EXAMINING PERCEPTUAL AND CATEGORICAL INFLUENCES ON VISUAL WORKING MEMORY

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ABSTRACT

Visual working memory (VWM) refers to the limited capacity storage of visual information used for behaviors like problem-solving, planning, or reasoning. VWM is a crucial component of cognition, and individual differences in capacity during childhood have been linked to outcomes in academic achievement, fluid intelligence, and socioemotional development. VWM increases in capacity and precision throughout development. Very few studies have investigated what factors influence changes in VWM abilities in preschool-aged children. The first goal of this study was to examine VWM precision development in this age-range. This was accomplished by administering a delayed estimation task. In this task, children touched a color wheel to indicate the color of an item in memory from a two-item array. Mixture modeling was used to measure the likelihood of reporting the target color and precision of the color represented in memory. The second goal of this project was to investigate the underlying neural, perceptual, and categorical mechanisms of VWM development. To measure perceptual mechanisms, children completed a discrimination task where they touched a color wheel to indicate the color of a visually presented color. For categorical mechanisms, children completed production and comprehension tasks for colors. To assess comprehension, children touched a color wheel to indicate the location of ‘blue’ and ‘green’. Lastly, for production, children provided ‘blue’ or ‘green’ labels for stimuli that were randomly sampled between canonical blue and green color values. Forty-four children aged 36-48 months completed these tasks across two sessions, as well as nine adults. Results showed deactivation across the delayed estimation and discrimination tasks in left postcentral

gyrus, as well as activation for both in right middle temporal gyrus. In addition, right inferior gyrus was more strongly activated for the discrimination task, and left inferior frontal gyrus was more strongly activated for the delayed estimation task. Activation during both tasks was associated with behavioral measures such as the location of children's color category boundary during production, suggesting a relationship between VWM precision and perceptual and categorical mechanisms.

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SECTION 1: BACKGROUND

Working memory refers to the limited capacity, temporary storage of information used for behaviors such as problem solving, planning, or reasoning. Working memory is a crucial component of cognition, and individual differences in capacity during early childhood have been linked to later outcomes in academic achievement, fluid intelligence, and socioemotional development (Alloway et al., 2009; Burgess et al., 2011; Fry & Hale, 1996; Gathercole et al., 2003; Gathercole et al., 2006; Gray et al., 2003; Jaeggi et al., 2008; Sabol & Pianta, 2012). In addition, adults with low working memory capacity have more difficulty attending in daily life, while children with language and learning disabilities are more likely to have low capacity (Kane et al., 2007; Henry, 2001). Therefore, understanding the development of working memory, especially early in childhood before children attend school is critical.

Visual working memory (VWM) is one aspect of working memory that has been the focus of much research (e.g., Cowan, 2011; Luck & Vogel, 2013; Ma et al., 2014). Very little, however, has been conducted on the development of VWM in preschool-aged children and even less has involved studies of the neural mechanisms involved in VWM development. In general, there are two primary measures of VWM: capacity and precision. VWM capacity increases as children develop, even up to 10 years of age (Heyes, et al., 2016). Capacity is typically assessed using change detection tasks, which identify the number of items that can be stored. In these tasks, children are presented with an array of shapes or objects that vary in set size. After a brief delay, children are either shown the exact same array or an array in which some aspect of one of the items has

changed (e.g., color, shape). They then determine whether the array changed or did not change.

VWM precision, on the other hand, is typically assessed in a delayed estimation task. Compared to change detection tasks, beyond measuring whether an item is remembered, delayed estimation tasks can provide information about the precision of the representation and the types of errors that people make. These tasks require participants to recall elements of stimuli on a continuous scale (Bays & Husain, 2008; Ma et al., 2014). There are three main advantages to using delayed estimation tasks. First, they provide a precision metric of VWM beyond the number of items remembered. Second, they are also more sensitive to individual differences. For instance, one study found that a VWM task that assessed precision was able to detect working memory changes in patients with early, untreated Parkinson's disease, but a span task could not (Zokaei et al., 2015). Third, they can give information about the types of errors people make. For example, a participant may fail to accurately remember the color of a circle because they simply forgot it or because another circle's color interfered (a mis-binding error). Although they have been used extensively with adults, more continuous tasks have rarely been used to understand the development of VWM in young children. The first goal of this study is to use a delayed estimation task to investigate the development of VWM precision in preschool-aged children. Given the importance of VWM to later outcomes, the second goal is to shed light on the neural, perceptual, and categorical mechanisms underlying the development of VWM precision.

VWM Development: Behavior

Children's VWM capacity improves across development, up to adult-like performance by age seven in certain tasks (Simmering, 2016). Most studies of VWM in childhood use change detection tasks. Using a modified version of the task for preschoolers, Simmering (2012) found that 3- and 4-year-olds had a capacity of around two or three items, whereas children between the ages of 5 and 7 could remember up to three or four items. VWM precision of adults is highly dependent on the number of items presented (Bays & Husain, 2008; Bays et al., 2009). As set size increases, each item can be stored with less precision.

However, very few studies of VWM in childhood have used delayed estimation tasks or studied the precision of VWM resolution specifically. One study examined the development of VWM precision in 7- to 13-year-old boys using one and three item tests (Burnett Heyes et al., 2012). In these tests, children were presented with single-colored bars (red, green, or blue) and after a delay, were asked to use a dial to rotate another probe bar to match the orientation of the target. In the task with the set size of three, the three bars were presented sequentially one at a time, and the target was indicated by the color of the probe bar. Results indicated that performance in both set sizes increased over age. In order to investigate possible mechanisms in VWM improvement, the authors fit a probabilistic mixture model to each participant's dataset. They found that older children's memory improvement was due to reduced noise and higher resolution of the stored items, not due to fewer guesses or mis-binding errors. In a second study, the same researchers followed some of these children longitudinally and tested their VWM precision on the

same task two years later. They found that precision increased over the two-year span, and that this was again due to decreased noise in the representations of the stored items (Heyes et al., 2016). Not all studies have found this increase in precision across age, however. Another study that used a continuous measure of precision for visuospatial working memory with 7-to 12-year-old children found that while the 10- to 12-year-olds were less likely to guess than the 7- to 9-year-olds, the older age group was still no more precise than the younger age group when they did remember the target (Sarigiannidis et al., 2016). Similarly, Shimi and Scerif (2021) gave adults and 6- to 7-year-olds a color delayed estimation task and, on some trials, provided them with a spatial cue (an arrow) pointing to the location of the target item slightly before the actual cue appeared. They found that this retro-cue improved precision for both adults and children, although to a lesser degree for children. In addition, this increased precision was due to a higher probability of selecting the target, along with decreased chances of random guessing and mis-binding errors, but children were still not more precise when they did remember the target.

Literature with working memory precision with children younger than 7 years of age is therefore highly limited. The only studies to investigate the precision of VWM resolution have been conducted with children 4-years-of-age and older, and those showed contradictory findings on how precision changes through development. By the age of seven years, children are well into school. The outcomes that VWM is linked to are incredibly important, not only for academic success but for everyday functioning such as emotion regulation and fluid intelligence (Alloway et al., 2009; Burgess et al., 2011; Fry

& Hale, 1996; Gathercole et al., 2003; Gathercole et al., 2006; Gray et al., 2003; Jaeggi et al., 2008; Sabol & Pianta, 2012). Given the relationship between VWM and these later life outcomes, understanding the underlying mechanisms of its earlier development is important, and yet, very few studies have accomplished this. This project will therefore seek to investigate how VWM precision changes before children enter school. We focused on three mechanisms underlying the development of VWM: neural, categorical, and perceptual. Exploring categorical and perceptual mechanisms in this age range specifically will allow us to examine the influence that individual experiences have in VWM development, especially in an age group that could be a target for possible interventions.

VWM Development: Perceptual

One open question that remains to be answered is whether the fidelity of the working memory representation for colors is associated with color VWM precision. Simmering and Miller (2016) investigated this by studying the relationship between VWM capacity and VWM resolution. Based on a dynamic neural field model, the authors hypothesized that these two facets of VWM should be associated because they arise from the same underlying increases in excitatory and inhibitory connections. Five to 8-year-old children completed a change detection task, in addition to a color discrimination task. In this task, children were first shown a colored mitten, and then after a short delay were shown a second mitten of the same or a similar color. The authors assessed resolution by manipulating the similarity of the target and test mittens. Children were then instructed to state whether the mittens were the same color or different. Results indicated that

children's VWM capacity and resolution were indeed associated with one another, providing evidence for the role of strengthening connectivity. A question that remains to be answered after this study is whether a perceptual skill like color discrimination is related to VWM precision in young children, given the connection between VWM and later outcomes. The color discrimination task used by Simmering and Miller (2016) was similar to a single item change detection task in that children had to remember the color of the first mitten over the delay and compare that representation to the color of the second. It is unclear whether performance in a color discrimination task that does not tax working memory might be related to VWM precision. Furthermore, Ovalle-Fresa et al. (2021) gave synesthetic adults who see letters as colors, adults with color expertise due to their job or hobby, and adults from the general population a color perception task and memory task. In the perceptual task, participants saw a colored disc and had to adjust a second disc to match that color as closely as possible. They also completed a memory task in which they saw one, three, or five colored objects and, after a delay, had to adjust the color of one of those objects to match what they had seen before. They found that both the synesthetic adults and adults with color expertise had better performance on both tasks in comparison to adults from the general population. This indicates that experience can influence such a core component of cognition as VWM.

VWM Development: Categorical

One type of categorical skill that may be related to VWM development is dimensional label learning. Dimensional label learning is one mechanism that may strengthen connectivity between language and perceptual areas. Children improve in their

comprehension and production of labels for colors up until the age of 5 (Pitchford & Mullen, 2002; Pitchford & Mullen, 2005). This learning involves pairing dimensional labels (e.g. “color”) with feature labels (e.g. “blue”) and feature labels with the visual features of objects (e.g. a blue box). Sandhofer and Smith (1999) developed a series of tasks to probe children’s representation of dimensional labels. In the production task, children are asked to provide a label (“red”) when presented with a stimulus and asked, “What color is this?”. Early in development, children can reliably produce a color label before they are able to reliably produce the correct color label (Sandhofer & Smith, 1999), suggesting that children first learn that certain labels belong to the category of ‘color’ (termed a word-word mapping). Successfully answering this question, however, also requires children to understand that the label ‘color’ is associated with a particular visual dimension in order to select the correct feature from stimuli (termed a word-word-property mapping).

It is currently unclear whether dimensional label learning, specifically production and comprehension, is associated with changes in VWM. Vales and Smith (2015) demonstrated that labeling can influence performance in tasks that require VWM. Three-year-old children were given a series of visual search tasks, and results showed that providing the children with labels for the target of their search led to decreased reaction times across all iterations of the visual search tasks. The authors concluded that the labels may have led to stronger representations for those items in VWM, facilitating faster search performance. Given these findings, it may be that production and comprehension of dimensional labels is associated with VWM precision and discrimination for the

associated visual features. Children with better dimensional label learning may therefore have better VWM capacity and precision. Furthermore, the successful production of basic color labels is also a component of the Bracken School Readiness Assessment, which seeks to determine whether children are ready to enter school. Given that VWM is also related to school readiness outcomes, we may see an association between it and children's dimensional label learning.

