MIND, BRAIN, AND EDUCATION

Home Enrichment Is Associated with Visual Working Memory Function in Preschoolers

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ABSTRACT— Home enrichment plays an important role in shaping children's development. In the current study, we inquired whether home enrichment was associated with pre-schoolers' visual working memory (VWM) function, a critical cognitive system necessary for maintaining information for short periods of time. Home enrichment was assessed using an adapted version of the Home Observation Measurement of the Environment Interview. VWM behavior and brain function were collected as children engaged with a color change detection task. Home enrichment was associated with right-lateralized fronto-parietal engagement. Specifically, greater home enrichment was linked to increased activation in the right angular gyrus, important for working memory maintenance, and suppression in the right inferior frontal gyrus (rIFG), important for re-orienting attention to distracting events. Critically, home enrichment-related rIFG suppression was linked to better VWM performance. This work sheds light on potential mechanism(s) through which enrichment in homes might be involved with cognitive function during the preschool years.

Cognitive stimulation during the first 5 years of life plays an integral role in establishing children's readiness to begin formal schooling. During this period, the home environment is a stable and consistent source from which children might derive such stimulation. Some examples of home enrichment include the availability of educational and learning resources such as books, puzzles, toys, games, etc., and engagement in activities such as counting, playing number games, conversations, and interactions with family, etc. Previous work has shown that the learning environment in homes is associated with the development of academic abilities (Anders et al., 2012; Molfese, Modglin, & Molfese, 2003). The quality of the home learning environment during the preschool period is also linked to numeracy development in the first year of preschool (Anders et al., 2012). Within the context of literacy, the home learning environment at 3 years of age is predictive of reading scores between the ages of 8 and 10 years (Molfese et al., 2003). Importantly, reading scores are better predicted by the home learning environment at 3 years of age compared to the home learning environment between the ages of 8 and 10 years—underscoring the profound influence of the home environment during the preschool period on academic outcomes in later years.

Executive functions, a critical class of neurocognitive systems important for regulating thoughts and behaviors also undergo a dynamic shift during the preschool period. What role might the home environment play in shaping these functions, given that individual differences in these functions are predictive of academic achievements in preschool and school-age children (Brod, Bunge, & Shing, 2017; Davidson, Shing, McKay, Rafetseder, & Wijeakumar, 2023; Gathercole, Pickering, Knight, & Stegmann, 2004a; McKay, Wijeakumar, Rafetseder, & Shing, 2021)? One study showed that quality of stimulation in the home environment is linked to inhibitory control, but not working memory or cognitive flexibility in children (Sarsour et al., 2011). In a separate study, home cognitive stimulation was positively associated with working memory, inhibitory control, and cognitive flexibility (Rosen et al., 2020). Thus, there is mixed evidence

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for the association between home enrichment and executive functions. Further, the *mechanism(s)* through which this association might become forged remains unclear.

In the current study, we posit that home enrichment will be linked to visual working memory (VWM) processing, responsible for maintaining and manipulating visual information over a short period of time. This system is measurable as early as 6 months of age (Delgado Reyes, Wijeakumar, Magnotta, Forbes, & Spencer, 2020; Ross-Sheehy, Oakes, & Luck, 2003), dynamically changes across childhood (Simmering, 2012), and is linked to academic outcomes (Gathercole et al., 2004) and intelligence (Swanson & Beebe-Frankenberger, 2004). Further rationale for investigating this system comes from abundant evidence highlighting the association between WM processing and vocabulary and mathematics abilities in preschool and school children (Bull, Espy, & Wiebe, 2008; Gathercole et al., 2004; Gathercole & Pickering, 2000). For instance, children who performed poorly in WM tasks also performed below expected standards in national curriculum assessments of mathematics and English (Bull et al., 2008; Gathercole et al., 2004; Gathercole & Pickering, 2000). WM function measured at 4 years of age is also significantly associated with vocabulary acquisition at 5 years of age (Gathercole, Willis, Emslie, & Baddeley, 1992). Given this link, it is possible that children exposed to high-quality and quantity of resources and activities promoting literacy and mathematics development in their homes might first learn to successfully adapt and efficiently utilize their VWM system, which in turn might determine how information they receive becomes crystallized as knowledge, and flexibly utilized for more complex cognitive operations. If so, understanding the link between home enrichment and VWM processing will shed important insight into how home environment-based interventions must be designed to promote healthy behavior and brain development in these formative childhood years.

In the current study, we investigated how varying levels of household enrichment were associated with individual differences in VWM behavior and frontoparietal activation in preschool children. We assessed home enrichment using an adapted version of the parent-reported interview of the Home Observation Measurement of the Environment (HOME) (Rosen et al., 2020). From the parental responses in the interview, we extracted codes representing children's access to and/or engagement with resources and activities promoting literacy and mathematics development. VWM performance was assessed using a color change detection task (McKay, Shing, Rafetseder, & Wijeakumar, 2021; Simmering, 2012) and brain function was recorded using a portable neuroimaging system whilst the children engaged with the task. In line with previous findings linking WM function with literacy and mathematics abilities, we predicted that better home enrichment would be associated with better VWM function. Concretely, we expected that home enrichment would be associated with higher VWM performance and increased activation in regions of the parietal cortex, a region responsible for guiding visuo-spatial attention and WM maintenance.

METHODS

Participants

One hundred and twenty-six 4.5-year-olds (62 females, $M_{\text{Age}} = 53.7$ months, $SD = 0.08$) participated in the study during the summer months of 2018 and 2019. Additionally, one of the parents of each child also took part in the study by completing questionnaires and taking part in an interview. Study information packs were distributed through nurseries and primary schools to reach parents of children born in January or February of 2014/2015. Thus, all the children were around 4.5 years of age at the time of their participation. Interested parents contacted the research team and were screened to ensure that they met the inclusion criteria. These criteria required that children had a normal or corrected-to-normal vision, a normal delivery term (37–42 weeks), no exposure to drug or alcohol use during pregnancy, no family history of mental illness, no neurological conditions, no color blindness linked to themselves or relatives, and spoke English as their primary language. After confirmation, testing sessions were scheduled. All data was collected in the homes of the children. Informed consent was obtained from the parents and assent was obtained from the child prior to the commencement of the study. Ethical approval was granted by the local University Ethics board.

