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Exploring the Effects of Response Type in a Visual Working Memory Task: An fNIRS Study

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To the Graduate Council:

I am submitting herewith a thesis written by Rachel Eddings entitled "Exploring the Effects of Response Type in a Visual Working Memory Task: An fNIRS Study." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Experimental Psychology.

Aaron T. Buss, Major Professor

We have read this thesis and recommend its acceptance:

Caglar Tas, Shannon Ross-Sheehy

Accepted for the Council:
Dixie L. Thompson

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(Original signatures are on file with official student records.)

Exploring the Effects of Response Type in a Visual Working Memory Task: An fNIRS Study

A Thesis Presented for the

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Degree

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Rachel Nicole Eddings

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Abstract

Visual working memory (VWM) allows us to hold visual information in mind to be manipulated for a task. Previous research shows that performance varies based on factors such as stimulus modality and number of distractors. This study aimed to explore the effect of response type on VWM performance in 4.5- and 5.5-year-olds. A single-item probe color change detection task and a cued recall with labeling task were administered. The tasks were identical in structure until the response phase of the trial. Neural data were collected using functional near-infrared spectroscopy. Both tasks used set-sizes 1-3 and six canonical colors (red, orange, yellow, green, blue, purple). All children were given the change detection task first. Behavioral analyses show a main effect of set size for both the change detection task, $F(2, 618) = 85.37$, $p < .001$, and the cued recall task, $F(2, 711) = 131.19$, $p < .001$, with a significant decrease in performance as set size increased. Moreover, VWM capacity was estimated to be higher in the change detection task (k_4=2.12, k_5=2.36) compared to the cued recall task (k_4=1.18, k_5=1.84) ($p < .001$). When we look at the neural data, both tasks activated bilateral temporal and parietal cortices. Comparing same and different response in the change detection task, we saw a distinct network of activation for both in the 5-year-old group but not the 4-year-old group, suggesting a developmental shift in neural activity. The cued recall task elicited decreased activation patterns in the 5-year-old group in frontal and temporal regions which suggest a need for a greater amount of neural resources due to greater difficulty in the younger age group.

Keywords: visual working memory, working memory, change detection, functional near-infrared spectroscopy, developmental psychology

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Background

Visual working memory (VWM) is an essential mechanism which allows us to hold visual information in mind without the original stimulus present in order to access and manipulate that information for a task. One key aspect of VWM is that it is limited in the number of items that can be remembered, referred to as capacity. VWM gradually develops during early childhood, reaching levels of performance comparable to adults by age 9 (Cowan, Elliot, Saults, Morey, Mattox, Hismjatullina, and Conway, 2005). Further, performance on VWM tasks is influenced by factors such as stimulus modality, stimulus complexity, and the presence of distractors (Simmering, 2008). Several different types of working memory tasks have been developed to probe VWM that use responses ranging from simple looking behavior to overt verbal responses (Simmering & Perone, 2013). In this project we examined how task demands can influence behavioral and neural measures of VWM during early childhood. Specifically, we examined performance when children were asked to compare a visual stimulus with VWM representations or to provide a verbal label of VWM representations.

Measuring VWM

One task that is commonly used in the VWM literature in adults is the change detection (CD) task. The CD task is comprised of the short presentation of a stimulus array (e.g., 500ms) that the participant is instructed to remember, a delay during which the array is removed (e.g., 1500 ms), then the presentation of a second array of objects that is either identical to the memory array or that has had one object changed. From performance on this task, a capacity of VWM can be estimated (Pashler, 1988; Cowan, 2000; Rouder, Morey, Morey, & Cowan, 2011). Research shows that 3-year-olds can remember around 1.5 items and by age 9 participants can remember 3 to 4 items similar to adults (Luck & Vogel, 1997; Cowan, et. al., 2005; Riggs, McTaggart, Simpson, & Freeman, 2006; Simmering, 2012; Simmering & Perone, 2013).

One challenge with measuring VWM is that the status of VWM is typically assessed by requiring participants to perform some task using VWM. In this case, participants must perform a comparison task to make a same/different decision. Although the change detection task is relatively simple, it nevertheless imposes the non-VWM demand of comparison between a VWM representation and a present visual stimulus. Other tasks have used free responses to measure representations in VWM. In these tasks, VWM is used for a recognition task. For example, in the cued recall (CR) task (Emrich & Lockhart, 2017), a color wheel is presented during the test array and one of the locations from the memory array is cued. Participants are instructed to click on the color value in a color wheel that matches the color from that location in the memory array. Beyond measuring whether an item is maintained in VWM, this task also provides a measure of the precision of representations in VWM based on the standard deviation of responses and can also reveal responses that are resulting from reporting non-target items or guesses (Emrich & Lockhart, 2017). In this way, the cued recall task provides a powerful and complementary tool to the CD task. One of the drawbacks of this task, which makes it challenging to use with children, is that a large number of trials is required in order to reliably estimate the precision and probability of correct reports (note that other work has adapted this task with a smaller array of options from which participants can choose; Simmering & Patterson, 2012).

One way to potentially obtain a more direct read out of VWM that may minimize task demands is to have children verbally report color responses. The literature on label learning for color features suggests that children master their color labels by age 3 as assessed in simple comprehension and production tasks (Sandhofer & Smith, 1999). Operating under this assumption of proficiency with the use of labels, the addition of the labeling aspect to our task should require minimal use of non-VWM resources. In other words, we would not expect labeling to have a negative impact on VWM performance in 4.5- and 5.5-year old children. Moreover, previous research has shown that using labels in visual attention and memory tasks improves performance. For example, when searching for a target feature hearing the relevant feature label decreases search time (Vales & Smith, 2014). Thus, having a target object labeled helps to enhance the encoding process and object representation in working memory (Vales & Smith, 2014). In this way, it could be that children's performance improves when responding with a verbal label rather than performing change detection. On the other hand, it is also possible that labelling items in VWM presents other unique challenges. Previous work on label learning have required children to label stimuli that are visually present. Requiring children to produce a label for what they hold in their WM after encoding the visual stimuli could be more difficult because VWM representations are weaker and more fragile than representations of stimuli that are being visually processed.

It is also important to consider the impact of verbal strategies on WM performance since one of our tasks will require a labeling response. There is evidence that the use of these strategies enhances WM performance. In one study, it was shown that 5-year-olds can make use of an articulatory loop during WM tasks, and its use varies based on the difficulty level of the task (Fatzer & Roberts, 2012). Furthermore, articulatory suppression during a cognitive control task impairs performance in adults (Cragg & Nation, 2010). For our purposes in this study, knowing beforehand that a feature label will be asked of them might make participants more likely to make use of some type of articulatory loop between the presentations of the memory array and recall portion of the task in order to help them remember the task-relevant information. In this case, we would expect higher levels of performance since children could use verbal processing to support performance.

Neural Basis of VWM

It has been previously shown that a frontoparietal network is activated during working memory tasks. A common neural signature seen during working memory tasks is an increase in activation as set size increases (Todd & Marois, 2004). Specifically, activation of intraparietal sulcus (IPS) increases in magnitude as the number of items in the memory increases, but activation asymptotes at the capacity of VWM around 3 or 4 items (Todd & Marois, 2004). Other research has revealed that the temporal parietal junction (TPJ), which has been implicated as a part of the ventral attention network which is the major network involved in stimulus-driven attention (Corbetta, Patel, & Shulman, 2008), shows suppressed activation over the delay phase of the change detection task (Todd & Marois, 2004; Ambrose, Wijeakumar, Buss, & Spencer, 2016). This suppression is proposed to prevent the visual system from reorienting attention to distracting stimuli (Corbetta, et. al., 2008) which could override the items being held in WM. This pattern of results has been interpreted to suggest that TPJ acts as an inhibitory filter that shows suppressed activation relative to the items being remembered (Todd, Fougnie, & Marois, 2005) (i.e. more suppression as set size increases).

A study dealing with domain-general (involved in working memory as a whole) and domain-specific (involved in certain types of working memory) brain regions involved in WM found evidence that posterior IPS is activated during visual information encoding (Li, Christ, & Cowan, 2014). Their findings also supported previous claims that posterior IPS is involved in VWM maintenance. Additionally, the comparison phase of VWM tasks has previously shown activation in the anterior cingulate cortex (ACC) (Mitchell & Cusack, 2008; Todd, Fougnie, & Marois, 2005). An EEG study looking at event related potentials found a temporal dissociation between the IPS and ACC during a VWM task. The IPS showed activation in the early stage of VWM (encoding and maintenance) while the ACC had later activation (during comparison) (Duma, Mento, Cutini, Sessa, & Baillet, 2019). This further exemplifies the frontoparietal network activation that is a staple of VWM. Another study used fMRI to measure activity when encoding and transforming visual stimuli in VWM and found evidence to suggest that the posterior parietal cortex is involved in encoding and maintaining information for VWM (Christophel, Cichy, Hebary, & Haynes, 2015).

In a more recent adult VWM study, researchers found that maintaining memory of features across different stimulus dimensions involves both distinct and overlapping brain regions in the frontal and parietal cortices (Yu & Shim, 2017). This study looked at both orientation features and color features, and while there was already evidence that frontoparietal regions played a role in memory maintenance of orientation features, Yu and colleagues found that color features were maintained in those areas as well. Relevant to the focus of this current study, their findings suggest that color feature maintenance is distinct in the inferior precentral sulcus, which has been linked to a broad visual-attention network through an analysis of functional connectivity using fMRI (Michalka, 2015). The inferior precentral sulcus also shows evidence of being involved in feature-location binding (Takahama & Saiki, 2014), which is a key component of successfully completing a VWM task like the change detection task.

Developmental research has identified changes in these neural networks as they relate to the development of VWM. A recent study used a version of the CD task adapted for use with infants to look at the neural signatures of VWM. The researchers used functional near-infrared spectroscopy (fNIRS) to measure neural activity and found that in early infancy the VWM network engages both frontal and posterior cortices (Reyes, Wijeakumar, Magnotta, Forbes, & Spencer, 2020). Additionally, while both hemispheres show activation, only activation in the left hemisphere correlated with behavioral scores of shift rate and total looking time, suggesting functional laterality of VWM in early years (Reyes, et al., 2020).

Another study measured fNIRS while 3- and 4-year-olds performed a shape change detection task (Buss, et al., 2014). They showed that left frontal and bilateral parietal regions were engaged during their shape change detection task. Additionally, whereas activation in adults asymptotes at the capacity limits, activation in children continues to increase beyond their behavioral capacity limits (Buss, et al., 2014). There seems to be some developmental difference underlying the disparity between the behavioral capacity limits of children's VWM and the neural activity observed when those limits have been surpassed.