VWM Development: Brain

There are several key neural signatures associated with VWM tasks in adults. First, activation in intraparietal sulcus (IPS) has been found to increase in accordance with memory load, up to a set size of three items (Todd & Marois, 2004). In set sizes of 4, 5, and 6 items, however, this increase in activation was not found, demonstrating that IPS may be sensitive to set size only up to behavioral capacity limits. Similarly, a study with EEG in adults found that amplitude of the contralateral delay activity was associated with memory load and that individuals with lower capacities had signals that asymptoted sooner than those with higher capacities (Vogel & Machizawa, 2004). Individual differences in VWM capacity are also positively associated with activity in posterior parietal cortex, such that as activation increased, participants had better performance (Todd & Marois, 2005). Other studies, however, found mixed results. For example, one study demonstrated a positive relationship between capacity and activity in left superior frontal sulcus and left IPS in 9- to 18-year-olds (Klingberg et al., 2002), while another with 9- to 12-year-olds only found an association using very lenient thresholds (p=.05

instead of p=.01) and that increased prefrontal-parietal coupling better predicted performance (Huang et al., 2016).

One neuroimaging method useful for work with young children is functional near-infrared spectroscopy (fNIRS), which monitors cortical activity through the flow of oxygenated and deoxygenated hemoglobin in the brain (Boas & Franceschini, 2009). Of the fNIRS studies to investigate VWM in childhood, many have used variations of a change detection task. For example, one study had 3- and 4-year-olds complete a change detection task while wearing an fNIRS cap measuring from bilateral frontal and parietal cortices (Buss et al., 2014). They found that children displayed similar task-specific activation in this fronto-parietal network as that found in adults and that 4-year-olds had a more robust parietal response as compared to younger children. However, not all results were consistent with the adult VWM literature. While fronto-parietal activation for adults typically increases only up to the set size limit, the children in this study displayed increased activation up to a set size of three items, even though their capacity was limited to less than two.

There are also other similarities in activation between children and adults. One study found that lateral prefrontal cortex (PFC) of both adults and 5- and 6-year-old children was sensitive to memory-load in an item-recognition task (Tsujimoto et al., 2004). Another study gave 4-month-olds, 1-year-olds, and 2-year-olds a preferential looking VWM task and found activation near six out of 19 regions-of-interest identified to be associated with the VWM network in adults (Delgado Reyes et al., 2020) In addition, they found changes between 4-month-olds and 1-year-olds near bilateral

anterior intraparietal sulcus (aIPS), left temporoparietal junction (TPJ), and left ventral occipital complex (VOC) with improvement in VWM. In another study, children between the ages of 3- and 7-years completed a spatial working memory task while fNIRS measured from middle and lateral PFC (Perlman et al., 2015). Overall, older children engaged lateral PFC during the working memory task significantly more than the younger children, suggesting developmental shifts over age. Other studies utilizing fNIRS to investigate working memory also showed PFC activation (Moriguchi & Hiraki, 2013; Smith et al., 2017; Tsujii et al., 2009; Yamamoto et al., 2018), including lateralization in right PFC for simultaneous stimuli presentation for 11- to 12-year-old children, but not 7- to 10-year-olds (Suzuki et al., 2018). Finally, one other study used fNIRS in rural India to study the effects of adversity on brain regions underlying VWM. They tested children aged 4- to 48-months and found that those with low family income and maternal education displayed weaker activation in left frontal cortex (Wijeakumar et al., 2019). Other research has studied the impact of stress on VWM (McKay et al., 2021). Parents completed questionnaires on stressful life events while their 4.5-year-old children completed a color change detection task. Results indicated that children with low performance had increased frontal-parietal activation as the set size increased, while those with high performance did not. Furthermore, this difference with low performers in left parietal cortex partially mediated parental reports of stress and their child's VWM performance. In summary, the neural development of VWM in children has shown deviations from adult data. PFC and parietal regions seem to be involved from childhood into adulthood, but there are also developmental differences, such as the lack of an

asymptote of parietal activation in children. The literature therefore does not yet provide a clear picture regarding the nature of VWM development.

Summary

In summary, VWM capacity improves from infancy on into adulthood (Simmering, 2016). However, there are several gaps in our understanding of VWM in childhood that have not yet been addressed. First, most studies of VWM with preschool-aged children have only used tasks that assess whether they remembered the stimuli or not. It is unclear how the precision of VWM develops in early childhood. Second, there has been very little research on the neural basis of VWM in early childhood, and very few published studies have investigated the role of temporal regions, which have been studied in adults (Olson et al., 2006; Ranganath et al., 2004). Thus, we do not yet understand the neural mechanisms involved in VWM development. Third, very little research has investigated how perceptual and categorical mechanisms may be related to VWM capacity and precision in children. This project will seek to address whether individual differences in experience and learning can influence VWM. We recruited children within the age range of 36- to 48-months. In the testing sessions, children were given two continuous response tasks to assess VWM precision and color discrimination, as well as color label production and comprehension tasks to assess the status of dimensional label learning. We measured neural activity from bilateral frontal, temporal, and parietal cortices using fNIRS (see Figure A1), as these regions have previously been used in an fNIRS study of VWM in early childhood (Buss et al., 2014). All following figures will appear in the appendix.

Current Study

The first aim of this study was to assess the development of VWM precision in preschool-aged children utilizing a more continuous task type. We gave 3–4-year-olds and adults a color delayed estimation task. We included adult participants for all tasks to better characterize where children might be developing toward, given that the tasks do not have typical correct or incorrect responses. In addition, we chose color visual working memory specifically because it allows us to have more continuous control over our stimulus properties. In this task, participants viewed two colored squares briefly, after which they disappeared. One of the square's locations was then cued, and participants touched the cued item's color on a color wheel. By using mixture modeling, we can fit participants' performance in this task to a gaussian structure with estimates of the probability of random guessing, selecting the target or distractor, and variability of VWM precision. We expect that precision will improve over age, with less guessing and a higher likelihood of selecting the color of the target item.

We also investigated categorical, perceptual, and neural mechanisms of VWM development. To assess categorical mechanisms, we administered color production and comprehension tasks for blue and green only. For production, participants were shown a colored square and were asked, "Is this blue or green?". After repeated presentations of these colors, we can use curve-fitting to extract parameters that assess how well participants categorized blue and green, in addition to both the location and sharpness of their color boundary. Given that dimensional label learning is an associative learning process which leads to more precise mapping between words and visual features, we

predict older children and adults will have a sharper boundary with less overlap between blue and green. For comprehension, we presented them with a color wheel and prompted them with, "Where is blue/green?". This task allowed us to measure participants' exemplars of blue and green, as well as the variability of those categories. To assess perceptual mechanisms, we used a color discrimination task. Children completed a task identical to delayed estimation, except the colors did not disappear, allowing us to examine performance without memory demands. For comprehension and discrimination, we expect less response variability from older children and adults. Overall, given the previous studies linking perceptual and categorical influences to VWM (Vales & Smith, 2015; Simmering & Miller, 2016), we expect that a sharper category boundary in production, as well as less variable comprehension and discrimination performance will be associated with better VWM precision. Finally, our last aim was to characterize the neural mechanisms associated with VWM precision for preschool aged children in a fronto-temporal-parietal network. During the delayed estimation task, we collected neural data from these regions using fNIRS. We can also examine whether activation during the delayed estimation task is associated with color discrimination, production, and comprehension performance. Simmering & Miller (2016) predicted that VWM capacity and resolution would be associated given they both arise from strengthening connectivity. Given this association, we could see a relationship between our measure of color discrimination and activation during delayed estimation. We could also see an association between the categorical skills of color production and comprehension with activation

during delayed estimation, meaning that children's experiences with colors could influence the development of VWM precision.

SECTION 2: METHODS

Participants

Forty-four children within the age range of 36- and 48-months of age participated in this study (19 girls). In order to ensure that we sampled evenly across this age range, we recruited children in three-month age increments: bin 1 (36-38.9 months; 12 children, M = 38.30, SD = 0.69), bin 2 (39-41.9 months; 10 children, M = 39.84, SD = 1.07), bin 3 (42-44.9 months; 11 children, M = 44.29, SD = 0.83), and bin 4 (45-48 months; 11 children, M = 46.84, SD = 0.79). Thirty-three additional children participated but were excluded due to the following reasons: three refused to wear the fNIRS hat, one due to parental interference, seven failed to follow task instructions, eight did not return for a second session, seven did not complete enough trials, two children's data were not saved, one due to probable color blindness, three because they did not know colors, and one due to experimenter error. All of the children's parents or guardians were given a consent form, in addition to a demographics form (including age, sex, handedness, vision, race, ethnicity, highest education level of parents, and SES) for their child. Children were scheduled for two sessions, one containing the production and comprehension DL tasks and the other containing the delayed estimation and discrimination tasks. Task type for the first session was counterbalanced between participants. Each session took no longer than an hour and a half, and children received a toy and $10 for participating.

Nine adults also completed these tasks in a single testing session, without fNIRS data collection (8 females, 1 male, aged 18- to 35 years). They were recruited by word-

of-mouth and completed a consent form and demographics form (including age, sex, handedness, and vision), and each session took no longer than an hour.

Behavioral Procedures

Participants completed all behavioral tasks on a 27-inch touchscreen enabled monitor with a PC running Psychtoolbox-3 software in 1920x1080 resolution. Tasks were administered across two visits for children and one for adults. The production and comprehension tasks were administered together in a block design (Figure A2), with half receiving production first, and the other half completing comprehension first. The VWM and discrimination tasks were administered together while fNIRS data were collected.

Color label production: Color label production was measured using a task similar to that of one previously used in the literature (Sandhofer & Smith, 1999). The production task involves showing participants a single object and asking, "What color is this?". Because the children in this study were expected to perform near ceiling in this task, however, we used a more continuous measure. In this version, participants were shown a colored square from the blue-green color spectrum and were asked, "Is this blue or green?" (Figure A3). For children, the experimenter then entered their response on the keyboard with 'z' for green and 'm' for blue. If the child refused to pick a single color (e.g., answered 'blue-green'), the experimenter prompted them with, "If you had to pick, is this more blue, or is it more green?". Adult participants entered their own keyboard responses. Previous research has shown that the blue-green color boundary for adults occurs around a Munsell value of 7.5 BG (Bornstein & Monroe, 1980; Pilling et al., 2003). An online tool was therefore used to convert a Munsell value of 7.5BG (with

chroma and lightness values of 6) to an RGB value of 61, 162, 161 (pteromys.melonisland.net/Munsell/). We used Matlab to extract all 360 color values from one of our HSV color space color wheels. The closest extracted value to this converted color had an RGB value of 53, 177, 178, which was used as a center point from which we sampled blues and greens in each direction. We sampled five colors in each direction (for a total of 11, including the center color) that were each separated by five degrees. In addition to these more ambiguous colors located along the boundary, we also chose two colors to serve as controls: one that was canonically blue (RGB value of 53, 96, 178), and one that was canonically green (RGB value of 53, 178, 59). These colors were not used in analyses but served to ensure that participants could accurately label blue and green reliably. Participants made judgments for each of these 13 colors five times, for a total of 65 trials. Responses were coded as a 0 for "blue" and 1 for "green" and summed for each stimulus type. Then, data for each participant were fit to a sigmoid function to estimate the parameters for the slope, crossover point, minY, and minY (Figure A4). These parameters were then used to characterize where participants transitioned from responding "green" to responding "blue" (cross-over point), the steepness (slope) of the category boundary, how well they categorized the bluest colors (minY), and how well they categorized the greenest colors (maxY).