Data from one participant was excluded because their experimental data contained outliers (outside of 3 * *SD* plus/minus mean). Thus, a total of 125 children (62 females, $M_{\text{Age}} = 53.7$ months, $SD = 1.2$) contributed data to the study. Out of the 125 children, 116 children contributed HOME data, 104 children contributed VWM behavioral data, 102 children contributed VWM brain data.

Adapted Version of HOME Inventory

The HOME Inventory is a combination of observations and interviews used to evaluate enrichment in the child's home environment (Bradley, Corwyn, Burchinal, McAdoo, & García Coll, 2001; Bradley, Corwyn, McAdoo, & García Coll, 2001; Caldwell & Bradley, 2003). For the current study, we focussed on questions from an adapted version of the HOME interview (Rosen et al., 2020). Experimenters presented these questions to the parent and parental responses were recorded by the researcher. From this version, we only included questions that probed the availability, access to, and utilization of resources and/or activities that might support childrens's' literacy and mathematics development in

Table 1
Questions Chosen From the Adapted HOME Interview (Responses to These Questions Were Subjected to Inductive Content Analyses to Extract Codes Relevant for Mathematics and Literacy Development)

Introduction: A good way to start, is to talk about some of the toys you have gotten for [Child's name]. Maybe before [he/she] gets started with [her/his] tasks, she could show us her room and where she likes to play?	
Q1	Do you know if any of these toys are designed to teach [Child's name] colors? Or do you use any toys in such a way?
Q2	Does [Child's name] like playing puzzles? How many Puzzles does [he/she] have? Are they complete? Do any of these Puzzles have numbers or animals on them?
Q3	Does [Child's name] like listening to music? Does [he/she] have [her/his] own songs, and can play them when [he/she] likes?
Q4	Does [Child's name] like art? Does [he/she] have any art supplies of [her/his] own to play with at home—like clay, crayons, or paint?
Q5	Does [Child's name] like to play with dolls or trains, or doing crafts like beaded necklaces?
Q6	I know [Child's name] has not started school yet but has [he/she] begun to learn numbers? How is [he/she] learning them? Do any of [her/his] toys specifically teach numbers?
Q7	Does [Child's name] like to read at all? How many books does [he/she] have?
Q8	Does your child like toys with animals on them? For example, books or stuffed animals? How many does [he/she] have? Has [he/she] begun to learn the names of these animals?
Q9	Has [Child's name] begun to learn things like, "the ball is round" or "the box is square"? How did [he/she] learn this?
Introduction: When children reach [Child's name]'s age, we often begin teaching them little things to say for us or for others. Let us talk about some of the things you have tried to teach [Child's name]. Incidentally, you do not have to have been successful in these attempts!	
Q10	Has [child's name] begun to learn about the alphabet at all? For example, have you begun teaching [her/him] how to sing the alphabet song, or write [her/him] own name?
Q11	Have you begun teaching [Child's name] any simple verbal manners, such as "please" and "thank you"? How did you go about teaching this?
Q12	I know we have discussed whether [Child's name] has specific toys to teach colors, but have you used other methods to teach [Child's name] colors?
Q13	Does [Child's name] know any nursery rhymes or songs? How did [he/she] learn these?
Q14	Does [Child's name] know the difference between things like "up and down," "under and over," or "big and little"? Has [he/she] learned this at home with you?
Q15	We also talked about toys that help teach numbers, have you encouraged [Child's name] to learn numbers through other methods? For example, teaching [her/him] how to count using [his/her] fingers?
Q16	Has [Child's name] begun to learn how to read any words? How have you taught or encouraged [her/him] how to learn this?
Q17	Is [Child's name] a big talker, does [he/she] like to talk to you? If [he/she] goes to a birthday party, can you get [her/him] to talk about it later? Have you ever tried getting him/her to talk to you about a video or TV program? How does that go?
Q18	Is [he/she] a good eater? How do you decide what to give [her/him] for breakfast? For lunch? What if you are a bit slow in getting it ready? How does [he/she] act? What do you do when that occurs?

the home. Further, we only included questions that inquired about resources and activities that the children could directly engage in. The chosen questions are presented in Table 1.

VWM Task

The color change detection task was used to assess VWM performance (McKay, Shing, et al., 2021; Simmering, 2012). The experimenter used 3 × 3 inch flashcards with colored squares to explain the task and practice the task with the children. Each practice card had between 1 and 3 colored squares. The experimenter placed the first card (with one colored square) on the table for approximately 2 s and asked the child to remember the card. Then, the experimenter turned over the first card and placed a second card (with one square of the same or different color) on top. The child was asked if the two cards were the same or different. Once the child responded, the experimenter turned over both cards and praised the child if they had correctly answered the question and corrected them if they had given the wrong answer. The flashcards were displayed again if the child made a mistake. Once the child had correctly answered all the practice trials, the experimental task was run in E-prime V.3 software on an HP laptop with a 14-in. screen. The computer task began with three practice trials, the first trial had one square, the second trial had two squares and the third trial had three squares. Children were corrected if they made a mistake before commencing the experimental trials. Each trial of the experimental task began with a memory array of colored squares presented for 2 s, followed by a delay of 1 s, and finally, by the test array of colored squares (see Figure 1a). The test array remained on the screen until