Current Project

In this study we administered two VWM tasks to 4- and 5-year-olds. First, children performed the standard CD task. During the test array, a color was presented at a single location from the memory array and children indicated whether it was the same or different from the color presented at that location in the memory array. Next, children performed a cued recall task. During the test array, a black square was presented at a single location from the memory array and children responded verbally with a label for the remembered features. In both tasks, children were presented with 1, 2, or 3 items to remember. A total of 6 canonical colors were used and children were tested to ensure that they could produce the labels for these colors. We measured fNIRS from bilateral frontal, temporal, and parietal cortices to compare activation as the number of items to remember increased and as the response demands changed. By comparing activation between tasks, we can identify regions that are engaged in similar ways between task, identifying regions that may be involved in the WM demands of these tasks. We can also identify regions that are engaged in distinct ways between tasks that may be related to the type of response. Although research has not yet examined the neural basis of dimensional label learning, it is suggested that this process requires the formation of long-range connections between frontal and posterior cortices to form associations between labels and visual features (Buss & Spencer, 2018; Buss & Kerr-German, 2019). By directly comparing neural activation when children respond with labels against when children perform change detection it should be possible to elucidate the neural regions engaged for label production or change detection.

Methods

Participants

Participants were recruited through the Child Development Research Group database maintained at the University of Tennessee Knoxville. Eligibility was determined based on birthdate (+/- 4 weeks of target age group). We analyzed data from 20 four and a half-year-old children (7 female, M=54.5 months) and 18 five and a half-year-old children (12 female, M=66.4 months). Data were collected from 20 additional children (16 four-and-a-half and 4 five-and-a-half) that had to be dropped (8 due to technological issues with the tasks, 4 due to issues with neural data, 6 due to child refusal to complete the tasks, 1 due to parent refusal after consent was signed, and 1 due to inability to understand the rules of the tasks).

Stimuli

The stimuli for our tasks were generated with PsychToolbox3. Stimui were presented on a 27-inch (23.5 in. x 13 in) ViewSonic monitor with 1280 x 720 resolution. Both tasks used 50 x

50 pixel square shaped stimuli that were one of six canonical colors (red, orange, yellow, green, blue, or purple). The stimuli were presented on 430 x 490 pixel grey “cards” and appeared around a 150 pixel radius from the center of the card.

fNIRS Collection

During the experimental sessions, fNIRS data were collected from all participants using a Techen CW6 system. The probe used had 24-channels (8 sensors and 16 detectors) and measured from bilateral frontal, temporal, and parietal regions. The center point of the subject’s head was found by measuring from nasion to inion and then from right to left ear and locating the cross section of these two mid-points. Digitization of the probe alignment was done using a Polhemus system to mark nasion, right ear, left ear, center point, inion, sensors A-E, and detectors 1-16 in that order. The digitization was checked for accuracy using Homer2 AtlasViewerGUI in MATLAB.

Procedure

When the subjects arrived for their sessions, their parent(s) were given an informed consent statement, a demographic survey about the child, and a vocabulary survey. After the parent was walked through the details of the informed consent and provided their signature, the subject was seated in a highchair and fitted with the fNIRS cap. After digitization was complete and checked for any anomalies, the subject was turned to face the computer monitor, a video camera was set up to record the session, and the tasks began.

The experimental sessions consisted of two main tasks: change detection and cued recall. Tasks were administered in a fixed order to avoid priming effects of the label production aspect of the cued recall task. The first of the two main tasks is the change detection task (Figure 1).

This task used set sizes 1-3 of our canonical color stimuli. Participants went through six practice trials on physical cards, one for each condition (match/no match for set sizes 1-3). Physical cards were used in lieu of a computerized version for ease of repeating certain practice trials when needed for ensuring the participant fully grasped the rules of the task. The experimenter debriefed the participant after each practice trial to ensure the participant understood that the "match/no match" response was based on the spatial location of the color on the second card ("These two match/do not match because they are in the same spot and are the same/different color"). Each trial alternated between the left and right side of the screen to help ensure each trial was perceived as separate by the participants. The memory-array card appeared first for 0.5 seconds, followed by a delay of 1.5 seconds, with a test card appearing then until a response was given and entered by the experimenter. The test card showed a stimulus in the same location as the first generated color, and its color was either identical to that of the memory card or changed to a different color that was not present on the memory card. The participant was asked whether the color on the second card matched what was in that location on the first card, and the experimenter recorded their response using the keyboard (1=match, 2=no match, 3=do not know/was not paying attention). The experimenter would prompt the participant up to 3 times to respond to each trial. If no response was given, the response was coded as "do not know/was not paying attention." There was a total of 90 experimental trials in this task, 30 per set size. Within each set size there were 15 match trials and 15 no match trials. An algorithm for change trials was used to randomly assign which of the set of stimuli would change, and to which color it would be changing. If the trial was a change trial, the target object would change to a color that was not a part of the first array. Positions of the stimuli were also randomly assigned. Delay times between trials were jittered (2 second delay 50% of the time, 3 second delay 25% of the time, and 5 second delay 25% of the time).

Before moving on to the cued recall task, we administered a short color label test to determine whether the participant would be able to accurately complete the cued recall task. During this test the participant was shown a series of physical cards with enlarged versions of our canonical color stimuli. The participant was shown each color twice and was asked to produce the correct color label ("What color is this?"). Presentation of the colors were randomly ordered. Responses were kept track of by the experimenter, and if the child failed to correctly label two or more of the six colors for at least one of the two presentations, they did not proceed to the cued recall task. The only error we came across was in distinguishing between red and orange physical cards. When presented individually, 18 of the participants gave the wrong color label, however, when the two were presented side by side those participants were able to provide

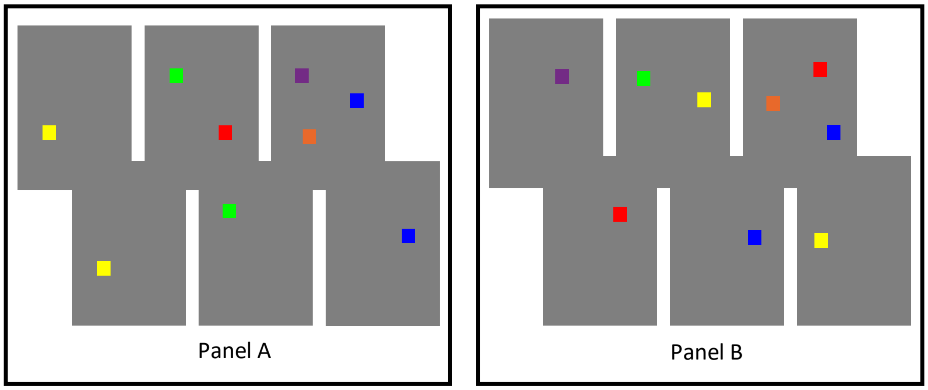

Figure 1

All Trial Types and Conditions Used in Change Detection Task the correct color label. We believe these errors were made due to printer quality altering the hue of the red and orange cards, and not due to lack of mastery of the color labels “red” and “orange.”

The final task was the cued recall task (Figure 2). We did not choose to administer physical practice trials for this task, instead giving the following verbal instructions: “The next game we are going to play is a little different from the first game. You are still going to see two cards, one at a time. You will still see colors on the first card, but now on the second card there will be a box where one of those colors was. It’s your job to remember and tell me the color that was on the first card wherever that box shows up.” Similar to the change detection task, set sizes 1-3 were tested using the same canonical color stimuli. All trials in this task were presented in the middle of the screen. The memory card first appeared for 0.5 seconds, followed by a delay with a blank screen for 1.5 seconds, with the test card appearing last. The test card showed a blank box in the spatial location of one of the stimuli from the trial card. Participants were asked to tell the experimenter what color was present on the first card in the place where the box appeared on the second card. The responses were recorded by the experimenter using the keyboard with the option to record a response for “I don’t know”. There were a total of 54 experimental trials in this task (18 per set size with each color probed an equal number of times). Colors and positions of the stimuli were randomly assigned in the same way they were in the change detection task. Delay times between trials were jittered in the same way they were during the change detection task.

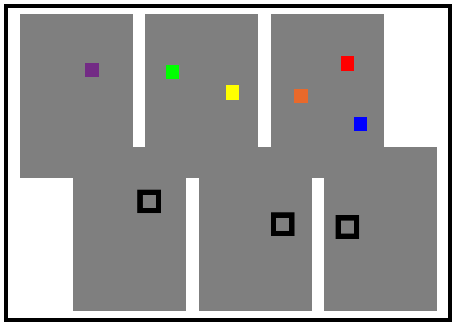

Figure 2

All Trial Types Used in Cued Recall Task

Results

Behavioral Results

For behavioral results of the CD task data, a 2x3x2 repeated measures ANOVA was conducted to compare accuracy as a function of age, set size, and trial type (Figure 3). There was a main effect of set size, $F(2, 618) = 85.37$, $p < .001$. Follow-up t-tests showed accuracy decreased across all increases in set sizes ($p < .01$). There was also a main effect of trial type (match/no-match), $F(1, 619) = 98.42$, $p < .001$. Follow-up t-tests showed accuracy during no-match trials was significantly better than accuracy during match trials ($p < .001$). There was a main effect of age, $F(1, 619) = 107.58$, $p < .001$. The 5-year-old group had significantly higher accuracy scores than the 4-year-old group ($p < .001$). There were interactions between set size and age, $F(2, 618) = 3.86$, $p = .021$, with 5-year-olds performing better that 4-year-olds on all set sizes. Between trial type and age we found significant differences between age on same trials, but not different trials, $F(1, 619) = 9.11$, $p = .003$. Finally, the interaction between set size and trial type showed a stronger drop in performance during same trials when compared to different trials as set size increased, *F*(2, 618) = 20.32, *p* < .001.

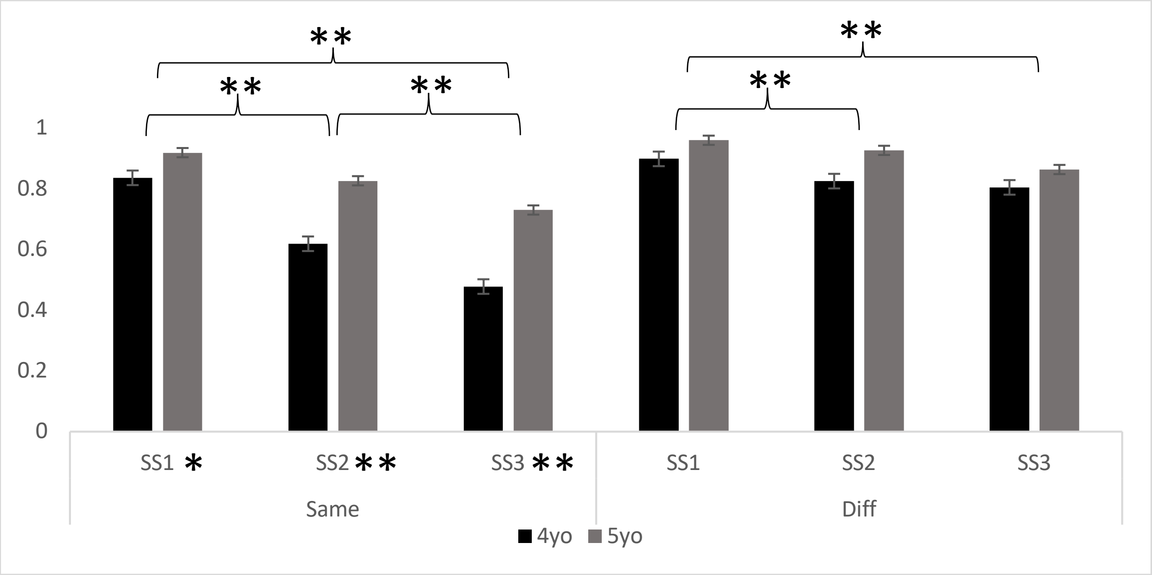

Figure 3

Average Accuracy Scores for Change Detection Task

*Note. *p<0.05, **p<0.01*

Each participant's raw scores were averaged for hits, false alarms, correct rejections, and misses for each set size. Those averages for hits and false alarms were used to compute capacity (Cowan's k, modified from Pashler's k for a single item probe task (Cowan, Fristoe, Elliott, Brunner, & Saults, 2006)) for each participant and then those capacities were averaged within each age group. The max value capacity for the CD task in the four-year-old group was k=2.12 items, and for the five-year-old group was k=2.36 items. An independent samples t-test was run to compare the capacity of the two age groups with no significant differences found, *t*(36) = -

0.88, $p = .384$. The estimated capacity of four- and five-year-old children were not different in the CD task.

