SOCIOECONOMIC RISK AND NEURAL CORRELATES OF WORKING MEMORY IN PRESCHOOL-AGED CHILDREN: AN FNIRS STUDY

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ABSTRACT

Children exposed to early childhood poverty are at increased risk for learning and academic problems. Recent work has shown that poverty may affect neurocognitive systems that support higher level cognition, which may explain increased risk for delays. In this study, we investigated how variability in poverty exposure, based on family income, influences neural function and behavior during a working memory task in children aged 4 to 7 years. Children (n = 25) participated in a spatial working memory task while their DLPFC was monitored using functional near infrared spectroscopy (fNIRS). We found that low SES, based on family income, was associated with lower DLPFC activation. This points to one mechanism by which children exposed to poverty are at increased risk for problematic outcomes and has implications for early intervention and prevention.

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Associations between socioeconomic risk and neural correlates of working memory in preschool-aged children: an fNIRS study

The Effects of Poverty on Working memory

Numerous studies show that poverty poses a multitude of risk factors to the developing brain, increasing the risk for social emotional difficulties and poor academic outcomes (Jensen, 2013; Blair, 2016; Hair, Hanson, Wolfe, & Pollak, 2015). It has been proposed that poverty and associated risks have a negative impact on the development of a core set of skill involving in executive functioning, which are key for academic success (Hanson et. al, 2012; Moriguchi & Shinohara, 2019). An emerging line of work has revealed that poverty shapes underlying brain systems that sub serve executive functions, which may serve as a mechanism driving associated behavioral alterations.

Research over the past decade has converged on the idea that that poverty has a lasting impact on neurodevelopmental trajectories (Farah, 2017). Working memory, or the ability to hold and manipulate information in one's mind, is a key affected domain. Research on older children shows that working memory is impaired in children who are exposed to adverse/traumatic events that are presumed to be correlated with socio-economic risk factors. For example, Tine (2014) compared working memory performance among children with low-(SES) to children with high-SES. Each student completed four computerized and randomized working memory tasks that lasted for a total of 30 minutes. Results revealed that low-SES children showed working memory deficits compared to their high-SES counterparts, specifically symmetrical, asymmetrical, verbal and visuospatial working memory deficits.

The impact of poverty on working memory extends even into adulthood. Some evidences suggest that these long-term effects are due to chronic stress exposure (Evans & Schamberg, 2009). Evans and Schamberg used allostatic load (an index of cumulative wear and tear, or chronic stress, on the body due to repeated physiological responses to an environment) to measure chronic stress in children and found that the greater the time growing up in poverty, the greater the reduction in young adult's sequential working memory (2009).

Although less studied, some work suggests that poverty affects the underlying neural systems that subserve working memory. Work from animal studies has provided some insight into how poverty and socio-economic risk influences key brain regions that subserve working memory. A study with male rats showed that chronic stress significantly altered the morphology of neurons in the medial prefrontal cortex (mPFC; Cook & Wellman 2004, Garrett & Wellman, 2009). Furthermore, dendritic morphology of the mPFC is particularly sensitive to stress (Brown et al., 2005) and it was found that the pre frontally mediated behaviors in the male rats were altered (Liston et al., 2006).

Findings from human work mirror more basic effects discovered in animal work. For example, Farah and her colleagues' study on poverty and its association with neurocognitive development found SES to be significantly related to different cognitive systems specifically, the lateral prefrontal cortex and working memory (2017). Kindergarten-aged children with low SES were given a behavioral task designed to tax the working memory system. Their results, compared to middle-SES children, showed that middle-SES children had a more developed working memory. MRI scans showed regional gray matter volumes of low-SES children was 3 to 4 percent below the developmental norm and this correlated to their below- average scores on standardized tests (Hair et al., 2015). Another MRI study showed that cumulative life stress and

spatial working memory were related to a smaller volume of prefrontal gray and white matter in the PFC (Hanson et al., 2012). Reduced gray matter volume in the frontal cortex of children in poverty were found in another cross-sectional study that examined 389 children aged 4-22 years of age (Blair & Raver, 2016). Recently, Wijeakumar and her colleagues conducted an fNIRS study on low-SES children in rural India. 4-48-month-old children performed a working memory task while their brain activity was recorded. Low brain activity in the left frontal cortex was associated with low maternal education and poorer distractor suppression (2019). Although this study was conducted in a different economic environment, Wijeakumar and her colleagues collected data from a population where human development and nutrition indices of the location in India are similar to the average UP index (2019).

Some work has focused on identifying environmental risk factors that mediate links between poverty and neurocognitive problems. Risks associated with poverty include lack of proper nutrition, pollutant exposure (Farah et al., 2006) and the physical burden of chronic stress (Wadsworth, Raviv, Reinhard, Wolff, Santiago, & Einhorn, 2008; Evans & Schamberg, 2009). Guo and Harris (2000) have shown that limited cognitive stimulation (defined in their study as a lack of books, magazines, exposure to reading, and enriching experiences) are among the key factors that explain neurocognitive risk.

Working Memory - What is it?

Working memory is the ability to temporarily store information in order to perform cognitive tasks such as solving math problems, reading, or completing any activity that requires memory-in-action (Baddely, 1983). Working memory plays a crucial role in cognition as it works and develops in frontal cortical areas and subcortical structures (Eriksson, Vogel, Lansner,

Bergström, & Nyberg, 2015). Although working memory develops during infancy, its abilities expand in childhood as it begins to integrate with other executive functions (Perlman, 2015).

The beginnings of working memory development can be seen in infants as early as 6.5 months based on Káldy and Leslie's (2005) variation of Piaget's A-not B task. In this experiment, infants became familiarized with two differently shaped objects in the middle of a stage repeatedly. The objects were then moved to the sides of the stage and the side that the two objects were presented on was alternated from trial to trial. Results of this experiment show that 6.5-month-old infants could associate featural information in order to identify the objects by location, but only with the last hidden object (Káldy and Leslie, 2005).

Children's processing speed of working memory increases along with their age (Cowan, 2017) and this can be seen through numerous behavioral studies (Zoelech, Seitz, & Shumann Hengteler, 2005; Cowan, AuBuchon et al., 2010; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010); Vogel, McCollough, and Machizawa (2005); Cowan, Saults, and Clark (2015). In addition, researchers have used neuroimaging to study neural development in young children. Buss and his colleagues were one of the first to use functional near infrared spectroscopy (fNIRS) to measure working memory development in young children (2014). During the study, three- and four-year-old children watched shapes on a screen and detected any change in shapes while their cortical activity was monitored by fNIRS. Significant activation was shown in the left frontal parietal regions in both groups of children during the activity but four-year-old's showed higher activation than the three-year-old's. Another fNIRS study like this was conducted with children aged 3-7 years and they had found significant activation in the LPFC (Perlman, Huppert, & Luna, 2015). Increased LPFC activation and accuracy was positively correlated with age as well. A longitudinal study used MRI to detect neural changes in the working memory of

children aged 8-22 years (Tammnes, et al., 2013). They found that working memory improvement was related to cortical volume reduction in bilateral prefrontal and posterior parietal regions. Cohen's fMRI study of working memory development in children aged 9-11 showed increased dorsolateral prefrontal activation during a working memory task.