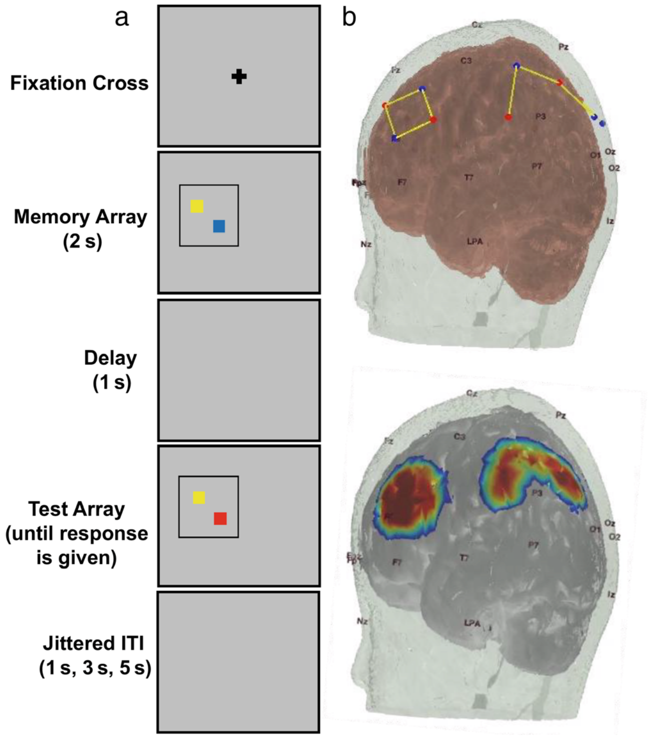

Fig. 1. (a) An example of a medium load, different trial in the color change detection task. Children were presented with a sample array of colored squares, followed by a blank screen delay, and finally a test array of squares. They were asked to compare both arrays and inform the experimenter whether the colors of the squares were the same or different between arrays. (b) Top panel shows probe geometry covering the left fronto-parietal cortex (only left visualized here). Sources are shown in red, detectors are shown in blue, and channels are shown in yellow. Bottom panel shows sensitivity profiles from running Monte Carlo simulations with 1 million photons for left fronto-parietal channels. ITI, inter-trial interval.

a response was made. During "same" trials, the colors in both arrays were identical. During "different" trials, the color of one square in the test array was different from the otherwise identical memory array. At the end of each trial, the experimenter asked the child if the two arrays were the same or different. Children gave a verbal response, which the experimenter recorded on the laptop. An inter-trial interval of 1 s (50% of the trials), 3 s (25% of the trials) or 5 s (25% of the trials) was used at the end of each trial. During every trial, the memory and test arrays were presented one after another, occupying the same position on the screen. Across trials, arrays were presented on alternating sides of the screen to avoid confusion in children who tried to compare the test array in trial 1 with the sample array in trial 2. To assess how behavioral performance and brain function varied as a function of VWM load, the number of colored squares was varied from 1 to 3 square items (1 item = low load; 2 items = medium load; 3 items = high load). Each load was presented in a block consisting of randomized presentations of eight same and eight different trials.

fNIRS Data Acquisition

A fNIRSport v2.01 portable device (sampling rate: 7.81 Hz, wavelengths 860 and 750 nm) with 8 sources and 8 detectors was used to measure brain function while the children engaged with the VWM task. Source-detector separation was scaled according to cap size (50 cm: 2.5 cm; 52 cm: 2.6 cm; 54 cm: 2.7 cm; and 56 cm: 2.8 cm). The probe geometry consisted of 14 channels, with 8 channels covering bilateral frontal cortex (4 left; 4 right) and 6 channels covering bilateral parietal cortex (3 left; 3 right)—see Figure 1b. The probe geometry was anchored to the 10–20 system of electrode placement. Channel positions overlaid critical VWM regions of interest identified from previous neuroimaging VWM studies (Wijeakumar, Spencer, Bohache, Boas, & Magnotta, 2015).

Socioeconomic Status Questionnaire

The parent was also asked to fill out a questionnaire that assessed their own and their partner's income and educational attainment—producing four variables. We collected this information to inquire whether any associations observed between the home enrichment score and VWM function could be explained by household income or parental educational attainment (Wijeakumar, Kumar, Delgado Reyes, Tiwari, & Spencer, 2019). For example, more affluent households might be able to afford more stimulatory resources for children. Similarly, parents with greater educational attainment might be aware of the importance of and be able to engage in more stimulating activities/exercises with their children. For income, the parent was asked to choose from one of the following 10 categories: under £10,000, £10–20,000, £20–30,000, £30–40,000, £40–50,000, £50–60,000, £60–70,000, £70–80,000, £90–100,000, and over £100,000. The percentage of parents whose income fell within each of the set brackets has been presented in Table S1. For educational attainment, the parent was asked to choose one from the following 12 categories: Clerical or Commercial Qualification (e.g., typing/book-keeping/commerce), Recognized Trade Apprenticeship completed, Secondary Education (GSCE/Standard Grade), Post-secondary Education (A-levels/Higher School Certificate), HNC/HND, BEC/TEC Higher, BTEC Higher/SCOTECH Higher, Nursing qualifications, Teaching qualification, Undergraduate Degree (BA, BSc, etc.), Postgraduate Degree (MA, MSc, etc.), Doctorate (PhD) and none of the above. The categories were converted into numeric values in order of increasing income/educational attainment and used as controlling variables in correlational analyses. The percentage of parents whose educational attainment fell within each of the set brackets has been presented in Table S2.

