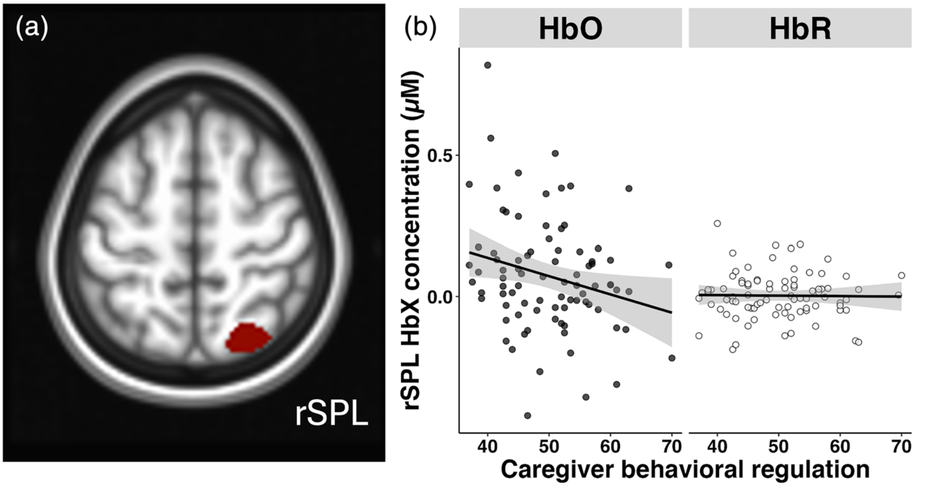

FIGURE 4 (a) Interaction between chromophore and caregiver behavioral regulation in the right superior parietal lobule (rSPL). (b) Better caregiver behavioral regulation was associated with increased rSPL HbO concentration. Note that better behavioral regulation is represented by lower scores.

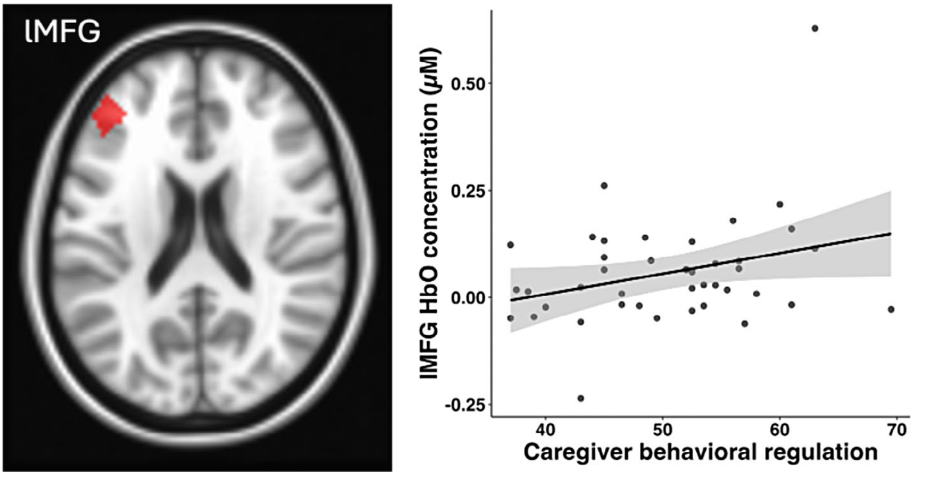

FIGURE 5 Four-way interaction between chromophore, caregiver behavioral regulation, load, and infant CP scores in the left middle frontal gyrus (lMFG). Follow-up tests revealed that there was a borderline insignificant association between caregiver behavioral regulation and lMFG HbO concentration in infants with high CP scores ($p = 0.053$). Note that better behavioral regulation is represented by lower scores.

increasing VWM load suppresses right temporal cortex, a region involved in re-orientation of attention to distractions/irrelevant events (Todd et al., 2005; Wijeakumar et al., 2023). Previous work in infants has also shown overall suppression effects in the same region during VWM processing, although unlike in adults, without an effect of load (Wijeakumar et al., 2023). In the current study, it is possible that caregivers with better behavioral regulation abilities are more aware of and/or able to inhibit irrelevant behaviors, thus, better guiding and shaping visuo-spatial attention and VWM brain regions in their infants. In concert, caregivers with better metacognition and emotional control abilities might be able to organize and engage in activities that encourage their infants to stay fixated on current goals and not reorient attention to irrelevant events, thus, suppressing their temporal cortex.