For behavioral analyses of the CR task data, a 2x3 repeated measures ANOVA was conducted to compare accuracy as a function of set size and age (Figure 4). There was a main effect of set size, $F(2, 711) = 131.19$, $p < .001$. Follow-up t-tests showed accuracy decreasing across all increases in set size ($p < .001$). There was also a main effect of age, $F(1, 712) = 114.76$, $p < .001$. Follow-up t-tests showed significantly higher accuracy scores in the 5-year-old group compared to the 4-year-old group ($p < .001$). Finally, there was an interaction between age and set size, $F(2, 711) = 9.07$, $p < .001$, with both age groups showing decreased accuracy at each increase in set size, and with 4-year-old children exhibiting this trend more robustly than 5-year-old children.

We analyzed the proportion of responses made that were “I don’t know.” This response made up 15% of the total responses for 4-year-olds and 7.4% for 5-year-olds. The proportion of incorrect responses that did not match any of the options from the memory array was also calculated for each age group. For 4-year-olds, 38.2% of their incorrect responses were a color that was not present in the memory array. For 5-year-olds, 55.3% of incorrect responses were a color not present in the memory array. It should be noted that only 15 of the 20 four-year-olds had data regarding the colors that were present in the memory array, so this percentage does not account for all of that age group.

Each participant’s raw scores were averaged to a proportion correct for each set size. Those averages were used to compute capacity (a modified Cowan’s k) for each participant and then those capacities were averaged within each age group. Using the logic that in a task with C

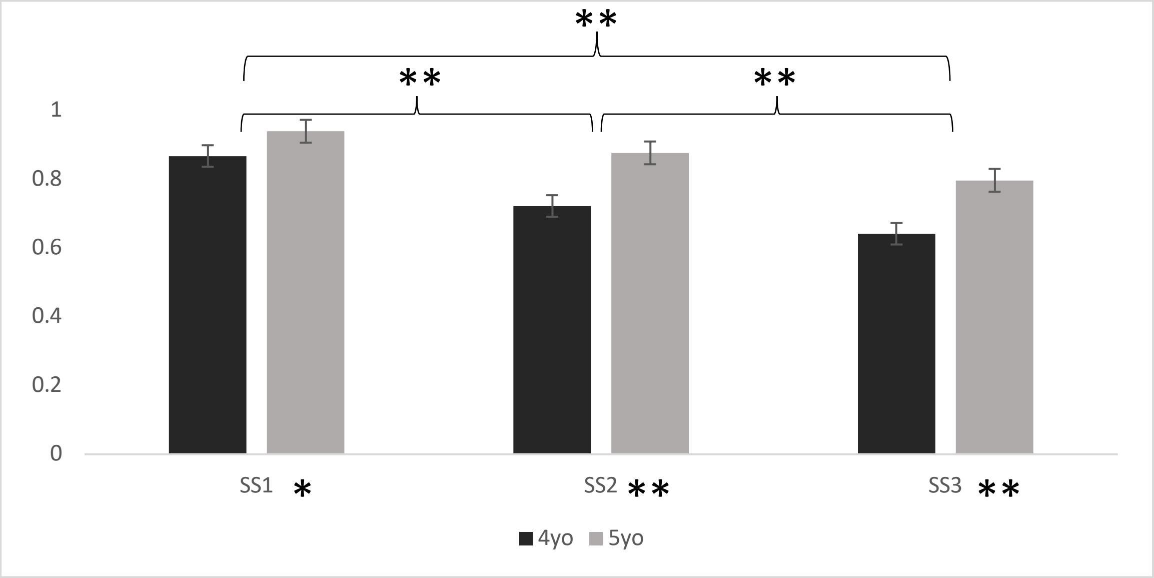

Figure 4

Average Accuracy Scores for Cued Recall Task

*Note. *p<0.01, **p<0.001*

colors to choose from and an array of N colors, you have (k/N)+(1-(k/N))(1/(C-k)) probability of guessing the correct response when you do not know the answer. From this we derived a polynomial equation to solve for K or capacity. In the equation below s is the set size and h is a matrix containing the hit-rate for each participant at each set size.

k=(c-1+h*n-sqrt(c^2-2*c-2*c*h*n+1-2*h*n+h^2*n^2+4*n))/2

The maximum capacity for the CR task in the four-year-old group was k=1.18 items, and for the five-year-old group was k=1.84 items. An independent samples t-test was run to compare capacity of the two age groups, $t(36) = 4.59$, $p < 0.001$. The estimated capacity of 5-year-olds was significantly higher than that of 4-year-olds in the CR task.

The capacity estimates for CD and CR for each age group were compared using paired samples t-tests. The difference between CD capacity and CR capacity was significant for the 4-year-old group, $t(19) = 4.12$, $p = 0.001$, and for the 5-year-old group, $t(17) = 3.59$, $p = 0.002$. The capacities for CD were significantly greater than those for CR in both age groups.

When correlating between individual capacity and change in neural activation between set sizes, we found three significant correlations in the CR task. There was a moderate positive correlation between capacity in cued recall and difference in activation between SS1 and SS2, $r(36) = 0.375$, $p = 0.02$, as well as between capacity and the difference in activation between SS1 and SS3, $r(36) = 0.448$, $p = 0.005$, with an increase in activation as capacity increased. When broken down by age, we found that there was a moderate correlation in the 5-year-old group between capacity and the difference between activation in SS2 and SS3, $r(16) = 0.492$, $p = 0.038$, again with an increase in activation as capacity increased.

Image Based Analysis Results

The fNIRS data collected from each participant was run through a series of imaged based analyses. The raw data were preprocessed using EasyNIRS where they were converted to optical density and motion artifacts were filtered out using Wavelet (iqr = 0.5). Data was then converted to concentration values using modified Beer-Lambert equations (dpf=ppf=6.0). Finally, average HbO and HbR values were calculated within a 4-6 second time window for each task. Volumes for each participant were constructed using their head volume along with Colin’s atlas to create a brain surface model. The activation values from the preprocessing stage were projected into that model and a group activation mask was created using voxels in which all subjects contributed data. Individual interaction masks were created from the full mask and clusters containing a grouping of a certain number of voxels that touched at their edges were found within each interaction mask. This number of voxels needed to make a significant cluster was determined using 3dMVM and 3dClustSim with a p-value of 0.001 and familywise error correction α of 0.01.

The nature of the interactions is characterized by the relationship between HbO and HbR values. We characterized neural activation as a significant difference between the increase in HbO and decrease in HbR. We can also see deactivation, which is characterized by a significant difference in HbO and HbR where HbO is significantly lower than HbR ($p < .001$).

Post-hoc t-tests were conducted to find significant differences ($p < .001$) between HbO and HbR at each level of each variable. Difference values between HbO and HbR were calculated for each level of set size and t-tests were conducted for any interaction involving set size in order to determine the exact differences between levels which were driving the interaction. Bonferroni-Holm adjustments were made after these t-tests to account for multiple tests being run ($p < 0.0003$).

Change Detection ANOVA Activation during the change detection task was analyzed with a 2 (Oxy: HbO, HbR) x 2 (Response: same, different) x 3 (set size (SS): 1, 2, 3) x 2 (Age: 4.5-, 5.5-year-old) ANOVA with Oxy, Response, and SS as within-subjects variables, and Age as the between-subjects variable. Only neural data for trials with correct responses (hits and correct rejections) was analyzed. The minimum voxel level required for significant clusters within this ANOVA was determined to be 51 voxels. A total of 7 interactions with Oxy as a covariate, as well as an overall Oxy effect, contained one or more significant clusters of neural activation. Table 1 shows the full pattern of results from follow-up tests for each cluster.

There were five clusters in which there was an overall Oxy effect. Four of these clusters showed significant neural activation (left angular gyrus, right superior temporal gyrus, right superior occipital gyrus, and right inferior frontal gyrus-p. triangularis). One of these clusters showed deactivation (right inferior frontal gyrus-p. opercularis).

Six clusters showed an interaction between Oxy and Age. Five of these clusters (left inferior parietal lobule, right middle occipital gyrus, left middle frontal gyrus, right superior temporal gyrus, and right postcentral gyrus) showed significant activation in the 5.5-year-old group. The remaining cluster (right inferior frontal gyrus-p. opercularis), showed deactivation in the 5.5-year-old group. (See Figures A1 & A2).

The interaction between Oxy and SS was significant in five clusters. After Bonferroni adjustments were conducted, only one cluster showed significant differences between the levels of SS. In left middle frontal gyrus, there was significant activation during SS3, and this activation was significantly greater than that of SS1. (See Figures A3 & A4).

The interaction between Oxy and Response was significant in five clusters. Three of these clusters (left inferior parietal lobule, right postcentral gyrus, and right middle occipital gyrus) showed significant activation for same responses and deactivation for different responses. The other two clusters (left angular gyrus and left inferior frontal gyrus-p. triangularis) showed significant activation for different responses only. (See Figures A5 & A6).

There were eight clusters found for the interaction among Oxy, Age, and SS. Seven of these eight passed the Bonferroni-Holm adjustment. All significant Oxy by SS changes occurred in the 5.5-year-old group. Two clusters showed increased activation on SS3 (left inferior parietal lobule and left middle frontal gyrus). Three clusters showed increased activation on SS2 (right middle temporal gyrus, right postcentral gyrus, and right middle occipital gyrus). Lastly, two clusters (bilateral inferior frontal gyrus-p. opercularis) showed deactivation. (See Figures A7 & A8).

