Western Undergraduate Psychology Journal

Volume 5 | Issue 1 Article 7

2017

Age-Related Differences in Dorsolateral Prefrontal Cortex BOLD Activity during Cognitive Control Task: An fMRI Study

Hunster Yang
hyang322@uwo.ca

Age-Related Differences in Dorsolateral Prefrontal Cortex BOLD Activity during Cognitive Control Task: An fMRI Study

Hunster Yang*

Cognitive control is used in everyday life to inhibit inherent thoughts and actions to successfully complete a given task. The current investigation used a subset of the overall data set from a larger study (Wilk & Morton, 2012). Participants completed a size-congruency task, while their blood-oxygen-level dependent (BOLD) activity was measured through functional magnetic resonance imaging (fMRI). Region of interest analyses revealed no significant age-related differences in the dorsolateral prefrontal cortex (dlPFC) BOLD activation. Nonetheless, the findings of this study confirmed that the left and right dlPFC are indeed involved during cognitive control processing. Additionally, through exploratory analyses, the right inferior frontal junction (IFJ) and right dorsal premotor cortex (dPMC) were revealed to have significant age-related increases in BOLD signal. Future studies should further examine the potential age-related changes in the dlPFC, along with other various brain regions to investigate possible functional networks that may be responsible for cognitive control.

Every day, cognitive control is used to synthesize reasoning processes using rules to reach internal goals during a complex task (Koechlin, Ody, & Kouneiher, 2003). Additionally, cognitive control involves the capability to ignore irrelevant information or usual thinking procedures, in order to successfully complete a given duty (Garavan, Ross, & Stein, 1999). In turn, cognitive control is necessary for everyday life, and assists cognition procedures such as planning, decision-making, and reasoning (Koechlin et al., 2003). Therefore, examining how individuals respond to cognitive control tasks is important, as it can assist with understanding how one thinks, acts, and arrives at conclusions in various situations. In particular, an area of research that is of growing interest is whether there are age-related differences in certain regions of the brain to identify areas that could be responsible for the development of cognitive control (Ezekiel, Bosma, & Morton, 2013; Friedman, Doreen, Cycowicz, & Horton, 2009; Rubia et al., 2006; Tsujimoto, 2008; Wendelken, Munakata, Baym, Souza, & Bunge, 2012).

Functional magnetic resonance imaging (fMRI) indirectly measures the neural activity of various brain areas through analyzing the BOLD signal, to suggest which specific regions in the brain could perhaps be accountable for the demands of cognitive control (Luna, Padmanabhan, & O'Hearn, 2010). Neurons that are active during a task would require more oxygen to function, and as a result, there would be an increased blood flow towards those neurons. Consequently, BOLD activity would rise in those areas, which can be detected by fMRI. As a result, through the use of fMRI, it can be possible to discover which specific brain regions are more activated during a task that requires cognitive control.

*Initially submitted for Psychology 3485F at the University of Western Ontario. For inquiries regarding the article, please email the author at *hyang322@uwo.ca*.

Studying the development of the brain associated with cognitive control is vital since the brain is dynamic and changing (Stiles & Jernigan, 2010). Throughout past literature, cognitive control development has been found to be measurable and linked with task performance. Exploring how the brain changes over time and how it affects executive function can provide insight to why children and adults may act differently in particular scenarios. For instance, Friedman and associates (2009) found that cognitive control elicited in children, young, and older adults were different, suggesting that there are age-related performance differences linked to cognitive control. In similar ways, Rubia et al. (2006) discovered increased BOLD activation in the prefrontal cortex (PFC) which was positively correlated with age and task performance. They suggested that as critical structures developed throughout childhood, so did cognitive control. Likewise, Ezekiel and colleagues (2013) proposed that there are age-related changes in the activation of specific PFC areas during a Dimensional Change Card Sort (DCCS) task, a procedure that assesses cognitive control. Therefore, it has been shown that the prefrontal regions of the brain are commonly emphasized in research regarding the development of cognitive control.

Within the PFC, the dorsolateral prefrontal cortex (dlPFC) specifically is an area that has been found to be strongly associated with cognitive control processing (Bahlmann, Korb, Gratton, & Friederici, 2005; Morton, Bosma, & Anasari, 2009; Wendelken et al., 2012). There have been numerous empirical studies that have found age-related changes in the dlPFC during cognitive control procedures. For instance, Morton and associates (2009) found that there are numerous regions in the brain, one of them being the dlPFC, that are correlated to cognitive control processes, such as dimensional shifts of attention. In similar ways, Bahlmann and colleagues (2005) also suggested that the bilateral dlPFC and rostral PFC are heavily involved in cognitive control processing. Likewise, the lateral PFC has been found to reveal age-related differences during the administration of the DCCS task, as rule switching appeared to occur more slowly in children than adults (Ezekiel et al., 2013). In the same way, Waxer and Morton (2011) discovered that children had slower response times overall during the completion of the DCCS task. Lastly, Wendelken et al. (2012) found age-related changes in the left dlPFC BOLD activation, as children updated task rules more slowly than adults. It is evident that there has been vast research on the link between dlPFC BOLD activity and the development of cognitive control. Furthermore, it has been revealed that the PFC is late developing, and may take up to two decades until it reaches full maturity (Diamond, 2002). By comparing the BOLD activity in the dlPFC between children and adults, it could be determined which age group involves more recruitment in the dlPFC, and as a result, can attempt to explain various performance differences associated with cognitive control amongst children and adults.