Color label comprehension: Typically, color comprehension is assessed by presenting participants with an array of objects and asking them, "Which one is blue?". Like the production task, however, participants were given a more continuous measure of color comprehension. In this version, instead of an array of objects, participants were shown a

randomly oriented color wheel and the experimenter asked either, “Where is blue?” or “Where is green?”. Participants responded by touching the section of the color wheel corresponding to the cued color. They were only prompted with the color labels of blue and green to reduce the total number of trials needed. Participants completed 20 trials for blue and 20 trials for green, for a total of 40 comprehension task trials. We randomized the order of colors for both the comprehension and production tasks. The color wheel orientation was also randomized between 36 possible orientations, each rotated 10 degrees. We then calculated the mean and standard deviation of responses for both blue and green, and used these values to create gaussian plots of response distributions.

Delayed estimation and discrimination tasks: VWM precision was assessed using a delayed estimation task (Figure A5). In this task, participants were shown two colored squares and, after a delay, touched a color wheel to indicate the color of one of the squares. The probed square was indicated by the presence of a bolder box outline in the square’s location. Children were told, “You are going to see two colors. The colors are going to go away after a little bit, so we need you to try to remember them. Your job will be to find the color that is in the bigger box.” If children had difficulty understanding the cueing, they were asked, “See how this one has black around it? We need you to find the color in this one!”. Adults were told, “You are going to see two colors. One of them will be cued with a bold outline, and you will select that color on the wheel”. The colored squares were displayed for 2 s, while the delay lasted for 900 ms, which is consistent with previous work with a modified change detection task that allowed children as young as 3.5 years to participate (Simmering, 2012). Participants also completed a baseline

condition of this task without VWM demands to assess color discrimination. In this color discrimination task, the colored squares remained visible over the 500 ms delay and during the response phase with the color wheel. Children were told, “For this game, the colors are not going to go away. Your job is still to find the color in the bigger box”. For both tasks, when participant’s responses were within 30º of the correct color location, they heard a positive bell sound. The orientation of the color wheel was randomized between 36 orientations rotated ten degrees, and the colors of the squares were selected randomly, with the restriction that the second item’s color must be at least 30 degrees away from the first item’s color. Participants were given a set size of two items only to minimize task demands for the children. They completed a total of 60 trials of delayed estimation and 40 trials of color discrimination in a block design with 20 trials per block. We always presented the color discrimination task first to serve as an introduction to the more difficult delayed estimation task. In addition, for the children, experimenters first demonstrated three trials of both tasks to ensure that children understood both the task instructions and cueing. To better understand the nature of participants’ performance in the delayed estimation task, we used MemToolbox (Suchow et al., 2013; memtoolbox.org) to apply a probabilistic mixture model to each participant’s data set. Specifically, we used the model of Bays et al., 2009 (Figure A6). This model provides four parameters: variability of precision for remembered items and probability of random guessing, selecting the target, and selecting the distractor (a misbinding or “swap” error). In this equation, θ is the target color value, $\theta\hat{}$ is the reported color value, m is the number of distractor items, β is the probability of making a misbinding error, y is the probability

of guessing at random, and $\phi\sigma$ represents the Von Mises distribution (the circular approximation of a Gaussian distribution), with a mean of 0 and a standard deviation (concentration parameter) of σ. We calculated maximum likelihood estimates for parameters σ, β, and y for each participant.

fNIRS Procedure

We used functional near-infrared spectroscopy (fNIRS) to measure the flow of oxygenated and deoxygenated hemoglobin in the brain during the color discrimination and delayed estimation tasks for children only. We collected this data at 25 Hz using a 36-channel TechEN CW7 system with wavelengths of 830nm and 690nm. Children wore an fNIRS hat outfitted with eight sources and sixteen detectors to measure neural activation over bilateral frontal, temporal, and parietal cortices. Frontal and parietal areas have been implicated as being important for VWM in both children and adults (Kane & Engle, 2002; Klingberg, 2006; Wijeakumar et al., 2017). In addition, very few published studies utilizing fNIRS to study VWM in early childhood have investigated the activation of temporal regions, even though numerous studies with adults have shown temporal activation in VWM tasks (Olson et al., 2006; Ranganath et al., 2004). We used the Polhemus Digitizing System to project the source and detector positions, in addition to five landmarks on each participant's head (vertex (CZ), right ear, left ear, nasion, and inion) onto an individual atlas in AtlasViewer (https:www.nitrc.org/projects/homer2/).

We used HomER2 software to subtract the mean baseline from the raw fNIRS data and convert them into an optical density measure (Huppert et al., 2009). fNIRS data collection with children of this age range is especially susceptible to motion artifacts due

to movement. In order to use a method with the potential to preserve more task trials, we used the modified wavelet-filtering technique to correct motion across each channel successively using an IQR threshold of 0.5 (Molavi & Dumont, 2012). The data was then band-pass filtered to preserve frequencies between .01 and .5 Hz. We next converted them to concentration values using the modified Beer-Lambert Law and the known extinction coefficients of oxygenated and deoxygenated hemoglobin with differential and partial pathlength factor values of 6.0.

Volumetric timeseries data was constructed from these cleaned data following the procedure outlined by Forbes et al. (2021). First, we prepared an atlas used to create a structural image aligned to each participant's anatomical landmarks. We used 42- and 48-month-old child atlases, depending on the individual participant's age. After, spatial coordinates of source-detector positions were used to create a light model. Using AtlasViewerGUI, photon migration simulations were performed to create sensitivity profiles by estimating the path of light for each channel using parameters for absorption and scattering coefficients for the scalp, CSF, gray and white matter (Bevilacqua et al., 1999; Custo et al., 2006). We used Monte-Carlo simulations of 10,000,000 photons to create a sensitivity profile for each channel, detailing its spatial sensitivity (Fang & Boas, 2009). These sensitivity profiles were then thresholded at 0.0001 and combined to create participant-specific masks reflecting the cortical volume of all channels. After, these masks were used to create a group mask which includes voxels in which at least 75% of participants contributed data.

Image reconstruction in NeuroDOT integrates the simulated light model with the pre-processed channel-space data to generate volumetric timeseries data. We down-sampled channel data from 25 Hz to 10 Hz to reduce processing demands. Proper estimation of near infrared light diffusion in biological tissue is an issue specific to optical imaging, as image reconstruction of the NIRS data is subject to rounding errors and may lead to an under-determined solution (Calvetti et al., 2000). We used the Tikhonov regularization method to create voxel-wise timeseries data for HbO and HbR (Eggebrecht et al., 2014; Tikhonov, 1963; Wheelock et al., 2019). General linear modeling was then used to estimate the amplitude of HbO and HbR for each condition and participant across the measured voxels. We used AFNI's 3dMVM function to perform group analyses (Chen et al., 2014). Specifically, we conducted a 2 (chromophore: HbO, HbR) x 2 (task: VWM, Discrimination) ANOVA. Effect masks were thresholded with a voxel-wise threshold of $p<.05$. We then extracted average HbO and HbR values for any clusters with significant interactions, using SPSS (IBM, version 25) for any follow-up tests. We used Greenhouse-Geisser corrections for sphericity violations and Bonferroni corrections for multiple comparisons. We examined voxels displaying developmental differences and also those correlated with task performance.

SECTION 3: RESULTS

Behavioral Results

Delayed Estimation: For the delayed estimation task, we measured probability of random guessing, selecting the target, selecting the distractor, and standard deviation of participants' responses. Figure A7 displays four individual children's response distributions for the target for two high-performing and two low-performing participants. Data is summarized for each age group in Figure A8 and Table 1. To examine whether performance in the delayed estimation task varied across age, we performed two-tailed bivariate correlations, using Bonferroni-Holm adjustments to account for multiple comparisons. We compared children's age in months with their probability of random guessing, selecting the target, selecting the distractor, and their standard deviation of responses. Age was not associated with any of these measures.

Color Discrimination: For the color discrimination task, we measured participants' mean error and standard deviation of error from the target color and created Gaussians from these values to help visualize the shape of children's response distributions. Figure A9 displays these Gaussians over each age group's raw response distribution, and Figure A10 displays each age group's mean error and SD. To investigate whether age is associated with color discrimination performance, we performed bivariate correlations between children's age in months with their mean error and error SD. There were no significant associations between age and color discrimination measures.

Color Production: In the color production task, participants' data were fitted to a sigmoid function that allowed us to obtain the following measures: minY (how well the bluest

colors were labeled), maxY (how well the greenest colors were labeled), crossover (where participants switched from labeling blue to labeling green), and slope (the steepness of this boundary). Figure A11 illustrates the raw and fitted data for each child age group, and Figure A12 depicts these fitted curves for children and adults. The adult plot displays one curve per participant, while the child plots display one curve per age group. To examine effects of age, we correlated children's age in months with their minY, maxY, crossover, and slope values. There were no associations with age.

Color Comprehension: For color comprehension, we obtained each participant's mean angle on the color wheel for blue and green, in addition to their standard deviation for each color. We then used these values to create Gaussians of participant performance to help visualize their response distributions (Figures A13 and A14). We investigated whether children's performance was associated with age by correlating their age in months with their mean color angles for blue and green, in addition to their standard deviation for each color. There were no associations with age. We also examined whether children's mean color angle for each color was associated with their variability for each color. We found that children's mean color values for both blue (r=-.432, p=.003) and green (r=.838, p<.001) were associated with their standard deviation for each color. The closer children's average color value was to adults', the less variable they were (Figure A15).

Between Task Comparisons

Perceptual vs. Categorical: To assess whether the perceptual color discrimination task was associated with the categorical color comprehension and production tasks, we

correlated each task's relevant variables. The only significant association we found was between children's mean discrimination error and their standard deviation for green (r=.432, p=.003, Figure A16). Children who were more accurate with color discrimination had a less variable category for green.

Perceptual vs. VWM Precision: We investigated whether the color discrimination task was associated with performance in the delayed estimation task. We performed correlations between the probabilities of guessing, selecting the target and distractor, and average SD in the delayed estimation task with mean error and standard deviation on the color discrimination task. There were no significant associations.

Categorical vs. VWM Precision: We also examined the relationship between color production and comprehension and VWM precision. We conducted correlations between same four measures of VWM precision as before and production minY, maxY, crossover, and slope and comprehension mean blue/green and standard deviation for blue/green. There were no significant associations.

Neural Results

Neural activity during the delayed estimation and color discrimination tasks was analyzed with a 2(Oxy: HbO, HbR) x 2(Task: Delayed Estimation, Discrimination) within-subjects ANOVA. Activation was inferred by a significant increase in HbO, corresponding with a significant decrease in HbR. Paired-samples *t*-tests were used for follow-up analyses. The minimum voxel size for clusters was 198. All clusters are displayed in Table 2.