The interaction among Oxy, Age, and Response had four significant clusters. Again, all significant changes occurred in the 5.5-year-old group. Two clusters (left inferior parietal lobule and right post central gyrus) showed activation for same responses and deactivation for different responses. Two clusters (left middle occipital gyrus and left middle frontal gyrus) showed activation for different responses. (See Figures A9 & A10).

The interaction among Oxy, Response, and SS was significant in six clusters, four of which passed the Bonferroni adjustment. Two cluster showed increases in activation over SS for same trials (left superior parietal lobule and right middle occipital). Another cluster showed increases in activation over SS for different trials (left middle frontal gyrus). Finally, one cluster (right superior temporal) showed increased activation on SS2 and 3 for same trials and increased activation on SS3 for different trials. (See Figures A11 & A12).

Four clusters showed a significant four-way interaction among Oxy, Age, SS, and Response. All significant changes occurred in the 5.5-year-old group. One cluster (left superior parietal lobule) showed increased activation at SS2 for same responses but increased deactivation at SS2 for different responses. One cluster (left middle frontal gyrus) showed increased activation at SS2 for same responses as well as increased activation at SS3 for different responses. One cluster (right superior temporal gyrus) showed increased activation at SS2 and SS3 for same responses. Finally, one cluster (right inferior frontal gyrus-p. opercularis) showed increased deactivation at SS2 for same responses and increased deactivation at SS3 for different responses. (See Figures A13 & A14).

Table 1

Significant Clusters from the Change Detection ANOVA

Effect	Voxels	MNI Coordinates			Location	Trend
		(x)	(y)	(z)		
OXY	3246	37.4	67.2	43.1	Left Angular Gyrus	HbO > HbR
	1601	-63.6	39	19.3	Right Superior Temporal Gyrus	HbO > HbR
	980	-30.6	79.1	42.4	Right Superior Occipital Gyrus	HbO > HbR
	471	-60.4	-12.8	7.7	Right Inferior Frontal Gyrus (p. Opercularis)	HbR > HbO
	158	-57.3	-28.7	22.6	Right Inferior Frontal Gyrus (p. Triangularis)	HbO > HbR
OXYxAGE	2519	36.7	61.6	50.3	Left Inferior Parietal Lobule	5yo > 4yo
	632	-60.2	-14	8.6	Right Inferior Frontal Gyrus (p. Opercularis)	4yo > 5yo
	528	-39.3	79.1	34.2	Right Middle Occipital Gyrus	5yo > 4yo
	427	42.8	-28.4	32	Left Middle Frontal Gyrus	5yo > 4yo
	293	-64.8	30.9	17.3	Right Superior Temporal Gyrus	5yo > 4yo
	231	-63.6	0.8	27	Right Postcentral Gyrus	5yo > 4yo
OXYxSS	1819	44	-18.5	39.4	Left Middle Frontal Gyrus	SS3 > SS1
OXYxSD	2600	35.3	61.1	54.4	Left Inferior Parietal Lobule	Same > Diff
	1090	43.3	71.1	29.4	Left Angular Gyrus	Diff > Same
	770	-63.5	3.1	22.6	Right Postcentral Gyrus	Same > Diff
	651	42.8	-33.9	27.1	Left Inferior Frontal Gyrus (p. Triangularis)	Diff > Same
	434	-46.4	75.3	30.1	Right Middle Occipital Gyrus	Same > Diff
OXYxAGExSS	2439	34.5	59.3	56.1	Left Inferior Parietal Lobule	SS3 > SS1^
	493	-64.3	45.4	8.1	Right Middle Temporal Gyrus	SS2 > SS3^
	490	-60.7	-13.4	8.2	Right Inferior Frontal Gyrus (p. Opercularis)	SS3 > SS1&2^
	472	55.6	-12.3	23.3	Left Inferior Frontal Gyrus (p. Opercularis)	SS2&3 > SS1^
	419	-63.3	0.7	23.3	Right Postcentral Gyrus	SS2&3 > SS1^
	326	33.4	-26.7	47.6	Left Middle Frontal Gyrus	SS2&3 > SS1^
	154	-45.2	78.7	29.8	Right Middle Occipital Gyrus	SS2&3 > SS1^
OXYxAGExSD	2239	35.6	60.8	54.9	Left Inferior Parietal Lobule	Same > Diff^
	818	40.8	73.1	31.4	Left Middle Occipital Gyrus	Diff > Same^
	615	40.4	-36.7	29	Left Middle Frontal Gyrus	Diff > Same^
	540	-62.1	-0.9	18.5	Right Postcentral Gyrus	Same > Diff^
OXYxSDxSS	2482	32.5	60.6	58.6	Left Superior Parietal Lobule	**Same**: SS2>SS3>SS1
	2368	44.5	-23.3	33.4	Left Middle Frontal Gyrus	**Diff**: SS3>SS1&SS2
	1547	-63.9	31	19.9	Right Superior Temporal Gyrus	**Same**: SS2&SS3>SS1, **Diff**: SS3>SS2
	149	-38.6	83.8	32.8	Right Middle Occipital Gyrus	**Same**: SS3>SS1
OXYxAGExSDxSS	2874	32.8	61	57.1	Left Superior Parietal Lobule	**Same^**: SS2&3 > SS1, **Diff^**: SS1&3 > SS2
	1749	42.7	-28.9	32.2	Left Middle Frontal Gyrus	**Same^**: SS2 > SS1, **Diff^**: SS1&3 > SS2
	1624	-63.6	34.5	19.9	Right Superior Temporal Gyrus	**Same^**: SS2&3 > SS1, **Diff^**: SS2&3 > SS1
	1158	-60.2	-13	13.7	Right Inferior Frontal Gyrus (p. Opercularis)	**Same^**: SS1&2 > SS3, **Diff^**: SS1&2 > SS3

Note. ^ indicates interaction occurred in 5-year-old group

Cued Recall ANOVA The cued recall ANOVA was a 2 (Oxy: HbO, HbR) x 3 (SS: 1, 2, 3) x 2 (Age: 4.5-, 5.5-year-old) ANOVA with Oxy and SS as within-subjects variables, and Age as the between-subjects variable. Only neural data for trials with correct responses (correct color label of the cued object) were analyzed. The minimum voxel level required for significant clusters within this ANOVA was determined to be 51 voxels. A total of 3 interactions with Oxy as a covariate, as well as an overall Oxy effect, contained one or more significant clusters of neural activation. Table 2 shows the full pattern of results from follow-up tests for each cluster.

There were four clusters (left inferior parietal lobule (2 clusters), left inferior frontal gyrus-p. opercularis, and right Rolandic operculum) in which there was an overall Oxy effect. Two clusters (both left inferior parietal lobule) showed significant neural activation, and two clusters (left inferior frontal gyrus-p. opercularis and right Rolandic operculum) showed deactivation.

There were two clusters in which there was an interaction between Oxy and Age (left inferior frontal gyrus-p. opercularis and right superior temporal gyrus). One cluster (left inferior frontal gyrus-p. opercularis) showed significant deactivation in the 5.5-year-old group. The other cluster (right superior temporal gyrus) showed activation in the 4.5-year-old group and deactivation in the 5.5-year-old group. (See Figures A15 & A16).

There was one cluster (right middle temporal gyrus) in which there was an interaction between Oxy and SS. This cluster showed increased activation for SS2. (See Figures A17 & A18). Finally, there was one cluster (right middle occipital gyrus) in which there was an interaction among Oxy, Age, and SS. This cluster showed overall deactivation for SS3 in the 5.5-year-old group. (See Figures A19 & A20).

Table 2

Significant Clusters from the Cued Recall ANOVA

Effect	Voxels	MNI Coordinates (x)	(y)	(z)	Location	Trend
OXY	362	56.6	38.8	38.5	Left Inferior Parietal Lobule	HbO > HbR
	343	35.6	65.1	51.2	Left Inferior Parietal Lobule	HbO > HbR
	279	55.3	-12.4	29	Left Inferior Frontal Gyrus (p. Opercularis)	HbR > HbO
	191	-61.7	-10.4	6.4	Right Rolandic Operculum	HbR > HbO
OXYxAGE	1218	55.4	-10.6	22.7	Left Inferior Frontal Gyrus (p. Opercularis)	4yo > 5yo
	923	-65.9	25.1	15	Right Superior Temporal Gyrus	4yo > 5yo
OXYxSS	428	-65.6	47	5.1	Right Middle Temporal Gyrus	SS2 > SS1
OXYxAGExSS	239	-37.1	80.3	35.5	Right Middle Occipital Gyrus	SS1&2 > SS3^

Note. ^ indicates interaction occurred in 5-year-old group

Full ANOVA The full ANOVA was a 2 (Oxy: HbO, HbR) x 2 (Task: CD, CR) x 3 (SS: 1, 2, 3) x 2 (Age: 4.5-, 5.5-year-old) ANOVA with Oxy, Task, and SS as within-subjects variables, and Age as the between-subjects variable. Only neural data for trials with correct responses (hits and correct rejections for CD, correct color label for CR) was analyzed. The minimum voxel level required for significant clusters within this ANOVA was determined to be 47 voxels. For the purposes of our study, we are only going to focus on interactions that included both Oxy and Task as covariates, as we are interested in the differences in activation between our two tasks. A total of 3 interactions with Oxy and Task as covariates, as well as an overall Oxy effect, contained one or more significant clusters of neural activation. Table 3 shows the full pattern of results from the follow-up tests.

There were two clusters (left supramarginal gyrus and left superior parietal lobule) in which there was an overall Oxy effect. One cluster (left inferior frontal gyrus) showed an interaction between Oxy and Task. There was significant deactivation in this region during the cued recall task. (See Figures A21 & A22). Two clusters showed an interaction among Oxy, Age, and Task. The first was located in the left inferior frontal gyrus and was driven by significant deactivation during the cued recall task in the 5.5-year-old group. The second cluster was in the right superior temporal gyrus and was driven by significant activation during the cued recall task for the 4.5-year-old group, along with significant deactivation during the cued recall task for the 5.5-year-old group. (See Figures A23 & A24). One cluster (right middle temporal gyrus) showed an interaction among Oxy, SS, and Task. During the cued recall task, SS2 activation was stronger than SS1 activation. (See Figures A25 & A26).

Table 3

Significant Clusters from the Full ANOVA

Effect	Voxels	MNI Coordinates			Location	Trend
		(x)	(y)	(z)		
OXY	215	55.7	36.7	36.7	Left SupraMarginal Gyrus	HbO > HbR
	141	32.3	67.1	51.8	Left Superior Parietal Lobule	HbO > HbR
OXYxTASK	272	55.6	-12.2	27.2	Left Inferior Frontal Gyrus (p. Opercularis)	CD > CR
OXYxAGExTASK	936	55.7	-10.5	22.1	Left Inferior Frontal Gyrus (p. Opercularis)	CD > CR^^
	565	-66.6	29	14.3	Right Superior Temporal Gyrus	CR > CD^; CD > CR^^
OXYxSSxTASK	189	-66.6	48.7	1.6	Right Middle Temporal Gyrus	**SS2:** CR > CD

Note. ^ indicates interaction occurred in 4-year-old group, ^^ indicates interaction occurred in 5-year-old group

Discussion

In this study, we administered two versions of a VWM task to 4.5- and 5.5-year-old children. These tasks were identical except for the type of response performed by participants. In the CD task, children compared a visually presented color with an item in VWM. In the CR task, children provided a label of a color from VWM. The general hypothesis going into this study was that modifying the task response by asking children to provide a label would reduce the task demands and result in increased VWM performance. Somewhat surprisingly, we found the opposite: This modification actually impaired performance on the VWM task. Specifically, children had significantly lower percent correct and capacity estimates on the CR task compared to the CD task. The 4.5-year-old group showed average capacity estimates for CD and CR of 2.12 items and 1.18 items respectively, while the 5.5-year-old group had capacity estimates of 2.36 items and 1.84 items respectively.