Procedure

Data was collected by two experimenters from children in their homes. Upon arrival to the homes, their head circumference was measured, and the corresponding fNIRS cap size was selected. The child was given a tablet to watch cartoons while the fNIRS cap was fitted on their head. The distances between the left and right peri-auricular points and inion and nasion were measured to correctly align the vertex of the cap with the center of the head. After the fNIRS set-up was complete, one of the experimenters introduced the VWM task as "the color game" and explained the rules using flashcards. Then, the experimenter moved to the practice and experimental versions of the game. Brain activation was recorded as children completed the experimental task. Stickers were awarded once they completed each load condition to sustain their motivation, regardless of performance. Once the VWM task was completed, the experimenters removed the cap. As part of other objectives for the project, children also completed an inhibitory control task (McKay, Wijeakumar, et al., 2021), a counterfactual reasoning task, and academic assessments. All children were remunerated with £10 and a toy upon completion. While children completed the task with one experimenter, a second experimenter completed an interview using the adapted version of the HOME Inventory with the parent. The interview lasted approximately 15 min. Finally, the parent completed the socioeconomic status questionnaire.

DATA ANALYSES

HOME Questionnaire Content Analysis

To address the objectives of the current study, parent responses to the adapted version of the HOME Inventory were examined using inductive content analysis (Elo & Kyngäs, 2008). From these responses, we created codes for resources and activities that could promote literacy and mathematics development in children (e.g., codes for literacy development included books, dolls/action figures and codes for mathematics development included using fingers, number-specific toys). Based on the parental responses, 12 codes were created for literacy development and 11 codes were created for mathematics development. The description and an example for each code for literacy and mathematics development are presented in Tables 2 and 3, respectively. After these codes were created through inductive content analysis, we then went through each parent's response and assigned a value of "1" or "0" for each child and for each code. For each code, a value of "1" was assigned if the parent's response indicated that their child engaged in an activity/used a resource linked to that code. A value of "0" was assigned if the parent's response did not indicate that their child engaged in an activity/accessed a resource linked to that code. One trained coder (CD) completed this assignment for the full dataset. A second trained coder (LC) independently coded a random sample (20%) of the parental responses to determine the kappa inter-rater reliability. The inter-rater reliabilities were in the range of 0.80 and 1.00 for all codes with the exception of the code "Other" for literacy which had a moderate reliability (0.55).

A home enrichment literacy score was calculated by summing across the 12 codes for literacy development. Similarly, a home enrichment mathematics score was calculated by summing across the 11 codes for mathematics development. Both scores were highly correlated with each other ($r(115) = 0.38$, $p < .001$). Therefore, we averaged both scores to create a composite score, that is, home enrichment score (see Figure 2 for histogram of this score). Here, a higher home enrichment score suggested greater access to, and utilization of resources and activities that might promote literacy and mathematics development in homes. The Cronbach's alpha of this home enrichment score was 0.61, which is considered as acceptable.

Behavioral Data Analyses from VWM Task

For each participant, at each load, we summed up the number of correct same trials (correct rejection [CR]), incorrect same trials (false alarm [FA]), correct different trials (Hit [H]), and incorrect different trials (Miss [M]). For each participant, we calculated FA rate at each load by dividing the summed FA trials by the sum of FA and CR trials, and H rate at each load by dividing the summed H trials by the sum of H trials and M trials. Next, we calculated capacity (K) at each load for each participant using Pashler's formula presented below (Pashler, 1988; Simmering, 2012; Simmering, 2016). In general, K represents the number of items that are successfully stored in VWM. For any load, K can range from 0 to the number of items presented at that load. For example, K equal to 3 at load 3 would mean that the participant was able to successfully store all 3 items in VWM.

$$K = \text{Load}^{*}\,(\text{H rate} - \text{FA rate})/(1 - \text{FA rate}).$$

We then estimated maximum K, which was the highest value across all loads and represented the maximum number of items that the participant could hold in VWM. Thus, maximum K can, at most, equal the highest load presented in the task.

Table 2
Codes Related to Literacy Development (12 codes, Their Descriptions, an Example for Each Code and the Percentage of Families Indicating Using Activity/Resource Related to Each Code Are Presented)

Codes related to literacy development

	Codes	*Description*	*Example*	*Percentage of families using activity/resource related to the code*
a	Listening to music	Child listens to existing music that are not nursery rhymes.	"Likes music, sing along to things, sings to songs on radio"	97
b	Making up their own songs	Child sings songs they have made up.	"Yes (definitely), both makes up his and adapts song"	40
c	Books	Child has a good selection of books and likes engaging with books (e.g., being read too, exploring books by themselves).	"He likes reading a lot, and has 2 books at bedtime every evening"	99
d	Dolls/action figures	Child uses dolls/figures to roleplay scenarios and conversations	"She likes dolls and will always do role play"	66
e	Stuffed animals/toys	Child uses stuffed toys for roleplay or to learn names of animals	"Loves animals, lots of stuffed toy, wants to be vet/doctor, learning names"	76
f	General conversations	Child engages in general conversations with family and friends	"He enjoys talking; often describes everything that has happened at nursery; when watching TV, he can tell what his favorite part of the program was"	95
g	Gaming toys/jigsaws	Child uses word-specific toys and/or jigsaws	"Yes, jigsaws, a lot, over 20, all complete, yes animals, letters"	57
h	Rhymes	Child listens to and/or sings nursery rhymes	"Enjoys nursery rhymes and sings them often; he is very good at picking them up"	100
i	Learning to recognize/read name or familiar words	Child is learning full words and/or names	"Few words, his own name, bat, names of shops and so"	91
j	Learning to recognize/read different letters	Child is learning the alphabet	"He can identify certain letters (e.g., 'this letter is in my name')"	99
k	Games within practical activities	Child is taught words while engaging in practical tasks/activities	"Being at the farm, asked to point to certain animals"	51
l	Other	Child has access to toys and/or engages in activities to stimulate vocabulary that the other codes do not cover	"Sign language, for example, down from the table, made up signs for different things, for example, drink, milk"	44

FNIRS ANALYSES

fNIRS Pre-Processing

fNIRS pre-processing was carried out in *EasyNIRS* using HOMER2. Raw data was pruned to remove noisy channels using *enPruneChannels*. Intensity was converted to optical density units (dRange = 0.01–3, SNRthresh = 2, *SD*range = 0–45) using *hmrIntensity2OD*. Principal components analyses were conducted to identify and remove motion artifacts using *hmrMotionCorrectPCArecurse* (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5, nSV = 0.97, maxIter = 5). Following this, the data were scanned again for motion artifacts using *hmrMotionArtifactByChannel* (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5). Stimulus markers within specified windows of uncorrected artifacts were removed using *enStimRejection* (tRange = −1 12). This window was chosen to capture any motion during the memory array, delay, test array, response, and jittered inter-trial interval for each trial. The data were band-pass filtered using *hmrBandpassFilt* (hpf = 0.016, lpf = 0.5).