We found two clusters that showed an Oxy effect. One of these was located in left postcentral gyrus and showed that HbO (M=-0.024) was lower than HbR (M=0.010, t(43)=-3.907, p<.001), indicating that this region was deactivated across both the delayed estimation and discrimination tasks (Figure A17). We also found an Oxy effect in right middle temporal gyrus, where HbO (M=0.042) was higher than HbR (M=-0.007, t(40)=2.794, p=.008), indicating activation across both tasks (Figure A18).

We next looked at whether neural activation differed according to task type and found three significant clusters. The first was in right inferior frontal gyrus (Figure A19). Follow-up t-tests revealed that this interaction was driven by discrimination HbO (M=0.014) being higher than delayed estimation HbO (M=0.001, t(41)=3.325, p=.002). There was also a significant Oxy by Task interaction in left inferior frontal gyrus (Figure A20). Interestingly, this region showed the opposite trend, where the interaction was being driven by delayed estimation HbO (M=0.015) being higher than discrimination HbO (M=-0.003, t(42)=-3.116, p=.003). The last cluster was in left postcentral gyrus (Figure A21) and displayed deactivation for the delayed estimation task only (M HbO=-0.046; M HbR=0.016, t(43)=-3.811, p<.001).

Brain-Behavior Relationship

To examine the brain-behavior relationship, we also conducted correlations between the HbO of the clusters and behavioral performance for all tasks. For the first oxy effect cluster in left postcentral gyrus, we found a marginal association between HbO and crossover in the production task (r=-.287, p=.059), indicating that children with category boundaries closer to green displayed more deactivation in this region for the

delayed estimation and discrimination tasks (Figure A22). For the second oxy effect cluster in right middle temporal gyrus, we found an association with age (r=.350, p=.025). Older children activated this region more strongly across both tasks (Figure A23). There was also an association between discrimination HbO from the first Oxy x Task interaction in right inferior frontal gyrus and production crossover location (r=.338, p=.028), and a marginal association with slope (r=.302, p=.052). Children with sharper category boundaries closer to green displayed higher activation in this region for the discrimination task (Figure A24). We also found associations with the third Oxy x Task cluster in left postcentral gyrus. HbO in this region during the delayed estimation task was associated with production crossover (r=-.328, p=.03) and marginally associated with mean discrimination error (r=.289, p=.057), and discrimination error SD (r=.287, p=.059). Children with less deactivation in this region during the delayed estimation task had a color category boundary closer to blue and had higher error and variability of responses for color discrimination (Figure A25).

SECTION 4: DISCUSSION

In this study, we administered a delayed color estimation task to children between the ages of 36- and 48-months, as well as adults. Participants saw two colored squares, and after a delay, selected the color of the cued square on a color wheel. We also administered tasks assessing color production, comprehension, and discrimination. For color production, we presented participants with a square sampled from the green-blue color spectrum and asked, “Is this blue or green?”. For color comprehension, we asked participants, “Where is blue?” or “Where is green?”, and they selected their response on a color wheel. Finally, for color discrimination, participants completed a task identical to the delayed estimation task, except the target colors never disappeared. Our first goal was to characterize the development of VWM precision in preschool-aged children. We found that rates of guessing, selecting the target or distractor, and response variability did not change between the ages of 36- to 48-months. Overall, children had a 24% probability of selecting the target item, an 18% probability of making a misbinding error and selecting the distractor and had a 54% probability of randomly guessing. This is not the first study to fail to find precision differences across childhood, however. Sarigiannidis et al., 2016 administered a delayed estimation task to 7- to 9- and 10-12-year-olds and found that there were no differences in precision for remembering the target between the two groups, although the older group showed less random guessing. It is possible that VWM precision changes in preschool children occur over a broader stretch of time. In addition, we also observed individual differences between participants across age groups (Figure A7), which is consistent with adult literature that VWM can vary widely across individuals (Vogel & Machizawa, 2004; Ovalle-Fresa et al., 2021).

We also assessed children's color production, comprehension, and discrimination performance. Overall, there were also no associations with age, perhaps implying that these skills are related more to individual differences in this age range. For the production task, we did observe individual differences in adults' slopes, with four of the adults having a sharper slope, and the other five being more gradual (Figure A12). In addition, we only examined changes across a single year, from 36- to 48-months. It could be that these skills are associated with age later on in development.

Another goal of this project was to characterize the neural mechanisms of VWM precision in preschool-aged children. Across both the delayed estimation and discrimination tasks, we found deactivation in left postcentral gyrus. This effect could be due to nearby brain regions taking up neural resources from this region. In addition, we found activation for both tasks in right middle temporal gyrus. This region has been found to be crucial for color perception and discrimination, as lesions to this area severely impaired color discrimination performance in monkeys (Buckley et al., 1997).

There were also differences in activation patterns between the delayed estimation and discrimination task. For example, children displayed higher HbO during the discrimination task in right inferior frontal gyrus, but higher HbO during the delayed estimation task in left inferior frontal gyrus. The bilateral inferior frontal gyri have been found to be associated with a wide variety of functions, especially those involved with general attentional control (Konishi et al., 1998; Swick & Ashley, 2008; Chikazoe et al., 2007). Right inferior frontal gyrus has been demonstrated to display activation when task relevant information is detected (Hampshire et al., 2010), and children did display higher

performance in the discrimination task than the delayed estimation. Perhaps children had a stronger grasp of task relevant information without the presence of the memory delay. Furthermore, Zhang et al. (2004) found that the left inferior frontal gyrus was more strongly activated when participants needed to select from one of two item sets to be remembered. Children could have displayed activation in this region due to the need to retrieve the cued square color from one of two options. PFC has frequently been found to display activation during working memory tasks, so this finding is consistent with the literature (Moriguchi & Hiraki, 2013; Smith et al., 2017; Tsujii et al., 2009; Yamamoto et al., 2018; Suzuki et al., 2018). We did not find any associations with IPS as has been found for both adults and children (Todd & Marois, 2004; Klingberg et al., 2002; Buss et al., 2014), however, we only included a single set size and therefore could not test for activation changes with memory load.

We also investigated whether perceptual and categorical mechanisms were related to VWM precision. While we did not find any associations between behavioral performance in the delayed estimation task and these mechanisms, we did find relationships with neural activation during the delayed estimation and discrimination tasks. Across both tasks, we found an association with deactivation in left postcentral gyrus and the location of children's color category boundary for blue and green. Children with boundaries closer to green displayed higher deactivation in this region than those with boundaries closer to blue. It could be that children with the most skewed color category boundaries have neural individual differences leading to resource withdrawal in this region. We also found an association in right middle temporal gyrus with age, as

older children displayed more activation in this region across both tasks. It is interesting that we found this neural association with age but did not find a relationship with behavioral performance. Perhaps these neural individual differences occur before behavioral differences emerge. Perlman et al. (2015) also found increasing activation with age during a working memory task, albeit in lateral PFC. In addition to regions that displayed activation across both tasks, we also found associations with those that were more task-specific. Activation in right inferior frontal gyrus for color discrimination was positively associated with production crossover and marginally with slope. Children with higher activation in this region had sharper boundaries further away from blue and closer to the average of the adult's boundary. Finally, we also found an association specifically for delayed estimation deactivation in left postcentral gyrus. Children who deactivated this region less strongly in the task had higher average error and variability of error in color discrimination, as well as a color category boundary closer to blue and further away from the average of adults. These results indicate that perceptual and categorical mechanisms are related to individual differences in VWM precision. Crucially, these mechanisms are not task-specific. Dimensional label learning is a general process that involves mapping verbal labels to visual features. While VWM training has been found to have minor effects, the effects are usually short-lasting and non-generalizable (Melby-Lervåg & Hulme, 2013). This study provides some evidence that experiences with color visual features and labels are related to individual neural differences during VWM precision, possibly allowing for the use of dimensional labels as an intervention target.

There were limitations to this study. For one, fNIRS is incapable of reaching deeper cortical regions. We could therefore be missing other regions of the brain displaying activation. In addition, thirty-three children failed to complete both sessions of the study, fourteen of those who specifically could not complete enough trials of the task while following instructions correctly. In an effort to minimize the number of trials while still investigating the nature of errors in VWM precision, we only gave children two-item delayed estimation trials. While we did see a wide range of individual variability in performance, some children were simply guessing. Due to this difficulty, perhaps the task was not as sensitive to individual differences in VWM precision in this age range. Future work into VWM precision with preschool-aged children should assess performance on a one-item task, as well.

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APPENDIX

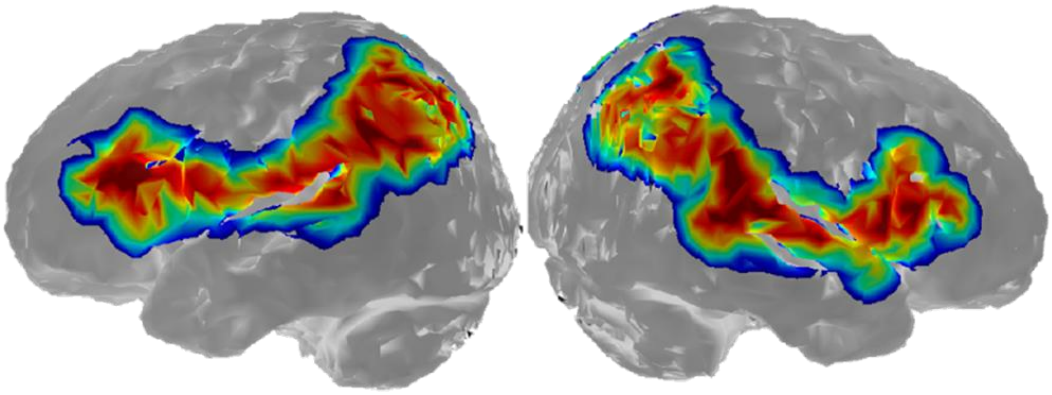


Figure A1

Sensitivity Profile of fNIRS Probe Over Bilateral Frontal, Temporal, and Parietal Regions