In terms of the fNIRS data, we first examined neural activation in the CD task. We observed a distinct network of regions that were engaged on same trials compared to different trials. Left inferior and superior parietal, right superior temporal, right middle occipital, and right post central regions all showed activation on same trials that interacted with Age or set size. In contrast, responses on different trials had activation in right inferior frontal (pars triangularis) and left angular gyrus for all children. Left middle occipital showed activation during different trials that interacted with Age, while left middle frontal gyrus was activated on different trials that interacted with both Age and SS. In particular, we see these activation patterns in the 5-year-old group, but not the 4-year-old group, suggesting that this is a network that develops with age to more accurately track changes in our environment. The activation patterns we see in middle and inferior frontal gyrus are consistent with previous fMRI research regarding neural activity during a change detection task with adults (Pessoa & Ungerleider, 2004). Other regions appeared to track task difficulty. That is, performance tended to be better on different trials compared to same trials, suggesting that change trials were easier for children. In line with this, we observed maximal neural responses in left middle frontal and right middle temporal regions on same trials at SS2 and different trials at SS3.

Next, we examined activation on the CR task. Similar to the CD task, right middle temporal regions showed maximal activation at SS2, suggesting that this region activated in response to task difficulty. We also observed effects of Age in which younger children showed stronger activation than older children in both left inferior frontal and right superior temporal regions. Comparing activation between tasks, we observed developmental reductions in activation during the CR task in left inferior frontal cortex and right superior temporal cortex. In particular, 4-year-old children showed strong activation during the CR task, but 5-year-olds showed deactivation during the CR task in right superior temporal cortex. This suggests that the younger age group is needing to use a greater amount of neural resources to complete the task, implying a greater difficulty for them in the CR task compared to the CD task.

The differences we see in both behavioral and neural data between the two tasks leaves some questions regarding the underlying factors that could be impacting the children's VWM performance so heavily in the CR task. One possibility is that the addition of the labeling aspect made the task inherently something other than a visual working memory task – such as a verbal working memory task. However, we believe that our methods kept this task in the realm of visual working memory, as all aspects prior to the response portion were kept the same as the CD task. The stimuli were encoded and maintained as visual stimuli, not verbal or auditory stimuli. It was only after the recall portion that the participants had to assign a label to what they held in their VWM. We can also refer to studies that are directly measuring verbal working memory and see that children in our age range normally exhibit anywhere from 3-4.5 word capacity when performing a verbal working memory task dealing with word recall (Simmering & Perone, 2013). These estimates are higher than ours in the CR task of 1.2-1.8 items, which would suggest that the children in our study were not verbally encoding our stimuli. This may also indicate that children have difficulty encoding a visually presented stimulus into a verbal format.

The most parsimonious explanation for the disparity between the CD and CR performance would be that, while children in this age range have a mastery of object labels, they have not yet reached adult levels of VWM. Although children have little trouble labeling a visually presented stimulus, the dynamics involved in the CR task may be fundamentally different. That is, fragile representations of labels in combination with fragile VWM representations may make the CR task particularly difficult. Future research should examine a wider age range in childhood (up to 9 years old, when adult levels of VWM performance are reached) and track the developmental differences in task performance. A comparison study with children and adults could also be performed to see if eventually performance between the two tasks evens out or if there is always a slight disadvantage to having to label an object in working memory rather than simply comparing it with a new object.

Previous neuroimaging studies have highlighted common neural trends that we see during VWM tasks. In adults, we see a rise in parietal activation as set size increases and then an asymptote when capacity limits are exceeded by set size (Todd & Marois, 2004). In contrast, children do not exhibit this asymptote at capacity and continue to show increases in activation with increases in set size. What we see in our data is largely consistent with this phenomenon. While behaviorally the children are showing around a 2.5 item capacity in the CD task and less than 2 item capacity in the CR task, parietal regions that interact with set size are showing increased activation at SS2 and SS3. This finding is also consistent with parietal activation seen in another fNIRS study on VWM (Buss, et al., 2014) with robust activation at the highest set sizes despite lower capacity estimates. When we break our results down further, we see that the 5-year-old group is the group exhibiting this trend, suggesting that they have not yet reached adult levels of VWM performance, both from a behavioral and neural standpoint. This is in line with studies that suggest that children do not reach adult levels of performance until age 9 (Cowan, et al., 2005).

This study was not without its limitations. Sample size was lower than originally anticipated due to technological issues and the extenuating circumstances of COVID-19. Replication of this study with a larger sample size (at least 30 in each age group) would be preferable to ensure that the trends we are seeing hold strong. Although we do not believe the labeling aspect diminished the integrity of the VWM task, this study only taps into two response types for a VWM task. It would be interesting to conduct a study with a third response type added, such as a different modification to the traditional cued recall task with the six color choices presented in lieu of a full color wheel or memory array.

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Appendix A

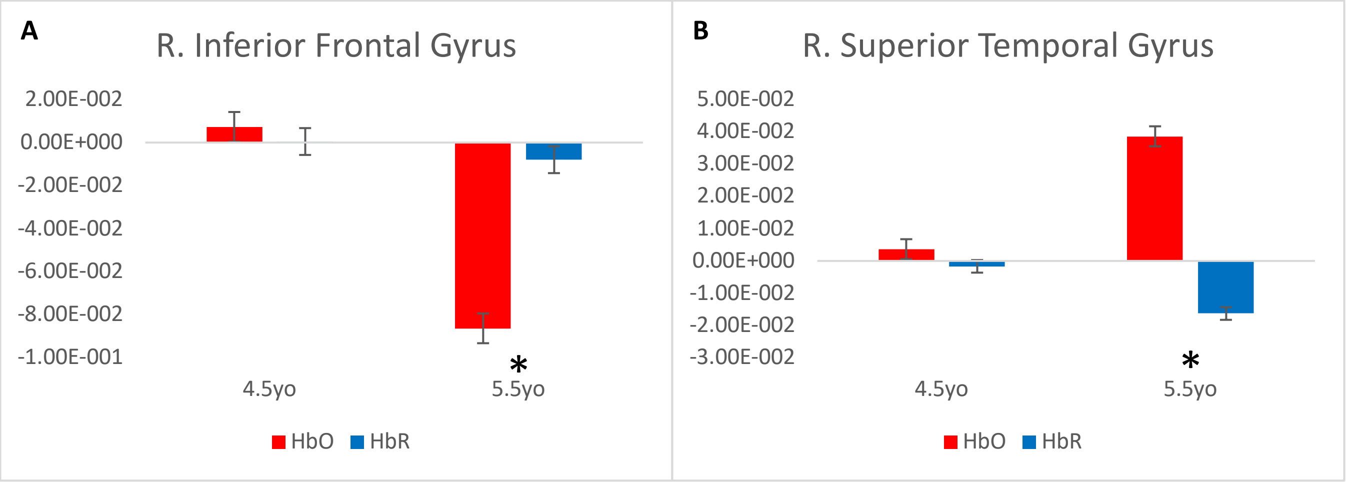

Figure A1

Bar Charts for Change Detection Oxy x Age Effect

Note. *$*p<0.001$*

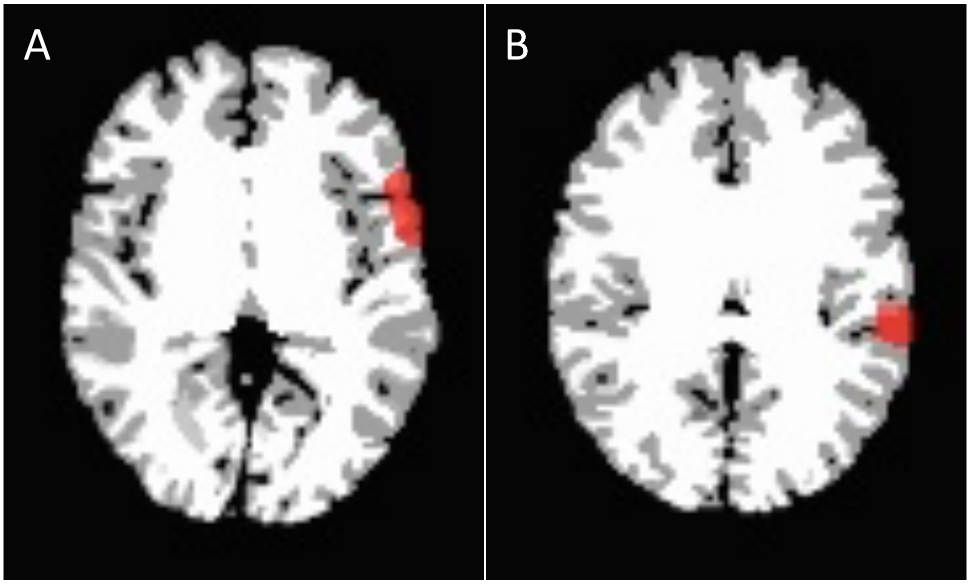

Figure A2

Brain Image for Change Detection Oxy x Age Effect

Note. Letter labels correspond to cluster panels on matching bar charts.

