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Home assessment of visual working memory in pre-schoolers reveals associations between behaviour, brain activation and parent reports of life stress

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Abstract

Visual working memory (VWM) is reliably predictive of fluid intelligence and academic achievements. The objective of the current study was to investigate individual differences in pre-schoolers' VWM processing by examining the association between behaviour, brain function and parent-reported measures related to the child's environment. We used a portable functional near-infrared spectroscopy system to record from the frontal and parietal cortices of 4.5-year-old children (N = 74) as they completed a colour change-detection VWM task in their homes. Parents were asked to fill in questionnaires on temperament, academic aspirations, home environment and life stress. Children were median-split into a low-performing (LP) and a high-performing (HP) group based on the number of items they could successfully remember during the task. LPs increasingly activated channels in the left frontal and bilateral parietal cortices with increasing load, whereas HPs showed no difference in activation. Our findings suggest that LPs recruited more neural resources than HPs when their VWM capacity was challenged. We employed mediation analyses to examine the association between the difference in activation between the highest and lowest loads and variables from the questionnaires. The difference in activation between loads in the left parietal cortex partially mediated the association between parent-reported stressful life events and VWM performance. Critically, our findings show that the association between VWM capacity, left parietal activation and indicators of life stress is important to understand the nature of individual differences in VWM in pre-school children.

KEYWORDS
fNIRS, home testing, individual differences, life stress, pre-school children, visual working memory

1 | INTRODUCTION

Visual working memory (VWM) is a short-term storage system responsible for detecting changes in the world as they occur. VWM capacity is reliably predictive of cognitive functions (Fukuda et al., 2010) and a host of academic skills (Alloway & Alloway, 2010; Bull & Scerif, 2001; Gathercole et al., 2004; Swanson & Beebe-Frankenberger, 2004). Critically, it accounts for around 40% of individual differences in global fluid intelligence (Fukuda et al., 2010), and for up to 46% of individual differences in performance on a cognitive battery of tasks (Johnson et al., 2013).

A common task for assessing VWM is the change-detection task (Luck & Vogel, 1997), where subjects are consecutively presented two arrays of items and asked to identify if the items were identical across both arrays. This task is particularly well-suited for examining human development, as age-related changes in capacity can be captured by varying the number of presented items. Using this task, Simmering (2012) found that 3-year-olds had a capacity of 1.5 to 2 items. Capacity increased to 2 to 3 items by five years of age. This finding was confirmed by Buss et al. (2014), who found that 3-year-old children had a capacity of 1.2 items while 4-year-old children had a capacity of 1.8 items when attending to a shape change detection task.

Consistent behavioural findings from manipulating VWM load have been accompanied by the involvement of a distributed brain network in adults. VWM capacity is associated with activity in the posterior parietal and superior occipital cortices, with activation increasing as the number of items in the array increases, and reaching a plateau at maximum capacity (Todd & Marois, 2004). Activity in the posterior parietal cortex has also been shown to predict individual differences in capacity in adults (Todd & Marois, 2005). Furthermore, load-dependent responses have been found in the right intra-parietal sulcus and the right superior intra-parietal sulcus (Ambrose et al., 2016). Koenigs et al. (2009) assessed a wide range of memory functions in patients with lesions in either hemisphere of the superior parietal cortex and found that this area was directly involved in the manipulation and rearrangement of information for both auditory-verbal and visuospatial stimuli. Separately, another body of research has shown that the prefrontal cortex is responsible for maintaining and encoding representations of task-relevant information into working memory (Baddeley, 2003; Miller & Cohen, 2001). More recently, Christophel et al. (2017) proposed that working memory relies on the interplay between sensory regions in the posterior cortex that retain low-level features and frontal regions that retain more abstract stimuli that are gradually transformed to an appropriate behavioural response. Taken together, these findings suggest that working memory emerges from a coordinated system involving a distributed network of brain regions across the posterior and anterior cortices.

While fMRI studies have provided valuable insights into the neural processes underlying VWM in adults, there are limitations in its application in early development. fMRI scanners are noisy, and participants are required to lie still, an obstacle for young children. More recently, early developmental work has employed an alternative technique - functional near-infrared spectroscopy (fNIRS). fNIRS systems shine near-infrared light (ranging from 650 to 1000 nm) through the head to detect changes in oxygenated haemoglobin [HbO] and de-oxygenated haemoglobin [HbR] (Boas et al., 2014). fNIRS has been reliably used across the lifespan to study changes in activation in the frontal and parietal networks underlying VWM (Buss et al., 2014; Sato et al., 2013; Tsujimoto et al., 2004; Wijeakumar et al., 2019; Wijeakumar, Huppert, et al., 2017; Wijeakumar, Magnotta, et al., 2017). Using fNIRS, Tsujimoto et al. (2004) examined VWM performance on a change-detection task in a sample of adults and five-year-old children. They found that activity in the bilateral areas of the prefrontal cortex was similar in both groups, characterized by an increase in HbO with the onset of the memory array. These results demonstrated for the first time that the left prefrontal cortex is also involved in VWM processing in pre-schoolers. An fNIRS study examining VWM using a shape change-detection task in three- and four-year-old children found more robust activation in the parietal cortex in 4-year-olds compared to 3-year-olds (Buss et al., 2014). However, in contrast with what has been consistently found in the adult literature, the haemodynamic response did not plateau at maximum capacity – suggesting this neural effect may develop only after four years of age. Wijeakumar et al. used a portable fNIRS system to investigate the neural networks underlying VWM processing in infants and children in rural India. They found that VWM performance was inversely correlated with activation in the bilateral frontal cortices, such that increased activation in this area was associated with poorer VWM performance (Wijeakumar et al., 2019). This study highlighted another crucial advantage of fNIRS over other neuroimaging modalities - its portability, allowing researchers to freely explore cognitive processes outside of a traditional lab setting.

Individual differences in the development of VWM are predictive of subsequent academic achievements such as math abilities (Bull et al., 2008) and reading comprehension (Swanson & Berninger, 1996). These individual differences might stem from exposure to specific parental and home environmental factors. Fishbein et al. showed that cognitive function in children was associated with certain home child-rearing conditions (Fishbein et al., 2019). Specifically, positive aspects of the home environment predicted better performance on two tasks assessing visual information processing and working memory. Parental/home measures might also be associated with brain structure and brain function. Higher family income has been linked to greater white

Research highlights

- Home-assessments of brain activation and behavioural performance on a visual working memory (VWM) task.
- Low-performing children showed increasing activation with increasing load across the left frontal and bilateral parietal cortices.
- High-performing children showed no modulation of activation with increasing load.
- The difference in activation between the highest and the lowest load in the left parietal cortex partially mediated the association between parental life stress and VWM performance.

matter integrity in cortical and subcortical brain areas (Noble et al., 2015; Ursache et al., 2016). Early childhood deprivation is also associated with prefrontal cortical volume and surface area (Mackes et al., 2020). In rural settings in India, weaker activation in parts of the frontal cortex in response to a preferential looking VWM task in children was linked to poorer maternal education and income (Wijeakumar et al., 2019). It is possible that such associations between a specific brain structure or function and parent/home measures could inform effects on behavioural performance and/or other cognitive functions subserved by the same areas in later development. However, the nature of trivariate associations between behavioural performance, brain function and parental and home environment measures are not well-understood. In the current study, we probe this association by investigating how individual differences in VWM performance and underlying brain function are related to parental and home environment factors. We recruited a specific group of pre-schoolers with little variation in age to investigate individual differences during the critical period before children begin formal education. The present study capitalized on the portability of the fNIRS system and, to the best of our knowledge, is the first to examine individual differences in VWM processing using home-based testing. Laboratory testing allows for experiments to be conducted under strictly controlled conditions. However, in doing so, children are tested in an artificial and stressful environment. By conducting all testing in a home environment, we hope to provide children with the opportunity to perform the task in a relaxed environment and increase the ecological validity of the paradigm.