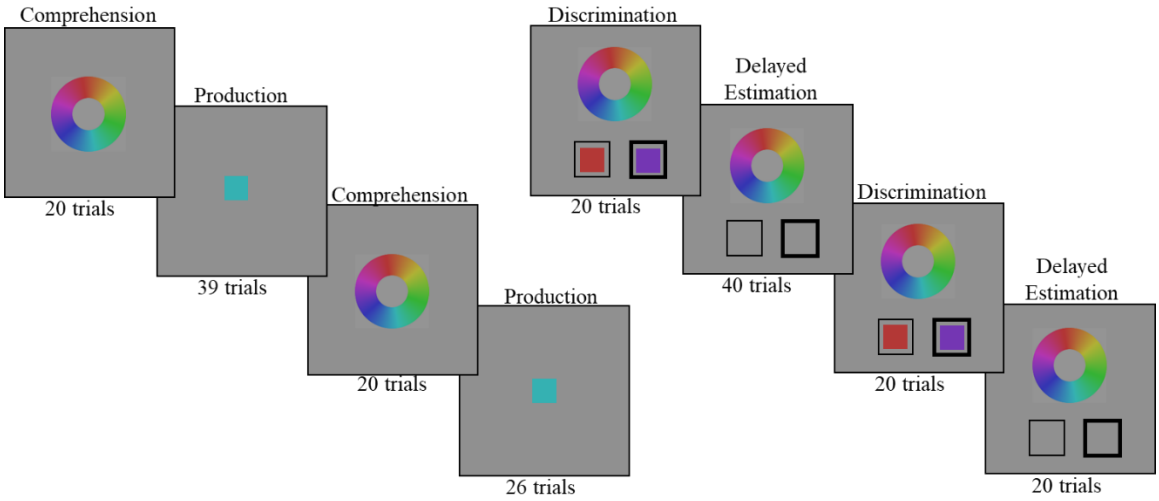


Figure A2

Block Layout of Tasks

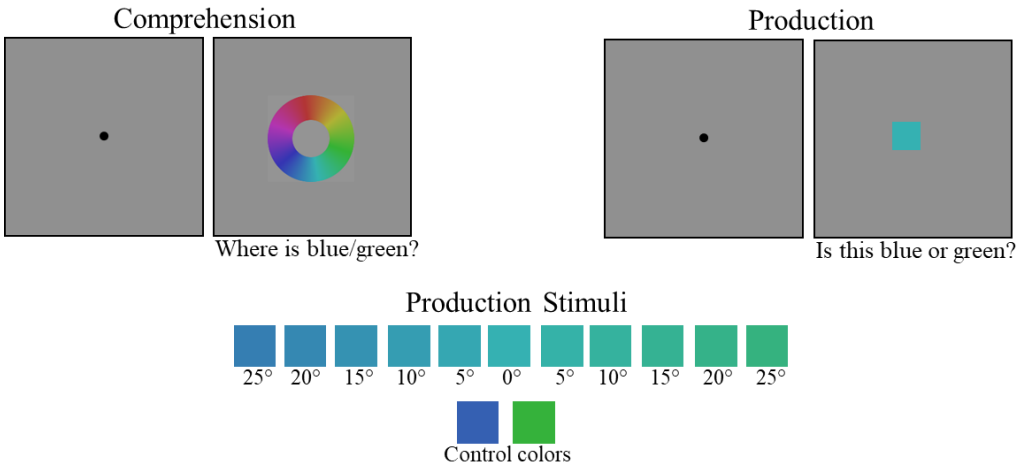


Figure A3

Continuous Production and Comprehension Dimensional Label Learning Tasks

$$y = \frac{maxY - minY}{1 + e^{\frac{-4*slope}{(maxY-minY)*(x-crossover)}+minY}}$$

Figure A4

Equation of Sigmoid Function for Production Task With Relevant Variables

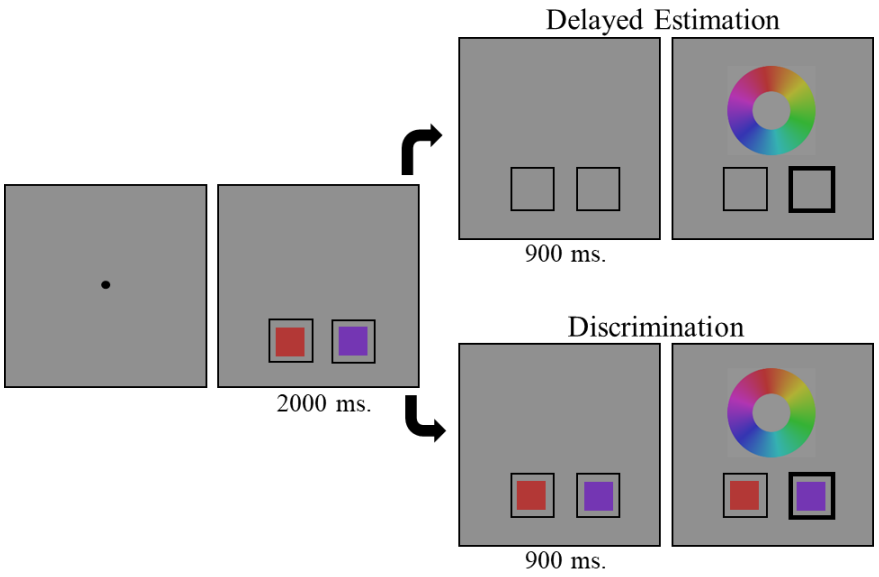


Figure A5

Trial Layout of Delayed Estimation and Discrimination Tasks

$$p(\hat{\theta}) = (1-\gamma-\beta)\emptyset_\sigma(\hat{\theta}-\theta) + \gamma\frac{1}{2\pi} + \beta\frac{1}{m}\sum_{i}^{m}\emptyset_k(\hat{\theta}-\emptyset_i) + \gamma\frac{1}{2\pi}$$

Figure A6

Model from Bays et al., 2009.

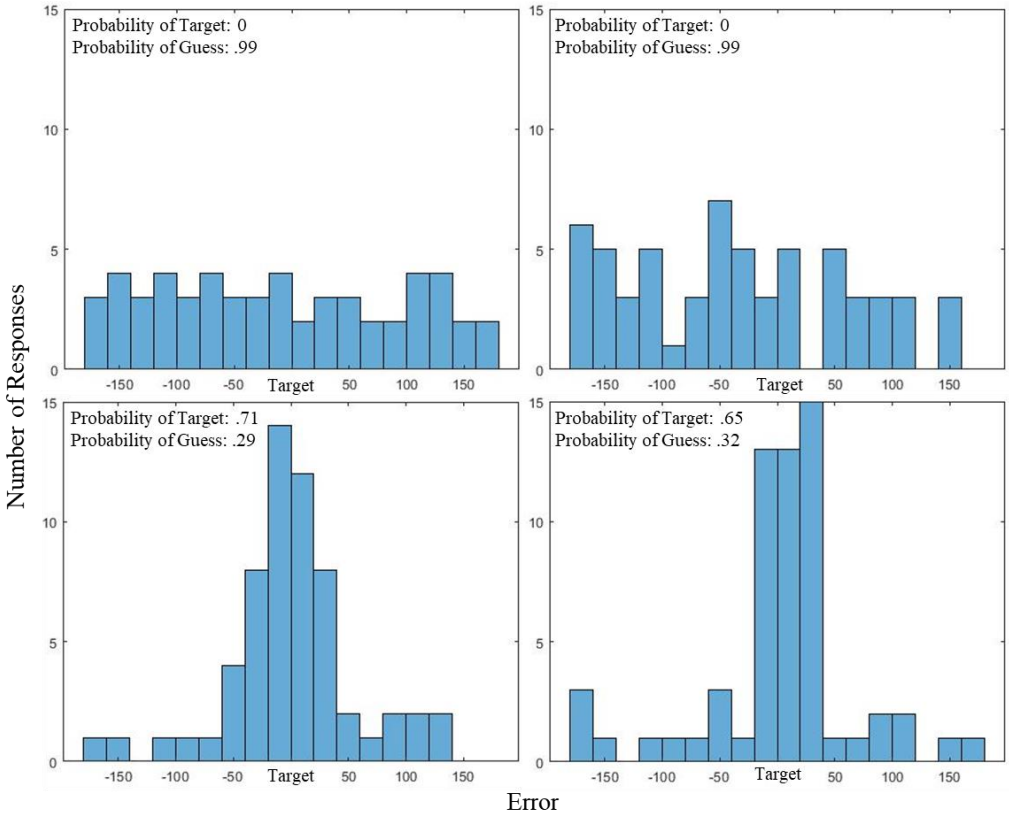


Figure A7

Histograms of Four Children's Response Distributions for the Target in Delayed Estimation Task

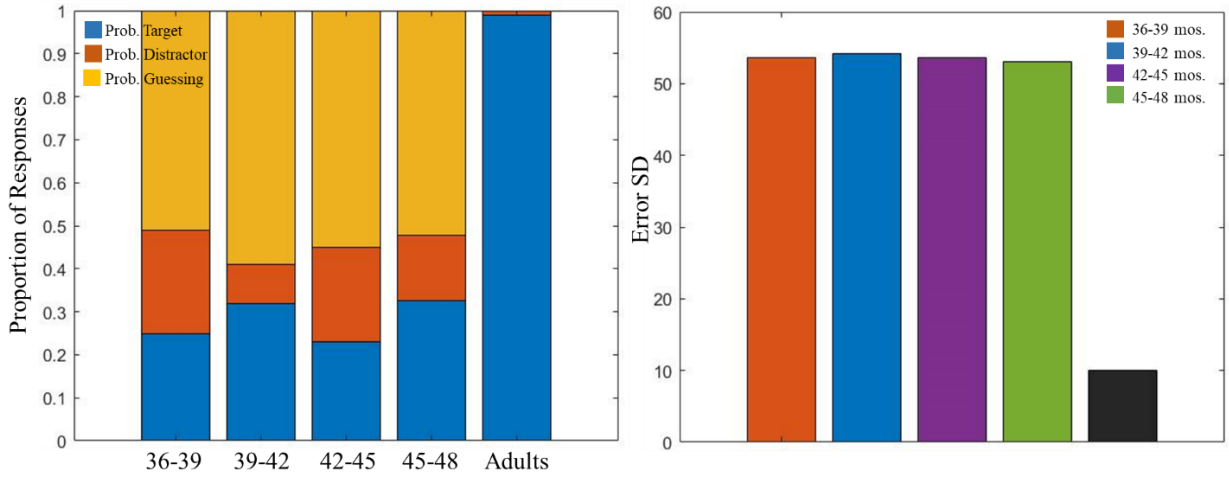


Figure A8

Summary of Delayed Estimation Behavioral Results

Table 1

Delayed Estimation Behavioral Results

Age Group (mos.)	*Prob. Target*	*Prob. Distractor*	*Prob. Guess*	*Absolute Error SD*
36-39	.25	.24	.25	53.68
39-42	.32	.09	.32	54.22
42-45	.23	.22	.23	53.64
45-48	.32	.15	.32	53.05
Adults	.99	.01	.99	10.02