As an extension of previous literature, the current investigation explores and aims to answer the question of whether or not the blood-oxygen-level dependent (BOLD) activation in the dorsolateral prefrontal cortex (dlPFC) is greater in adults compared to children during the administration of a cognitive control task. This investigation uses a subset of the overall data set from the Wilk and Morton (2012) study. Cognitive control is measured by a standard stimulus–response compatibility task of size-congruency that involves compatible and incompatible trials, in which participants select the numerically larger digit. This procedure assesses cognitive control based on the size-congruity effect (Henik & Tzelgov, 1982), since the incompatible trials require the inhibition of the intrinsic tendency of selecting the physically larger digit, despite it being smaller in numerical value. The measure of cognitive control would then be determined by taking the difference found between incompatible and compatible. The main goal of the present study is to explore how the neural activity in the dlPFC differs in children and adults during their performance of

this specific cognitive control task. This study aims to serve as an extension of previous literature, as this experiment solely examines the left and right dlPFC, along with whether or not there are age-related increases in the BOLD activation. In contrast, past research has analyzed multiple brain areas to suggest regions that are involved during the performance of other cognitive control tasks, such as DCCS task, dimensional shifts of attention, Stroop task. This study will aim to confirm past research findings, specifically the role of the dlPFC during cognitive control tasks. Additionally, the current experiment will be extending past literature by using a different cognitive control measure, one that involves size-congruency; as well as comparing the dlPFC BOLD activation between children and adults, through conducting region of interest (ROI) analyses on the dlPFC bilaterally.

Based on the aforementioned studies and as an extension from the foundation of past literature, it is hypothesized that in comparison to children, adults will have greater BOLD activity in the dlPFC bilaterally during the incompatible trials of the cognitive control task. Since the PFC is late developing (Diamond, 2002), it is predicted that children will possibly not have substantial BOLD activity during the demanding incompatible condition, and thus there should not be a significant difference between their BOLD signal during the incompatible and compatible trials. It is hypothesized that adults will likely have an easier time completing the task, and with their matured PFC, they will have greater BOLD activity in the dlPFC during the incompatible trials than compatible trials, as the former will likely require more cognitive control. Therefore, it is expected that there will be age-related increases in the dlPFC BOLD activity, through adults displaying greater BOLD activation in the dlPFC bilaterally than children, during the administration of a cognitive control task. In terms of behaviour, children should have greater response times than adults, due to their underdeveloped PFC and decreased ability to elicit cognitive control. It is predicted that there will be significant age-related differences in response times between incompatible and compatible trials. Likewise, it is hypothesized that all participants would be more accurate during compatible trials, since incompatible trials are more cognitively demanding and would require more cognitive control.

Method

This investigation used a subset of the overall data set from a larger study conducted by Wilk and Morton (2012), thereby all procedures were approved by the University Research Ethics Board for Health Sciences Research at Western University, Canada, and are in agreement with the 1964 Declaration of Helsinki.

Participants

There were a total of 12 participants in this study; six children aged 9 to 12 years ($M = 10.76$, $SD = 0.85$), and six adults aged 18 years and older ($M = 26.40$, $SD = 3.51$). Participants who were younger than 18 years of age ($n = 6$) were recruited from Western University's Child Development Participant Pool. Written consent was acquired from parents of these participants for their child's participation, and the children provided verbal assent. Participants who were 18 years of age and older ($n = 6$) were recruited from the undergraduate and graduate student populations of Western University, and they provided written consent for their participation. All participants were right-handed, and had normal or corrected-to-normal vision.

Size-Congruency Task

Participants were administered a cognitive control task, a stimulus–response compatibility task of size-congruency, that involved compatible and incompatible trials. Participants were presented concurrently with two white Arabic digits that differed in physical font size and numerical value for 1950 ms on a black background, however they were to only press the button that corresponded to the numerically larger digit. The numbers ranged in value from 1 to 9. Physically larger digits were

presented in a 60-point font, while physically smaller numbers were presented in a 30-point font. The compatible stimuli involved numerically larger numbers that were also physically larger, while the incompatible stimuli had numerically larger numbers that were physically smaller than the other numbers (see Figure 1). Participants were presented with compatible trials 75% of the time and incompatible trials 25% of the time, along with a random distribution of trials during a 16-trial block. Hence, 75% of the trials (i.e., 12 of 16) were compatible, and 25% of the trials (i.e., 4 of 16) were incompatible. At the beginning, there were three start trials added to offset expectations, and these were solely compatible stimuli. As well, trials were randomly jittered by means of an inter-trial interval that ranged from 1500 ms to 4500 ms. Through a mirror attached to the head coil in the fMRI, participants viewed the stimuli and responded with their right index and middle fingers via a button box. A total of four separate 7.8-minute runs were administered, however the current study only analyzed the data from the first two runs.

This procedure measured cognitive control based on the size-congruity effect (Henik & Tzelgov, 1982), since the incompatible trials required the inhibition of the inherent tendency of selecting the physically larger digit, despite it being smaller in numerical value. As well, the presentation of incompatible stimuli was rare and infrequent, which will likely require more cognitive control from participants to inhibit the normal, inherent decisions involved with the compatible stimuli.

fMRI Data Acquisition

A 3 T Siemens Tim Trio MRI System with a Siemens 32-channel head coil was used to collect data. Participants under 18 years of age received training in a 0 T mock-scanner to allow them to become comfortable with the scanning environment, while alleviating fear and uncertainty in regards to the experimental procedure. Two T2*-weighted functional scans were collected from each participant in a single scanning session, each run consisting of 234 whole-brain volumes. Functional volumes consisted of 32 slices, each with a thickness of 3 mm, resulting in a 3 x 3 x 3 mm voxel resolution. There were no gaps between slices. Additionally, to aid the visualization of the functional analyses, one T1-weighted anatomical scan was collected from each participant. It contained 192 slices, each with a thickness of 1 mm, yielding a 1 × 1 × 1 mm voxel resolution.

fMRI Data Preprocessing

Data were preprocessed using Statistical Parametric Mapping (SPM) software. Four preprocessing procedures were applied in order to remove uninteresting variability from the data, in order to increase the functional signal to noise ratio, and prepare the data for statistical analyses. Firstly, data were motion-corrected by using the first volume from the first run as a reference volume, and realigning subsequent functional volumes to the reference by applying transformations. Motion graphs were generated for each participant. Motion was restricted to 3.0 mm of drift across each run, and random spikes could not be greater than 1.5 mm. Based on these restrictions, no participants were excluded from further preprocessing on the basis of excessive motion. After realignment, co-registration was conducted where the T2*-weighted functional volumes were overlapped onto the T1-weighted anatomical scan, in order to achieve the high resolution from the anatomical volumes. In order to compare various participants' brains, the functional volumes were then normalized by warping the images onto a standardized stereotaxic space (i.e., a T1-weighted anatomical template within SPM). Lastly, smoothing was applied to the functional volumes using an 8 x 8 x 8 mm Gaussian blurring kernel to remove variations in functional and gyral anatomy. In other words, this process averaged out the intensities from neighbouring voxels, in order to increase the signal to noise ratio.