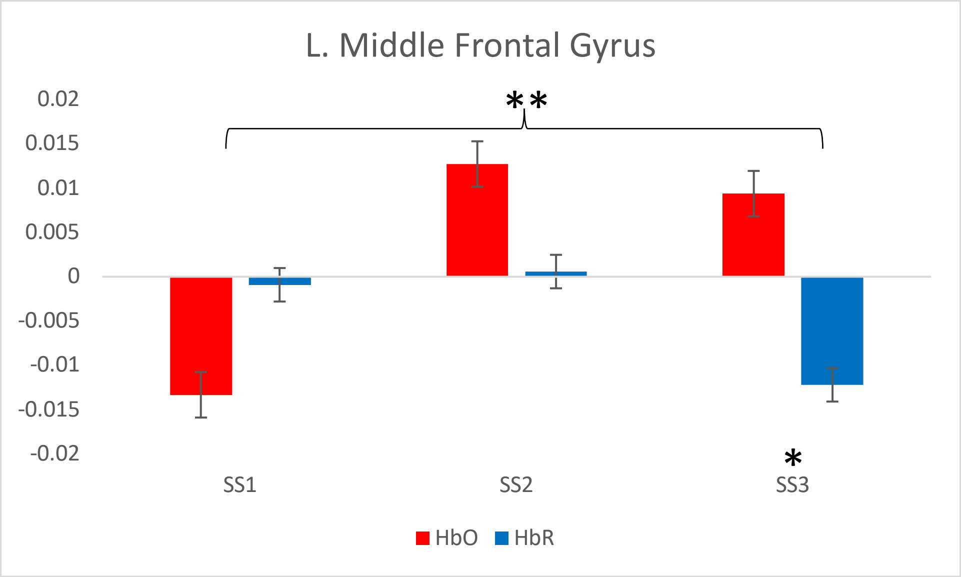

Figure A3

Bar Chart for Change Detection Oxy x SS Effect

Note. *$p<0.001$, **$p<0.0003$

Figure A4

Brain Image for Change Detection Oxy x SS Effect

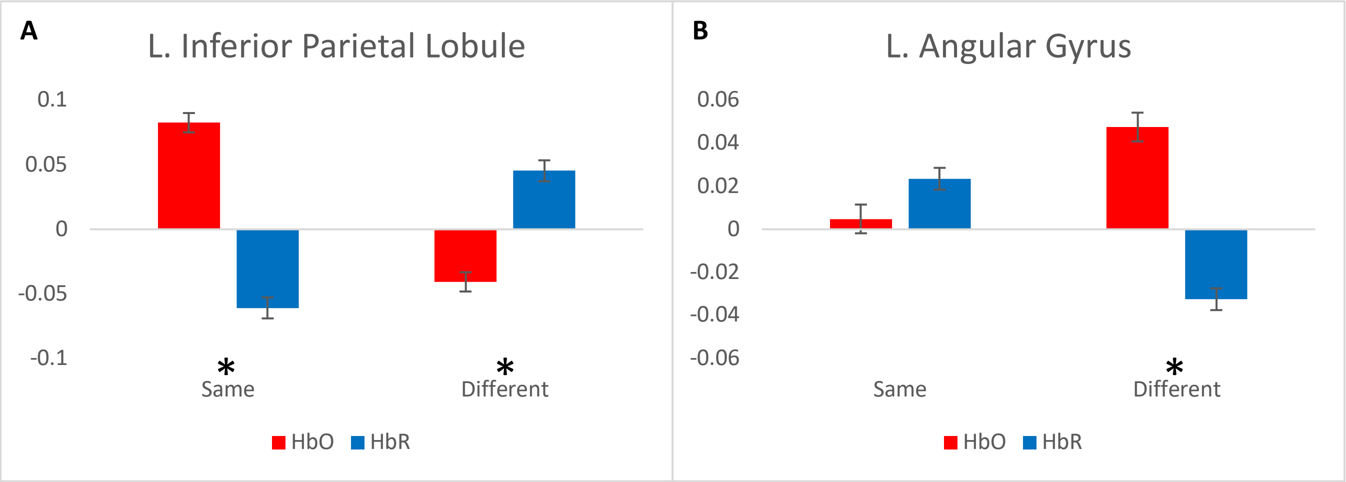

Figure A5

Bar Charts for Change Detection Oxy x Response (SD) Effect

Note. *$*p<0.001$*

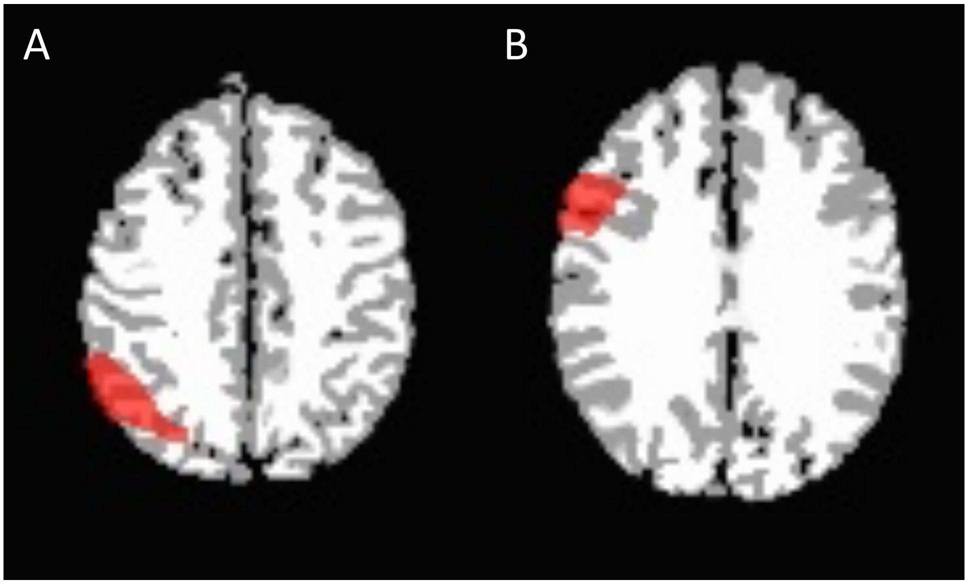

Figure A6

Brain Image for Change Detection Oxy x Response (SD) Effect

Note. Letter labels correspond to cluster panels on matching bar charts.

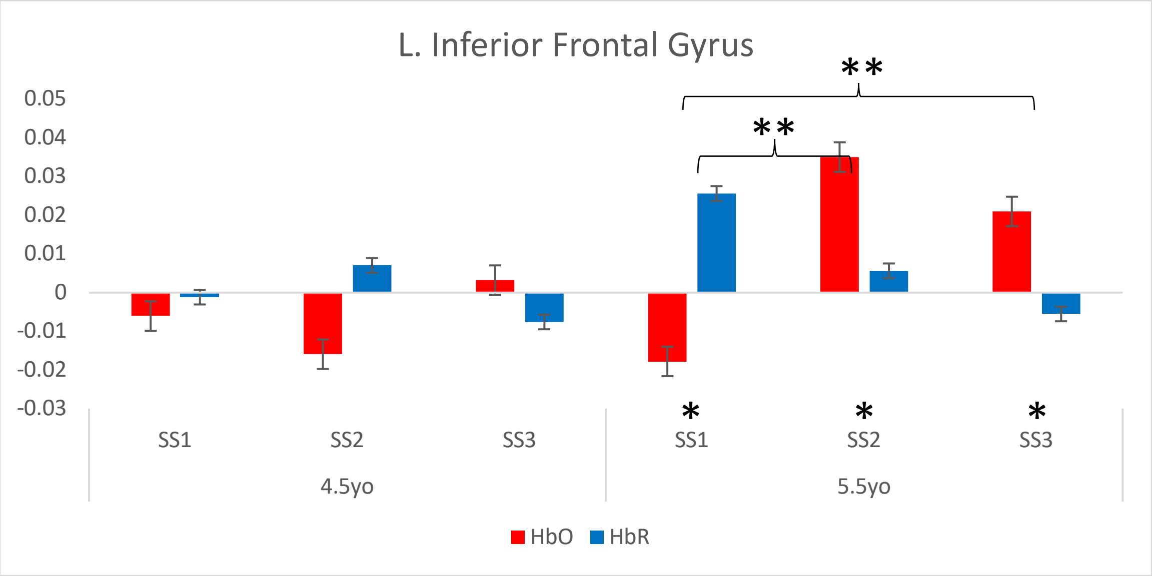

Figure A7

Bar Chart for Change Detection Oxy x Age x SS Effect

*Note. *p<0.001, **p<0.0003*

Figure A8

Brain Image for Change Detection Oxy x Age x SS Effect

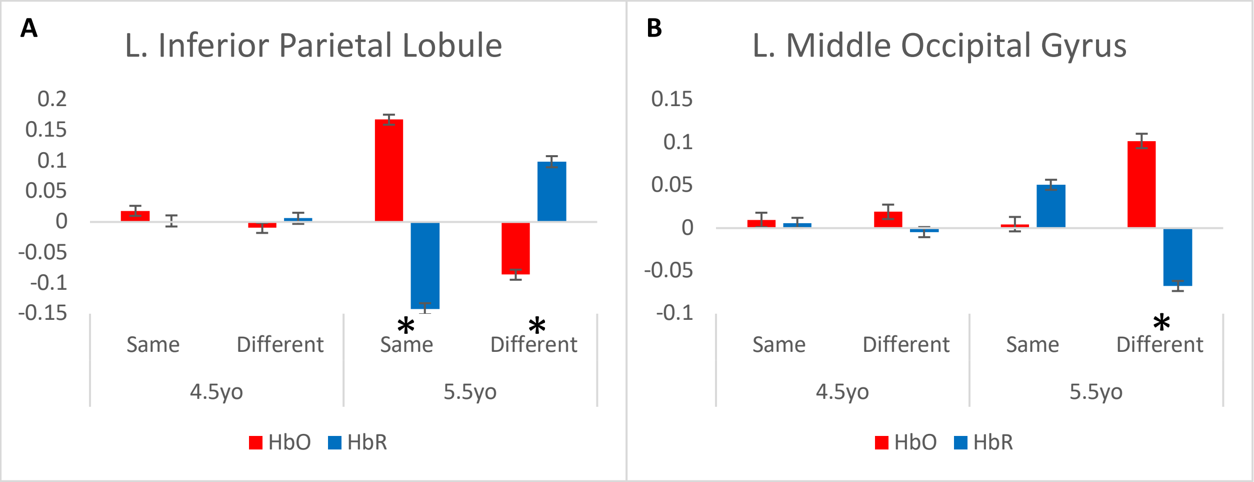

Figure A9

Bar Chart for Change Detection Oxy x Age x Response (SD) Effect

Note. * $p<0.001$

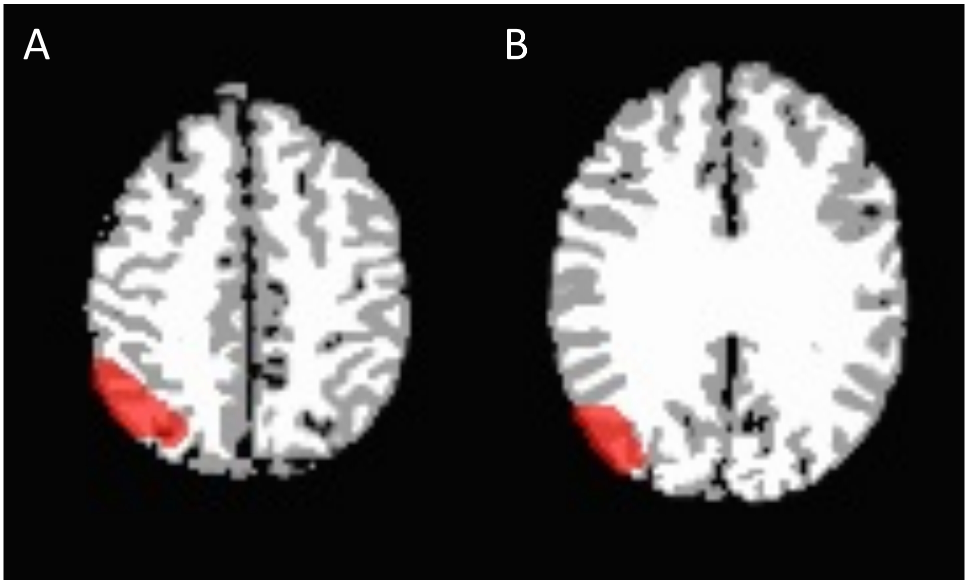

Figure A10

Brain Image for Change Detection Oxy x Age x Response (SD) Effect

Note. Letter labels correspond to cluster panels on matching bar chart.

