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Age-related changes in brain activation associated with dimensional shifts of attention: An fMRI study

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ABSTRACT

Brain activation associated with dimensional shifts of attention was measured in 14 children and 13 adults using 4 T fMRI. Across all participants, dimensional shifting was associated with activity in a distributed frontoparietal network, including superior parietal cortex, dorsolateral prefrontal cortex, inferior frontal junction, and the pre-supplementary motor region. There were also age-related differences in brain activity, with children but not adults showing an effect of dimension shifting in the right superior frontal sulcus, and adults but not children showing an effect of dimension shifting in the left superior parietal cortex and the right thalamus. These differences were likely not attributable to behavioral differences as children and adults performed comparably. Implications for neurodevelopmental accounts of shifting are discussed.

Introduction

The ability to switch mental operations is a core aspect of executive functioning that develops gradually through childhood and early adolescence (Diamond, 2002). Evidence from functional neuroimaging studies suggests that age-related advances in switching are associated with changes in the function of medial and inferior prefrontal cortices, parietal cortex, and the basal ganglia (Casey et al., 2004; Crone et al., 2006; Rubia et al., 2006), with adults typically showing stronger activity in these regions compared to children. These findings are broadly consistent with evidence that cognitive flexibility is supported by a distributed frontoparietal network (Barber and Carter, 2005; Cole and Schneider, 2007) that follows a protracted developmental trajectory as reflected by measures of myelination (Yakovlev and Lecours, 1967), regional volume (Sowell et al., 2001), grey matter thickness (Giedd et al., 1999; Sowell et al., 2003), synaptic density (Huttenlocher, 1978), and functional connectivity (Fair et al., 2007).

Much of the evidence concerning developmental changes in the neural correlates of switching however is based on studies of response-switching (Crone et al., 2006; Rubia et al., 2006). By contrast, relatively little is known about functional brain changes associated with the development of dimensional switching, despite a sizeable cognitive–behavioral literature on this topic (Jordan and Morton, 2008; Kirkham et al., 2003; Perner and Lang, 2002; Towse et al., 2000; Yerys and Munakata, 2006; Zelazo et al., 2003). Closer empirical attention to this issue seems warranted as dimensional- and response-switching tasks can be distinguished both in terms of their computational demands and their associated patterns of neural activation. Computationally, response-switching tasks require that responses to a particular stimulus be reversed—respond "right" to a stimulus in one condition, respond "left" to the same stimulus in a different condition. Cued dimensional switching tasks by contrast involve voluntary shifts of attention between different dimensions of a stimulus (e.g., color and shape). As such, they require that participants direct their attention to features of a stimulus that were previously ignored (Jordan and Morton, 2008; Kirkham et al., 2003; Mueller et al., 2006) and use these as a basis for describing the stimulus in a new way (Perner and Lang, 2002). Dimension-switching tasks are also mastered later in development (Perner and Lang, 2002), impose larger switch costs (Nagahama et al., 2001; but see Rushworth et al., 2001), and activate distinct regions in parietal (Molenberghs et al., 2007; Rushworth et al., 2001) and prefrontal cortices (Nagahama et al., 2001) compared with response-switching tasks.

To date, only one study has examined developmental changes in neural activity associated with dimensional shifts of attention (Casey et al., 2004). Seven adults (mean age 20.8-years) and seven children (mean age 7.8-years) were administered a forced-choice discrimination task. On each trial, three stimuli were presented, and participants had to indicate by means of a button press which of the three was unique. On some trials, the target stimulus was unique in color, as when stimuli consisted of two black circles and one white circle for example; on other trials, the target was unique in shape, as when stimuli consisted of a black circle, a white circle, and a black square for example. On switch trials, the feature that defined the target as unique changed from the previous trial, whereas on repeat trials it remained the same. All participants showed switch-related activity in the caudate nucleus. There were also age-related differences with adults showing greater switch-related activity in the middle frontal gyrus, superior parietal cortex, precuneus, fusiform gyrus, and temporal

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cortex compared to children. The findings suggest that the development of dimensional attention shifting is associated with changes in frontoparietostriatal circuits.

Whether these findings reflect age-related differences in top-down attention processes thought to be at the core of dimensional-switching tasks however is unclear as the forced-choice discrimination task used in this study was unlike standard cued dimensional shift tasks in several important respects. Most critically, shifts of attention were not cued in advance but exogenously driven by the characteristics of the stimulus array, did not require the suppression of previously relevant stimulus–response associations as participants were never required to make the opposite response to the same array of stimuli, and were not associated with behavioral switch costs for either adults or children. Cued dimensional shift tasks by contrast are reliably associated with behavioral switch costs (i.e., slower RT on switch trials than on repeat trials) and rely on endogenous attentional shifts as the cue rather than some feature of the stimulus alerts participants of the need to switch. In light of this, it is unclear how the Casey et al. (2004) findings might generalize to more standard dimensional switching paradigms.

Thus while previous studies have revealed age-related changes in the neural networks underlying switching, there is a paucity of neuroimaging evidence concerning developmental changes in dimensional switching. Given the vast behavioral literature on dimensional switching and its importance for the development of cognitive flexibility (Jordan and Morton, 2008; Kirkham et al., 2003; Perner and Lang, 2002; Towse et al., 2000; Yerys and Munakata, 2006; Zelazo et al., 2003), an investigation of the neural correlates may help to understand the neurocognitive mechanisms underlying this process and how they both converge with and differ from other forms of switching. The present study therefore examined developmental changes in neural activity associated with performance in the Dimensional Change Card Sort (DCCS; Zelazo, 2006), a cued dimensional shifting task that has been well-utilized in developmental studies of cognitive control. Of interest was whether patterns of brain activity associated with dimensional-shifting in the DCCS show age-related change between late childhood and early adulthood.