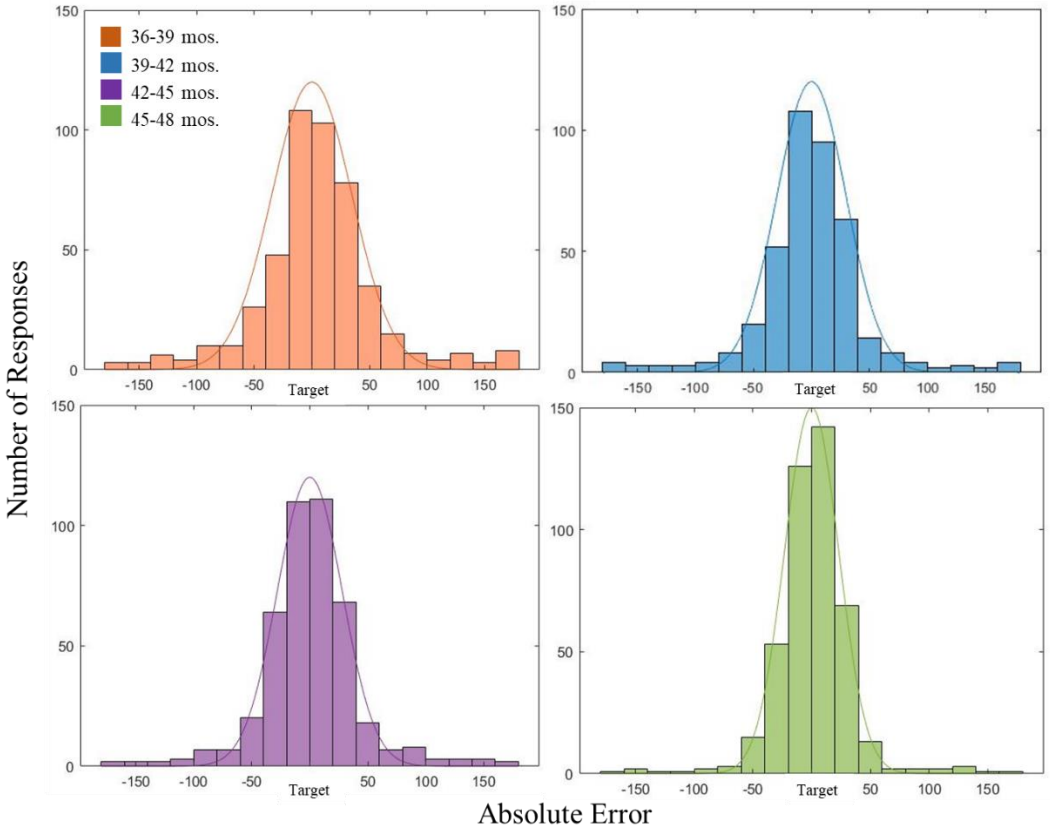


Figure A9

Gaussians and Response Distributions for the Discrimination Task Per Age Group

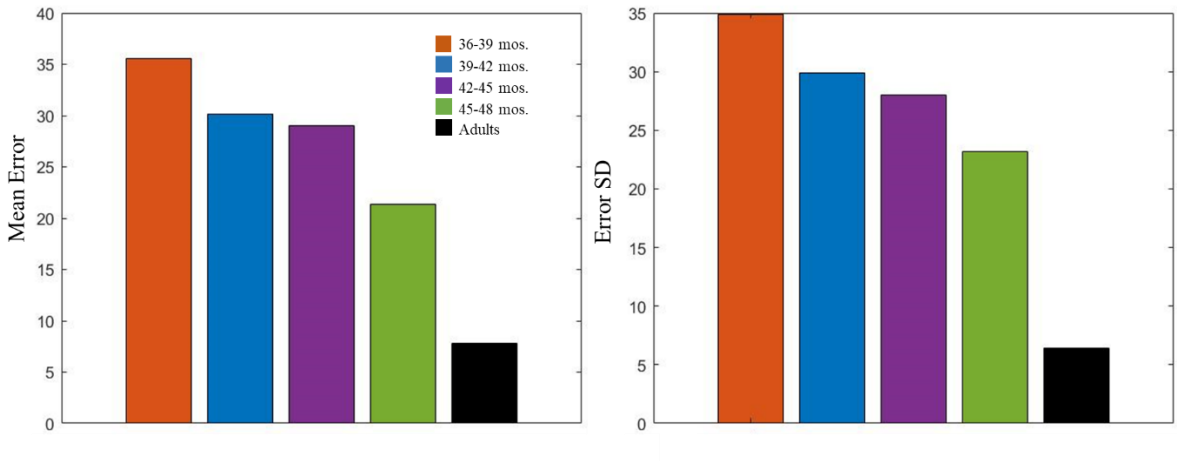


Figure A10

Mean Error and Error Standard Deviation Per Age Group on the Discrimination Task

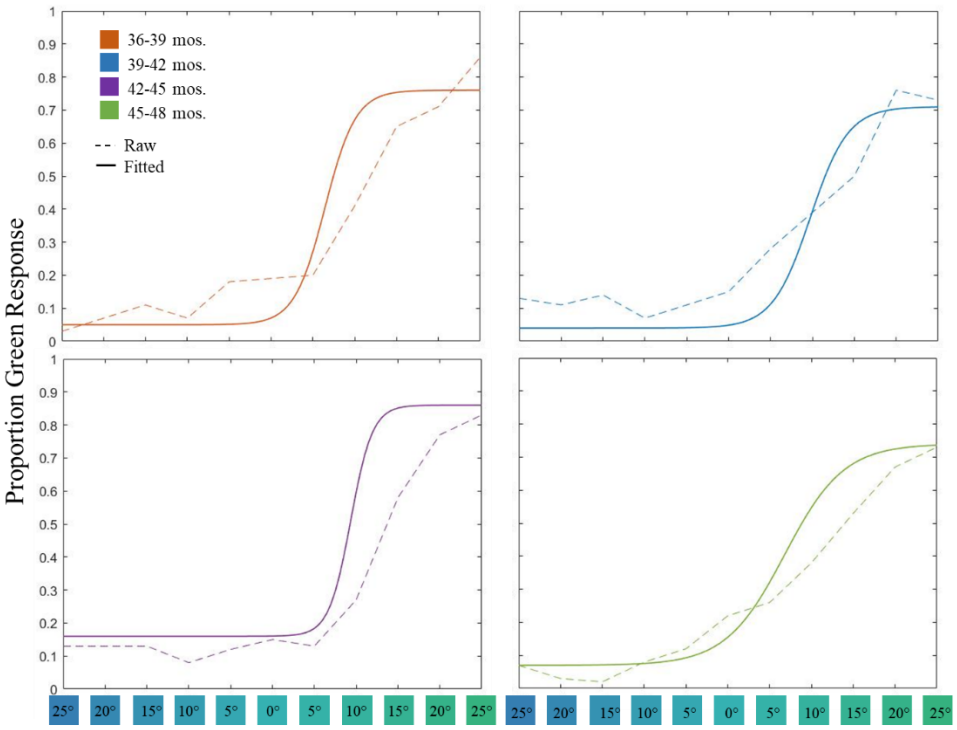


Figure A11

Raw and Fitted Curves for the Production Task Per Child Age Group

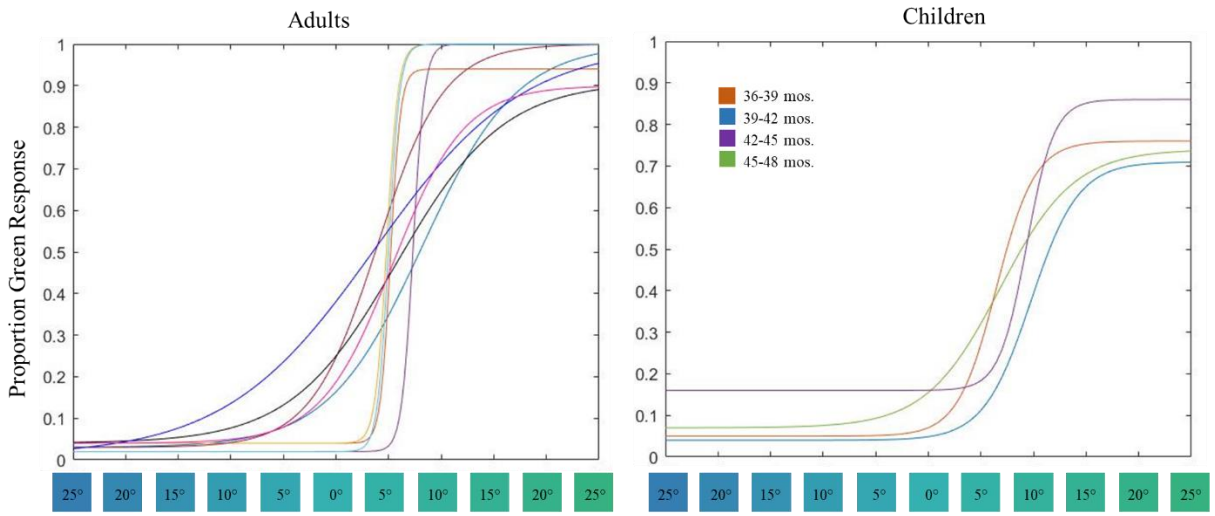


Figure A12

Fitted Sigmoid Curves for Adults and Children in the Production Task

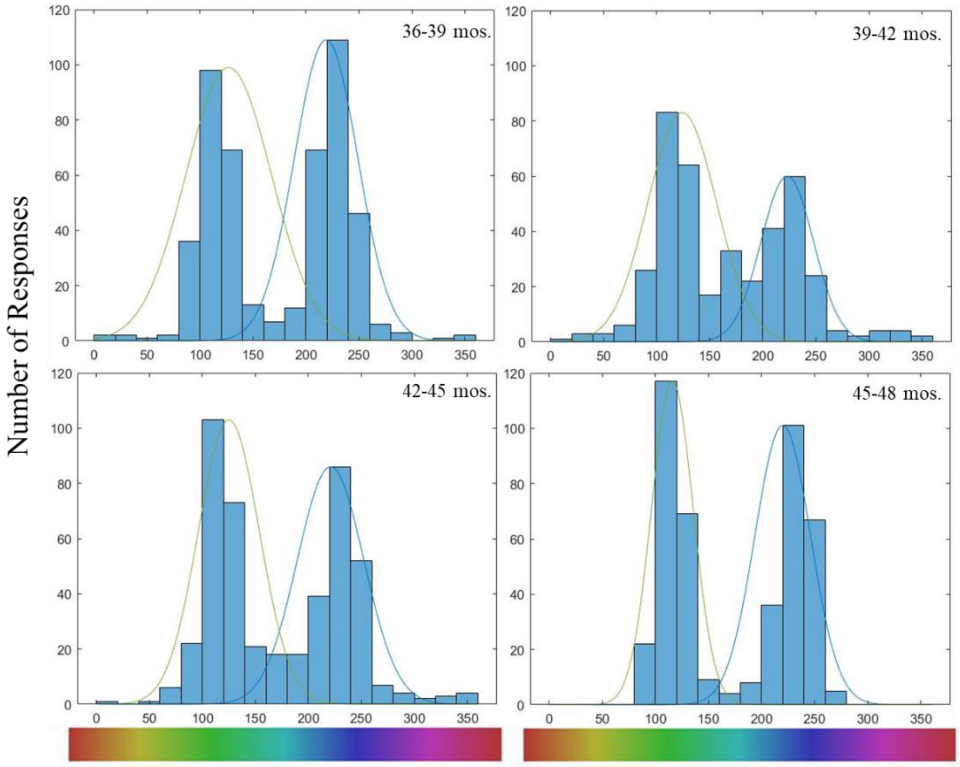


Figure A13

Raw Response Distributions and Gaussians for Comprehension Performance

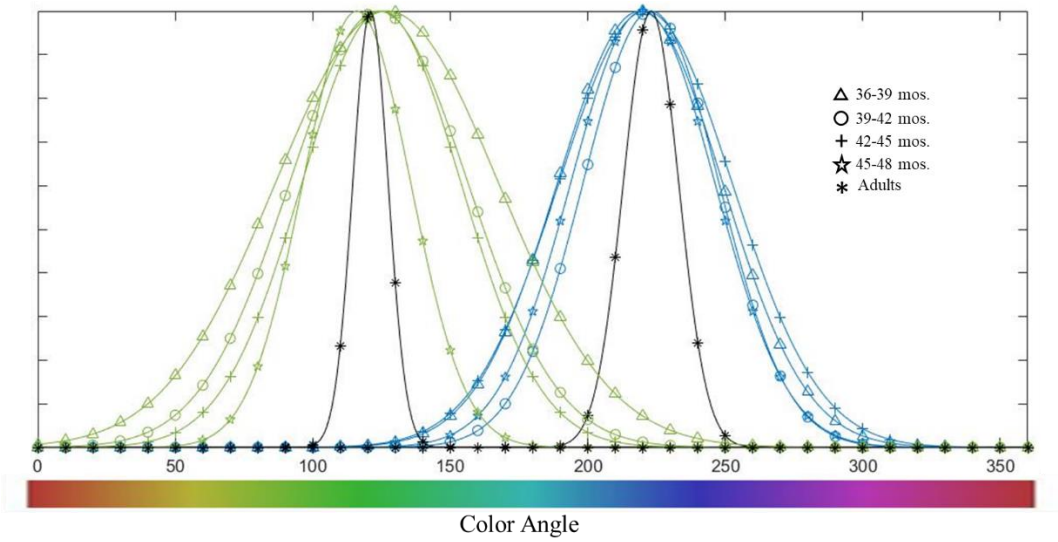


Figure A14

Comprehension Performance for Children and Adults

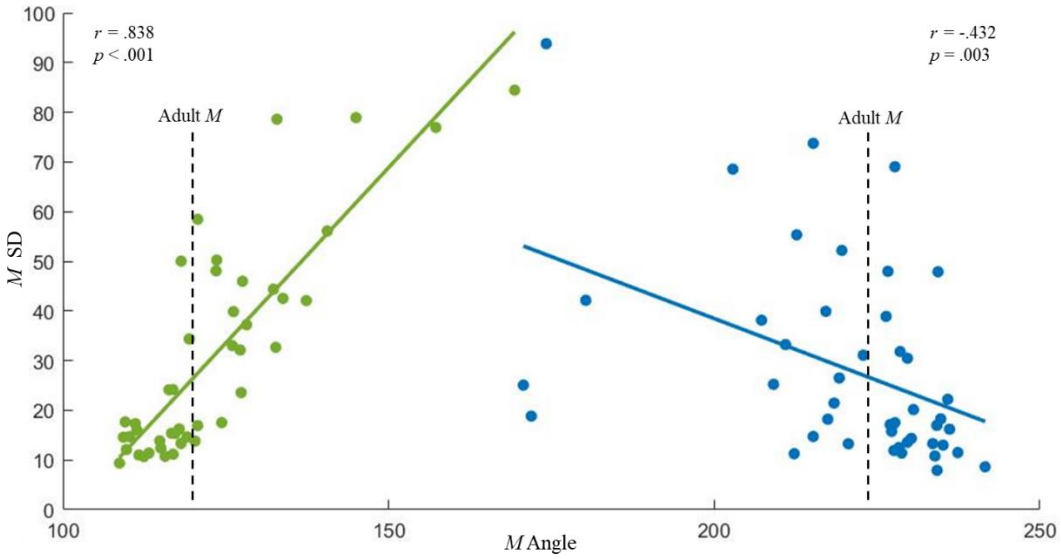


Figure A15

Correlations Between Mean Color Angle and Standard Deviation for Comprehension

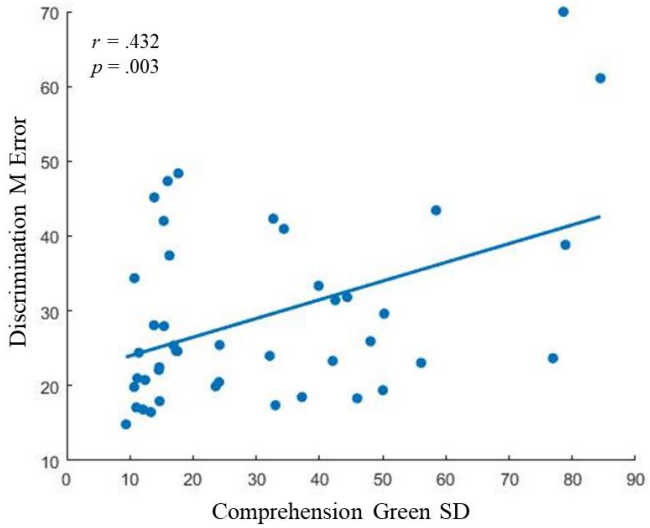