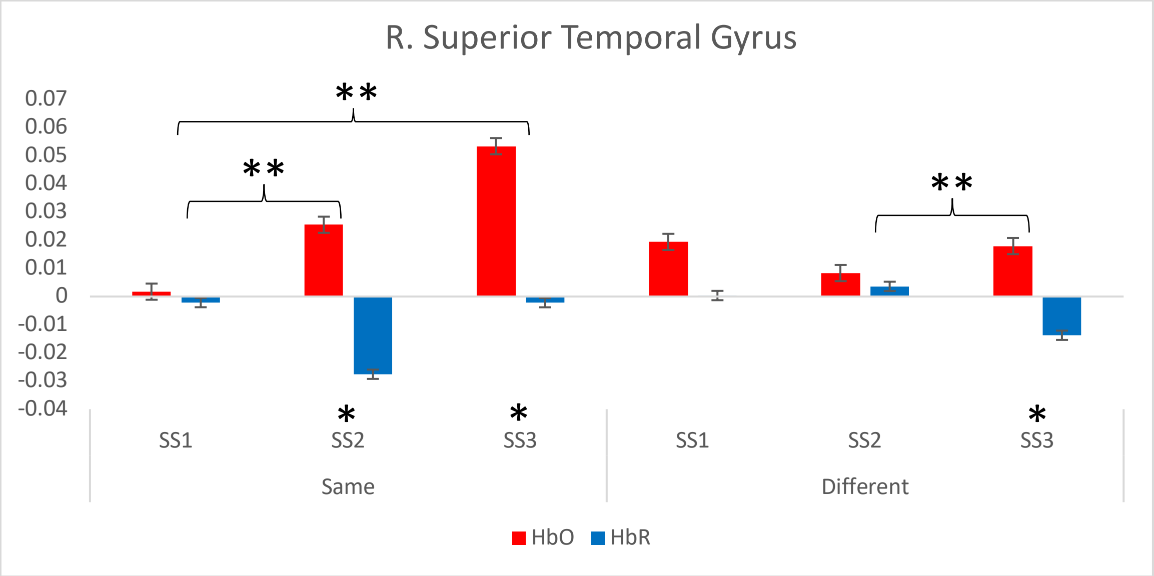

Figure A11

Bar Chart for Change Detection Oxy x SS x Response (SD) Effect

Note. **p<0.001, **p<0.0003*

Figure A12

Brain Image for Change Detection Oxy x SS x Response (SD) Effect

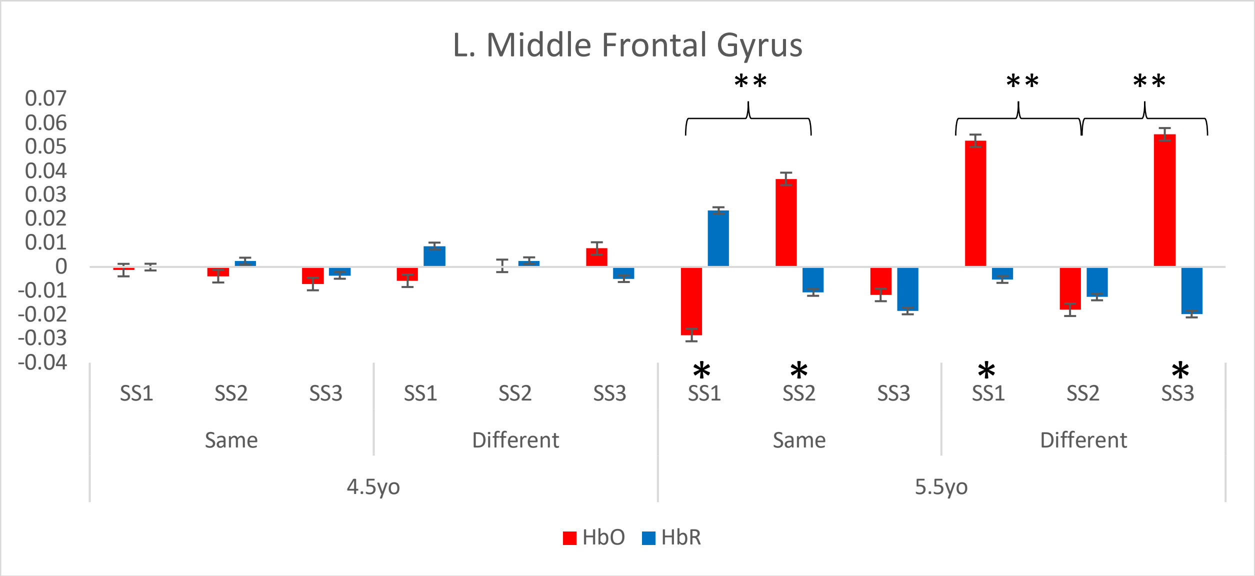

Figure A13

Bat Chart for Change Detection Oxy x Age x SS x Response (SD) Effect

Note. $*p<0.001$, $**p<0.0003$

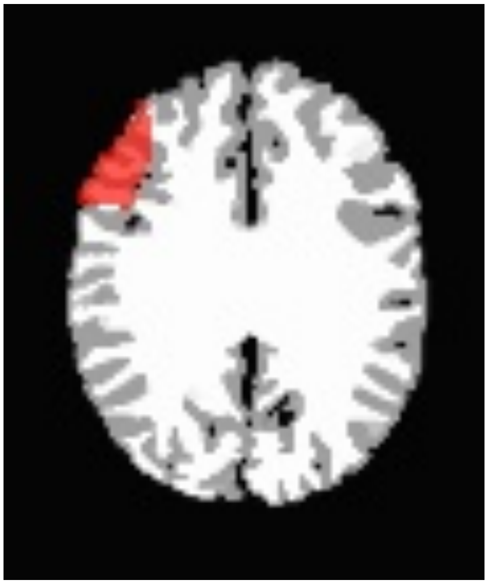

Figure A14

Brain Image for Change Detection Oxy x Age x SS x Response (SD) Effect

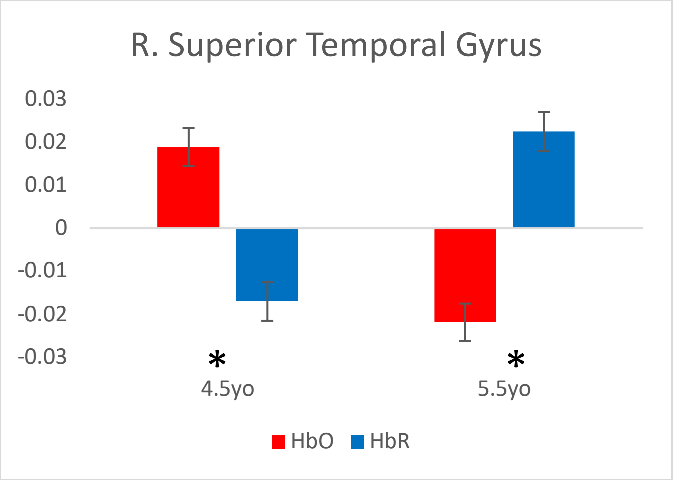

Figure A15

Bar Chart for Cued Recall Oxy x Age Effect

Note. $^*p<0.001$

Figure A16

Brain Image for Cued Recall Oxy x Age Effect

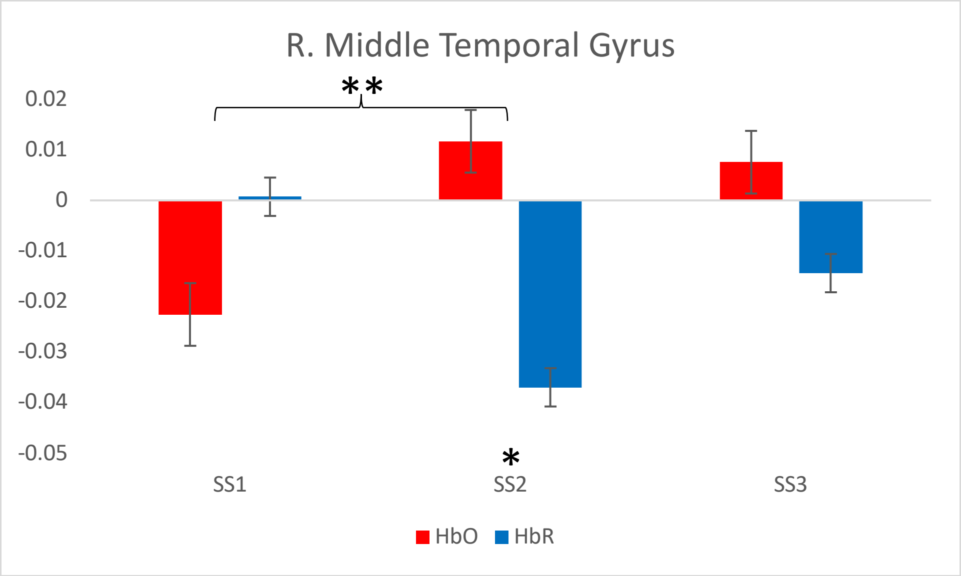

Figure A17

Bar Chart for Cued Recall Oxy x SS Effect

Note. **p<0.001, **p<0.0003*

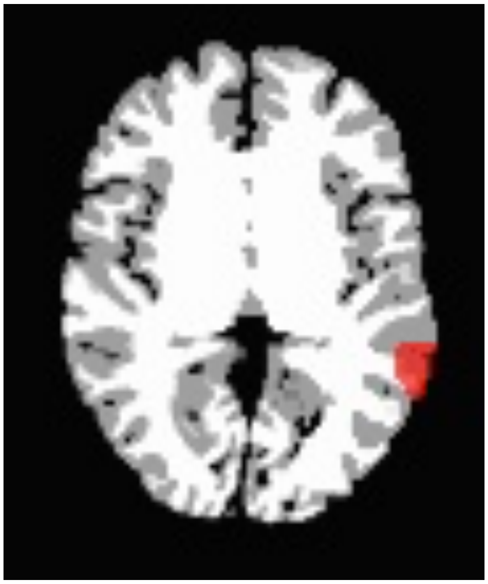

Figure A18

Brain Image for Cued Recall Oxy x SS Effect

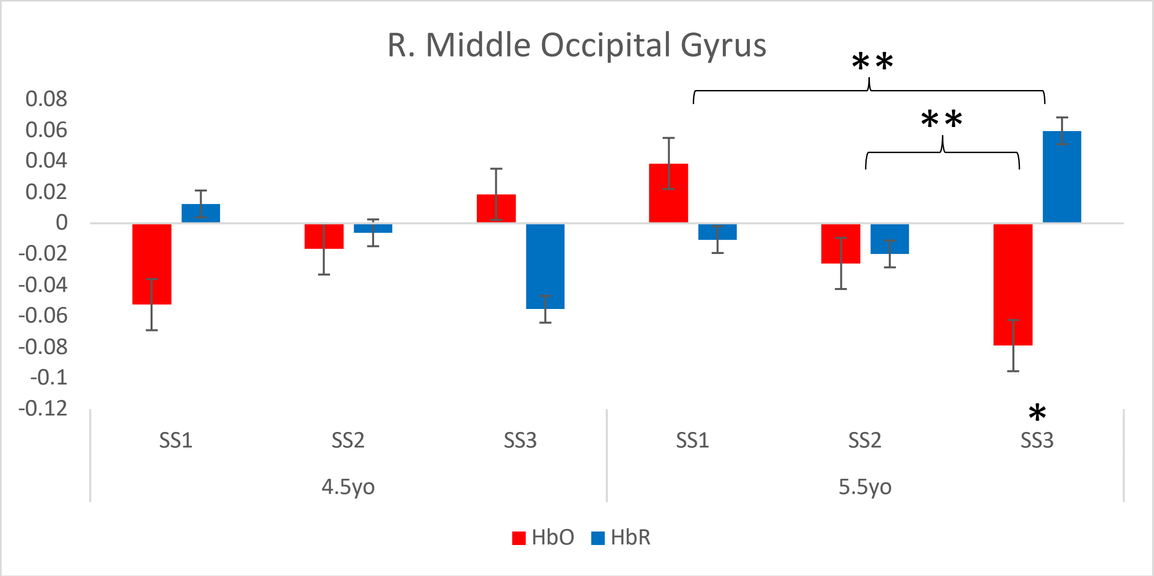

Figure A19

Bar Chart for Cued Recall Oxy x Age x SS Effect

Note. *$^*p<0.001$, $^{**}p<0.0003$*

Figure A20

Brain Image for Cued Recall Oxy x Age x SS Effect

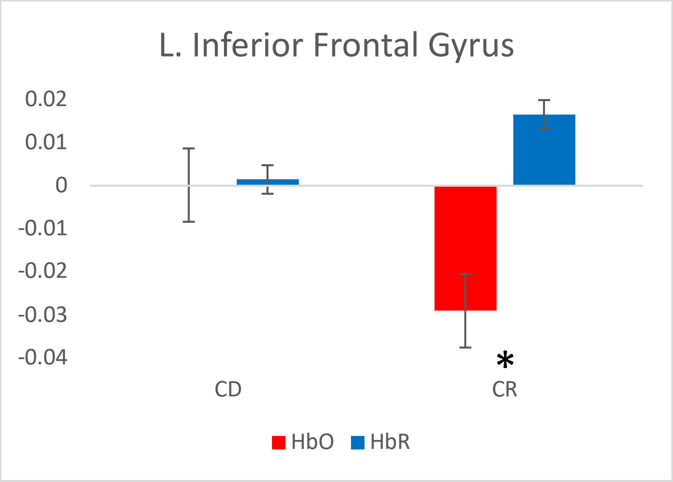

Figure A21

Bar Chart for Full Oxy x Task Effect

Note. *$*p<0.001$*

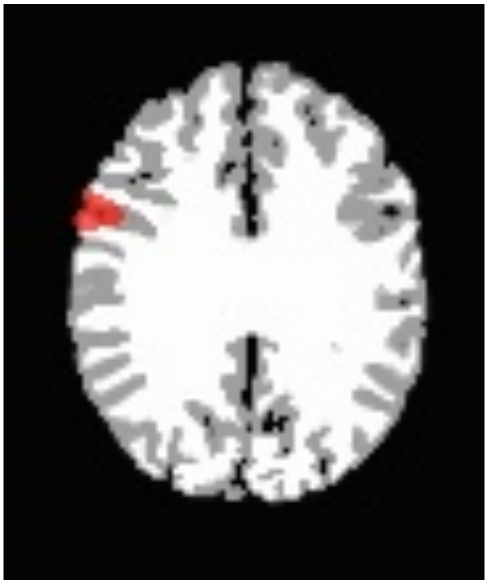

Figure A22

Brain Image for Full Oxy x Task Effect

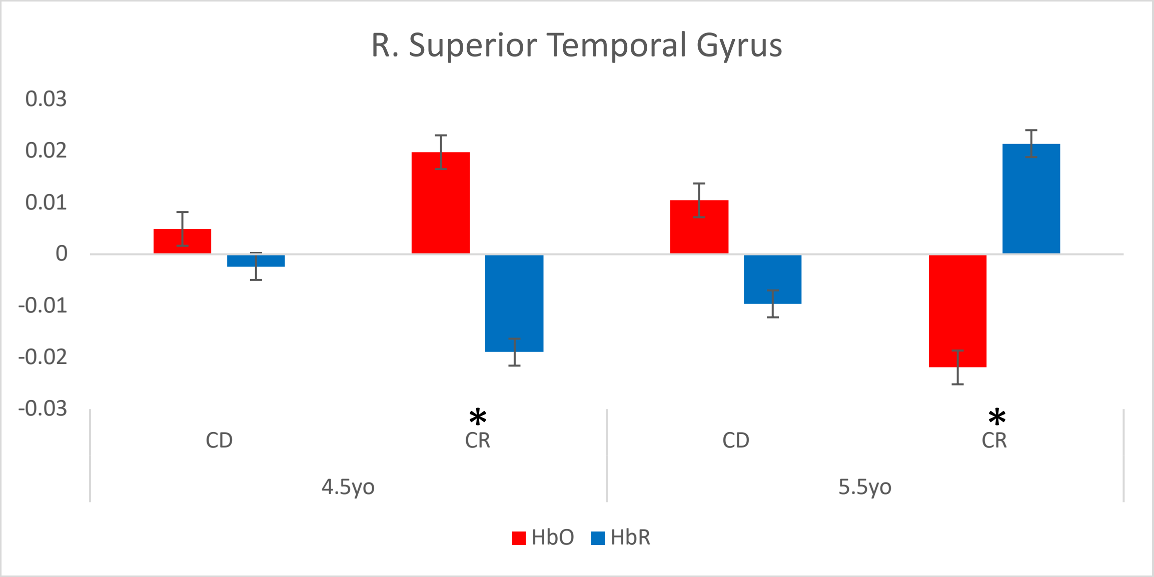