Based on findings by Simmering (2012), we hypothesized that overall, VWM performance would decrease as load increased. Our predictions of brain activation patterns in low and high-performing children are informed by contrasting accounts from previous findings. First, in general, challenging task demands through increasing VWM load elicits increasing brain activation in adults until capacity limit is severely strained (Linden et al., 2003; Rypma & D'Esposito, 1999; Todd & Marois, 2004, 2005). Second, along the same vein, Jaeggi et al. (2007) showed that low-performing adults elicited greater load-dependent activation than high-performing adults in parts of the frontal cortex. Here, the authors argued that low-performers might recruit additional attentional and strategy-related mechanisms during difficult conditions that might even be detrimental to their performance, whereas, high-performers were able to demonstrate efficient processing, stabilize their resources and improve performance. Third, in contrast with these two previous set of findings, Buss et al. (2014) showed that 4-year-old children showed better performance and greater activation in the parietal cortex compared to 3-year-old children suggesting that behavioural gains were associated with greater, and not lesser activation. However, Buss et al. investigated *developmental* changes and not *performance-related* changes, affording the question whether with a larger sample of 4-year-old children and testing performance differences, they might have observed similar findings to that of Jaeggi et al. (2007). Furthermore, they did not formally test the association between behavioural performance and brain activation. Lastly, Wijeakumar et al. found that greater activation in parts of the frontal cortex was associated with poorer VWM performance in a preferential looking task where a changing and non-changing flashing display of items were presented side by side (Wijeakumar et al., 2019). They suggested that the inability to suppress distraction from the non-changing side elicited greater activation in children with poor VWM performance. Taking these accounts into consideration, we predicted that low-performing children from our sample would require greater cognitive effort to meet the demands of increasing VWM loads of the task, and as a result, would elicit more activation than high-performing children.

2 | METHODS

2.1 | Participants

Ninety-five 4.5-year-olds (45 females, M_{age} = 53.5 months, SD = 1.2) participated in the study. Additionally, one of the parents of each child also took part in the study by filling out a series of questionnaires. We recruited participants by contacting gateway organizations such as nurseries and leisure centres and providing them with our study information. Parents of eligible children got in touch with us via our website, email or over the phone to schedule a testing session. Data were collected on participants in their homes across Scotland. Children received a small honorarium and gift for participation. All participants had normal or corrected to normal vision, no history of colour-blindness, no neurological conditions, and all mothers experienced a full-term pregnancy (37 to 42 weeks) with an uncomplicated birth. Parents gave written informed consent and children gave verbal assent prior to testing. The research was approved by the General University Ethics Panel (GUEP 375) at the University of Stirling.

Data from 21 children had to be excluded from analyses; five children refused to participate in the task, 12 children interfered with the neuroimaging set-up (pulled the cap off) before the completion of the task, two children had thick hair that prevented contact between the optodes and the scalp and caused poor signal quality, and data from two children was lost due to experimenter error. A total of 74 children (37 females, M_{age} = 53.5 months, SD = 1.3) contributed to the final analyses.

2.2 | Experimental task

The colour change-detection task (Simmering, 2012) was used to measure VWM performance in children. The task was explained using 3 × 3 inch flashcards with coloured squares, to ensure children understood the rules. The experimenter placed the first card (with one coloured 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 colour) 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. This practice session was repeated with flashcards containing two and then, three coloured squares. 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-inch 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 coloured squares presented for 2 s, followed by a delay of 1 s, and finally, by the test array of coloured squares (see Figure 1). The test array remained on the screen until a response was made. During 'same' trials, the colours in both arrays were identical. During 'different' trials, the colour 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 cards 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. VWM load was manipulated from 1 to 3 square items (load 1, load 2 and load 3). Each load was presented in a block consisting of randomized presentations of eight same and eight different trials.

2.3 | fNIRS data acquisition

fNIRS data were collected at 7.81 Hz using a NIRSport system 8 × 8 (8 sources 8 detectors)/release 2.01 with wavelengths of 850 and 760 nm. Fibre optic cables carried light from the machine to a NIRS cap. Probe geometry was designed by collating regions of interest (ROI) from previous fMRI VWM literature (Wijeakumar et al., 2015). Probe geometry consisted of four channels each on the left and right frontal cortices, and three channels each on the left and right parietal cortices (see Figure 2). Note that short-source-detector channels were not used to regress scalp haemodynamics as all the channels were directed toward maximizing coverage of the frontal and parietal cortices. Four cap sizes (50, 52, 54, and 56 cm) were used to accommodate different head sizes. Source-detector separation was scaled according to cap size (50 cm cap: 2.5 cm; 52 cm cap: 2.6 cm; 54 cm cap: 2.7 cm and 56 cm cap: 2.8 cm). To synchronize behavioural and fNIRS data, a McDaq data acquisition device (www.mccdaq.com) was used to send information from the task presentation laptop to the fNIRS system. The trigger was sent at the start of the memory array in each trial.