Methods and materials

All procedures were approved by the University Research Ethics Board for Health Sciences Research at the University of Western Ontario, London, Ontario, Canada and are in accordance with the 1964 Declaration of Helsinki.

Subjects

Subjects included 14 children (9 females) and 13 adults (5 females). Children ranged in age from 11- to 13-years ($M = 12.2$), were from middle- and upper-middle class families, and were of above average intelligence as reflected by an average standardized Peabody Picture Vocabulary Test (Dunn et al., 1997) score of 119. Adults ranged in age from 19- to 25-years ($M = 23$), were of middle- and upper-middle class background, and were all students enrolled in advanced graduate training. Adults provided written consent to their participation. Parents provided written consent to their children's participation. All participants were screened for prior neurological and psychiatric disorder. Thirteen of 14 child participants reported being right-handed. All 13 adult participants reported being right-handed.

fMRI data acquisition procedure

Data were collected using a whole-body 4 T system (Varian, Palo Alto, CA; Siemens, Erlangen, Germany). A transmit only receive only (TORO) cylindrical birdcage radio frequency (RF) head coil (Barberi et al., 2000) was used for transmission and detection of the signal.

A series of anatomical T1-weighted sagittal scans were used to define imaging planes for the functional scans. Twenty-five functional planes of 3 mm thickness were prescribed at a slightly oblique angle to ensure coverage from the top of the head down to a plane extending from the frontal pole to the top of the cerebellum and avoiding the nasal sinuses. A constrained three-dimensional phase shimming procedure (Klassen and Menon, 2004) was implemented to optimize the magnetic field homogeneity over the functional volume. During each run, T2*-weighted functional images were acquired with an interleaved, four segment, optimized spiral imaging protocol (volume collection time = 3000 ms, repeat time (TR) = 750 ms, time to echo (TE) = 15 ms, flip angle = 40°, matrix size 64 × 64, 22.0 cm × 22.0 cm field of view (FOV), 3.44 mm × 3.44 m × 3.0 mm voxel resolution). Spiral sequences help to mitigate susceptibility-induced field gradients that lead to T2* signal loss in regions of the prefrontal cortex, especially at high static-field strengths (Preston et al., 2004), and are used frequently in cognitive neuroimaging research (e.g., Cant and Goodale, 2007). In the same scanning session, a corresponding high-resolution T1-weighted structural image was acquired using a 3D spiral acquisition protocol (TE = 3 ms, inversion time (TI) = 1.3 s, TR = 50 ms, slice thickness = 2 mm, matrix size 256 × 256, FOV = 22.0 cm × 22.0 cm, 0.86 mm × 0.86 mm × 2.00 mm voxel resolution). Immobilization of the head was achieved by means of a wooden cradle and foam packing.

Experimental design

In the standard DCCS (Zelazo, 2006), participants sort bivalent test cards (e.g., red trucks) into bins marked by bivalent target cards (e.g., a red rabbit and a blue truck). In pre-switch trials, participants sort the cards using one pair of rules (e.g., rules based on color), and then in post-switch trials, are required to switch and sort the same cards using a contradistinctive pair of rules (i.e., rules based on shape). The standard task was modified in the present study to make it suitable for use with older participants in a neuroimaging environment (see Fig. 1). Two bivalent target images (a red rabbit and a blue truck) appeared at the bottom of the screen throughout the task. Trials consisted of a 1750 ms instruction period in which participants were cued to the sorting rule for that trial ("s" for shape; "c" for color), followed by a 2000 ms response period in which participants were presented with and responded to a centrally-presented bivalent stimulus (blue rabbit/red truck) that matched each target on a single dimension. Participants responded by depressing one of two buttons on a two-button keypad using the index and middle-finger of their right hand. Depressing the left key sorted the stimulus to the location of the left target (i.e., the blue truck); depressing the right key sorted the stimulus to the location of the right target (i.e., the red rabbit). Trials were separated by a 750 ms inter-trial interval. Trials were administered in 36 s (12 volumes) blocks of eight trials. Switch blocks consisted of four switch trials and four repeat trials administered in a different random order for each switch block; repeat blocks consisted of eight repeat trials. The rule on the first trial of a block was always the same as the rule on the last trial of the previous block. Therefore, the first trial of every block was coded as a repeat trial. Blocks were administered in 234 s runs (78 volumes) that consisted of two switch and two repeat blocks (48 volumes) and five 18 s rest periods (30 volumes). The order of the blocks was counter-balanced across runs. Twelve adults completed 10 runs; one adult completed only 7 runs due to head discomfort. Thirteen children completed 10 runs; one child completed only 7 runs due to fatigue.