Analysis

Single-Subject Analysis

Using SPM, BOLD responses were estimated by a General Linear Model (GLM) through event-related predictors for every participant. This design matrix had a total of 20 predictors; nine predictors were created for each run, and one predictor per run accounted for residual error or noise. The first two predictors for each run described when the compatible and incompatible trials were administered by using a vector of onsets. The third predictor explained errors participants made, while the fourth to ninth variables accounted for motion. The two behavioural predictors had to be converted into physiological predictors by creating box-car functions for the correct compatible and incompatible onsets. The box-car functions created were uniform distributions between zeros and ones, which corresponded to when the specific trials were off or on respectively. These functions were then convolved with the hemodynamic response function, which resembles the BOLD signal of blood flow directed to active neurons. The hemodynamic response function consists of a spike that relates to increased oxygenated blood, followed by a subsequent decrease to return blood flow to homeostatic levels.

The GLM generated 20 beta-coefficients associated with each of the event-related predictors. The beta-coefficients were positive when the magnitude of BOLD response increased with the onset of the corresponding type of trial, and negative when the magnitude of the BOLD response decreased with the onset of the respective type of trial. Contrast of the first two beta-coefficients for each run, the compatible and incompatible trials, were computed for each voxel, to identify brain regions associated with cognitive control. A t-statistic for each voxel was calculated using the equation t–statistic = (β(incompatible)-β(compatible))/variance. Scaled images for each participant were produced, and it demonstrated voxels in which the t-statistic differed from zero, using p = .05 (uncorrected).

Group Analysis

The beta-coefficients computed from the difference between incompatible and compatible trials for each voxel in every participant were averaged across all child and adult participants. However, only four of the six adult participants were included due to file formatting issues within SPM. Nonetheless, two group analyses were processed resulting in two group contrast maps; one group contrast map (n = 6) was for child participants, and one contrast map (n = 4) was for adults. These group contrast maps represented areas of increased BOLD activity common to all participants when comparing incompatible trials to compatible. The resulting maps were not corrected for multiple comparisons, and the significance threshold was set at p = .05, in order to display an adequate amount of voxels that were activated. Additionally, the group contrast maps were overlapped on top of each other using Adobe Photoshop software, to demonstrate similarities and differences in spatial distribution of BOLD activation. Lastly, exploratory examinations of the group maps were conducted to discover any notable regions in the brain that were activated during the cognitive control task.

Region of Interest (ROI) Analysis

Using MarsBaR ROI toolbox within SPM, ROI analyses were conducted for the left and right dlPFC. In order to create the ROI, Montreal Neurological Institute (MNI) coordinates for the left and right dlPFC had to be determined. Based on Cohen, Gallen, Jacobs, Lee, and D'Esposito's (2014) experiment, they determined the MNI coordinates for left and right dlPFC as (-43, 21, 38) and (43, 21, 38) respectively. To confirm that these coordinates were the left and right dlPFC, we compared the ROIs to an anatomical visual brain map. The ROIs created were 7 mm spheres surrounding the centre coordinates, with a volume of 1344 mm3. The ROI analyses were conducted through averaging the beta-coefficients from the

two ROIs in every participant, resulting in two averaged beta-coefficients for the left and right dlPFC. Beta-coefficients for all the child and adult participants were then averaged separately for the left and right dlPFC. Unpaired t-tests for the ROIs were computed for the left and right dlPFC in children and adults, in order to determine whether or not there were age-related differences in the dlPFC BOLD activation bilaterally during a cognitive control task.

Results

Behaviour

Analyses of variance (ANOVA) were conducted to analyze potential age-related differences in behaviour. In general, response times diminished as age increased (Figure 2). Children had significantly greater behavioural response times than adults, $F(1, 10) = 64.59$, $p < .001$. Similarly, the averaged difference scores between incompatible and compatible stimuli for response times were greater in children ($M = 37.99$ ms, $SD = 54.68$ ms) than adults ($M = 18.30$ ms, $SD = 21.08$ ms). However contrary to predictions, there were no statistically significant age-related differences between the response times during incompatible and compatible stimuli, $F(1, 10) = 0.68$, $p = .43$.

In terms of accuracy, participants of all ages made significantly fewer errors when responding to compatible stimuli ($M = .99$, $SD = .01$) than incompatible stimuli ($M = .97$, $SD = .01$) as expected, $F(1, 10) = 14.27$, $p = .001$. There were no significant age-related differences in accuracy between incompatible and compatible stimuli, $F(1, 10) = 2.29$, $p = .16$.

Single-Subject Analysis

A total of 12 contrast maps ($p = .05$, uncorrected) were produced from the single-subject analyses (Figure 3). The regions that were associated with greater BOLD activity during incompatible trials than compatible trials were the areas highlighted in the maps. In order to test for age-related differences, solely comparing single-subject contrast maps were inadequate.

Group Analysis

Two group contrast maps ($p = .05$, uncorrected) were produced, one for children ($n = 6$) and another for adults ($n = 4$) (Figure 4). Statistically, multiple comparisons were not corrected for, as it would not have demonstrated substantial areas that were activated in the contrast maps. There were increases in BOLD activation of the dlPFC in both children and adults during the cognitive control task, by analyzing the group maps visually. Moreover, by overlaying the two group contrast maps together, it illustrated multiple similarities and differences in spatial distribution of BOLD activation (Figure 5). In addition to the dlPFC, exploratory analyses were conducted by comparing the child and adult group contrast maps. As shown in Table 1, three supplementary regions were visually found to have increased BOLD activity, which included the left anterior cingulate cortex (ACC), right inferior frontal junction (IFJ), and left dorsal premotor cortex (dPMC).