2.4 | Procedure

We collected data from children in their homes which allowed us to move away from a traditional lab setting. Two researchers were present during each session. One researcher was responsible for checking the quality of the fNIRS signals, while the other researcher attended to the child and parent. We requested all children to sit on a chair at a table to make sure that all the equipment could be safely set up. The head circumference of the child was measured so that the researchers could select the appropriately sized fNIRS cap. Once the cap was fitted to the child's head, measurements were taken from the inion to the nasion and from the two peri-auricular

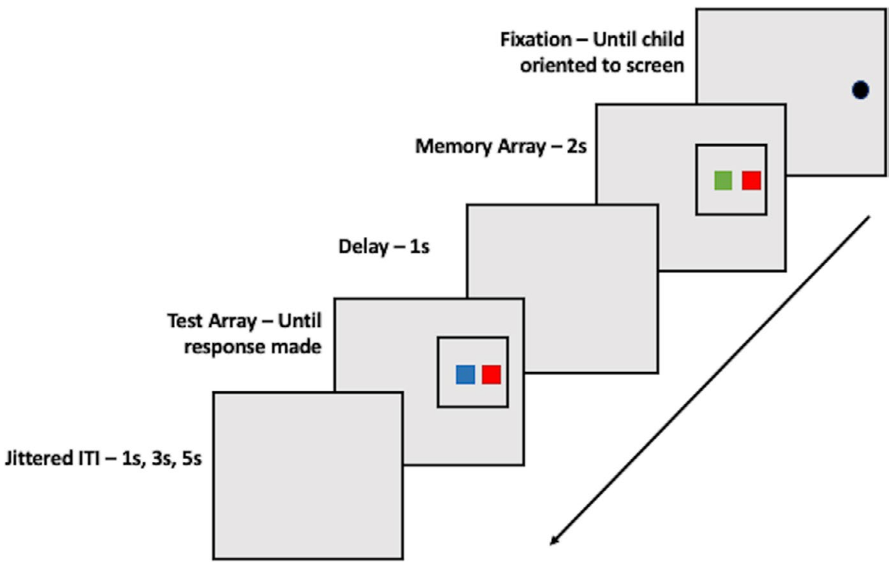

FIGURE 1 Colour CD task – Load 2 different trial

points to make sure that the cap was centred. Children were given an iPad to watch cartoons during the set-up process. Once the set-up was complete (approx. 15 min, see Figure 3), the experimenter began the session by introducing the task as "the colour game" and explained the rules using the flashcards. Children were then told that they were going to play the same game on the computer. Children were rewarded with one sticker after they completed all the trials in each load regardless of their performance (correct or incorrect) to maintain their motivation.

2.5 | Parental questionnaires

Parents were given a booklet of questionnaires to complete. Variables from these questionnaires have previously been shown to be associated with cognitive function in children. The Strengths and Difficulties Questionnaire (Goodman, 1997) assesses children's behavioural and emotional characteristics. This questionnaire has been used to investigate individual differences in pre-schoolers executive function (Dias et al., 2017; Hughes et al., 1998, 2000; Sulik et al., 2015). The Parenting Daily Hassles scale (Crnic & Booth, 1991; Crnic & Greenberg, 1990) assesses the frequency and impact of events that routinely occur in families with young children. The Confusion, Order and Hubbub Scale (Matheny et al., 1995) measures the amount of noise, confusion and disorganization present in the home. Twin studies have found that chaos in the home is an independent predictor of cognitive outcomes (Hart et al., 2007; Petrill et al., 2004). The Parenting Stress Index (Abidin et al., 2013) assesses the degree of stress in the parent–child relationship. Two previous studies found that parenting stress predicted lower cognitive scores in children (de Cock et al., 2017; Harewood et al., 2017). Lastly, a socioeconomic scale that assessed income, education and parental aspirations was also included. Several studies have shown a strong association between socioeconomic status and children's cognitive ability and achievement (Ardila et al., 2005; Duncan et al., 2011; Hackman et al., 2014, 2015; Hackman & Farah, 2009; Noble et al., 2012; Wijeakumar et al., 2019). For a detailed list of subscores, see Table S1.

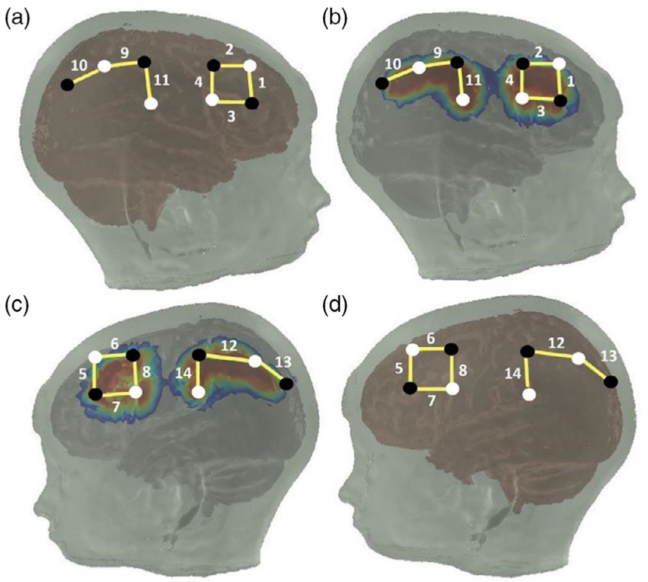

FIGURE 2 (a, d) Probe geometry over the right and left hemispheres. The white circles represent the sources and the black circles represent the detectors. (b & c) Sensitivity profiles after running Monte Carlo Simulations with 100 million photons

2.6 | Data analyses

2.6.1 | Behavioural analyses

Accuracy (A') and capacity (K) was calculated from hits (H) and false alarms (FA) based on the behavioural responses. A' was calculated using Grier's (1971) formula, updated by Aaronson and Watts (1987), where A' = 1 indicates perfect performances, and A' = 0.5 indicates chance performance. The following formula is calculated to account for a "yes" bias.

$$\text{If } H \geq \text{FA}: A' = 1/2 + \left\{ \left[(H - \text{FA}) * (1 + H - \text{FA}) \right] / \left[4 * H * (1 - \text{FA}) \right] \right\}$$

$$\text{If } H < \text{FA}: A' = 1/2 - \left\{ \left[(\text{FA} - H) * (1 + \text{FA} - H) \right] / \left[4 * \text{FA} * (1 - H) \right] \right\}$$

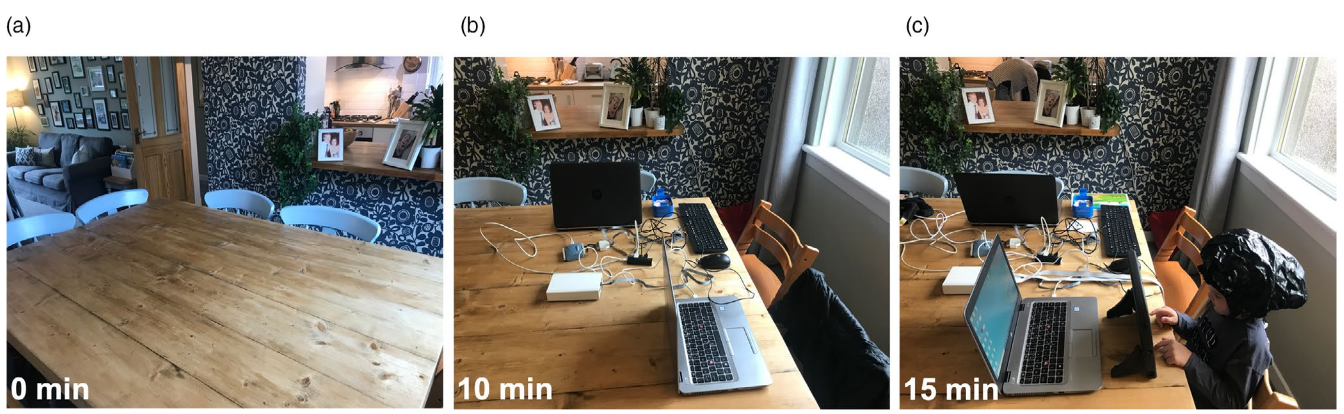

FIGURE 3 Experimental set-up inside a participant's home. (a) Beginning of set-up (b) 10 min into set-up (c) Complete set-up after 15 min

As demonstrated in Simmering (2016), for the cases where H and FA were equal to each other, accuracy was set to 0.5. A' represents how accurately individuals perform at each load in the task.