MRI data preprocessing

fMRI data preprocessing was performed with BrainVoyager QX (Brain Innovation BV, Maastricht, Netherlands). Timecourses were visually inspected for artifacts and motion parameters for each

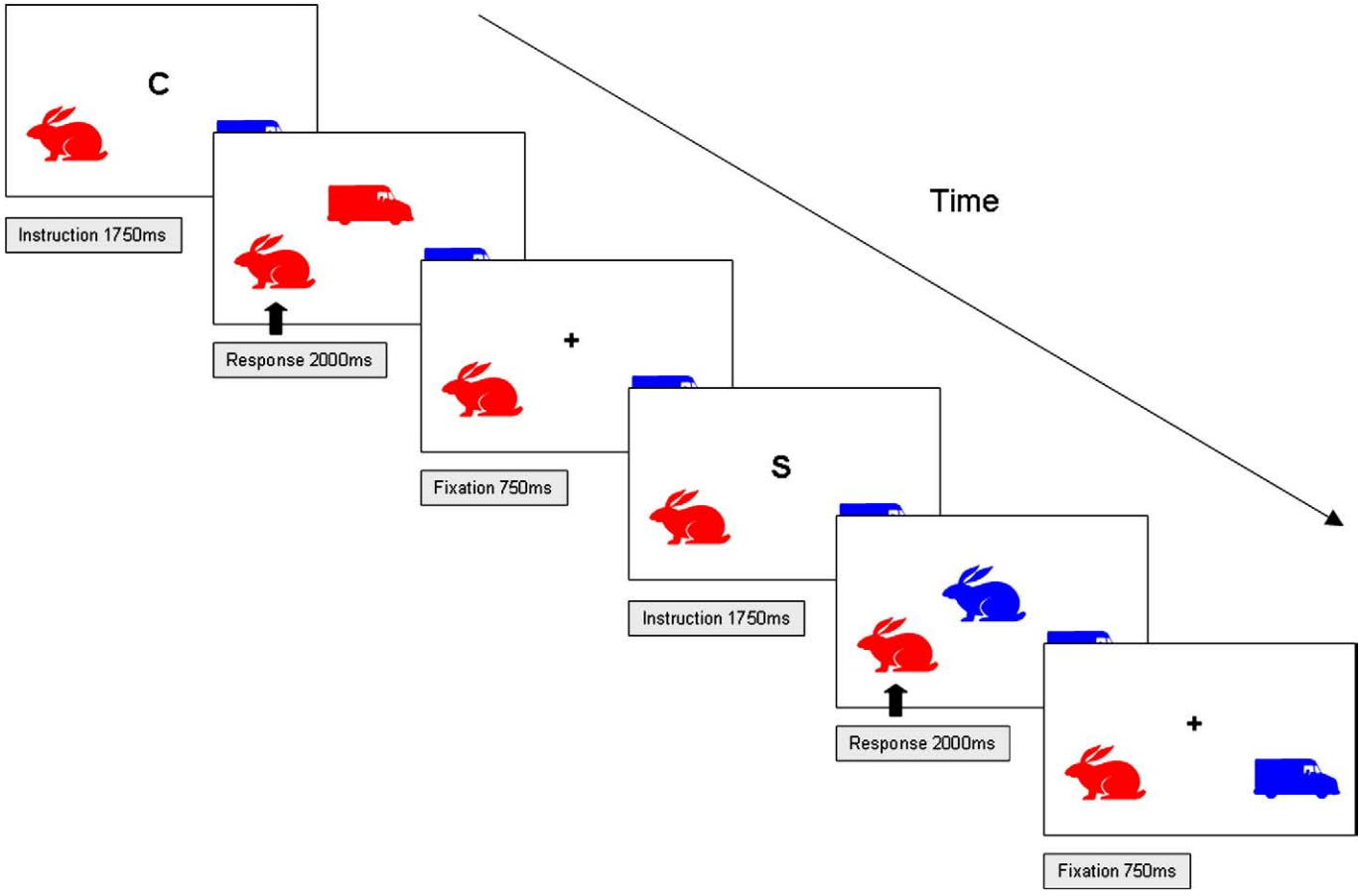

Fig. 1. An illustration of two representative trials from the modified Dimensional Change Card Sort task used in the present study. Trials began with an instruction cue indicating the rule on that trial, followed by the presentation of a stimulus to which participants responded, followed by a fixation point. On switch trials, the rule was different than on the previous trial; on repeat trials, the rule was the same as on the previous trial. Individual trials were administered in the form of a block design.

individual run calculated. Following criteria employed in other studies involving participants naïve to the rigors of the imaging environment (Berkowitz and Ansari, 2008), movement across the entire run was not allowed to exceed 3 mm. Runs in which this threshold was exceeded were removed from the analysis, resulting in a loss of 0 runs for the 13 adults and 20 runs for the 14 children. For runs that were included in the analysis, abrupt movements of between 1 mm and 2 mm were removed from the time courses by confining the analysis to volumes that came after a movement in instances in which the movement occurred at the beginning of the run, or the volumes that came before the movement in instances in which the movement occurred near the end of the run. This resulted in the loss of 0 additional volumes for adults and 156 additional volumes for children. With these motion criteria in place, each adult participant contributed an average of 762 volumes (range 546–780) and each child an average of 658 volumes (range 280–780). This led to a full dataset that consisted of 127 runs and 9906 volumes from adult participants and 120 runs and 9204 volumes from child participants and in which there were no differences in motion between adults and children.