Figure A23

Bar Chart for Full Oxy x Age x Task Effect

Note. **p<0.001*

Figure A24

Brain Image for Full Oxy x Age x Task Effect

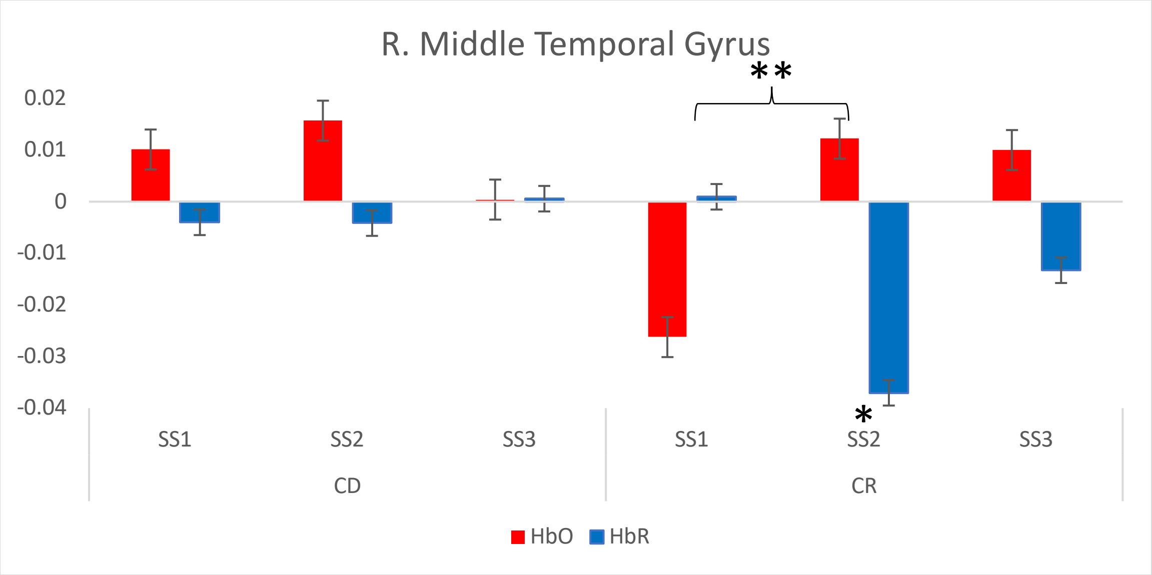

Figure A25

Bar Chart for Full Oxy x SS x Task Effect

Note. *$^*p<0.001$, $^{**}p<0.0003$*

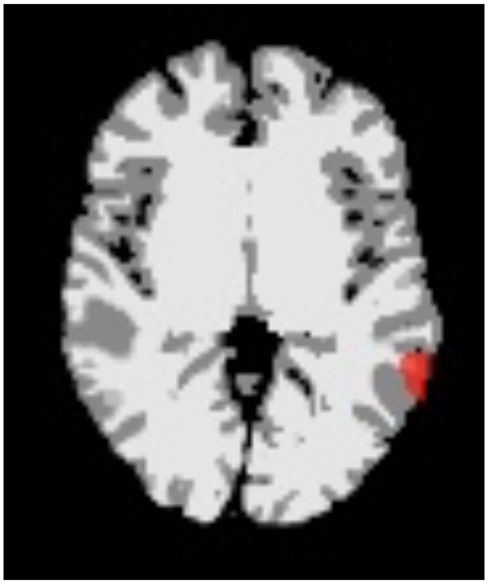

Figure A26

Brain Image for Full Oxy x SS x Task Effect

Vita

Rachel Eddings was born in the Washington, D.C. area and grew up in Accokeek, Maryland. Rachel attended Henry G. Ferguson Elementary School, followed by Eugene Burroughs Middle School and Walker Mill Middle School, and graduated from Oxon Hill High School in May of 2014. She attended the University of Tennessee Knoxville for her undergraduate education, where she received a Bachelor of Arts Degree in Psychology in May of 2018. After graduation, Rachel continued her education at the University of Tennessee Knoxville in the Master's Program for Experimental Psychology with a concentration in developmental psychology. She has been a member of the Attention, Brain, and Cognition Lab under the supervision of Dr. Aaron Buss, with her research focusing on the neural development of executive function in children, specifically visual working memory. Upon graduating with a Master of Arts degree, Rachel plans to take over as full time Lab Manager for the Attention, Brain, and Cognition Lab.