Table 3
Codes Related to Mathematics Development (11 Codes, Their Description, an Example for Each Code and the Percentage of Families Indicating Using Activity/Resource Related to Each Code Are Presented)

Codes related to mathematics development

	Codes	*Description*	*Example*	*Percentage of families using activity/resource related to the code*
a	Number-specific toys	Child has toys specifically designed to teach numbers	"She was encouraged to learn numbers, dominos, building blocks with numbers"	20
b	Puzzles	Child engages with puzzles featuring numbers	"Loves jigsaws, will sit and do them for hours, lots of wooden ones with numbers"	45
c	Books	Child engages with books featuring numbers	"Counts aloud, a lot of reciting numbers, number books, for example, hungry caterpillar"	37
d	Using fingers	Child uses fingers when counting	"Yes, by counting things, she also uses fingers to count as well"	55
e	General conversations	Child engages in general conversations with family and friends about numbers	"Yes, counting out, in everyday life, how many cars or whatever, talking to her all the time, lots of opportunities to do so"	63
f	General toys	Child learns numbers using non-specific toys	"Counting toys as he plays with them and can recognize/count numbers on the dice when playing board games"	25
g	Using songs or rhymes	Child listens to and/or sings songs/rhymes that teach numbers	"Learnt numbers through songs"	13
h	Computer games	Child plays electronic number games	"He uses the laptop as well for learning numbers"	10
i	Flashcards	Child uses flashcards to learn numbers	"Flashcards to teach numbers"	3
j	Learning within practical activities	Child is taught numbers while engaging in practical tasks/activities	"We count the number of objects, if I chop a carrot, he'll count the pieces"	64
k	Other	Child has access to toys and/or engages in activities to stimulate number learning that the other codes do not cover	"Number blocks on Children's British Broadcasting Corporation"	25

fNIRS Image Reconstruction

The methodological pipeline used in the current study has been described in detail elsewhere (Davidson et al., 2023; Delgado Reyes, Wijeakumar, Magnotta, Forbes, & Spencer, 2020; Eggebrecht et al., 2014; Forbes, Wijeakumar, Eggebrecht, Magnotta, & Spencer, 2021; Wijeakumar et al., 2019; Wijeakumar, Spencer, et al., 2015). We outline the steps below. First, scalp landmarks and probe geometry on the 50 cm, 52 cm, 54 cm, and 56 cm head-size caps were digitized for a single participant using a Polhemus Patriot Motion Tracking System. Next, a 4.5-year-old MRI atlas from the Neurodevelopmental MRI database (Richards, Sanchez, Phillips-Meek, & Xie, 2016) was obtained and segmented into four tissue types (scalp, cerebro-spinal fluid, gray matter, and white matter). The probe geometry for each head size was projected onto the segmented head volume. Sensitivity profiles were generated for each channel and head volume by running Monte Carlo simulations with 1 million photons in *AtlasViewerGUI* in HOMER2—see Figure 1b. The optical density time-series data were integrated with volumetric sensitivity profiles using a novel image reconstruction technique (Eggebrecht et al., 2014; Forbes et al., 2021) to create 3D images with time-series data for each voxel, participant, and time-point. These images were used for running general linear models described below.

General Linear Modeling of Each Participant's fNIRS Data

An event-related design was used to analyze each participant's fNIRS data (Delgado Reyes et al., 2020; Forbes,

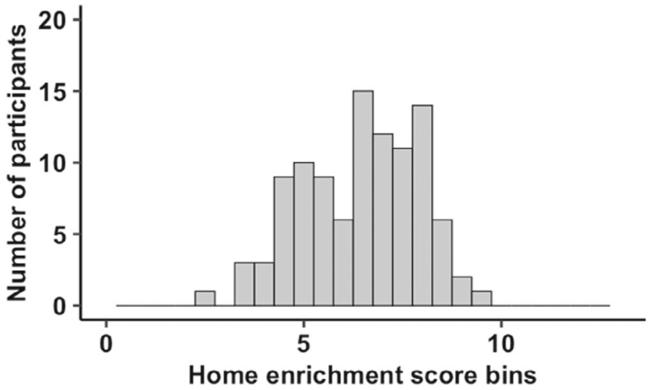

Fig. 2. Histogram of the home enrichment score with bin size = 0.5.

Wijeakumar, Eggebrecht, Magnotta, & Spencer, 2021; Huettel, 2012; McKay, Wijeakumar, et al., 2021; Wijeakumar et al., 2019; Wijeakumar, Huppert, Magnotta, Buss, & Spencer, 2017). A general linear model with 12 regressors (3 loads [low, medium, and high] × 2 trial types [same and different] × 2 accuracy conditions [correct and incorrect]) was run for each voxel, chromophore and participant by convolving a modified gamma function from the SPM toolbox (delay of response = 4; delay of undershoot = 15, dispersion of response = 1; dispersion of undershoot = 1; ratio of response to undershoot = 6; onset = 0; length of kernel = 16) with a boxcar of duration 4 s. This boxcar window accounted for the sample array presentation of 2 s, delay period of 1 s, and part of the test array presentation. This process generated beta coefficient maps for each of the 12 conditions. These maps were registered to the MNI space and used in group analyses described below.