Motion correction was performed by aligning each functional volume to a reference volume, which for all subjects was the first functional volume of the first run that was administered after the acquisition of the T1-weighted anatomical scan. In this way, motion-correction corrected for both within- and between-run motion. Linear-trend removal was then applied to the signal time courses of each voxel on a run-by-run basis. T1-weighted anatomical scans were aligned onto the anterior commissure–posterior commissure (AC–PC) axis and then warped into the standardized space of Talairach and Tournoux (1998) using the six-point method. Motion-corrected functional volumes were manually aligned with the unwarped T1-weighted anatomical scan. Translation, rotation, and warping parameters used to spatially standardize the T1-weighted scan were then applied to the functional volumes. Finally, functional volumes were spatially-smoothed using an 8 mm full-width at half maximum Gaussian kernel.

MRI data analysis

Data were analyzed by means of a General Linear Model (GLM). Switch and repeat blocks were modeled separately as boxcar functions which were then convolved with a two-gamma model of the haemodynamic response function (Friston et al., 1998) to create two orthogonal predictors. Parameter estimates (beta weights) of each of the two predictors were computed by means of a whole-brain random-effects (RFX) analysis.

To examine the main effect of dimensional switching on neural activity across participants in both groups, beta weights of switch and repeat predictors were contrasted by means of a voxel-by-voxel, whole brain paired-sample *t*-test. This test therefore revealed regions that were significantly more modulated by switch *versus* repeat conditions across both groups of participants. The resulting *t*-statistics

Table 1
Behavioral data

	Mean response time (*SE*)		Mean accuracy (*SE*)	
	Switch trials	Repeat trials	Switch trials	Repeat trials
Adults ($n = 13$)	735.5 (52.0)	691.9 (48.1)	.95 (.02)	.97 (.01)
Children ($n = 14$)	745.6 (50.1)	711.4 (46.3)	.91 (.02)	.96 (.01)

Table 2
Summary of regions modulated by the main effect of dimensional switching

Region	BA	Hemisphere	*X*	*Y*	*Z*	*K*	B_{Repeat}	B_{Switch}
Activations								
Superior parietal cortex	40	R	30	−63	37	19224	.325[a]	.406[a]
Superior parietal cortex	40	L	−23	−74	32	1534	.082	.139[a]
Superior parietal cortex	40	L	−30	−47	42	117	.306[a]	.349[a]
Dorsolateral prefrontal cortex	9	L	−36	42	31	4100	.173[a]	.228[a]
Dorsolateral prefrontal cortex	9	R	51	20	34	173	.095	.139[a]
Pre-supplementary motor area	6	R	7	11	49	4081	.435[a]	.488[a]
Inferior frontal junction	6,9	R	44	5	36	3238	.317[a]	.372[a]
Fusiform gyrus	37	R	37	−47	−13	1035	.336[a]	.386[a]
Deactivations								
Post-central sulcus	5	L	−28	−33	62	1073	−.379[a]	−.423[a]
Post-central gyrus	4	R	1	−33	53	84	−.258[a]	−.291[a]

X, *Y*, and *Z* are Talairach coordinates of regions. *K* represents the size of the region in contiguous voxels in mm^3.
[a] $B \neq 0$.

were mapped onto a 3D high-resolution T1-weighted structural scan at a statistical threshold of $p<.005$, uncorrected. The resulting statistical map was subsequently corrected for multiple comparisons using a cluster-size thresholding procedure (Forman et al., 1995; Goebel et al., 2006) in which statistically uncorrected maps are submitted to a whole-slab correction criterion based on an estimate of the map's spatial smoothness and an iterative procedure (Monte Carlo simulation) for estimating cluster-level false-positive rates. After 1000 iterations, the minimum cluster-size that yielded a cluster-level false-positive rate (α) of .05 (5%) was used to threshold the statistical maps. Only activations whose size met or exceeded the cluster threshold were allowed to remain on the statistical maps.

Regions of interest (ROI) analyses were conducted on the statistically corrected map for the sole purpose of extracting parameter estimates from regions showing significant whole-brain effects. These ROI analyses were not driven by *a priori* hypotheses about the roles of specific regions in dimensional switching, but were simply further explorations of voxel-by-voxel whole-brain effects. ROI's were defined in terms of contiguous voxels from areas that showed significant activations in the whole-brain analysis. A GLM was then performed across all of the voxels that comprised a given ROI, leading to an average parameter estimate (beta weight) within the ROI for each condition and subject. The resulting beta weights were expressed as standardized scores (*Z*-scores). A series of single-sample *t*-tests tested whether beta weights associated with the switch and repeat predictors in each ROI differed significantly from 0. These post-hoc tests ensured that differences observed were differences between predictors that reflected bona fide activations within an ROI rather than mere statistical differences between predictors where neither predictor resulted in a significant departure from baseline.

To examine age-related differences in switch-related brain activation, beta weights for child and adult participants were assigned to separate groups and the interaction of Group and Trial-type calculated by means of a two-sample *t*-test. This analysis, therefore, revealed brain regions that were significantly more modulated by the comparison of switch *versus* repeat in one group compared to the other. The resulting *t*-statistics reflected the extent to which the trial-type contrast differed across the two groups and were mapped at a statistical threshold of $p<.005$, uncorrected. The resulting *t*-map was subsequently corrected for multiple comparisons at a cluster-level false positive rate (α) of .05 (5%) by means of the cluster-thresholding procedure described earlier (Forman et al., 1995; Goebel et al., 2006). ROI's were defined on the basis of this map, and used to explore the average beta weights for all voxels within the ROI for each subject and each predictor. Post-hoc single sample *t*-tests were conducted separately for children and adults to test whether beta weights for the switch and repeat predictors differed significantly from 0.