ROI Analysis

ROI analyses were performed to determine whether or not there were age-related differences in the left and right dlPFC BOLD activity between children ($n = 6$) and adults ($n = 6$) during a cognitive control task. Unpaired t-tests were conducted to compare the left and right dlPFC BOLD activation in children and adults. For the left dlPFC, there was not a significant difference in the scores between children ($M = 0.91$, $SD = 1.18$) and adults ($M = 1.64$, $SD = 1.62$), $t(10) = 0.88$, $p = .40$. For the right dlPFC, there also was not a significant difference in the scores between children ($M = 1.77$, $SD = 1.89$) and adults ($M = 3.19$, $SD = 2.27$), $t(10) = 1.17$, $p = .27$. As shown in Figure 6, the BOLD activations in both left and right dlPFC were greater in adults than children, however these differences were not statistically significant. There were no age-related increases found in the BOLD signal of the dlPFC during a cognitive control task, which was inconsistent with the hypotheses.

Based on the additional supplementary regions found activated in the group contrast maps, ROI analyses were also conducted for the left ACC, right IFJ, and left dPMC (Table 1). For the left ACC, no significant differences were found in the scores between children ($M = 0.16$, $SD = 0.13$) and adults ($M = 0.75$, $SD = 1.18$), $t(10) = 1.23$, $p = .25$. However, for the right IFJ, there were significant increases of BOLD activation in adults ($M = 2.86$, $SD = 1.75$) compared to children ($M = 0.27$, $SD = 0.11$), $t(10) = 3.63$, $p < .01$. Similarly, for the left dPMC, there were also significant increases of BOLD activity in adults ($M = 1.45$, $SD = 1.20$) than children ($M = 0.23$, $SD = 0.10$), $t(10) = 2.49$, $p = .03$. Therefore, the findings revealed age-related increases in the BOLD signal of both the right IFJ and left dPMC, but no significant differences in the left ACC.

Discussion

The present study predicted that adults would have greater BOLD activation in the dlPFC bilaterally than children during the administration of a cognitive control task. In other words, age-related increases in the dlPFC BOLD signal were hypothesized. Contrary to expectations, adults were found to not have significantly greater BOLD activation in the left or right dlPFC compared to children, while they were performing a cognitive control task. There were no age-related differences in dlPFC BOLD activity during processes that require cognitive control. In terms of behaviour, it was predicted that children would have greater response times than adults, due to their underdeveloped PFC and decreased ability to elicit cognitive control, which was consistent with the findings of this study. However, contrary to expectations, there were no age-related differences in response times between incompatible and compatible stimuli. Participants were more accurate during compatible trials than incompatible, which was in agreement with the hypotheses.

Inconsistent with the findings of this study, past literature suggested that the dlPFC is an area of the brain that is a part of the cognitive control network and should reveal age-related differences. For instance, Morton and colleagues (2009) proposed that increased dlPFC BOLD activation are correlated to dimensional shifts of attention, a process that requires cognitive control. Likewise, Wendelken and colleagues (2012) suggested that there are age-related differences in the left dlPFC BOLD activation, as children reorganized task rules more slowly than adults. Similarly, the lateral PFC has been found to reveal age-related behavioural differences during the administration of the DCCS task (Ezekiel et al., 2013). As well, past research has found that children had slower response times during the incongruent trials of the DCCS task (Waxer & Morton, 2011). Therefore, there has been vast research indicating that there should be age-related differences in the dlPFC BOLD activity during a cognitive control task.

However, the results of the present investigation did not find significant differences between the left and right dlPFC BOLD activity in children and adults. Nonetheless, based on the group contrast maps generated, increased BOLD signal of the left and right dlPFC were found in both children and adults (Figure 4), thereby demonstrating that the dlPFC is involved with cognitive control processing. Furthermore, based on the ROI analyses, the overall trends of the findings demonstrate that the dlPFC may indeed play a greater role in cognitive control tasks for adults than for children (Figure 6). The pattern of findings suggests additional investigations that will analyze these possible age-related differences in the dlPFC BOLD activation.

Additionally, the results of this study found immense similarities as well as differences in spatial distribution of BOLD activity in children and adults. As seen in Figure 5, there were various areas activated only in children, only in adults, as well as in both children and adults. This confirmed that there could be numerous other regions involved during a cognitive control task that are not solely the left and right dlPFC. Likewise, this investigation found three supplementary regions in the brain that visually showed increased

BOLD activity in both children and adults during a cognitive control task, which were the left ACC, right IFJ, and right dPMC (see Table 1). Furthermore, through ROI analyses of these supplementary regions, significant age-related increases of BOLD activity in the right IFJ and right dPMC were revealed. Based on past literature, these areas have been found to be involved with cognitive control processes, hence it is not shocking to find age-related changes in these regions (Ezekiel et al., 2013; Wilk, Ezekiel, & Morton, 2012; Wilk & Morton, 2012). However, similar to the dlPFC, the left ACC was shown to not have significant age-related changes, despite past research demonstrating that this area is linked with cognitive control performance. Nonetheless, the current results confirmed that the left ACC does indeed play a role during processes that require cognitive control. Consequently, the findings of this investigation not only suggest future studies to examine age-related increases in dlPFC BOLD activity, but also to explore potential age-related differences in BOLD activation of the left ACC. As well, the right IFJ, right dPMC, and other various regions should be examined further for involvement in a cognitive control network.

There were many limitations to this experiment that may shed light on reasons why no significant differences were found between the dlPFC BOLD activity of children and adults. A major limitation was the sample size used in the ROI analyses. Only data from six children and six adults were used in the current study, and as a result, it decreased the statistical power of the findings. For instance, Wendelken and associates (2012) analyzed 36 individuals in their fMRI study, which found a significant effect in the left dlPFC for rule switching. This study also had notable inter-subject variability in BOLD activation. For example, through visually comparing single-subject contrast maps in Figure 3, there were various regions that showed greater BOLD signal in one participant compared to the other. Moreover, another limitation to this experiment was the limited age groups and variation amongst the participants. Child participants were aged between 9-12 years, though previous literature confirmed that PFC development occurs throughout childhood (Diamond, 2002), as a result, the PFC of a 9-year-old may be very different compared to one of a 12-year-old. This study only analyzed BOLD activity between children and adults, thereby it was not fully inclusive at examining age-related differences since adolescents aged 13-17 years were not analyzed.