Lastly, better caregiver behavioral regulation was associated with a trend towards greater left-lateralized frontal suppression in infants. This finding aligns with results from the same cohort of families in another study (Davidson et al., 2024). Specifically, caregiver efficiency of inhibitory control assessed using a Go-NoGo task was linked to greater lMFG suppression in infants. However, unlike the behavioral associations observed in the current study, there was no link between caregiver efficiency of inhibitory control and infant VWM behavior. Frontal suppression in infants engaging with the preferential-looking task is reportedly linked to the ability to suppress distraction from the unchanging side, and stay fixated on the changing side (Wijeakumar et al., 2019; Wijeakumar et al., 2023). Relatedly, in older children, visual and spatial WM processing and storage of distractor information is related to increased frontal activation (Olesen et al., 2007). It is possible that caregivers with better behavioral regulation can suppress distractions and/or irrelevant events, thus, reducing their infants' needs to recruit the frontal cortex to process this information. Interestingly, however, only high-performing infants exhibited this effect at the high load suggesting that high-performing infants require more support, namely, better caregiver behavioral regulation, at the high load when their VWM capacity is challenged.

Taken together, our findings suggest that caregiver EFs were associated infant visual cognition and underlying fronto-temporo-parietal activation in infants. This work adds to the growing body of literature demonstrating links between caregiver and child cognition as early as in the first year of life.

6.1 | Methodological limitations

There are some limitations in the current study that must be carefully considered in the context of future research. First, we were unable to acquire positions of sources and detectors from infants as the research facility did not have access to a digitizer. Future work should strive to collect this information to account for variations in head sizes and movement of the fNIRS cap. Second, while self-report measures can offer much-needed insight into individual differences, particularly within the context of caregiver-related or caregiving experiences, they are susceptible to subject bias and responses depend entirely on responder's perception of their cognitive abilities, which may not reflect ground truth. Basing on both common and distinct findings in experimental and self-report research, future work should incorporate both objective and subjective measurements.

6.2 | Implications

There is limited research on the association between caregiver and child EFs in the first year following birth. Furthermore, little is known about these links at the level of the brain. The current study lends unique insight into the neural mechanisms, leading to caregiver-infant behavioral associations. These findings hold implications for the development of early caregiver-led interventions; identifying robust pathways between caregiver cognition and infant cognition will allow researchers to develop tailored interventions that capitalize on those existing pathways to improve child outcomes. Further, individual differences in caregiver cognitive abilities could have a profound impact on how they interact with, and by extension, how they might execute such interventions with their infants. Finally, this research is essential to inform and update existing theories and frameworks on caregiver influences on child cognition (e.g., sociocultural theory, scaffolding theory, self-regulatory framework) that try to better characterize caregiver-child dyadic interactions and outcomes, however, they do not consider how caregiver cognitive characteristics can alter or shape the nature of these interactions.

AUTHOR CONTRIBUTIONS

Ghada Amaireh: Data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. **Line Caes:** Conceptualization; funding acquisition; methodology; supervision;

writing – original draft; writing – review and editing. **Aimee Theyer:** Formal analysis; methodology; writing – original draft; writing – review and editing. **Christina Davidson:** Formal analysis; methodology; writing – original draft; writing – review and editing. **Sobanawartiny Wijeakumar:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; visualization; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Anonymized data, materials and code availability will be available upon request.

ETHICS STATEMENT

Ethical approval was granted by the School of Psychology Ethics Committee (Approval Reference: F1415).

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