Results

Behavioral analyses

Mean response time and accuracy across switch and repeat trials for children and adults are displayed in Table 1. A 2 Group (Adults *vs.* Children) × 2 Trial type (Switch *vs.* Repeat) mixed Analysis of Variance (ANOVA) of response times confirmed that all participants responded more slowly on switch trials ($M=740.6$ ms) than on repeat trials ($M=701.6$ ms), $F\ (1, 25)=40.5$, $p<.0001$. Importantly, neither the effect of Group, $F\ (1, 25)=0.05$, $p=.8$, nor the Group × Trial-type interaction, $F\ (1, 25)=0.6$, $p=.5$, were significant, indicating that children and adults showed comparable response times and switch costs. A 2 Group × 2 Trial-type mixed ANOVA of accuracy confirmed that all participants responded less accurately on switch trials ($M=.93$, $SD=.01$) than on repeat trials ($M=.96$, $SD=.007$), $F\ (1, 25)=17.7$, $p<.0001$. However, a marginal effect of Group, $F\ (1, 25)=4.0$, $p=.051$, and a significant Group × Trial type interaction, $F\ (1, 25)=4.73$, $p<.05$, indicated that children were marginally less accurate and showed a greater switch cost in terms of errors compared to adults.

fMRI analyses

Main effect of dimensional switching

Analysis of the main effect of dimensional switching revealed wide-spread activity in frontal and parietal cortex (see Fig. 2). The

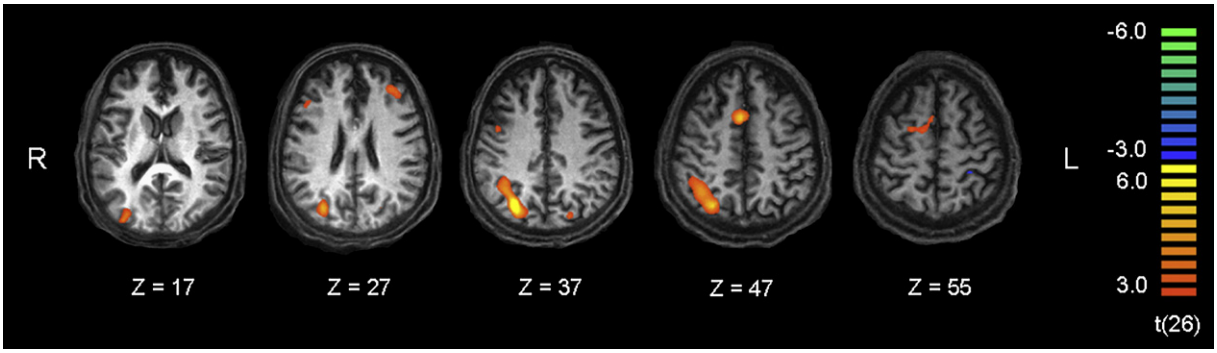

Fig. 2. A summary of the main effect contrast of switch blocks and repeat blocks at $p<.05$, corrected. Panels show activation in parietal cortex bilaterally (right: $z=17$ through 47; left: $z=37$), dorsolateral prefrontal cortex bilaterally ($z=27$), right inferior frontal junction ($z=37$), pre-supplementary motor area ($z=47$), and right superior frontal sulcus ($z=55$), and deactivation in left post-central sulcus ($z=55$).

Table 3
Summary of regions modulated by the interaction of age and dimensional switching

Region	BA	Hemisphere	*X*	*Y*	*Z*	*K*	*Children*		*Adults*	
							B_{Repeat}	B_{Switch}	B_{Repeat}	B_{Switch}
Superior frontal sulcus	6	R	19	0	51	12	.131[a]	.187[a,b]	.208[a]	.211[a]
Thalamus	–	R	14	−2	14	104	.088[a]	.090[a]	.172[a]	.231[a]
Superior parietal cortex	40	L	−24	−73	47	131	.116	.105	.116	.199[a,b]
Superior parietal cortex	40	L	−30	−58	48	143	.334[a]	.331[a]	.516[a]	.602[a,b]
Fusiform gyrus	20	R	49	−38	−16	259	.050	.050	.247[a]	.330[a,b]

X, *Y*, and *Z* are Talairach coordinates of regions. *K* represents the size of the region in contiguous voxels in mm^3.
[a] $B \neq 0$.
[b] $B_{Switch} > B_{Repeat}$.

findings are summarized in Table 2. By far the most robust activation was observed in the parietal cortex, particularly in the right hemisphere where the activation encompassed a large section of the superior parietal cortex and the intraparietal sulcus. Dimensional switching was also associated with activity in the dorsolateral prefrontal cortex bilaterally, the right inferior frontal junction, and the premotor cortex including the medial surface in the pre-supplementary motor area extending onto the lateral surface and into the superior frontal sulcus. Analysis of the beta estimates via one-sample *t*-tests confirmed that in all cases, activity in the switch condition represented a positive and significant departure from baseline, and that this was also true in most cases in the repeat condition (see Table 2). Thus, all participants showed robust switch-related activity in frontal and parietal cortex.