Additionally, another major limitation of the study was that this experiment only focused on the BOLD activation specifically in the dlPFC and three other supplementary regions. There were numerous other areas in the brain that could have been analyzed, which may have been of significance during cognitive control tasks (Figure 4 and Figure 5). Accordingly, there could have been many unreported findings in this study regarding age-related differences in BOLD activity of other brain regions.

Lastly, the method used to create the ROIs for the left and right dlPFC was a limitation. The ROIs created in the study adopted MNI coordinates that were used in a different study, and thus the ROIs created were not specific for the dlPFC of the participants in this particular experiment. This brings to question of whether or not the ROIs created were truly demonstrative of the left and right dlPFC.

One of the implications that could be drawn from the findings of this study is to question whether or not the size-congruency task is the best method to measure cognitive control activation in children and adults. Correspondingly, there were no differences found in the response times between incompatible and compatible trials, thereby bringing into question the validity of this measure. Many other studies that examined cognitive control processes used various other cognitive control methods, such as the Stroop Task, DCCS task, and Simon Task (Egner & Hirsch, 2005; Ezekiel et al., 2013; Liu, Banich, Jacobson, & Tanabe, 2004; Morton et al., 2009). The primary findings in this investigation were

inconsistent with past research, consequently it may be worthwhile to pursue a larger-scale study that incorporates multiple cognitive control tasks. Applying diverse cognitive control measures will allow the generalization of results to distinctive types of cognitive control, as well as discover whether various tasks would activate the same regions in the brain.

Furthermore, it is vital to examine age-related differences of the dlPFC during a cognitive control task, as it provides insight into the role of the dlPFC during cognitive control processing. For instance, based on Figure 4, the group contrast maps confirmed increases visually in BOLD activity during incompatible trials compared to compatible trials in the dlPFC. Additionally, studying age-related changes in BOLD activation of various brain regions can shed light to how those areas develop over time, how they affect cognition, and ultimately explain why children and adults may behave differently. Cognitive control is critical for functioning within everyday life; as a result, analyzing whether there are age-related differences could have applications to the education system, legal system, and understanding various diagnoses.

The present study suggests for future experiments to involve a larger sample size, in order to increase statistical power. Additionally, other investigations should include different age cohorts to be inclusive at examining age-related differences (i.e., 5-7 years, 8-10 years, 11-13 years, 14-16 years, 17-19 years, 20-22 years, 23-25 years, and 25+ years). Future studies should also include age as a regressor in the GLM, to be able to analyze age-related changes more accurately. Furthermore, another suggestion for future experiments involves the method of creating the ROIs for the left and right dlPFC. Instead of adopting MNI coordinates, utilizing anatomical brain mapping tools and templates could help in identifying the exact location of the dlPFC in participants, thereby creating the ROIs with more accuracy.

Moreover, future studies should also further analyze the dlPFC and the left ACC, since both areas revealed no significant age-related differences in BOLD activity. These statistically insignificant findings could have been due to some of the limitations as stated, and as a result, it may be worthwhile to examine these regions in future experiments. The other two supplementary regions, the right IFJ and right dPMC, that demonstrated significant age-related increases should also be examined further to confirm the findings of this investigation. Lastly, future studies should examine other brain areas because as shown in Figures 4 and 5, there were numerous areas activated that could have possible age-related differences during cognitive control tasks. Multiple regions activated in the brain could also suggest a functional network of regions working together to elicit cognitive control.

In conclusion, this fMRI study examined age-related differences in BOLD activity of the dlPFC during a size-congruency cognitive control task. It was hypothesized that adults would have greater BOLD activation in the dlPFC bilaterally than children, when comparing incompatible and compatible trials. However, no significant differences were found between children and adults in their left and right dlPFC BOLD signal. These results contradict previous research that have suggested age-related differences in the dlPFC BOLD activity during a cognitive control procedure. Nonetheless, the findings of this study indicate that the dlPFC does indeed play a role during processes that involve cognitive control. Additionally, through exploratory analyses, three supplementary regions of the brain were visually found to have increased BOLD activation, which included the left ACC, right IFJ, and right dPMC. The left ACC was shown to have no statistically significant differences in BOLD signal between children and adults; however, the right IFJ and right dPMC were revealed to have significant age-related increases in BOLD activity during a cognitive control task. The general trends of the results propose possible age-related increases in BOLD

activation of the dlPFC and left ACC, though future studies should be conducted to further analyze these potential differences. Finally, the right IFJ, right dPMC, and other various brain regions should be examined further in future investigations to analyze possible functional networks responsible for cognitive control.

First Received: 01/15/2017

Final Revision Received: 06/29/2017

References

Bahlmann, J., Korb, F. M., Gratton, C., & Friederici, A. D. (2012). Levels of integration in cognitive control and sequence processing in the prefrontal cortex. PLoS ONE, 7, e43774.

Cohen, J. R., Gallen, C. L., Jacobs, E. G., Lee, T. G., & D'Esposito, M. (2014). Quantifying the reconfiguration of intrinsic networks during working memory. PLoS ONE, 5, e106636.

Diamond, A. (2002). Principles of frontal lobe function. New York, NY: Oxford University Press.

Egner, T., & Hirsch, J. (2005). The neural correlates and functional integration of cognitive control in a stroop task. NeuroImage, 24, 539-547.

Ezekiel, F., Bosma, R., & Morton, J. M. (2013). Dimensional change card sort performance associated with age-related differences in functional connectivity of lateral prefrontal cortex. Developmental Cognitive Neuroscience, 5, 40-50.

Friedman, D., Nessler, D., Cycowicz, Y. M., & Horton, C. (2009). Development of and change in cognitive control: A comparison of children, young and older adults. Cognitive, Affective, & Behavioral Neuroscience, 9, 91-102.

Garavan, H., Ross, T. J., & Stein, E. A. (1999). Right hemispheric dominance of inhibitory control: An event-related functional MRI study. Proceedings of the National Academy of Sciences, 96, 8301-8306.

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. Memory & Cognition, 10, 389-395.

Koechlin, E., Ody, C., & Kouneiher, F. (2003). The architecture of cognitive control in the human prefrontal cortex. Science, 302, 1181-1185.