The Relationship Between the Prefrontal Cortex and Working Memory

It has been long established that the prefrontal cortex is a core brain region that supports working memory. In 1936, Jacobsen first showed that bilateral prefrontal lesions caused severe impairment in the delayed-response performances of rhesus monkeys. Further studies with lesions of the lateral prefrontal cortex (LPFC) resulted in significant and long-lasting deficits in delayed response tasks in both monkeys and humans (D'Esposito, 2004; Antonio &, Wallis, 2006).

Advances in neuroimaging have made it possible to examine prefrontal cortex activation during working memory tasks humans. Courtney et al. were able to identify that spatial working memory is heavily dependent on the superior frontal sulcus (a region in the prefrontal cortex) using functional magnetic resonance imaging (fMRI) (1998).

Cumulative research from fMRI studies implicate the dorsolateral prefrontal cortex (DLPFC) as sub serving working memory abilities. For example, the DLPFC has shown to be involved in performance on a delayed response task in adults (Courtney et al., 1998; Zarahn et al., 1999; Jha & McCarthy, 2000; Sakai et al., 2002). It has also been theorized that DLPFC assists in the maintenance of information (Curtis & D'Esposito, 2003).

The LPFC has been shown similar activity during working memory processes in preschool-aged children as in adults indicating that the LPFC has already developed enough to

use this cognitive function (Tsujimoto et al., 2004). A longitudinal study studied the cortical and subcortical thickness of participants aged 8-22 and demonstrated that improved working memory was related to LPFC volume reduction at a 2-year follow up (Tamnes et al., 2013).

Neural Correlates of Working Memory in Pediatric Populations

Although there are numerous studies on older children and adults, there are only a small number of studies that have examined neural correlates of working memory in preschool age children. This is partly due to methodological limitations and the fact that there is a need for child friendly approaches for examining task related brain function in children (Perlman, Huppert & Luna, 2015). Functional near-infrared spectroscopy (fNIRS) presents a solution to this methodological dilemma, in that it is a non-invasive, child-friendly neuro-imaging approach.

FNIRS. FNIRS is a recently developed neuroimaging method that captures the hemodynamic properties of the brain by assessing both oxygenated (HbO), deoxygenated (HbR), and total hemoglobin (HbT) changes in the cerebral cortex with near-infrared light (Pinti et al., 2015). The increased blood flow evoked by neural activity in a brain region usually results in an increase in HbO and a decrease in HbR. Previous studies have shown that HbO and HbR responses from fNIRS are temporally and spatially correlated with the Blood Oxygen Level-Dependent signal (BOLD) obtained from fMRI (Jahani et al., 2017; Huppert et al., 2006).

There are several advantages associated with fNIRS. First, it is relatively robust to motion artifacts in comparison to functional magnetic resonance imaging (fMRI). This makes it well suited for examining brain activation in high risk or pediatric population who are likely to engage in excessive motion (Wilcox & Biondi, 2016). Second, the localization of responses

allows for more accurate identification of the areas from which cortical responses were taken (Huppert, Barker, Schmidt, Walls, & Ghuman, 2017).

In the past decade, there has been an increase in the application of FNIRS to assess brain function in typically developing children. Perlman and her colleagues were able to show increased activation in the lateral prefrontal cortex (LPFC) with fNIRS during spatial working memory tasks in children aged 3 to 7 years of age (FIX THIS CITATION 2015). They had also found that increase in LPFC activation, response speed, and accuracy were positively correlated with age (Perlman, Huppert & Luna, 2015). Another fNIRs study compared pre-frontal activation in low-SES and middle-SES children in Japan during a Dimensional Change Card Sort (DCCS) task (Moriguchi & Shinohara, 2019), which requires working memory and cognitive flexibility. Low-SES children showed no significant activation in the PFC during the task when compared to middle and high-SES children, further revealing the direct relation between SES and the functional development of the PFC (Moriguchi & Shinohara, 2019). The relationship between working memory performance and cortical activation is important to understand because it can be used to measure intellectual fatigue within cognitive processes (Ogawa, Kotani, & Jimbo 2014).

Present Study Aims and Hypotheses

It is well established that poverty negatively affects developing working memory in children. However, given challenge children present for neuroimaging techniques, there is limited understanding how SES challenges functional neural activity associated with executive functions (i.e. working memory). During preschool, executive functions and their underlying neural systems begin developing rapidly (Gilchrist, Cowan, Naveh-Bejamin, 2010). Measuring brain function at an early point in development, when working memory functions are emerging,

has relevance for understanding the underpinnings of problematic cognitive development in this young population.

To study this important topic, we used fNIRS to examine how early life poverty exposure shapes neural function associated with working memory in preschool-aged children. An advanced and novel spatial working memory task called "New Monkey Task" was used while we monitored their frontal and temporal cortex using fNIRs as it is a suitable instrument for self-reliant assessment of working memory in preschool-aged children. This working memory task was similar to Perlman and her colleagues from their previous working memory study (2015). We hypothesized that the most activation will occur in the lateral prefrontal cortex during the working memory task given previous literature indicates lateral prefrontal cortex is a key region for working memory. Our final hypothesis was that there will be a significance between reaction time and brain activation in the lateral PFC. Thus, our questions for this study were:

Question 1:

Does poverty exposure, based on family income, correlate with the brain activation from the working memory task?

Question 2:

Do activation patterns correlate with reaction time as part of this task?

Materials and Methods

Participants of this study (N =25) consisted of low-socioeconomic status and families of multiple ethnicities ($Mean_{age}$ = 5.24 years, SD_{age}= 0.84) from the greater Houston area. Families were recruited from organizations and agencies that serve low income families including WIC centers,

Head Start Programs. Because 39% of the Houston population speaks Spanish only (Houston Population), we recruited both native English speakers and Spanish speakers. 9 male and 16 female children were identified as 32% Caucasian, -36% African American, 56% Hispanic, and 28% other/mixed. All subjects were reported by their parents or guardians to have no history of severe psychiatric diagnoses. Both mothers and children provided written informed consent. All recruitment and experimental procedures were approved by the Institutional Review Board at the University of Houston.

Parental SES status

Parents' SES were calculated using the Income-to-needs ratio. We calculated their annual income based on what the parents reported such as their monthly income and the subsidy they received from other resources. The parents' income was then divided by the poverty threshold for their family size. Figure 1 shows poverty thresholds based off family size and income (U.S. Census Bureau). Table 1 shows the average incomes of the families based off the income-to-needs ratio.