Interaction of group and dimensional switching

Age-related differences in switch-related activity were revealed by the Group × Trial-type interaction (see Table 3 and Fig. 3). Analysis of Covariance (ANCOVA) was then used to identify the loci of these interactions and to control for group differences in error rate across switch and repeat trials. Two regions in left superior parietal cortex (−24, −73, 47 and −30, −58, 48), close to foci revealed in the main effect, showed an effect of switching that was significant for adults but not children and that was not attributable to a group difference in performance accuracy. By contrast, a region in the right superior frontal sulcus, adjacent to an activation of the same region revealed in the main effect contrast, showed an effect of switching that was significant for children but not adults and that was not attributable to a group difference in performance accuracy (see Fig. 3). To test whether the 2-way interactions at frontal and parietal loci differed significantly from one another, a 3-way mixed ANCOVA with Group (Children *versus* Adults) as a between-subjects variable, Trial-Type (Switch *versus* Repeat) and ROI (Left Superior Parietal *versus* Right Superior Frontal) as within-subjects variables, and switch cost in accuracy as a covariate, confirmed, by means of a significant 3-way interaction, that the 2-way interactions at frontal and parietal loci differed significantly from one another, $F(1, 24) = 35.02$, $p < .0001$. In addition to these regions, there was also a significant Group × Trial-type interaction in the right thalamus and the right fusiform gyrus (Table 3). Analysis of the beta weights confirmed significant switch-related activity in these regions for adults but no effect of switching for children, and that these differences remained significant even after controlling for age-related differences in errors.

Discussion

Performance in cued dimensional shifting tasks such as the DCCS show protracted age-related improvements. Although these changes have been attributed to developmental changes in prefrontal cortex function (Bunge and Zelazo, 2006; Diamond, 2002; Kirkham et al., 2003; Morton and Munakata, 2002), there is relatively little direct brain-based evidence for this postulated association. The few studies that have examined neural correlates of switching and its development have either focused on response-switching (Crone et al., 2006; Rubia et al., 2006), or used tasks in which dimensional switching was exogenously cued by the stimuli (Casey et al., 2004). The current findings are therefore important as they represent a direct brain-based examination of the neural correlates of cued dimensional-switching and their development. There were several important results.

The most novel finding was evidence of age-related differences in the balance of activity among regions associated with dimensional switching, including differences in the left posterior parietal cortex, the right superior frontal sulcus, and the right thalamus. These differences were likely not attributable to differences in behavioral performance. Although children showed a marginally greater switch cost in terms of errors compared to adults, there was no difference in cost as measured by response time and in general both groups performed the task quite comparably. These findings may reflect age-related differences in frontoparietal interactions that subserve cognitive control (Klingberg et al., 2002). Consistent with this idea, the present data revealed a significant 3-way interaction of ROI (superior frontal sulcus, superior parietal cortex), Age (Children, Adults), and Condition (Switch, Repeat), confirming that whereas left posterior parietal cortex showed an effect of switching in adults but not children, the right SFS showed an effect of switching in children but not adults. One interpretation of this higher-level interaction is that dimensional shifting processes supported by superior parietal cortex operate less effectively in children compared to adults. To compensate, children rely on processes supported by dorsal premotor cortex in the superior frontal sulcus, processes that may include planning of goal-directed movement (Bunge and Souza, 2008), inhibition (Sylvester et al., 2003), or working memory and higher-order control of visual attention (Klingberg et al., 2002).

The present findings converge in several respects with the findings of Casey et al. (2004) in that both studies observed an age-related increase in switch-related activity in regions of the superior parietal cortex that have been implicated in dimensional shifting (Rushworth et al., 2001), and suggest an important role for midbrain structures in dimensional switching and its development. Casey et al. (2004) for example found that dimensional shifting was associated with activity in the caudate nucleus, and in the present study, there was a significant Age × Trial-type interaction in the right thalamus, with an effect of switching observed in adults but not children. Dopaminergic signals from the basal ganglia have been implicated in attentional and behavioral flexibility and are thought to play an important role in gating information into prefrontal cortex (Alexander et al., 1986). The thalamus is an important intermediary between the basal ganglia and the cortex and has been implicated in neurophysiological models of reflection and higher-order rule use (Zelazo, 2008). Taken together, these studies highlight the role of midbrain structures in the updating of attentional or behavioral sets and suggest these regions may be an important locus of developmental change. One important point of contrast though was evidence that dimensional shifting was associated with distributed fronto-parietal activity in the present study, but focal activation in the caudate nucleus in