Figure A16

Correlation Between the Color Discrimination and Comprehension Tasks

Table 2

Significant Clusters from the ANOVA

Effect	Voxels	MNI Coordinates			Location	Trend
		x	y	z		
Oxy	1401	60	16	20	L Postcentral Gyrus	HbR>HbO
	199	-47	73	22	R Middle Temporal Gyrus	HbO>HbR
OxyxTask	323	-56	-13	8	R Inferior Frontal Gyrus	Discrim. HbO > Delayed Estim. HbO
	266	46	-36	15	L Inferior Frontal Gyrus	Delayed Estimation HbO > Discrim. HbO
	198	62	9	14	L Postcentral Gyrus	HbR>HbO for Delayed Estim.

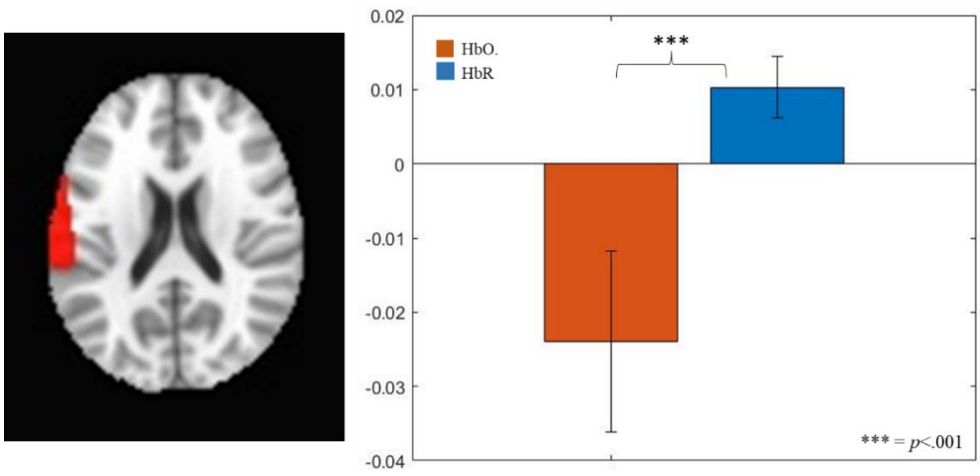


Figure A17

Brain Image and Bar Chart for Oxy Effect in Left Postcentral Gyrus

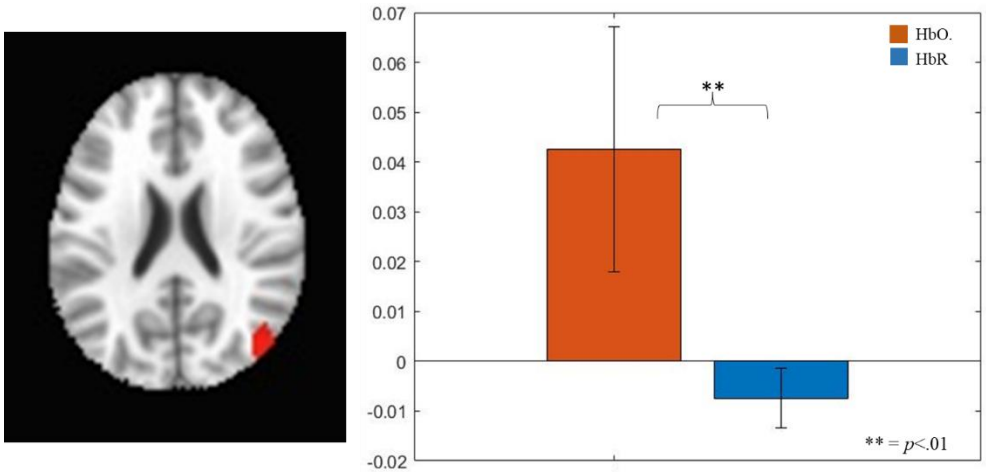


Figure A18

Brain Image and Bar Chart for Oxy Effect in Right Middle Temporal Gyrus

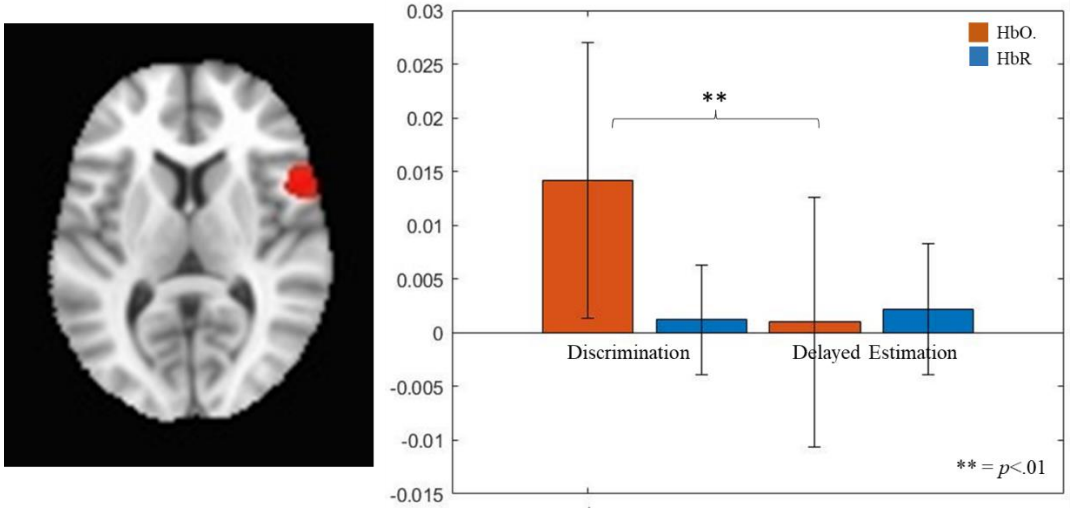


Figure A19

Brain Image and Bar Chart for Oxy x Task Interaction in Right Inferior Frontal Gyrus