Table 1

Demographics of families' annual income and income-to-need in this study

			Income-to-need		
Family income	N=25	%	mean	min	max
≥ 25,000	9	36	1.3547	0.3998	2.1097
25-50,00	12	48			
50-75,000	4	16			
75-100,000	0	0			
100,000+	0	0			

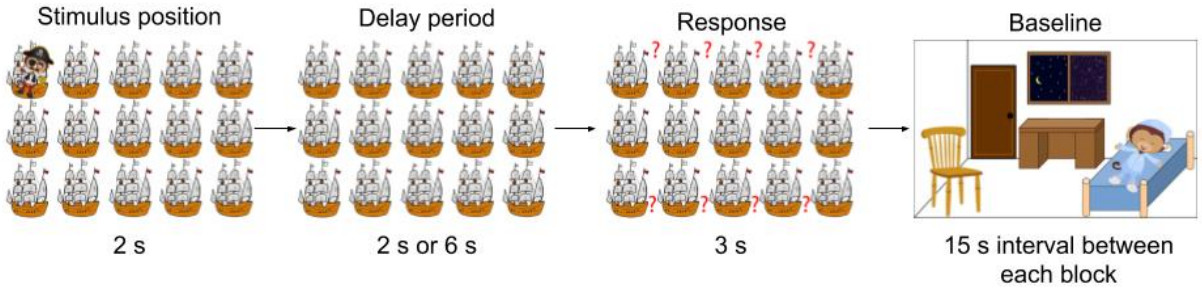
Size of family unit	Related children under 18 years								
	None	One	Two	Three	Four	Five	Six	Seven	Eight or more
One person (unrelated individual):									
Under age 65	13,300								
Aged 65 and older	12,261								
Two people:									
Householder under age 65	17,120	17,622							
Householder aged 65 and older	15,453	17,555							
Three people	19,998	20,578	20,598						
Four people	26,370	26,801	25,926	26,017					
Five people	31,800	32,263	31,275	30,510	30,044				
Six people	36,576	36,721	35,965	35,239	34,161	33,522			
Seven people	42,085	42,348	41,442	40,811	39,635	38,262	36,757		
Eight people	47,069	47,485	46,630	45,881	44,818	43,470	42,066	41,709	
Nine people or more	56,621	56,895	56,139	55,503	54,460	53,025	51,727	51,406	49,426

Figure 1. 2019 poverty thresholds by size of family and number of related children under 18 years.

Working Memory Task

In this task, we used a block design to measure participants' working memory. Children sat in front of a computer screen in a sound-attenuated recording chamber. First, task instructions were explained by a research assistant. The child's job was to remember where the monkey hid his bananas. For each trial, the monkey first appeared, holding a bunch of bananas, on one of the 12 objects for two seconds. The monkey then disappeared for two or six-second delay periods, requiring the child to hold the monkey's location in working memory for one of those two times. After the delay periods, red question marks appeared for 3 seconds, prompting the child to touch the tree in which the bananas were hidden. This concluded one trial out of four. Four trials created one block (see Fig. 2). After each test block, a 15-second interval was presented in a clip of the monkey going to sleep. Five block trials and five intervals were presented. Two long and two short delay periods were presented sequentially to create each block. The child needed to

pass one practice block in order to continue to the five test blocks. If the child could not pass the practice block for the second time (3 out of 4 trials correct) they were given a simpler version of this working memory task. A passing score was considered if the child could pass at least one practice block.



Note. A single trial of the working memory task. Participants were instructed to remember the object in which the monkey hid his bananas during the delay period.

Figure 2. New monkey working memory task.

fNIRS Recording during Working Memory Task

Our study was performed with a continuous wave fNIRS system (NIRScout, NIRx Medizintechnik GmbH, Germany) with a sampling frequency of 6.25 Hz. Children were fitted with the appropriately sized fNIRs head caps that were positioned in accordance with the international 10-5 coordinate system with the middle of the probe positioned at Cz **(**Figure 3). 16 dual tip light sources, that each emitted LED light at 760-nm and 850-nm and 16 detectors that each received the light travelling back from brain tissues were used. One source and one detector formed a channel that measures the hemodynamic responses underneath it. There were 50 channels in our probe. Table 2 displays the channels that measured DLPFC activity for this study (our regions of interest for this study). The MNI coordinates of channels were generated from fOLD, a MATLAB software that arranges probes guided by brain regions-of-interest, and

previous fMRI literature, that indicated DLPFC MNI coordinates, were used to verify which coordinates were within the vicinity of the DLPFC. Figure 4 shows a physical display of our DLPFC coordinates in HOMER2 Atlas Viewer software. Sensors and optodes were placed using spring-loaded caps onto a NIRX cap (NIRX). 2.3-meter long fiber optic cables were held by a research assistant in order to prevent its weight from affecting signal quality. The sensors were placed onto an appropriate-sized cap prior to the family arriving.