K was calculated for each load using Pashler's (1988) formula:

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

K represents the number of items that are successfully stored in working memory. Note that, at most, K can equal the maximum number of items at the presented load. Maximum K was estimated as the highest K value across all loads. Thus, maximum K can, at most, equal the highest load. We ran a repeated-measures ANOVA with a within-subjects factor of load to investigate how A' changed as a function of load. We also applied median-splitting on maximum K estimates to divide our sample into low-performers (LPs) and high-performers (HPs). We relied on maximum K for this categorization as the number of items stored is an important measure of visual working memory performance.

2.6.2 | Pre-processing fNIRS signals

fNIRS data were pre-processed using the Homer2 package (https://www.nitrc.org/projects/homer2/). Raw data were pruned using the *enPrunechannels* function (dRange = 0.01–300, SNRthresh = 2, SDrange = 0–45). Signals were converted from intensity values to optical density (OD) units using the *Intensity2OD* function. Data were corrected for motion using the *hmrMotionCorrectPCArecurse* function (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5, nSV = 0.97, maxIter = 5, turnon = 1). Data were scanned for motion artifacts using *hmrMotionArtifactByChannel* function (tMotion = 1, tMask = 1, STDEVthresh = 50, AMPthresh = 0.5). Then, the function *enStimRejection* (tRange = −1 to 10) was used to turn off stimulus triggers during any segments that contained motion artifacts. The data were band-pass filtered using *hmrBandpassFilt* to include frequencies between 0.016 Hz and 0.5 Hz. Using the function hmrOD-2Conc, the OD units were converted to concentration units (partial pathlength factor = 6 for each wavelength). Lastly, the function *hmrBlockAvg* was used to calculate the block average for a time window of −1 to 12 s. The mean activation from −1 to 0 s was used as the baseline to subtract from activation in the rest of the window (as specified in function *hmrBlockAvg*).

2.6.3 | fNIRS group analyses

Only correct trials were included in the fNIRS group analyses. We chose a haemodynamic response window from the 3rd to 6th second for further analyses. This time window was selected based on findings from Buss et al. (2014) and on our observations of the peak of the haemodynamic response of the task. Note that we do not consider a 'later' window (after the 6th second) as trials with shorter inter-trial intervals would also include signals elicited by succeeding trials. We computed the mean haemodynamic activation for the chosen window for each load (1, 2, 3), trial type (same, different), chromophore (HbO, HbR), channel (1 to 14) and participant (N = 74). Note that the mean number of correct trials included for HPs were 15 ± 0.17 trials for load 1, 14 ± 0.34 trials for load 2 and 12 ± 0.32 trials for load 3. The mean number of correct trials included for LPs were 15 ± 0.24 trials for load 1, 12 ± 0.43 trials for load 2 and 10 ± 0.27 trials for load 3. A repeated measures ANOVA was run for each of the 14 channels. Each ANOVA included within-subject factors of load (1, 2 and 3 items), trial type (same and different) and chromophore (HbO, HbR) and a between-subjects factor of group (HPs and LPs). We only focussed on effects that showed a significant interaction with chromophore to maximize the possibility of observing differences between HbO and HbR activation. We examined channels with a significant interaction between load and chromophore to assess if activation increased with increasing load as shown in previous studies. Next, we examined channels that showed a significant interaction between group, load and chromophore to examine differences between LPs and HPs. The Benjamini-Hochberg test was run with a false discovery rate of 0.05 to control for the number of channels that were included in the analyses. Here, individual p-values from interaction between group, load and chromophore for each channel were ranked in ascending order, with 1 being the smallest p-value, two being the second smallest value and so forth. We then calculated each individual p-value's critical Benjamini Hochberg value using the following formula: (i/m)Q, where, i = individual p-value rank, m = total number of tests, and Q = false discovery rate of 0.05. Finally, we compared our original p-values to the critical Benjamini-Hochberg value to find p-values that were smaller than the critical value. All channels with p-values for the interactions between group, load and chromophore below this highest p-value were considered significant. Lastly, Bonferroni correction was applied to the post-hoc tests conducted in following up these significant interactions.

2.6.4 | Correlations between behaviour, brain function and parental questionnaire data

The questionnaire data were log-transformed to account for skewed distributions. All data (questionnaires, behaviour and brain function) was screened for outliers that were 3 standard deviations above or below the mean. We identified nine outliers - one in the right parietal cortex, one in the left parietal cortex, three in the Strengths and Difficulties Questionnaire, one in the Parenting Daily Hassles Scale, two in the parental aspirations measure and one in the parental education measure. Next, we winsorized these outliers by replacing their values with the observation closest to them but are just below the threshold for defining outliers. Then we correlated our questionnaire variables with our behavioural and brain measures. The Benjamini-Hochberg test run with a false discovery rate of 0.1 was able 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.

3 | RESULTS

3.1 | Behavioural results

The repeated measures ANOVA on *A'* revealed that the main effect of load was significant (*F*[2, 146] = 90.37, p <.001, partial eta square (η_p^2) = 0.301). Follow-up pairwise comparisons revealed that accuracy at load 1 (*M* = 0.96, *SD* = 0.04) was greater than at load 2 (*M* = 0.86, *SD* = 0.17, *t*[73] = 5.29, *p* <0.001), and load 3 (*M* = 0.82, *SD* = 0.13, *t*[73] = 9.5, *p* <0.001). Furthermore, accuracy at load 2 was greater than accuracy at load 3, (*t*[73] = 2.27, *p* = 0.026) – see Figure 4a. These results were in agreement with previous findings (Simmering, 2012).

Median-splitting was applied to the maximum *K* estimates. The median maximum *K* was 2 items, with 13 children performing at the median. We decided to include these 13 children into the HP group because their individual accuracy scores at load 3 fell above the median accuracy. This resulted in a total of 39 HPs and 35 LPs. Figure 4b shows the mean maximum *K* estimates for HPs (2.4 ± 0.06 items) and LPs (1.5 ± 0.06 items).

3.2 | fNIRS results

Channels showing significant interactions between load and chromophore and group, load and chromophore are shown in Table 1. Note that only effects in channels that survived the Benjamini-Hochberg correction are reported. The interaction between load and chromophore was significant in channels overlying the left middle frontal gyrus (*F*[2,144] = 8.599, *p* = 0.000; *F*[2,144] = 4.857, *p* = 0.009) and left inferior frontal gyrus (*F*[2,144] = 7.542, *p* = 0.001). Posthoc tests revealed that activation at load 3 was greater than activation at load 1 and load 2. Figure 5 shows the change in HbO activation with load for channel 6 overlying the left middle frontal gyrus.