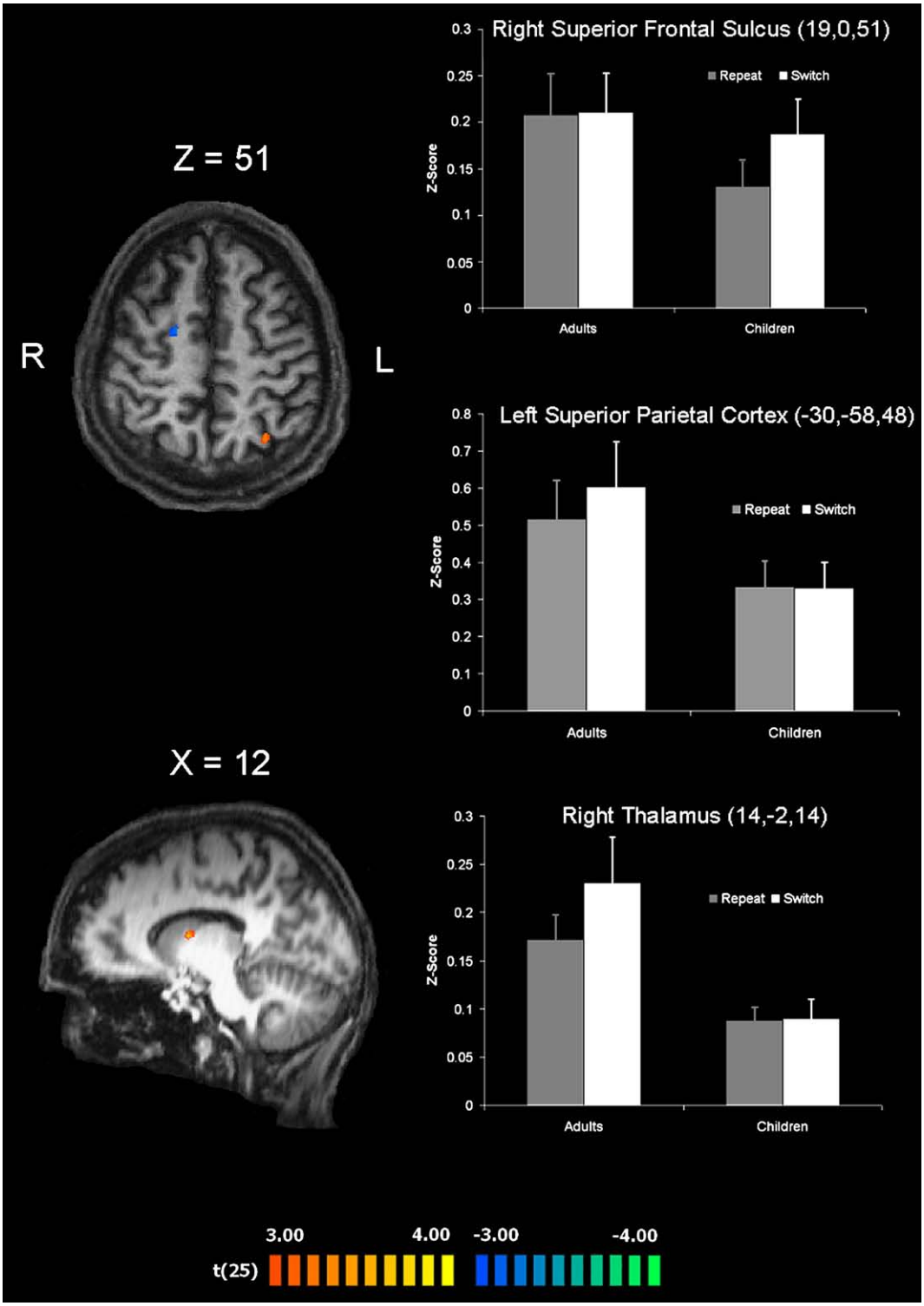

Fig. 3. A summary of the interaction of Age and Trial Type at $p<.05$, corrected. Orange clusters indicate regions where the effect of Trial Type was significant for adults but not children; blue clusters indicate regions where the effect of Trial Type was significant for children but not adults.

the Casey et al. (2004) study. These differences likely relate to differences in the tasks used to examine dimensional switching. Whereas dimensional shifts in a forced-choice discrimination task like the one used by Casey et al. (2004) can be driven largely by bottom-up pop-out effects, dimensional shifting in tasks such as the DCCS are critically dependant on endogenous top-down control processes mediated by frontal-parietal circuits.

The present findings also converge with findings from previous developmental studies of response-shifting (Crone et al., 2006; Rubia et al., 2006) that, like the current study, found widespread switch-related activity across superior parietal cortex, medial prefrontal cortex and lateral prefrontal cortex. Still, there are several interesting points of contrast. Like Casey et al. (2004), we found evidence of an age-related increase in the magnitude of switch-related activity in left parietal

cortex. Rubia et al. (2006) also found evidence of an age-related increase switch-related activity in left parietal cortex, but in a region anterior, more lateral, and superior to the region reported here. Differences in the loci of these age-effects may relate to the use of dimensional versus response-shift tasks in the respective studies. Consistent with this idea, Rushworth et al. (2001) observed that whereas dimensional shifting was associated with activity in left IPS, close to the locus of the interaction reported here, response-shifting was associated with activity in the supramarginal gyrus, close to the locus of the interaction reported by Rubia et al. (2006). Taken together, the findings highlight the importance of studying the neural correlates of switching in different tasks and underscore the possibility that switching is not a unitary phenomenon but engages distinct brain regions depending on whether switching is more endogenously- or exogenously-driven and involves dimensional- or response-shifting.

Another important point of contrast concerns the nature of age-related changes in frontal cortex activity observed across studies. Crone et al. (2006) report evidence of emerging functional specialization in medial and ventrolateral prefrontal cortex over development, with medial active for both rule representation and rule switching in children, but only rule switching in adults, and VLPFC active for rule representation in adults, but not adolescents or children. However, they found no evidence of age-related decreases in frontal cortex activity with increasing age. Using a whole-brain regression analysis, Rubia et al. (2006) found that switch-related activity in dorsolateral and medial prefrontal cortex was negatively correlated with age, although these associations were not observed when the authors used an ANCOVA. In the current study, robust switch-related activity was observed in the IFJ, DLPFC, and pre-SMA, but age-differences in the magnitude of these effects were confined to the superior frontal sulcus, with an effect of switching evident in children but not adults.