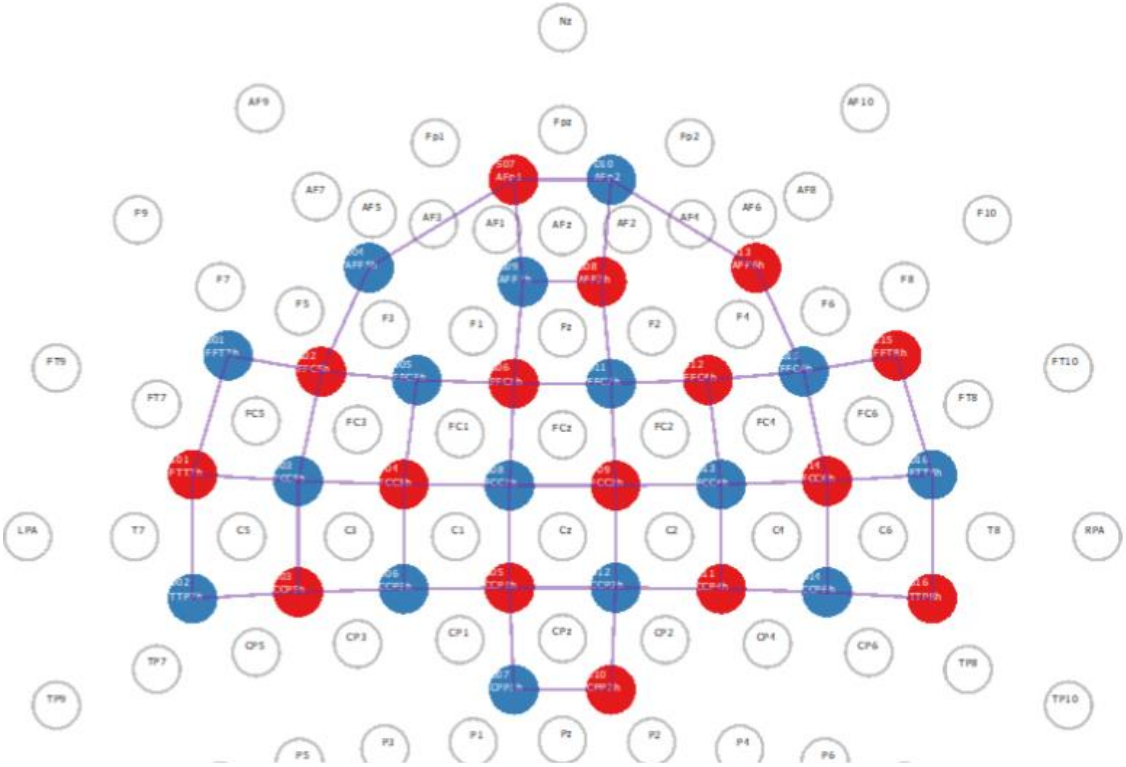
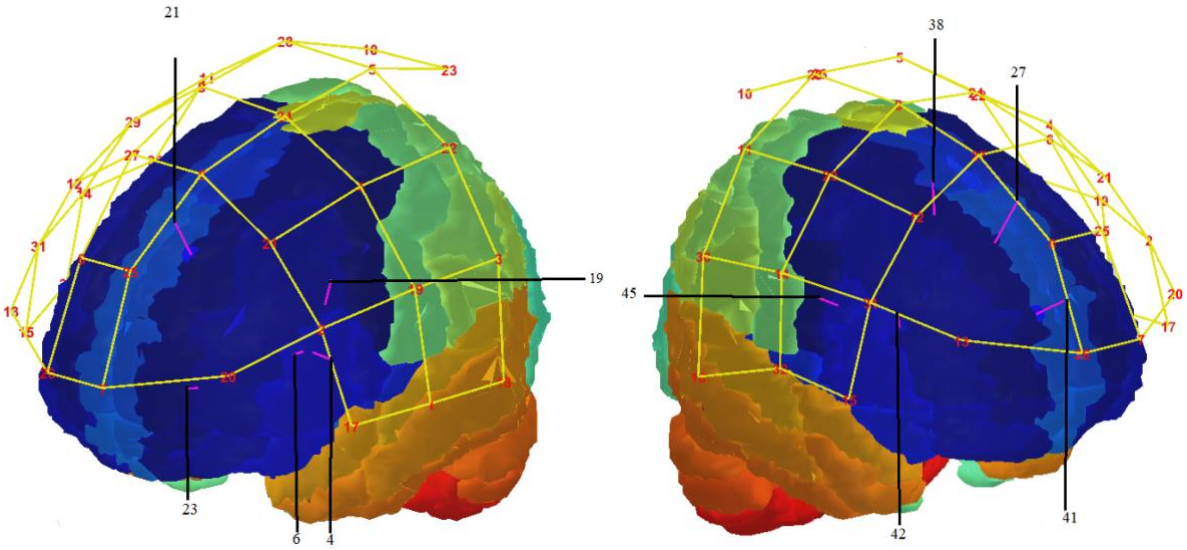


Figure 3. Head probe placement with the 10-5 coordinate system.



Note: A display of DLPFC MNI coordinates (pink pinpoints) in our study (HOMER2_UI).

Figure 4. Physical locations of DLPFC MNI coordinates on HOMER2 Atlas Viewer_GUI

Table 2

FNIRS optodes that measure the DLPFC

Channel number	Source number	Detector number	MNI coordinates (x, y, z)
21	6 (FFC1h)	9 (AFF1h)	-8, 38, 48
19	2 (FFC5h)	5 (FFC3h)	-43, 22, 39
23	7 (AFp1)	4 (AFF5h)	-26, 58, 14
6	2 (FFC5h)	4 (AFF5h)	-45, 35, 23
4	2 (FFC5h)	1 (FFT7h)	-45, 28, 22
42	13 (AFF6h)	15 (FFC6h)	46, 36, 26
38	12 (FFC4h)	11 (FFC2h)	24, 26, 54
41	13 (AFF6h)	10 (AFp2)	26, 58, 15
45	14 (FCC6h)	15 (FCC6h)	55, 17, 31
27	8 (AFF2h)	10 (FFC2h)	15, 47, 54

After cap placement, we used a 3D digitizer (Polhemus Inc., VT) to obtain the 3D locations of all the optodes placed on the child's head. The child was then asked to go into the

sound chamber and sit at a child sized desk. Before actual data recording, the signal was calibrated and adjusted using NIRStar (NIRx) and PHOEBE (placing headgear optodes efficiently before experimentation) (Pollonini, Bortfield, & Oghalai, 2016). NIRStar showed the detector gains after calibration, while PHOEBE measures and displays, in-real time, signal quality indicated by scalp coupling index (SCI). After making sure the signal quality was ideal (no excessive noise or motion artifacts), data recording began. During the task, we collected fNIRS data at a sample rate of 6.25 Hz through NIRSstar and used PHOEBE to monitor real-time signal quality among all optodes. Reaction time and responses were automatically recorded after each response by the software presenting the task.

Children completed the task using a touchscreen monitor. A research assistant remained next to the child in order to hold the fiber cables, read the task's directions, and make sure that the child understood the task. Children were visually recorded as they completed the working memory task. The total setup time took around 10 to 15 minutes.

Quality Check of fNIRS Data

Raw fNIRS data was quality checked through a real-time signal quality check and an offline signal quality check to minimize false readings during analyses and to maximize data quality. Since children present a challenge when attempting to obtain consistent quality data, we inspected all channels. These checks were used to see if strong cardiac pulsations can be detected in both wavelengths of the signal. The frequency of the cardiac pulsation of young children is usually between 1.5-2 Hz and it can even be seen in real-time signal with the naked eye. For real-time signal quality check, we monitored our channels through PHOEBE. One of the most robust indicators for a good fNIRS signal in this software is the cardiac pulsations (0.5-2.5 Hz). If the