A significant interaction between group, load and chromophore was observed in channels overlying the left middle frontal gyrus (*F*[2,144] = 4.773, *p* = 0.01 – Figure 6a,c,e), left inferior frontal gyrus (*F*[2,144] = 4.616, *p* = 0.011 – Figure 6b,d,f), right angular gyrus (*F*[2,144] = 6.604, *p* = 0.002 – Figure 7a,c,e), right supramarginal gyrus (*F*[2,144] = 6.005, *p* = 0.003 – Figure 7b,d,f), left inferior parietal lobule (*F*[2,144] = 4.843, *p* = 0.009 – Figure 8a,c,e) and left supramarginal gyrus (*F*[2,144] = 4.646, *p* = 0.011 – Figure 8b,d,f). Across all these areas, LPs showed greater activation at load 3 than at load 1. Importantly, HPs did not demonstrate this modulation of activation with increasing load. HPs showed greater activation than LPs at load 1 in channels overlying the left middle gyrus, left inferior frontal gyrus, right angular gyrus, right supramarginal gyrus and left supramarginal gyrus. Finally, LPs showed greater activation than HPs at load 3 in a channel overlying the left middle frontal gyrus.

3.3 | Correlations between behavioural performance, brain activation and parental questionnaires

We averaged activation across channels that showed a significant interaction between group, load and chromophore to create three brain clusters as they showed the same trend. The three brain clusters were left frontal cortex (averaging channel 6 and channel 8), right parietal cortex (averaging channel 9 and channel 11) and left parietal cortex (averaging channel 12 and channel 14). Next, we calculated the difference in activation between load 3 and load 1 in these brain areas (for each participant) as this key measure differentiated LPs from HPs. As expected, the difference in activation between loads in the three brain clusters was negatively correlated with maximum *K* suggesting that this association was still strong even when the variables were considered as continuous measures (see Figure S1). The difference in activation between loads in each of the three brain areas was correlated with data from the parental questionnaires. We pooled all 31 correlations and applied the Benjamini-Hochberg correction separately for each brain area (left frontal cortex, left parietal cortex, and right parietal cortex) with a false discovery rate of 0.1. Only those correlations that survived the Benjamini-Hochberg correction are reported. We found that the difference in activation between loads in the left parietal cortex was positively correlated with the life stress subscore from the Parenting Stress Index (*r* = 0.293, *p* =.011, see Figure 9). Life stress in this scale refers to any major life event that significantly increases life stress. We also found that the difference in activation between loads in the left parietal cortex was negatively associated with parental aspirations (*r* = −0.323, *p* = 0.006). Parental aspirations were the highest qualification parents hoped their children would achieve.

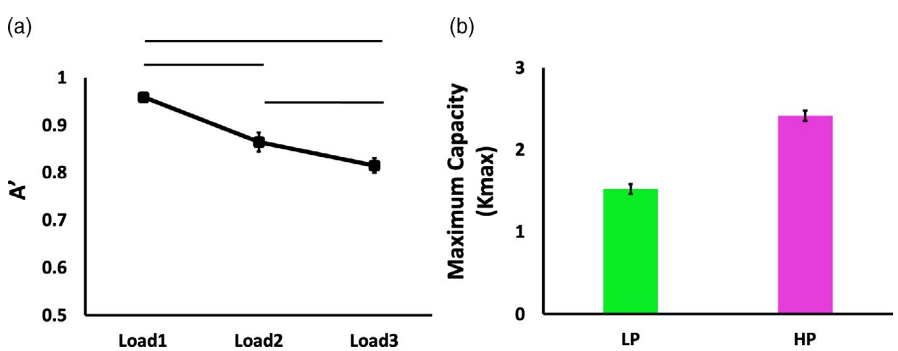

FIGURE 4 (a) *A'* decreased as load increased from 1 to 3 items. (b) Maximum *K* estimates for high and low performers. Error bars show SEM. '-' indicates significance at *p* < 0.05

TABLE. 1 Channels showing significant interactions between load and chromophore and group, load and chromophore. Posthoc results are shown for HbO activation

Channel No.	Brain area (MNI coordinates)	Load × Chromophore (HbO)	Group × Load × Chromophore (HbO)
Channel 1	Right middle frontal gyrus		
Channel 2	Right middle frontal gyrus		
Channel 3	Right inferior frontal gyrus		
Channel 4	Right inferior frontal gyrus		
Channel 5	Left middle frontal gyrus	Load 3 > Load 1 (p = 0.001) Load 3 > Load 2 (p = 0.002)	
Channel 6	Left middle frontal gyrus	Load 3 > Load 1 (p = 0.011)	Load 3: LPs > HPs (p = 0.037) LPs: Load 3 > Load 1 (p <.001) Load 1: HPs > LPs (p = 0.024)
Channel 7	Left inferior frontal gyrus	Load 3 > Load 1 (p = 0.01)	
Channel 8	Left inferior frontal gyrus		LPs: Load 3 > Load 1 (p = 0.004) LPs: Load 2 > Load 1 (p = 0.045) Load 1: HPs > LPs (p = 0.016)
Channel 9	Right angular gyrus		LPs: Load 3 > Load 1 (p = 0.004) Load 1: HPs > LPs (p = 0.001)
Channel 10	Right superior occipital gyrus		
Channel 11	Right supramarginal gyrus		LPs: Load 3 > Load 1 (p = 0.011) Load 1: HPs > LPs (p = 0.025)
Channel 12	Left inferior parietal lobule		LPs: Load 3 > Load 1 (p = 0.009)
Channel 13	Left angular gyrus		
Channel 14	Left supramarginal gyrus		LPs: Load 3 > Load 1 (p = 0.033) Load 1: HPs > LPs (p = 0.01) Load 2: HPs > LPs (p = 0.036)

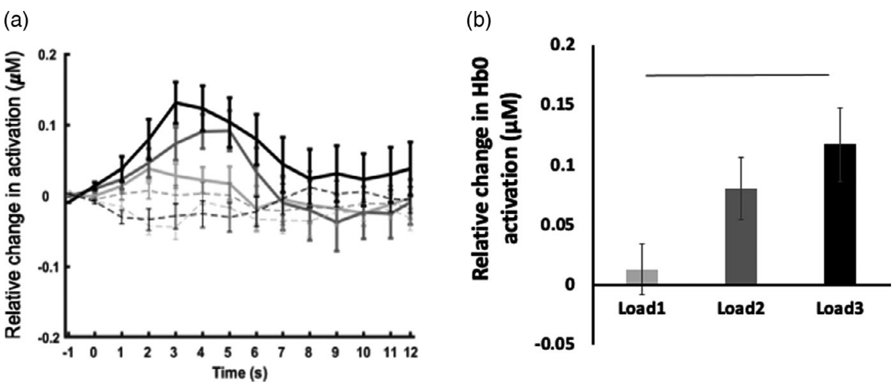

FIGURE 5 (a) HbO (solid lines) and HbR (dashed lines) activation in channel 6 overlying the left middle frontal gyrus. Load 1 is shown in light grey, load 2 in dark grey and load 3 in black. Error bars show 1 SE averaged over 1 s intervals. (b) Bar plot showing greater HbO activation for the time window between 3 and 6 s at load 3 compared to load 1. Error bars show SEM. '-' indicates significance at $p < 0.05$