Liu, X., Banich, M. T., Jacobson, B. L., & Tanabe, J. L. (2004). Common and distinct neural substrates of attentional control in an integrated simon and spatial stroop task as assessed by event-related fMRI. NeuroImage, 22, 1097-1106.

Luna, B., Padmanabhan, A., & O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? Brain and Cognition, 72, 101-113.

Morton, J. B., Bosma, R., & Anasari, D. (2009). Age-related changes in brain activation associated with dimensional shifts of attention: An fMRI study. NeuroImage, 46, 249-256.

Rubia, K., Smith, A. B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., & Brammer, M. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. Human Brain Mapping, 27, 973–993.

Stiles, J., & Jernigan, T. L. (2010). The basics of brain development. Neuropsychology Review, 20, 327-348.

Tsujimoto, S. (2008). The prefrontal cortex: Functional neural development during early childhood. Neuroscientist, 14, 345-358.

Waxer, M., & Morton, J. B. (2011). The development of future-oriented control: An electrophysiological investigation. NeuroImage, 56, 1648-1654.

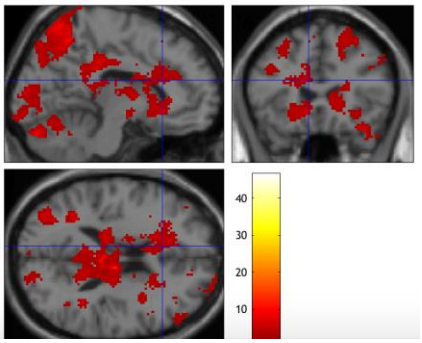
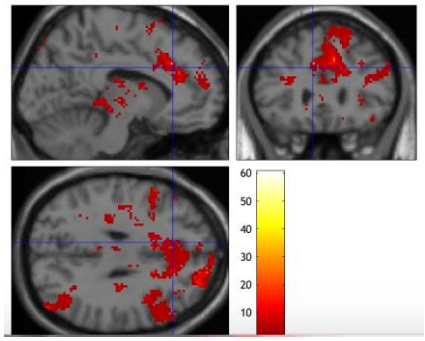
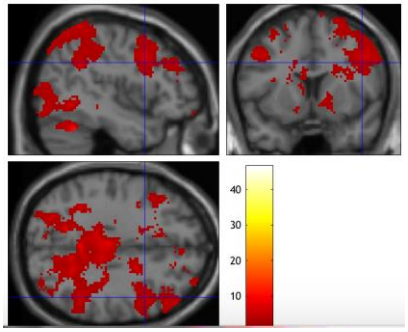
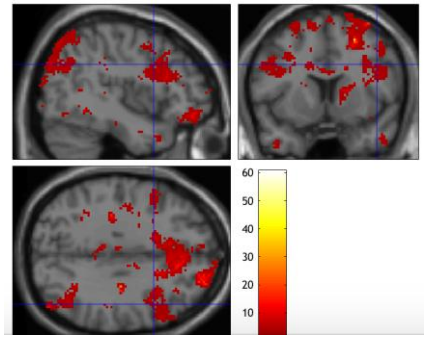
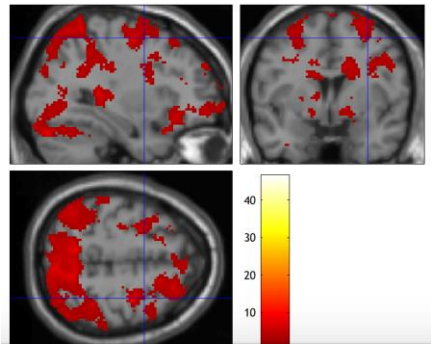
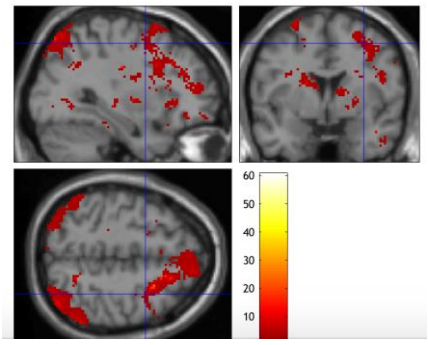
Wendelken, C., Munakata, Y., Baym, C., Souza, M., & Bunge, S. (2012). Flexible rule use: Common neural substrates in children and adults. Developmental Cognitive Neuroscience, 2, 329-339.

Wilk, H. A., Ezekiel, F., & Morton, J. B. (2012). Brain regions associated with moment-to-moment adjustments in control and stable task-set maintenance. NeuroImage, 59, 1960-1967.

Wilk, H. A., & Morton, J. B. (2012). Developmental changes in patterns of brain activity associated with moment-to-moment adjustments in control. NeuroImage, 63, 475-484.

Table 1.

Additional Activated Regions in Children and Adults During Cognitive Control Task

Region (Children)[a] $p = .05$	**Region (Adults)**[b] $p = .05$	**MNI Coordinate**	**Peak Voxel Statistic (Children)**[a]	**Peak Voxel Statistic (Adults)**[b]
 Left anterior cingulate cortex (ACC)	 Left anterior cingulate cortex (ACC)	(-12, 28, 20)	$t(4) = 3.50$	$t(2) = 3.68$
 Right inferior frontal junction (IFJ)	 Right inferior frontal junction (IFJ)	(43, 10, 32)	$t(4) = 3.52$	$t(2) = 2.87$
 Right dorsal premotor cortex (dPMC)	 Right dorsal premotor cortex (dPMC)	(30, 2, 52)	$t(4) = 2.08$	$t(2) = 2.56$

Note. [a]Children ($n = 6$). [b]Adults ($n = 4$).