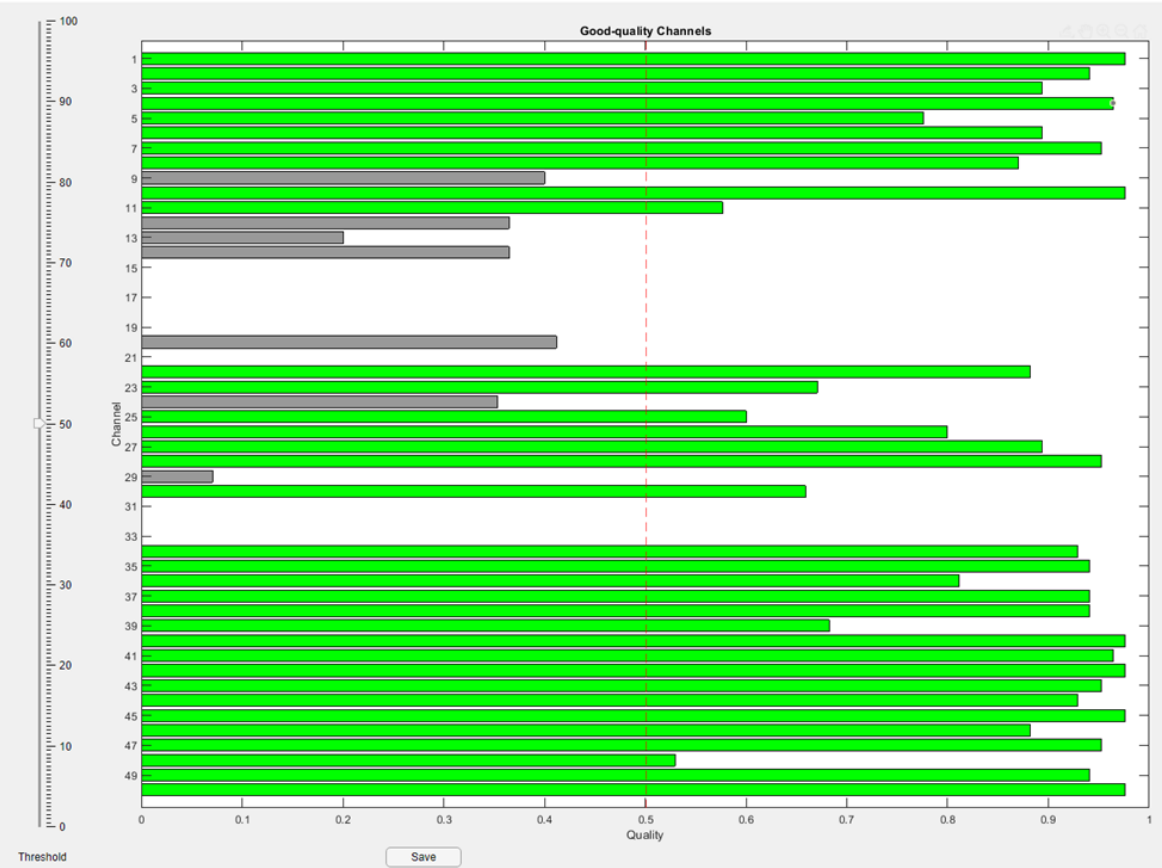
cardiac pulsations from an fNIRS channel can be identified, it indicates an ideal connection between the optodes. We can thus successfully measure the physiological changes of our subjects because the channel has an ideal signal to noise ratio (SNR).

Visual inspection of the raw signal was also used to check the signal quality. Cardiac pulsation was observed in each channel to ensure quality signal before the experiment. Subsequently, we used Nirsplot, a MATLAB GUI (graphical user interface) developed by co-I, Dr. Luca Pollonini, to assess if the cardiac pulsations, which are indicated by two indices, i.e., scalp coupling index (SCI) and its peak power, were strong in the fNIRS raw signal offline. If a channel met both criteria, then it was considered an ideal channel and kept in the raw signal. Otherwise, it was pruned from the raw signal. The channels that are pruned were excluded from further processing (Fig. 5).

We first filtered the raw signal with a bandpass filter to keep the cardiac bandwidth (0.5-2.5 Hz). Our raw signal consisted of two wavelengths (760-850 nm) that supposedly contained cardiac pulsations within the cardiac bandwidth so they correlated well if the signal was ideal. The two wavelengths were cross correlated within the cardiac bandwidth (0-1) and indicated our SCI (the empirical threshold was set at 0.8). Some wavelengths correlated due to motion artifacts (MA) which provided us a false positive. In order to combat this, we complemented the SCI with peak power (empirical threshold set at 0.1) in order to reduce the false positive rate. An adequate signal would have both, a high SCI and peak power values, whereas a false positive would have a high SCI but a low peak power.

Nirsplot then captured the time course of our experimental blocks and a 5-sec window was selected for individual signal inspection based on the two indices. An empirical threshold (ranging

from 0 to 1) determined if each channel was considered acceptable (Fig 5). If a channel demonstrated poor quality, it was confirmed with visual inspection using Homer2 (Fig 6).



Note: The x-axis is the threshold (the proportion of good time windows) that can be adjusted. The y-axis is the channel. A channel with ideal signal was represented by a green bar, while a channel with poor SNR was indicated by a grey bar or a blank line.

*Figure 5***.** The signal quality check panel in Nirsplot

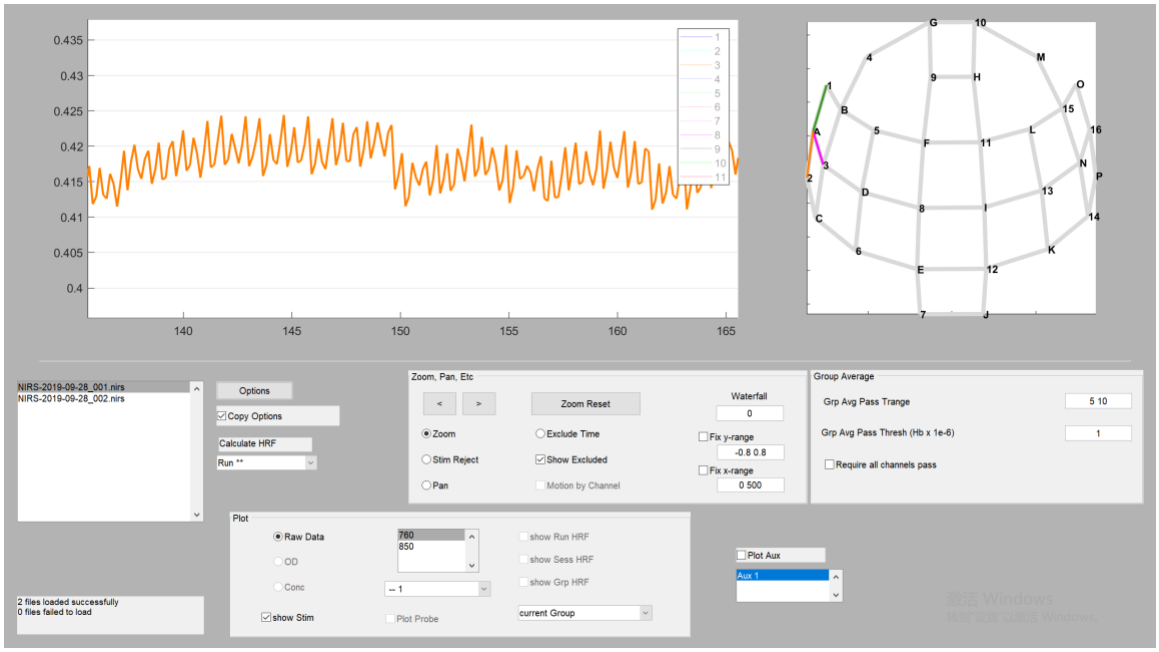


Figure 6. The cardiac pulsations in a single fNIRS channel of a preschool child in Homer2

fNIRS Data Analyses

After the signal quality check, Analysis of fNIRS data was collected using fNIRS Brain AnalyzIR Toolbox (Huppert, 2018), an open source software implemented in MATLAB (MathWorks, Natick, MA). Pre-processing consisted of converting to optical density and sequentially to HbO (oxygenated hemoglobin) and HbR (deoxygenated hemoglobin). In the first-level statistical analysis, the data was then regressed using an auto-regressive whitened robust regression model that reduces the false-discovery rate via removal of serial correlations by motion artifacts, physiological changes and drifts as described in Barker et al. (2013). We used this model to construct a regression model (see equation 1) where Y = measurement vector, X = design matrix, W is the pre-whitening matrix that is applied to both the left and right sides of Eq. (1), β = estimated and combined weights of the regressors and ε is the residual error. Single-subject results consisted of running one-sample t-test $q<0.05$) (on auto-regressive model stats,

producing individual β-values and the *p*-values that indicate the significance. In other words, the *p*-value indicates if the brain activation in a single channel is significant.