3.4 | Mediation analyses

We conducted mediation analyses to further understand the association between behaviour, brain activation and parental factors. Using mediation, we aimed to extend upon the two significant findings from the questionnaire correlation analyses and determine whether a trivariate relationship exists between behavioural performance, brain function and parental factors. Concretely, we investigated if the difference in brain activation was a potential mediator between the distal predictor (parental factor) and the outcome measure (behavioural performance). According to Shrout and Bolger (2002), when a predictor is not experimental-based and distal in nature (e.g., home environment), an association between the predictor and the mediator is sufficient to warrant a test for mediation. Therefore, we focused on the significant bivariate relationships we identified from the correlation analyses described in the previous section: (1) the association between the life stress score and the difference in activation between loads in the left parietal cortex and (2) the association between parental aspirations and the difference in activation between loads in the left parietal cortex. For our analyses, we used the mediation function with bootstrapping in R. We found that the difference in activation between loads in the left parietal cortex partially mediated the relationship between life stress and maximum K (indirect path =−0.1429, p = 0.016). To determine if socioeconomic factors had an indirect effect on this association, we controlled for both parental education and income. This association remained significant even after accounting for parental education and income (p = 0.0014). Specifically, we found that higher life stress was related to a larger difference in activation between loads in

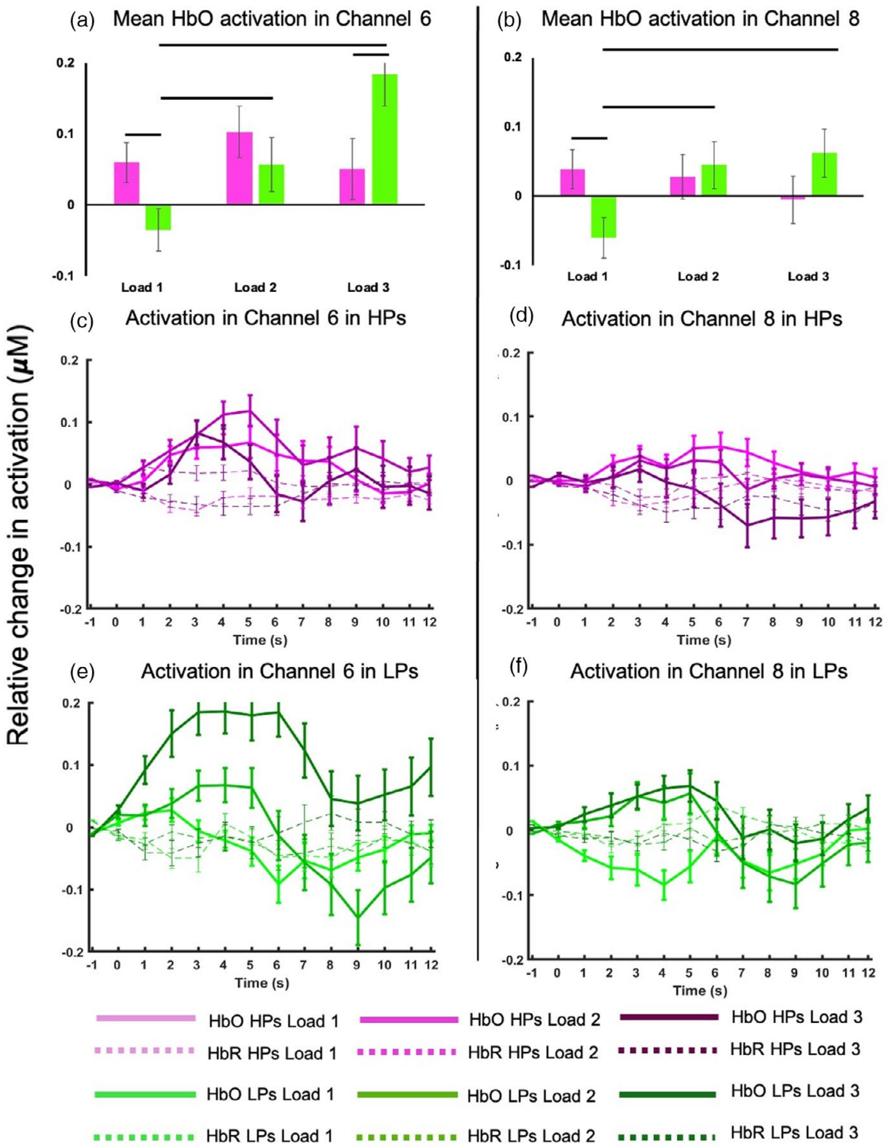

FIGURE 6 (a, b) Bar plots showing mean HbO activation for the time window between 3 and 6 s for LPs (green) and HPs (magenta) in channel 6 and channel 8 (overlying the left frontal cortex), respectively. (c) and (d) Haemodynamic activation for HPs in channel 6 and channel 8, respectively. (e) and (f) Haemodynamic activation for LPs in channel 6 and channel 8, respectively. Error bars show 1 SE averaged over 1 s intervals. '-' indicates significance at $p < 0.05$

the left parietal cortex, which in turn was related to lower maximum *K*. Next, we found that the difference in activation between loads in the same area partially mediated the relationship between parental aspirations and maximum *K* (indirect path = 0.4643, $p = 0.026$). However, this mediation effect did not hold after controlling for parental education and income suggesting an influence of socioeconomic factors on the association between behavioural performance, brain activation and parental aspirations for their children.

4 | DISCUSSION

VWM is an essential cognitive system with a highly limited capacity that is reliably predictive of future academic achievements, making it important to understand the nature of individual differences in children (Bull et al., 2008; Swanson & Berninger, 1996). Critically, it is important to try to fullfil this objective in experimental designs without the effect of varying age within the cohort. In the current study, we investigated how individual differences in VWM performance and brain function are linked to parental and home environment factors. We recorded behavioural and brain activation data from 4.5-year-old children with little variation in age as they completed a colour-change-detection task in their homes. Our research also demonstrated the feasibility of collecting neural data on children in their homes. Home-based testing present with unique challenges that require experimenters to be creative while maintaining a standardized procedure. As examples, experimenters are required to manage space constraints while setting up equipment and to deal with distractions for themselves and the children being tested in a respectful manner in different households. Despite these difficulties, we attribute the low drop-rate to an efficient experimental design, extensive training in collecting behavioural and brain imaging data with children and the resourcefulness of the experimenters to maintain a good rapport with children and their parents to create a fun and engaging atmosphere where children did not feel that they were being "tested".