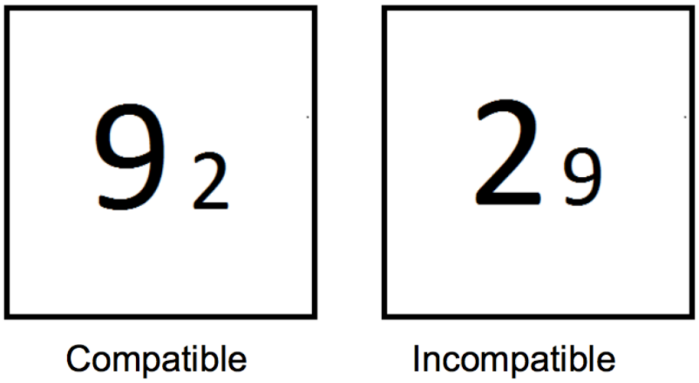


Figure 1. Size-congruency task administered to the participants in the Wilk and Morton (2012) study, which involved compatible and incompatible trials. An example of the compatible trial is shown to the left, where the numerically larger digit is also physically larger. An example of the incompatible trial is shown to the right, where the numerically larger digit is physically smaller.

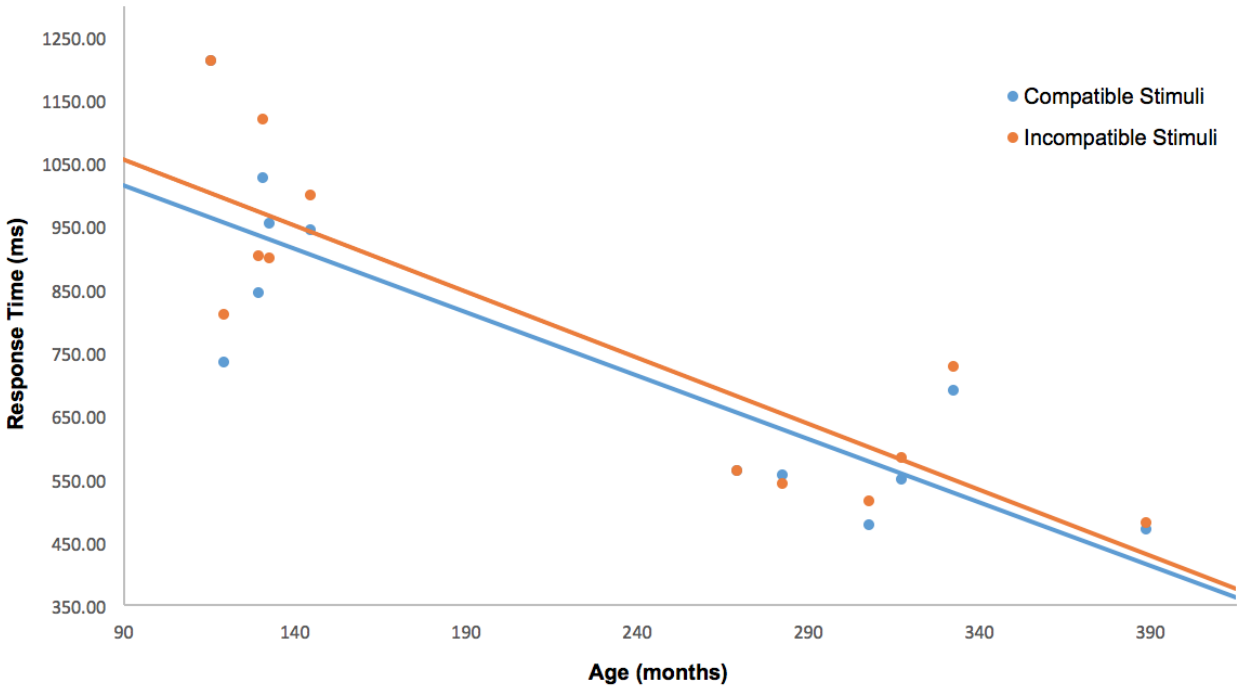


Figure 2. Relationship between behavioural response times and age during compatible and incompatible trials.

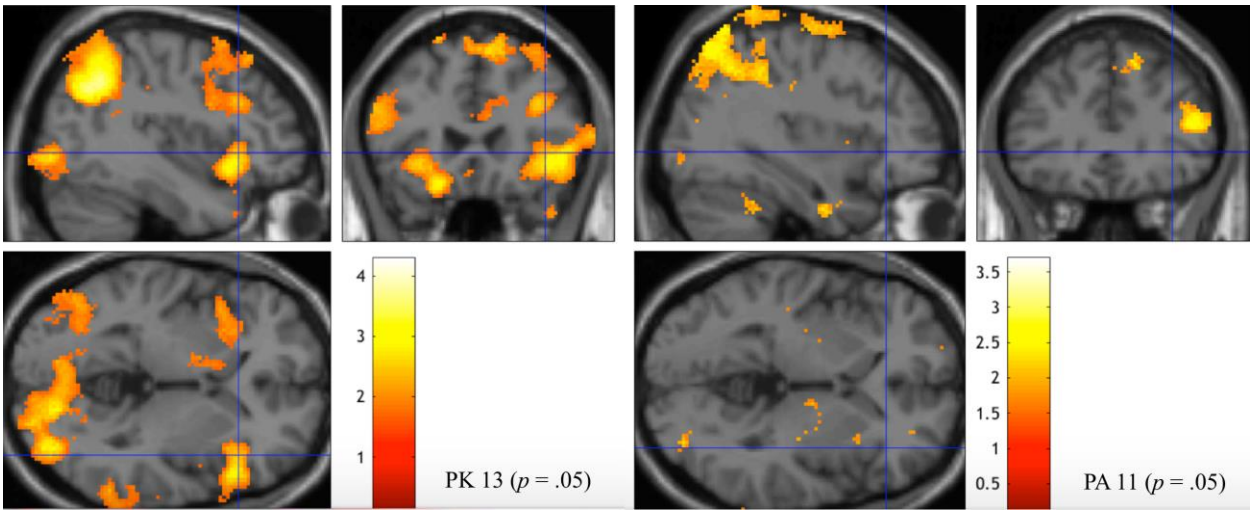


Figure 3. Samples of single-subject contrast maps (p = .05) produced for child participant, PK13, and adult participant, PA11.