A second important finding of the present study was revealed by the main effect analysis and suggests that dimensional shifting in the DCCS is associated with activity in a distributed network of regions including the dorsolateral prefrontal cortex, inferior frontal junction, the pre-supplementary motor region, and the superior parietal cortex. Dorsolateral prefrontal cortex is thought to be important for the higher-order representation of context (Miller and Cohen, 2001) or task-set (Rogers et al., 1998) and consistent with this account, shows cue-related or preparatory activity in a variety of interference paradigms (e.g., MacDonald et al., 2000; Ford et al., 2005). Several computational models have linked performance in task switching paradigms (Gilbert and Shallice, 2002) and attention shifting paradigms such as the DCCS (Morton and Munakata, 2002) to the active representation of contextual representations by lateral prefrontal cortex, although neuroimaging evidence for the role of dorsolateral prefrontal cortex in switching paradigms is less consistent (for reviews, see Barber and Carter, 2005; Derrfuss et al., 2005). The current findings however are consistent with claims that dimensional shifting in the DCCS is associated with dorsolateral prefrontal cortex function.

The most robust activation associated with dimensional shifting though was in the right superior parietal cortex and intraparietal sulcus. Although early models of superior parietal cortex function emphasized its role in spatial shifts of attention (Posner et al., 1984), subsequent research has shown that this region is also involved in dimensional and response-shifts that do not require spatial reallocation of attention (Li et al., 1998). Its precise role in dimensional shifting however remains unclear. One possibility is that superior parietal cortex provides a top-down biasing signal that helps to support lower-level perceptual representations of the currently relevant stimulus dimension (Corbetta and Shulman, 2002). An alternative hypothesis is that superior parietal cortex stores various stimulus–response associations, or rules with the selection among these representations being the purview of prefrontal cortex (Bunge et al., 2002b). Parietal cortex has also been implicated in the processing of stimulus conflict (Liston et al., 2006). Many studies of dimensional shifting, including the present study, utilize incongruent stimuli—that is, stimuli that can be legitimately sorted in two ways—and there is some evidence that the cost of stimulus incongruency increases on switch trials relative to repeat trials (e.g., Liston et al., 2006). As all of these accounts predict greater parietal activation on switch trials relative to repeat trials, further research is required to disentangle them and to understand their implications for dimensional shifts of attention.

Dimensional shifting of attention in the DCCS was also associated with activity in a large volume that extended medially from the pre-supplementary motor area (pre-SMA) to the dorsal premotor cortex (PMd) on the lateral surface, as well as activity in the right inferior frontal junction. Activity in the pre-SMA and PMd is frequently observed in dimensional and response-shifting paradigms specifically (for reviews, see Barber and Carter, 2005; Derrfuss et al., 2005) and executive functions tasks more generally (for review, see Duncan and Owen, 2000). Pre-SMA activity in switching tasks has been attributed to task-set reconfiguration and the suppression of previously relevant stimulus–response associations (Crone et al., 2006), although given increased error rates on switch trials relative to repeat trials, it may also reflect error-likelihood estimation (Brown and Braver, 2005) or conflict processing (MacDonald et al., 2000). Activity in the inferior frontal junction has been observed in a variety of cognitive control tasks, including task-switching paradigms (Derrfuss et al., 2005). More robust cue-related activity on switch trials relative to repeat trials in the IFJ has led to the hypothesis that this region is involved either in updating task-relevant representations (Derrfuss et al., 2005) or the representation of higher-order conditional associations (Petrides, 2008). Taken together, shifting attention between stimulus dimensions in the DCCS was not associated with focal activity in prefrontal cortex, but with distributed activity across DLPFC, SPC, IPS, IFJ, pre-SMA, and the PMd—regions that are thought to comprise a cognitive control network (Cole and Schneider, 2007).

One weakness of the present study is the fact that no measure of intelligence was administered to adult participants, making it impossible to assess whether the adults and children differed in intelligence. Intelligence is closely associated with executive functioning and prefrontal cortex function (Gray et al., 2003), and therefore should be more thoroughly assessed in future investigations of age-related differences in executive function and prefrontal cortex function.

Taken together with the present findings, evidence from developmental neuroimaging studies of switching (Casey et al., 2004; Crone et al., 2006; Rubia et al., 2006) add to what is already a complex body of evidence concerning developmental changes in cognitive control and their association with changes in prefrontal cortex functioning. Studies differ markedly in terms of whether they report age-related increases (e.g., Adleman et al., 2002), decreases (Casey et al., 1997; Durston et al., 2006), or qualitative differences (Bunge et al., 2002a) in patterns of prefrontal cortex activity associated with performance in tasks of cognitive control. Understanding the basis of these countervailing findings represents a fundamental issue in the field. Progress in this regard will require careful attention to differences in activation across different tasks and different subcomponents of control (Rubia et al., 2006), different procedures for controlling for age-related performance differences (Bunge et al., 2002a), and different data modeling procedures and their consequence for observed patterns of developmental change (Burgund et al., 2002). As well, a deeper understanding of age-related changes in prefrontal cortex function will demand consideration of the profound changes in prefrontal cortex morphology (Sowell et al., 2001) and functional connectivity (Fair et al., 2007) that occur between childhood and early adulthood.

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