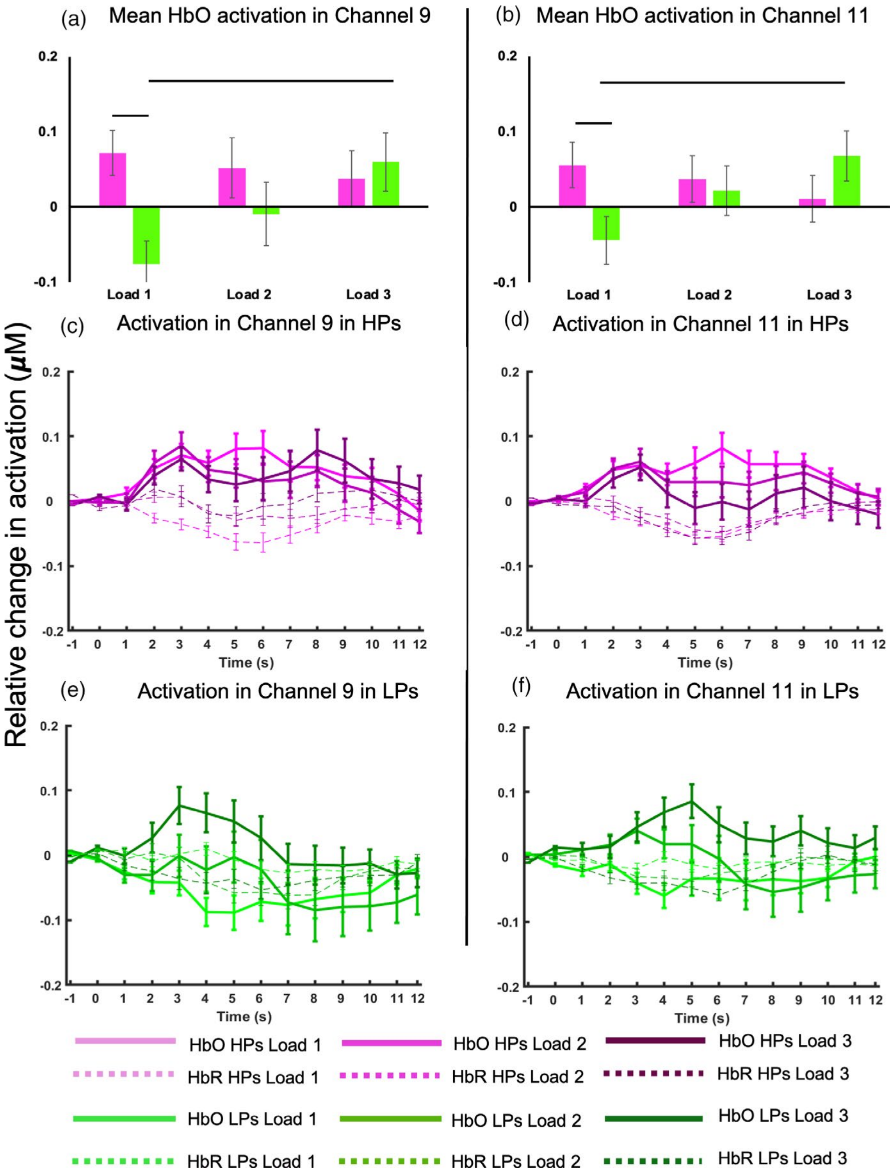

FIGURE 7 (a, b) Bar plots showing mean HbO activation for the time window between 3 and 6 s for LPs (green) and HPs (magenta) in channel 9 and channel 11 (overlying the right parietal cortex), respectively. (c) and (d) Haemodynamic activation for HPs in channel 9 and channel 11, respectively. (e, f) Haemodynamic activation for LPs in channel 9 and channel 11, respectively. Error bars show 1 SE averaged over 1 s intervals. '-' indicates significance at $p < 0.05$

In the current study, we observed load-dependent increases in accuracy and brain activation. In general, this finding is in agreement with previous VWM work in children and adults (Ambrose et al., 2016; Buss et al., 2014; Jha & McCarthy, 2000; Linden et al., 2003; Todd & Marois, 2004; Wijeakumar et al., 2017). Our first critical question was to investigate whether differences in activation in the fronto-parietal network would underlie differences in behavioural performance. We found that LPs showed greater activation at load 3 than at load 1 in the left frontal, left parietal and right parietal cortices. By contrast, the HPs showed no modulation of activation between loads. HPs showed greater activation than LPs at load 1 across all three cortices and LPs showed greater activation than HPs at load 3 in the left frontal cortex. We posit that HPs were more 'prepared' through achieving a *heightened state of attention* eliciting greater activation at the lowest load (at the start of the experimental task) compared to the LPs. We further suggest that HPs were able to efficiently manage the more challenging demands of increasing VWM loads by utilizing similar levels of neural resources as they did not show any significant increases in activation. On the other hand, LPs showed increasing activation and poor performance with increasing VWM load. We argue that LPs would have needed to *effortfully* attend to the demands of increasing VWM load by increasing activation and thus, recruited more neural resources. Critically, this increase in activation was not accompanied by an increase in performance in LPs. In agreement with our finding, Honey et al. (2000) found that adults who performed poorly on a verbal working memory task showed increased activation in the bilateral posterior parietal cortex. They surmized that this increase in parietal activation could be reflective of an increase in attentional demands and the use of visuospatial strategies. Along the same vein, Jaeggi et al. (2007) found that low-performing adults engaging in a challenging dual task displayed large load-dependent increases in activation when their capacity limitations were challenged. They reported that the increase in activation observed in low-performers was due to the additional recruitment of attentional and strategy-related resources. Furthermore, they found that high-performers did not