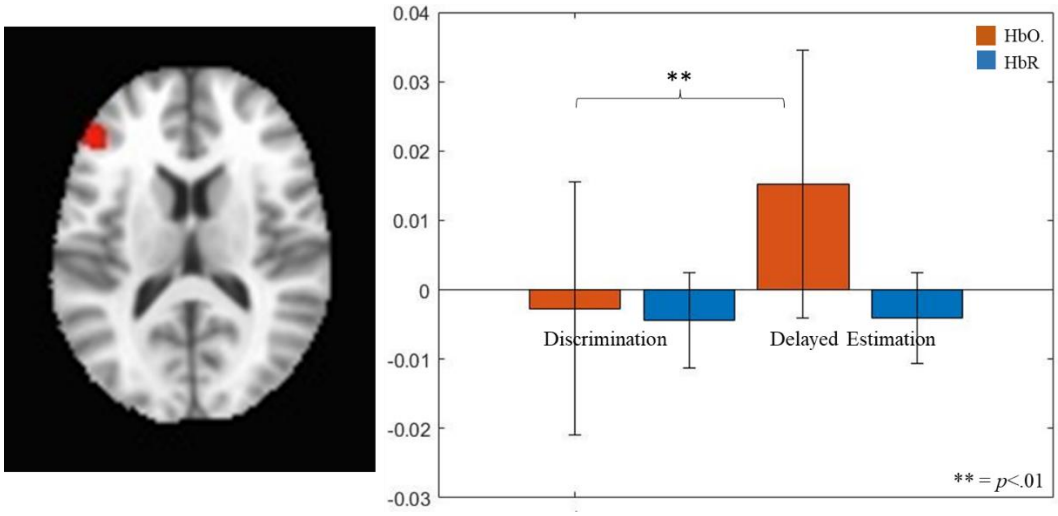


Figure A20

Brain Image and Bar Chart for Oxy x Task Interaction in Left Inferior Frontal Gyrus

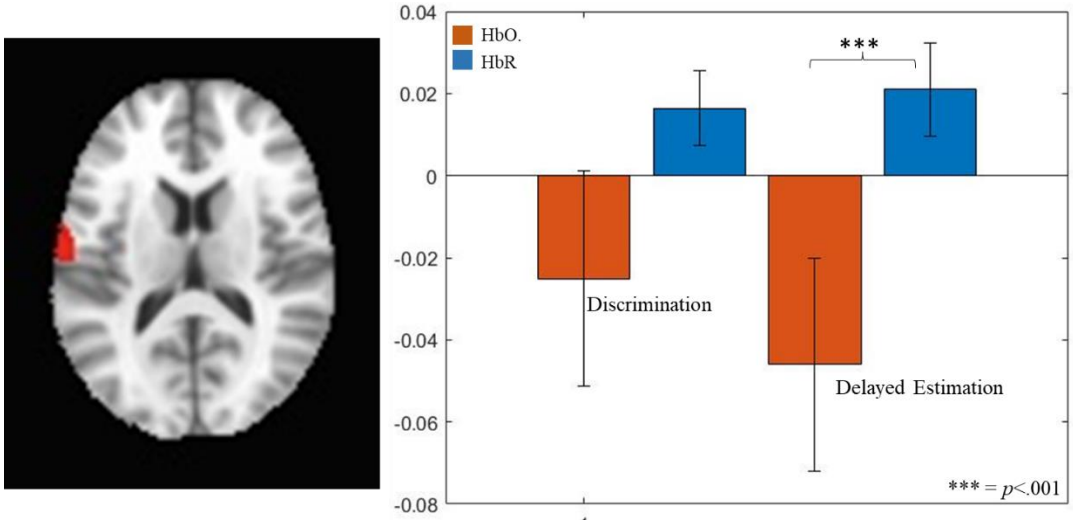


Figure A21

Brain Image and Bar Chart for Oxy x Task Interaction in Left Postcentral Gyrus

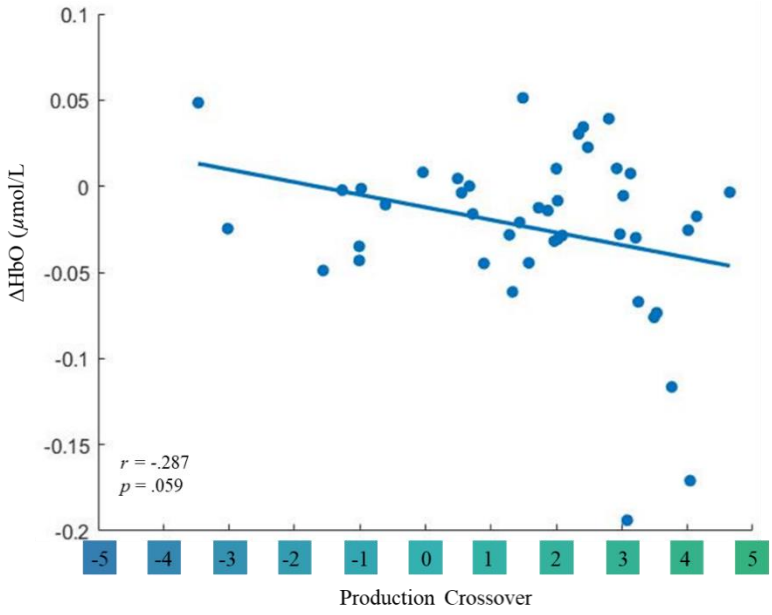


Figure A22

Correlation Between Delayed Estimation and Discrimination HbO and Production Crossover

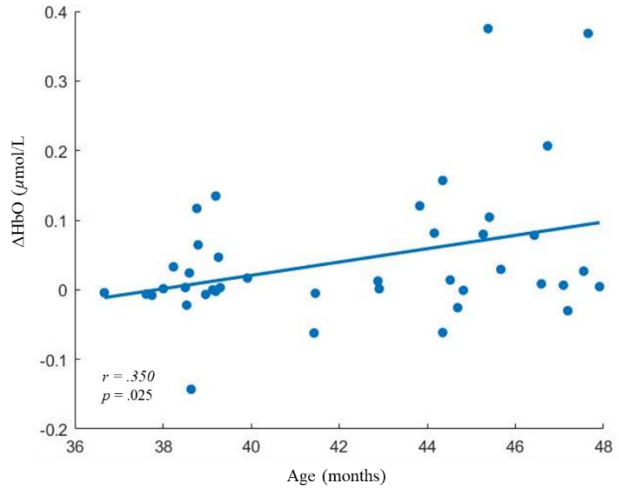


Figure A23

Correlation Between Delayed Estimation and Discrimination HbO and Age

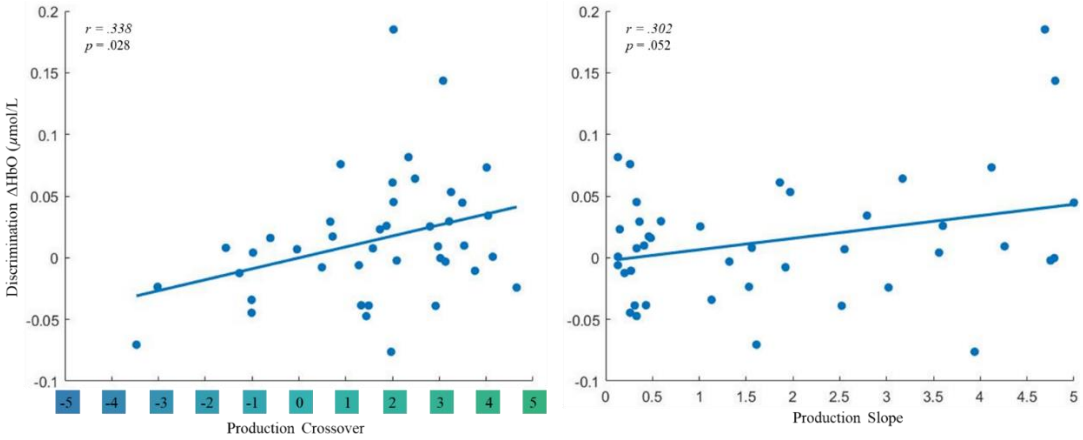


Figure A24

Correlations Between Discrimination HbO and Production Crossover and Slope

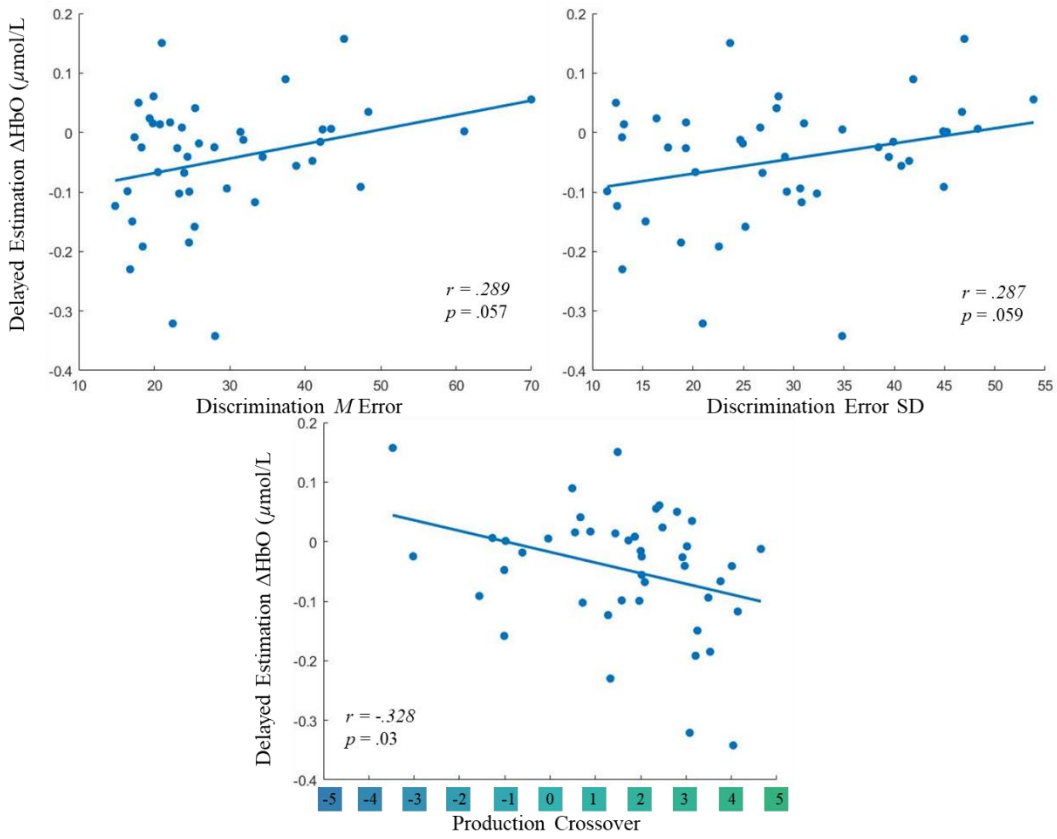


Figure A25

Correlations Between Delayed Estimation HbO, Discrimination Mean Error, Error SD, and Production Crossover

VITA

Kara Nicole Lowery was born on January 21, 1994, in Kalamazoo, Michigan. She graduated from Greensboro College Middle College in 2012. In May 2016, she graduated from the University of North Carolina at Greensboro with a Bachelor of Arts Degree in Psychology. In August of 2016, she entered the Experimental Psychology PhD program at the University of Tennessee, Knoxville, where she studied the development dimensional attention under Dr. Aaron Buss. Once she graduates with a PhD in December 2022, she plans to apply for industry jobs in user experience research.