Group Analysis of fNIRS Data

For group analyses, a linear mixed effects model was run on the beta coefficient images, using *3dLME* (in AFNI) (Chen, Saad, Britton, Pine, & Cox, 2013) with fixed within-subjects factors of load (low, medium, high), trial type (same, different) and chromophore (HbO, HbR) and home enrichment score as a quantitative variable. The model also included a random intercept for each participant to account for individual-level variance. Note that we only included beta coefficient maps for correct trials for these analyses. The model yielded an F-statistic image each for the main effects of, and interactions between load, chromophore, trial type, and home enrichment score. We only examined effects that showed an interaction with both chromophore and home enrichment score. Specifically, we focussed on chromophore-related effects as it would represent a difference between HbO and HbR concentrations (expecting either increasing HbO and decreasing HbR OR decreasing HbO and increasing HbR). We focussed on home enrichment score as it was directly relevant to our research question. Thus, possible interactions of interest included chromophore × home enrichment score, chromophore × home enrichment score × load, chromophore × home enrichment score × trial type, and chromophore × home enrichment score × load × trial type. We applied family-wise corrections to these F-statistic interaction images; these images were thresholded using a cluster-wise threshold voxel-wise p value of .001 and 15 voxels (using *3dClustSim*). Following this correction, only the interaction between home enrichment score and chromophore revealed significant clusters of activation. Average HbO and HbR concentration values were extracted for each significant cluster, chromophore, and participant and used in the correlational analyses described below.

Correlational Analyses

Pearson's correlation was run to examine the association between the home enrichment score and maximum K estimates. Correlational analyses were also carried out between average HbO concentration in each of the significant clusters and the maximum K score. We also ran a partial correlation to control for the impact of socioeconomic status variables. Benjamini-Hochberg correction was run with a false discovery rate of 0.05 to control for the number of significance tests on correlations that we performed. All correlations with p-values below the critical p-value were considered significant.

RESULTS

Descriptive Results from the HOME Questionnaire

The percentage of parents indicating the access to, or use of an activity/resource that might promote literacy and mathematics development are presented in the last column of Tables 2 and 3 respectively. With respect to enrichment promoting literacy development within homes, most environments offered activities such as listening to and singing to rhymes and music, offered access to a good selection of books, opportunities, and encouragement to engage in conversations with family and friends, and opportunities to learn the alphabet or full words and/or names (>90% families). On the other hand, fewer environments mentioned the use of word-specific toys or jigsaws, or other specific toys that could stimulate vocabulary, and engagement in activities such as singing made-up songs or learning words while engaging in practical tasks/activities (<52%). With respect to enrichment promoting mathematics development within homes, many environments presented opportunities for children to engage in general conversations with families and friends and learn through practical tasks/activities (>60%). In contrast, fewer environments mentioned access