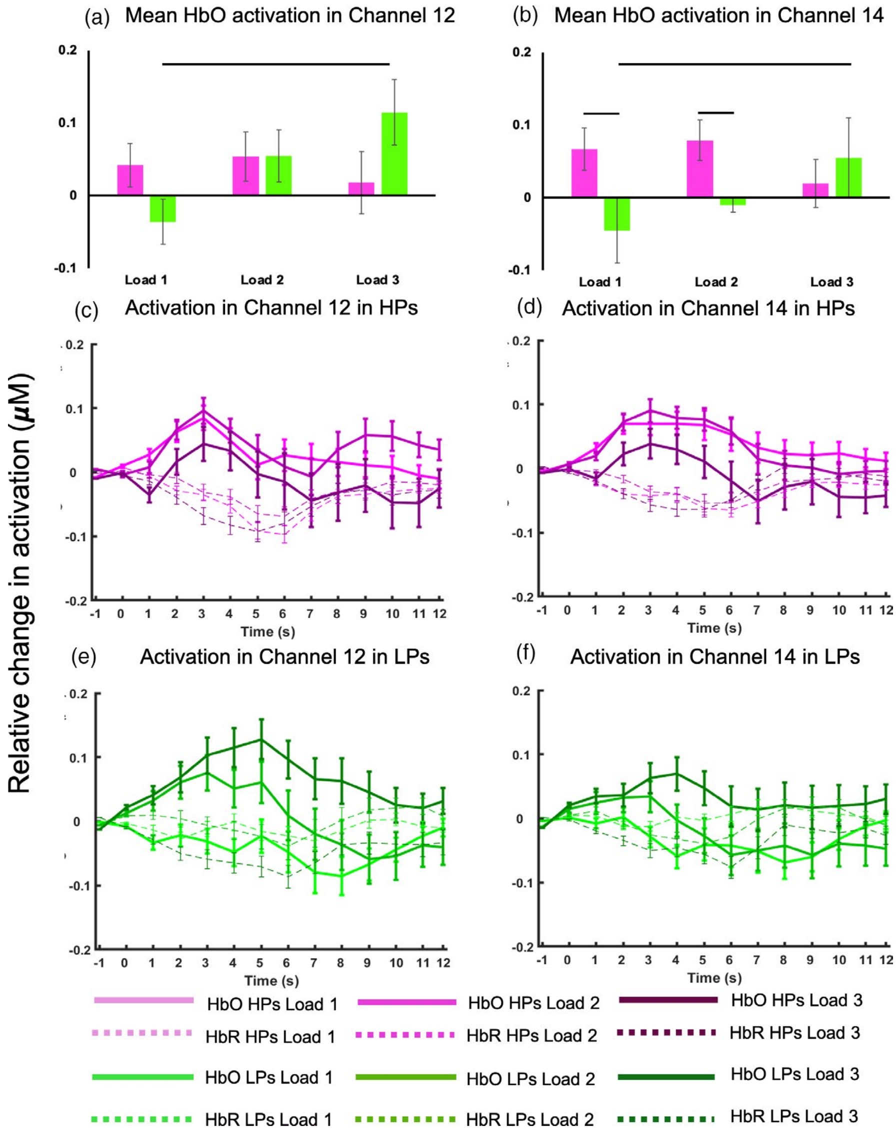

FIGURE 8 (a, b) Bar plots showing mean HbO activation for the time window between 3 and 6 s for LPs (green) and HPs (magenta) in channel 12 and channel 14 (overlying the left parietal cortex), respectively. (c, d) Haemodynamic activation for HPs in channel 12 and channel 14, respectively. (e, f) Haemodynamic activation for LPs in channel 12 and channel 14, respectively. Error bars show 1 SE averaged over 1 sec intervals. '-' indicates significance at $p < 0.05$

show an increase in activation with increasing task difficulty, which they suggested reflected more efficient processing. However, these findings are not in line with results from an adult study conducted by Nagel et al. (2009) who reported that young high-performing adults showed increasing activation with increasing load in a spatial working memory task. In the current study, it is also possible that LPs were unable to suppress distraction or irrelevant information in the event of increasing task demands, thus increasing activation with a decline in performance. The inability to suppress distraction to irrelevant information and as a result, poorer VWM performance during a preferential looking task has been associated with greater activation in the frontal cortex in children in rural settings in India (Wijeakumar et al., 2019).

Our second critical question was to examine whether home environment and parental factors could shed light on the nature of individual differences in behaviour and associated brain activation. We found that the relationship between the frequency of stressful life events and poor behavioural performance in the children in the VWM task was mediated by activation in the left parietal cortex. Higher life stress was measured as a greater number of stressful life events including but not limited to, divorce, change in job/school, death of a family member and substance abuse. Furthermore, this finding remained significant after we controlled for parental income and education, suggesting it is unrelated to socioeconomic factors. Our finding is in line with an EEG study by Troller-Renfree et al. (2020) who found that infants of mothers who experienced higher chronic physiological stress showed altered brain activation patterns during the first year of life. They posit that maturational lags in development can persist into later life and have an effect on cognitive processing. Furthermore, Hanson et al. (2012) assessed cumulative life stress in children and found a negative association with working memory performance. It is also possible that stressful life events can significantly affect the quantity and/or quality of time that parents spend with their children. Crnic et al. (2005) found that parent-reported life stress assessed over two years had a negative association with maternal parenting behaviour and the quality of parent–child interactions, which in turn contributed to poor behavioural functioning in children

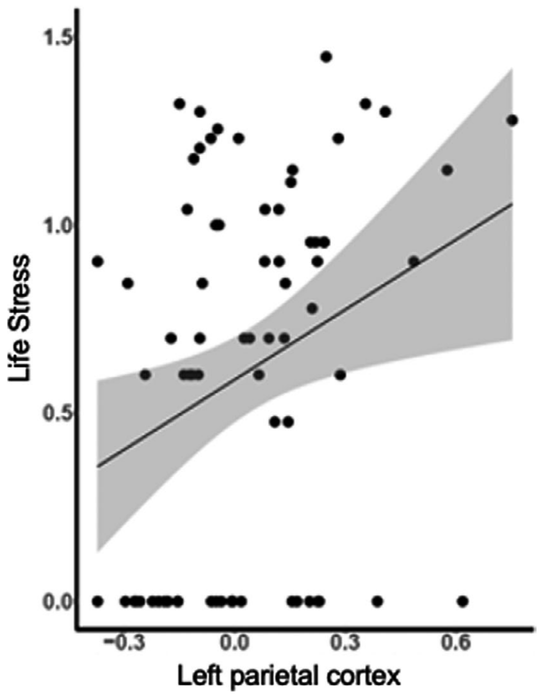

FIGURE 9 Plot showing a positive correlation between the difference in HbO activation in the left parietal cortex and the life stress subscore of the Parental Stress Index

at age 5. Taken together, in the current study, we suggest that a greater number of stressful life events might cause instability in the child's life, resulting in changes to their cognitive processing. In a household with shifting/shifted stability, children might be constantly distracted and unable to consistently sustain attention and maintain information to efficiently accomplish goals or tasks. In addition, it is also possible that parents distracted by stressful life events might struggle to fulfil daily goals to manage care-taking and might transfer poor skills of goal maintenance and traits such as easy distractability to their children. It is important to acknowledge that such children who are negatively impacted by a stressful home environment might have yielded a more pronounced atypical brain-behaviour response since they were after all subjected to home-based testing and assessments. We recommend that future studies should assess if brain-behaviour responses observed in such children during testing in their home environment can be similarly observed under controlled lab conditions.

In summary, our findings revealed that LP children showed a greater difference in activation between the low and high loads in a fronto-parietal VWM network. On the other hand, HP children did not show any modulation in activation with increasing VWM load. This difference in activation between loads in a left parietal cortex partially mediated the relationship between parent-reported life stress and VWM performance.

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CONFLICT OF INTEREST

No potential conflict of interest is reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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