$$W \bullet Y = W \bullet X \cdot \beta + W \bullet \varepsilon \quad (1)$$

For group-level analysis, we conducted a mixed-effects model (see equation 2) to detect the effect of SES on the brain activation elicited by the working memory task, where y is the beta values of all channels among all subjects, the fixed effects factor X is the SES and β is the unknown vector of it that we estimate, the random effects factor Z is the subject IDs and μ is the unknown vector of it that we estimate and ε is the residual error.

$$Y = X \cdot \beta + Z\mu + \varepsilon \quad (2)$$

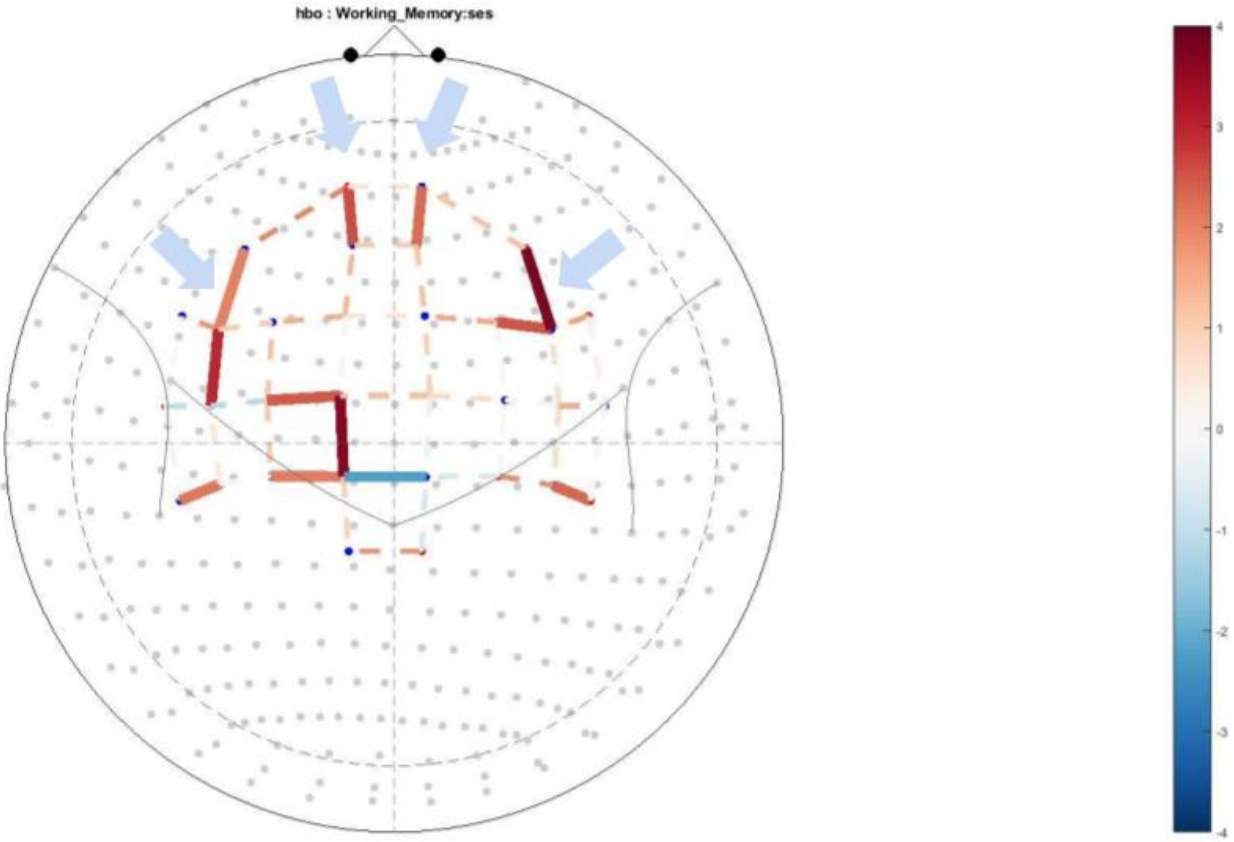
using

'beta ~ -1 + cond'.

Results

Associations between Socioeconomic risk and FNIRS activation patterns

The statistical contrast of group activation patterns for oxyhemoglobin and deoxyhemoglobin during the working memory task is shown in Figure 7. Optical measurements pairs located on the 10-5 coordinate of AFp1 (channel 23), FFC5h (channel 6), AFF2h (channel 27) and AFF6h (channel 42) showed to be significantly affected by SES ($P < 0.1$) in oxyhemoglobin. This indicated a correlation between brain activation and poverty, based on family income, during the working memory task. Activation in deoxyhemoglobin (Fig. 8) was not significantly affected by SES in any of the regions of interest. Table 3 shows the individual t-statistics and p-values of each DLPFC channel.