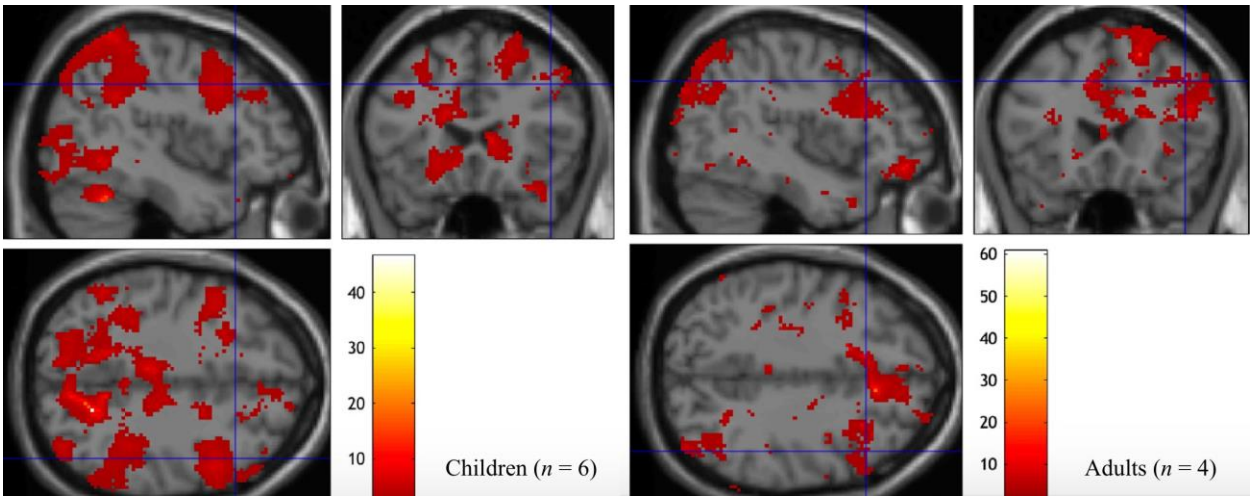


Figure 4. Group contrast maps (p = .05) generated for children and adults. Cross-section shows the right dorsolateral prefrontal cortex (dlPFC) at (43, 21, 38).

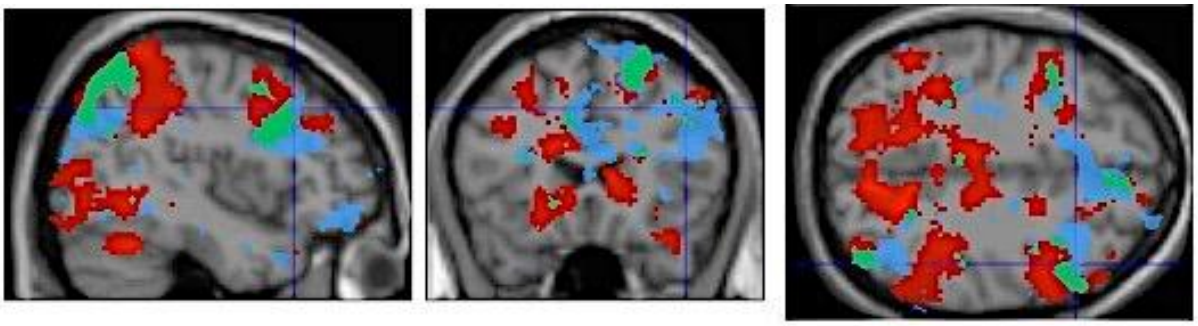


Figure 5. Overlapped group contrast maps (p = .05) of children and adults together. This shows vast similarities as well as differences in spatial distribution of BOLD activity in children and adults. Highlighted regions in red demonstrate activated areas solely in children. Areas in blue show activated areas only in adult participants. Lastly, regions in green reveal activated areas in both age groups.

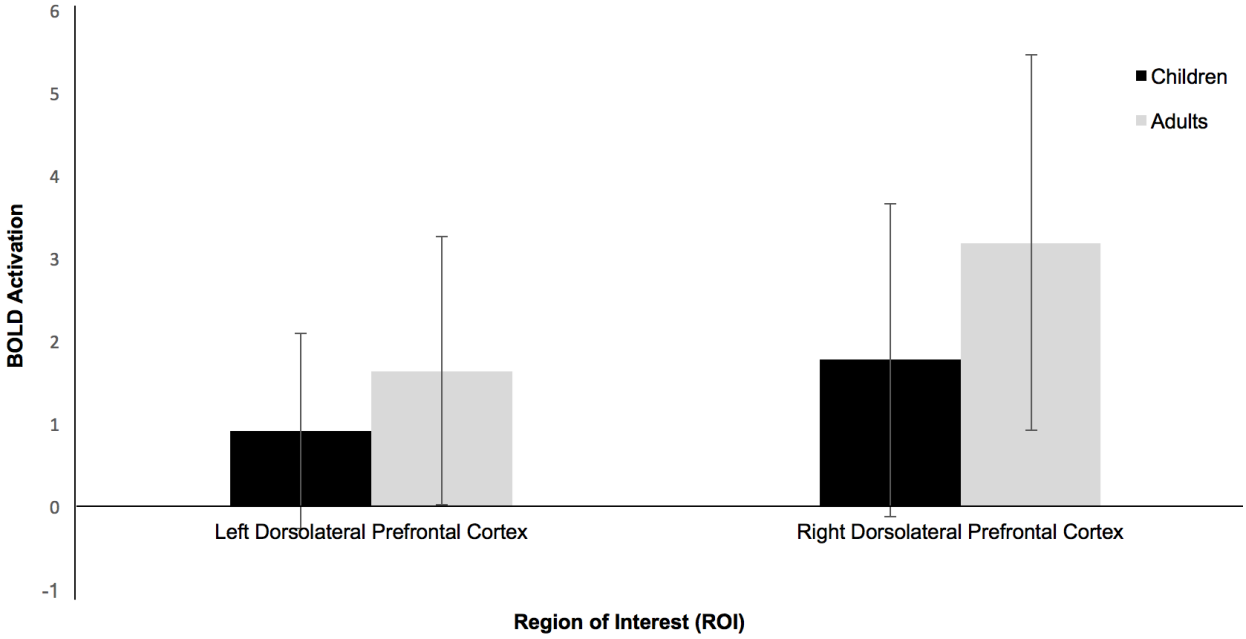


Figure 6. ROI analyses for the blood-oxygen-level dependent (BOLD) activity of left and right dorsolateral prefrontal cortex (dlPFC) in children and adults. Error bars represent standard deviation.