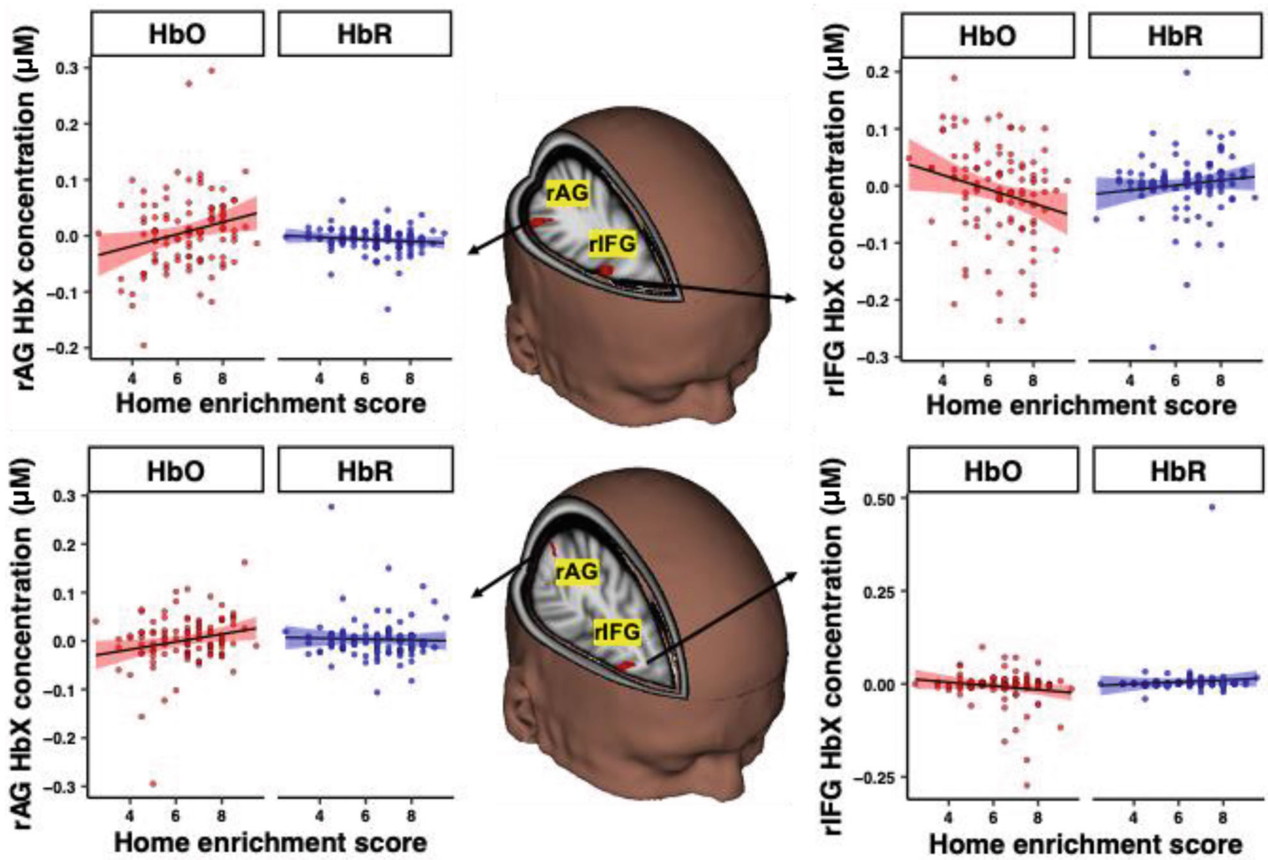

Fig. 3. Brain images and scatterplots showing significant interaction between chromophore and home enrichment score in four clusters—two clusters in right angular gyrus (rAG) (left panel) and two clusters in right inferior frontal gyrus (rIFG) (right panel). Association between home enrichment score and HbO concentration is shown in red and association between home enrichment score and HbR concentration is shown in blue. Results showed that increasing home enrichment score was associated with increasing activation in both rAG clusters and suppression in both rIFG clusters.

to, or use of toys or flashcards designed to teach numbers or stimulate number learning or books featuring numbers (<37%). Thus, the home enrichment score, calculated by taking an average of the literacy and mathematics scores showed a good distribution with a median of 6.5, standard deviation of 1.65, and range between 2.5 and 9.5 (see Figure 2).

Association Between Home Enrichment Score and Maximum *K*

Pearson's correlation was used to determine if there was an association between the home enrichment score and maximum *K* score. There was no significant association between both variables ($r(100) = 0.049$, $p = .62$).

Association Between Home Enrichment Score and Brain Function

Our linear mixed effects model revealed a significant interaction between chromophore and home enrichment score in four clusters—two clusters in the right inferior frontal gyrus (rIFG) (MNI coordinates: −52.3 −19.8 35.1 and −53.2 −26.8 10.0; 241 voxels and 16 voxels) and two clusters in the right angular gyrus (rAG) (MNI coordinates: −56.6 50.8 34.9 and −41.6 71.4 41.7; 66 voxels and 15 voxels)—see Figure 3. In both rIFG clusters, better home enrichment scores were associated with reduced HbO concentration and increased HbR concentration (rIFG suppression). On the other hand, in rAG, better home enrichment scores were associated with greater HbO concentration and reduced HbR concentration (rAG activation).

Association Between Home Enrichment-Related Brain Function and Maximum *K*

To determine if home enrichment-related brain function was also linked to VWM behavioral performance, Pearson's correlation was run between maximum *K* score and HbO concentration in all four clusters. Only in one rIFG cluster (shown top right in Figure 3), HbO concentration was negatively correlated with maximum *K* ($r(100) = -0.263$,

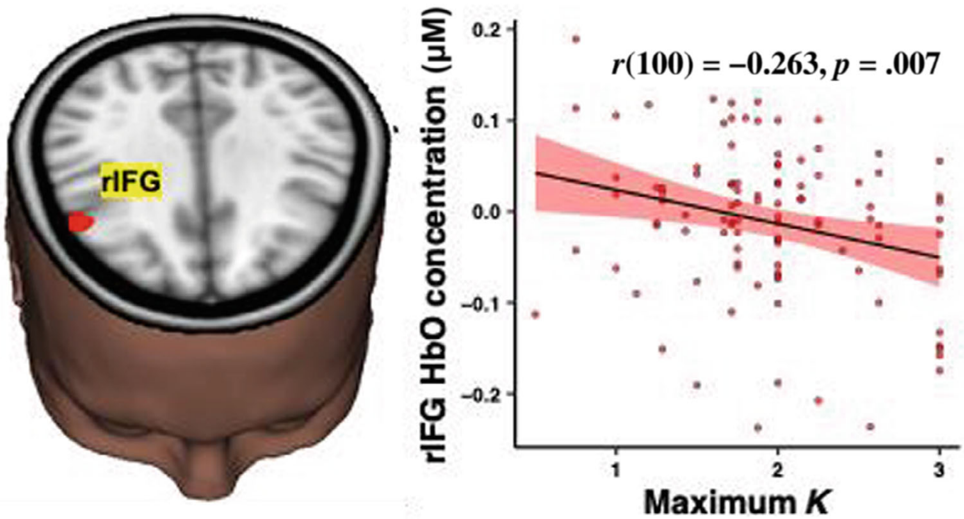

Fig. 4. Brain image showing right inferior frontal gyrus (rIFG) cluster from top right panel in Figure 3. Significant negative correlation between rIFG HbO concentration and maximum *K* score—children with greater rIFG suppression demonstrated a higher maximum *K* score (better visual working memory performance).

$p = .007$). Specifically, greater rIFG suppression was associated with better maximum *K* scores, and thus, better VWM performance—see Figure 4. This correlation survived the Benjamini-Hochberg correction carried out to control for the four correlations.

Finally, we wanted to determine if the association between home enrichment-related rIFG suppression and maximum *K* score could be driven by the socioeconomic status of the household. To do this, we ran a partial correlation between rIFG HbO concentration and maximum *K* score controlling for both parents' educational attainment and income together. We found that the association between rIFG HbO concentration and maximum *K* remained significant after controlling for the parents' income and educational attainment ($r(83) = -0.304, p = .006$). Our finding suggests that the association between home enrichment-related rIFG suppression and VWM behavior was not driven by access to more resources due to greater household income or opportunities for diverse activities due to greater parental educational attainment.