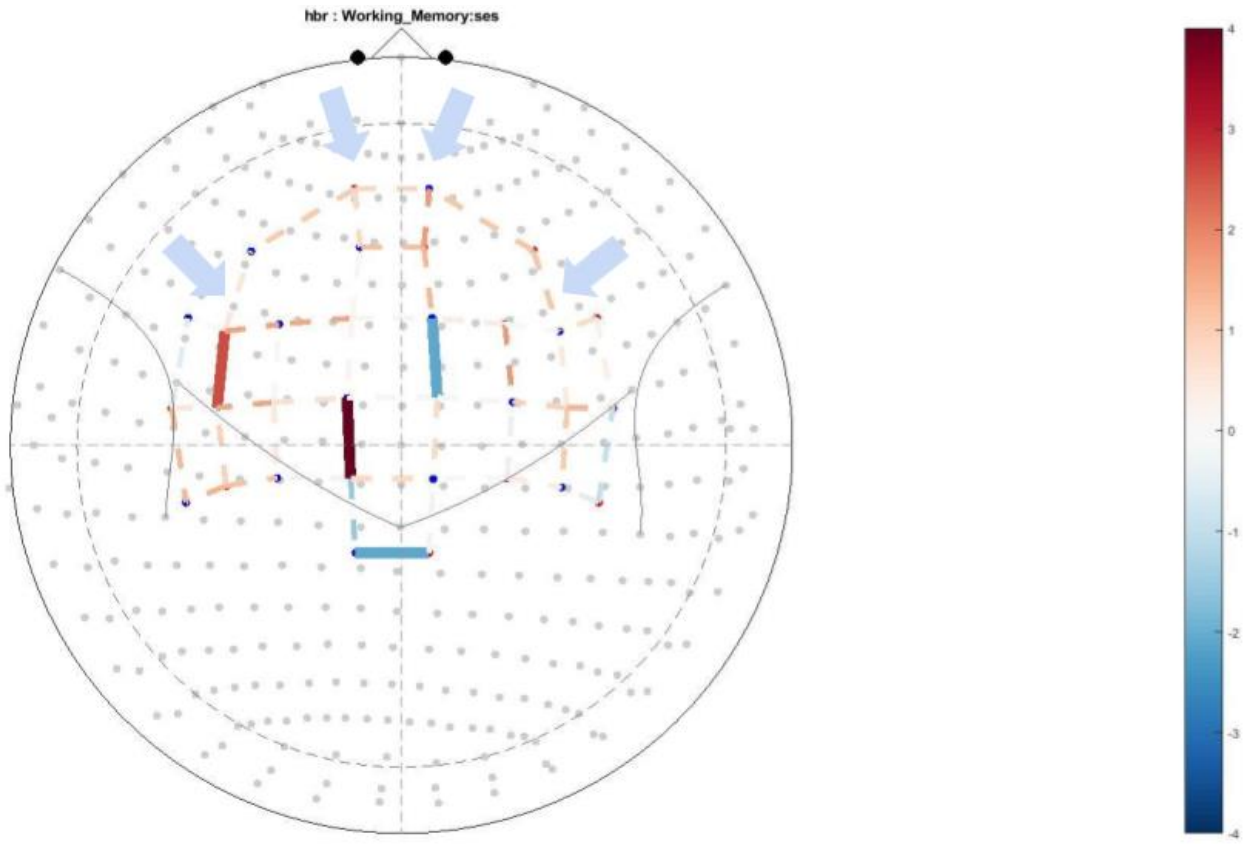
Note: Group results of SES effects on brain activation. Line color (under the arrows) indicates the t-statistic of whether the activation is significant or not.

Figure 7. Δ oxygenated hemoglobin

Table 3.

Individual Results of SES's effect on DLPFC Brain Activation

	HbO β values		HbR *β* values	
Channel Number	*t*	*p*	*t*	*p*
21	1.309	0.203	0.556	0.584
19	1.045	0.307	1.834	0.08
23	1.993	0.058	1.1719	0.253
6	2.447	0.022	1.155	0.26
4	1.756	0.092	0.252	0.803
42	4.022	0.001	1.519	0.142
38	1.852	0.077	0.709	0.485
41	1.1945	0.244	1.611	0.12
45	0.98	0.534	0.707	0.487
27	2.23	0.036	2.239	0.035



Note: Group results of SES effects on brain activation. Line color (under the arrows) indicates the t-statistic of whether the activation is significant or not.

Figure 8. Δ deoxygenated hemoglobin

Correlation between SES and reaction time during working memory task

Reaction times in milliseconds were averaged for each participant's test blocks and then correlated with the averaged β values for oxyhemoglobin and deoxyhemoglobin for DLPFC (Fig. 9 and Table 4). We found no significant correlation between these two variables for oxyhemoglobin or deoxyhemoglobin (Fig. 10 and Table 5).

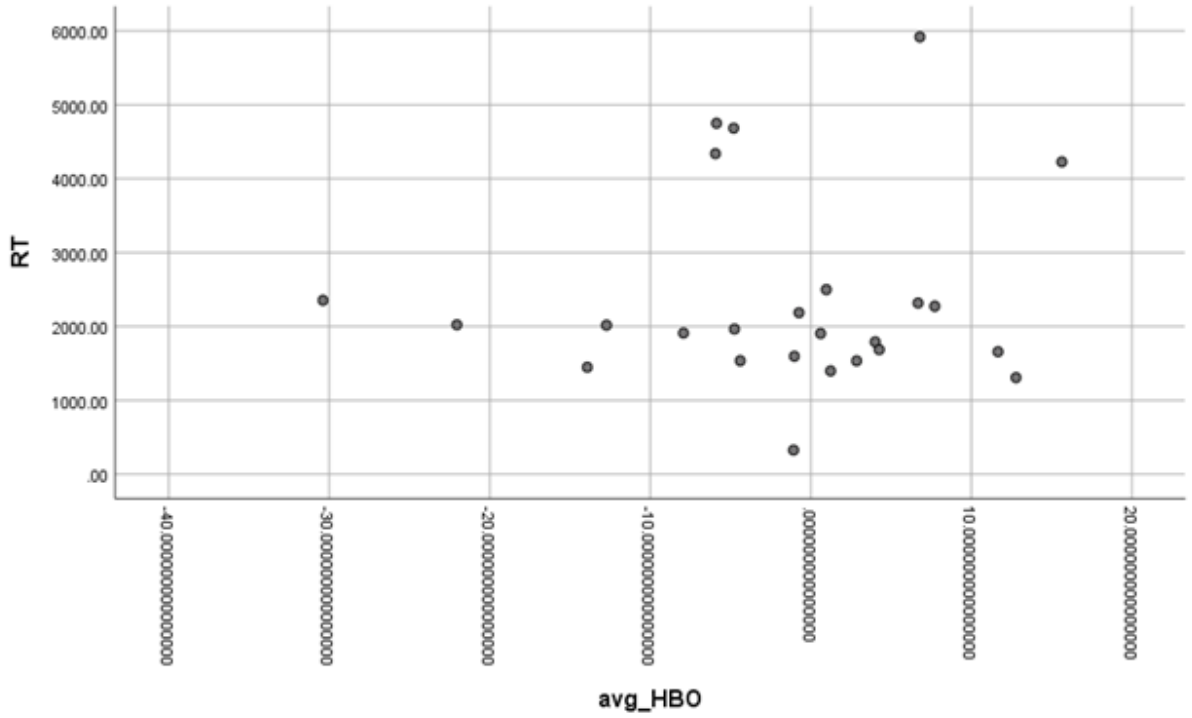


Figure 9. HbO β values for the DLPFC channels correlated with reaction times

Table 4

Statistics between the Correlation of HbO and reaction time

	Reaction Time (MS)	Avg_HbO
Pearson Correlation		0.069
Sig. (2-tailed)		0.745
N		25