DISCUSSION

The current study investigated how individual differences in children's exposure to home enrichment was associated with neurocognitive function. To this end, we administered a modified version of the HOME inventory to interview parents on resources and activities available in their home environments to support their children's literacy and mathematics development. We used inductive content analysis to create codes (indicative of resources and activities that supported literacy and mathematics development) based on parental responses during the interview. Then, we generated a home enrichment score by quantifying the extent to which codes were endorsed in each household. Finally, we examined the association between varying levels of home enrichment and individual differences in behavior and brain function involved in a critical cognitive system, VWM. Our findings revealed that greater home enrichment was not directly linked to VWM performance. Instead, individual differences in home enrichment were associated with changes in a key right-lateralized fronto-parietal VWM network. Specifically, greater home enrichment was associated with increased activation in rAG, a brain region important for guiding visuo-spatial attention and WM maintenance, and suppression in rIFG, an area important for suppressing distractors. Importantly, rIFG suppression linked to greater home enrichment was also associated with a greater ability to hold items in VWM, and by extension, better VWM performance. Thus, our findings demonstrate how aspects of home enrichment integral for promoting literacy and mathematics development are associated with VWM processing in preschoolers. We contextualize our findings within the previous literature below.

Contrary to our hypothesis, we found that greater home enrichment was not directly linked to VWM behavior in preschool children. This finding contributes to a mixed body of evidence. On the one hand, this result is in line with previous work showing that home enrichment is linked to inhibitory control, but not working memory or cognitive flexibility in children (Sarsour et al., 2011). However, it goes against more recent work demonstrating that home cognitive stimulation is positively associated with working memory, inhibitory control, and cognitive flexibility (Rosen et al., 2020). There is a significant methodological difference between the current study and previous studies that might explain the difference in findings. The current study adopted a targeted approach to only extract codes representing access to and engagement with resources and activities promoting literacy and mathematics development. We adopted this approach to identify environmental factors that can explain mechanism(s) underlying the evidenced link between WM processing and literacy and mathematics (Davidson et al., 2023; Gathercole, Pickering, Knight, & Stegmann, 2004). On the other hand, previous studies have derived home enrichment scores using items/questions representative of the general spectrum of cognitive stimulation in the household. Further, as we propose below, it is also possible that home enrichment is not directly linked to the ability to store a higher number of items in VWM (maximum *K* scores), instead, it might influence one or more VWM sub-processes indexed through the modulation of key cortical regions, which might then lead to the final behavioral outcome.

Our second finding was that home enrichment engaged key regions in the canonical fronto-parietal VWM network—rAG and rIFG. Specifically, greater home enrichment was associated with greater rAG activation. This parietal region is purported to be involved in orienting and guiding visuo-spatial attention based on stimulus familiarity in experimental tasks (Corbetta et al., 1998; Taylor, Muggleton, Kalla, Walsh, & Eimer, 2011). Relatedly, in the current study, we suggest that children who had greater access to and involvement with a diverse range of resources and activities in the household might become accustomed to more robustly engaging visuo-spatial attention to maintain items, goals, etc., in working memory—thus, perhaps, more readily engaged the right parietal cortex during the VWM task.

Contrary to our finding with rAG, greater home enrichment was linked to greater suppression in rIFG. Further, greater rIFG suppression (linked to better home enrichment) was associated with a greater ability to hold more items in VWM, and by extension, better VWM performance. This frontal region plays an important role in response inhibition, and executive and attentional control. In adults, rIFG engagement is elicited by detection and response to infrequent or salient events during response inhibition tasks (Erika-Florence, Leech, & Hampshire, 2014; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Wijeakumar, Magnotta, et al., 2015). Relatedly, in infants and children in low-resource settings, greater rIFG activation is associated with a poorer ability to suppress distracting events, and thus, poorer performance during preferential looking (Wijeakumar et al., 2019). Along a similar vein, older children showing greater frontal cortex engagement during distractor conditions in VWM tasks also demonstrate poor performance (Olesen, Macoveanu, Tegnér, & Klingberg, 2007). Taken together, in the current study, it is possible that better household enrichment likely affords multiple opportunities to repeatedly engage in diverse activities that improve sustained attention through suppressing distraction. Thus, children from these households might have been able to stay more focussed during the task by engaging rAG and suppressing distractors by suppressing rIFG, to eventually demonstrate better VWM performance.

It is important to consider why only rIFG, and not rAG, was linked to better maximum capacity scores. We speculate that shifts in visuo-spatial attention during encoding, maintenance and/or retrieval stages rendered through rAG activation might be important for maintaining the robustness of an item representation but might not contribute towards holding multiple item representations (related to maximum *K*). Instead, suppressing sources of distraction during these stages might be integral, and ultimately predictive of holding these multiple representations. Nonetheless, future work is necessary to investigate how VWM sub-processes might be indexed in different cortical regions, eventually leading to final behavioral outcomes in children.

Within the limitations of this study, it is also critical to carefully consider the *bi*-directional nature of the association between home enrichment and VWM function. Concretely, could our findings just imply that children with better VWM processing and underlying efficiencies in brain function are just better at engaging with sources of enrichment in their homes? These assumptions should be explicitly tested in future studies. However, it is important to note that VWM function and indeed any other neurocognitive process does not begin developing in vacuum—it is nurtured from birth through exposure to high-quality cognitive stimulation. Thus, at least within the first few years of life, it is reasonable to emphasize the *uni*-directional influence of household enrichment on neurocognitive development.

In summary, our findings reveal that home enrichment, as defined by access to and engagement with resources and activities supporting literacy and mathematics development in children, engaged key hubs of the canonical fronto-parietal VWM network. Specifically, better home enrichment was linked to rAG activation, responsible for guiding visuo-spatial attention and WM maintenance, and rIFG suppression, responsible for suppressing distracting events. Further, rIFG suppression linked to better home enrichment was also associated with a better ability to hold items in VWM. Our study contributes to the growing literature seeking to understand the mechanism(s) behind the association between environmental factors and neurocognitive development in the first few years of life.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Percentage of parents in each income bracket.

Table S2. Percentage of parents in each educational attainment bracket.

CONFLICT OF INTEREST STATEMENT

No potential conflict of interest is reported by the authors.

DATA AVAILABILITY STATEMENT

All group-level data and analysis scripts will be made publicly available via the Open Science Framework before publication is finalized.

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