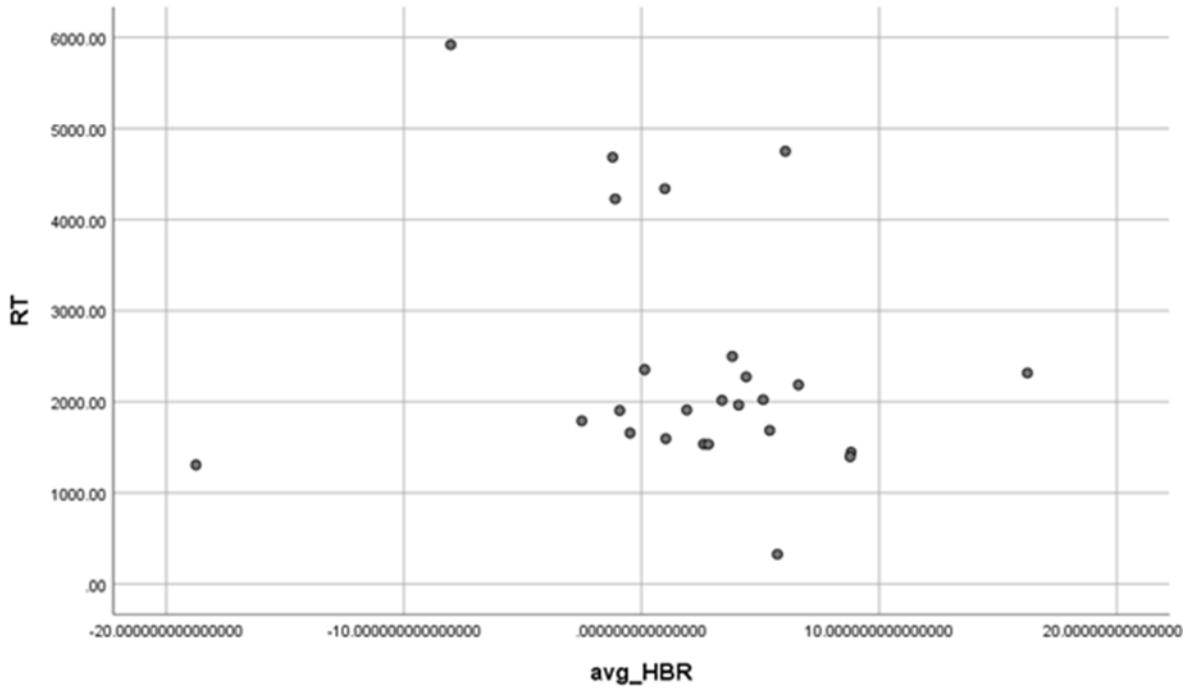


Figure 10. HbR β values for the DLPFC channels correlated with reaction times

Table 5

Statistics between the Correlation between HbR and reaction time

	Reaction Time (MS)	Avg_HbR
Pearson Correlation		-0.2
Sig. (2-tailed)		0.337
N		25

Discussion

This study used fNIRS to study associations between socioeconomic risk, based on family income, and brain activation in the dorsolateral prefrontal cortex (DLPFC) in preschoolers. It also attempted to bridge DLPFC brain activation in 4-7 year-aged children and reaction time on a working memory task together. As predicted, we found that low SES was significantly associated with low activation in both DLPFC hemispheres when children

completed the working memory task. Overall, our study supports the conclusion that low SES has a significant effect on developing working memory. Interestingly, socioeconomic status was not associated with behavioral performance on the task. This offers new information on how environmental risk factors shape key brain during a period of development when working memory is emerging (John et al. 2018; Gathercole, 2004).

Past neuroimaging literature has shown that children exposed to low SES display differential activation patterns in the lateral prefrontal cortex during working memory tasks compared to middle SES counterparts (Farah et al. 2006). More specifically, 4-48-month-old children with low income displayed lower brain activity in the left frontal cortex areas (inferior frontal gyrus and DLPFC) and limited abilities to ignore distracting information in a distractor suppression task (Wijeakumar et al. 2019).

Contrary to expectations, we found no associations between neural activation patterns and behavioral performance, as indicated by reaction time to complete each trial. We hypothesized that the HbO β values would be significantly higher if children took longer to answer questions on the working memory task. Across all participants, we found that most of their reaction times did not vary amongst the different levels of brain activation. 19 of the participants reaction time ranged from 1 second (1000 MS) to 3 seconds (3000 MS) across the HbO range of -30 μm and 15 μm. A potential explanation may be due to how we constructed our analysis between brain activation and reaction time. Our measures of brain activation were averaged across the entire block of trials, whereas our reaction time was quantified for each trial.

Second, it is possible that the practice trials have influenced the children's task performance. Children participated in 4 to 8 practice trials prior to starting the task. Practice trial reaction times were averaged for each participant and compared to the averaged reaction times of

their test blocks. We found a strong relationship between the time differences of practice and test blocks (p-value = 0.020). Participants' test reaction time were significantly slower during their practice blocks ($Mean_{practice} = 3586.2;\ Mean_{test} = 2392.2$) This could indicate that the amount of questions in the practice blocks caused our participants to practice enough to improve their reaction times.

Although this study has further investigated the relationship between poverty and prefrontal brain development in young children, there are potential methodological limitations. Our small sample size limited statistical power to detect effects. The infrared light fNIRS emits towards the cortex is sensitive to movement and hair type. Participants with dark hair or complex braided hair may have had reduced signal quality or lack of contact between optodes and scalp.

In this study, we had investigated whether brain activation was affected by SES and if reaction time would be affected by brain activation. There are other developmental behaviors that are heavily associated with working memory that have yet to be investigated with neuroimaging techniques in this study. The development of attention is a major turning point for the development of working memory since it determines how much material can be stored and how it is efficiently used to focus on relevant stimuli (Cowan, 1999). Multiple studies have shown that low-SES children perform more poorly than middle or high-SES children on tasks that call for selective attention (Bradley & Corwin, 2002; Mezzacappa, 2004; Stevens, Lauinger, & Neville, (2009)). In addition, past research has shown that the neural mechanisms of spatial selective attention and memory are linked early in life (Markant and Amso, 2013), indicating the importance of viewing the interactive effects of memory, selective attention, and SES (Markant, Ackerman, Nussenbaum, & Asmo, 2016). Future work should consider examining selective

attention with working memory from a neuroimaging standpoint to help us further understand the neural mechanisms of working memory in low SES children.

Conclusions

Our results of this study complemented previous neurodevelopmental studies by using FNIRS to evaluate the impact of child poverty on working memory. We found that SES risk, based on family income, was associated with DLPFC brain activation during a working memory task. This indicates that low income has an early negative effect on frontal development in children as young as 4 years of age, which may be a neurodevelopmental mechanism linking early life adversity with ongoing developmental risk. Furthermore, these data demonstrate innovative analysis methods that are different yet effective, as we used FNIRS data quality checks. In summary, results from our study point to further insight into the multifaceted effects of poverty on the developing brain.

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