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Neural development of selective attention and response inhibition

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Abstract

Brain activation differences between 12 children (9- to 12-year-olds) and 12 adults (20- to 30-year-olds) were examined on two cognitive tasks during functional magnetic resonance imaging (fMRI). Spatial selective attention was measured with the visual search for a conjunction target (red triangle) in a field of distracters and response inhibition was measured with a go no-go task. There were small developmental differences in the selective attention task, with children showing greater activation than adults in the anterior cingulate and thalamus. There were large developmental differences in the response inhibition task, with children showing greater activation than adults in a fronto-striatal network including middle cingulate, medial frontal gyrus, medial aspects of bilateral superior frontal gyrus, and the caudate nucleus on the left. Children also showed greater bilateral activation for the response inhibition task in posterior cingulate, thalamus and the hippocampo-amygdaloid region. The extensive developmental differences on the response inhibition task are consistent with the prolonged maturation of the fronto-striatal network.

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Introduction

Neural basis of selective attention

Mesulam (1999) has defined selective attention as a preferential allocation of limited processing resources to events that have become behaviorally relevant (Mesulam, 1999). He has also proposed a neuro-cognitive model for spatial selective attention (Mesulam, 1990). Three interconnected cortical regions form the core of this network: the superior parietal lobule, the lateral premotor cortex, and the anterior cingulate gyrus (Gitelman et al., 1999; Kim et al.,

1999; LaBar, et al., 1999; Mesulam et al., 2001; Nobre et al., 1999; Nobre et al., 2000; Nobre et al., 1997). The superior parietal lobule is involved in representing extra-personal space. The lateral pre-motor cortex or frontal eye fields are involved in orienting and exploratory movements, including voluntary eye movements. The anterior cingulate gyrus is involved in the executive aspects of attention including response monitoring (Botvinick et al., 1999). In support of this model, Corbetta (1998) showed that most studies using spatial selective attention tasks produced activation in the superior parietal lobule and lateral pre-motor cortex during both covert and overt tasks (Corbetta, 1998).

Several studies with adults have also examined spatial selective attention using feature versus conjunction search tasks. Treisman and Gelade (1980) showed that adults were faster at detecting an object based on one feature than on a conjunction of two features (Treisman, 1990, 1992; Treis-

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man and Gelade, 1980). They argued that feature tasks involve automatic parallel processing, whereas conjunction tasks are demanding on selective attention because they involve controlled serial processing. This interpretation was supported by their finding that the number of distracters for the feature tasks did not influence performance because the feature “popped-out”, whereas reaction time increased as a function of the number of distracters for the conjunction task. Although there are some null findings (Leonards et al., 2000), most studies show that conjunction search activates the superior parietal lobule more than feature search (Corbetta et al., 1995; Coull and Nobre, 1998; Donner et al., 2000). Indeed, transcranial magnetic stimulation over the parietal lobe interferes with conjunction and not feature search (Ashbridge et al., 1997; Walsh et al., 1999). Some studies also support the involvement of the lateral premotor cortex in conjunction search (Donner et al., 2000).

Neural basis of response inhibition

Responding appropriately in a task or situation involves not only attentional mechanisms for targeting relevant events but also mechanisms for inhibiting inappropriate responses. Clearly, these processes are normally coordinated. A failure to respond appropriately to a stimulus may result either from a deficit in sustained attention (increased distractibility) or a failure to inhibit a pre-potent response. Barkley (1997) has developed a cognitive model of response inhibition that involves three interrelated processes: (1) inhibition of an initial pre-potent response, (2) stopping of an ongoing response or delayed responding, and (3) limiting interference or distractibility during delay periods. Barkley's (1997) model of cognitive control is important because it addresses both inhibition and interference. The basal ganglia and prefrontal cortex seem to be involved in these two cognitive components (Casey et al., 2001). Casey et al. (2001) argue that the basal ganglia are involved in the inhibition of inappropriate behaviors (Mink, 1996), whereas the prefrontal region is involved in protecting representations of relevant information from interference due to competing information (Miller and Cohen, 2001). The caudate and putamen (neostriatum of basal ganglia) receive extensive neural inputs from the frontal cortex and send input back by way of the globus pallidus and then thalamus (Alexander et al., 1986; Goldman-Rakic, 1987). This fronto-striatal network modulates computations in the supplementary motor area which plays a primary role in motor planning, initiation and timing (Deiber et al., 1999). Both animal and human studies suggest that the supplementary motor area is involved in internally guided processing such as planning complex motor programs (Jenkins et al., 1994; Mushiaki et al., 1991).

Several studies with adults have used variations of a go no-go task to examine inhibitory processing. These tasks contain stimuli that elicit a response interspersed with those that necessitate an inhibition of responding. Generally, these

studies show activation in prefrontal, basal ganglia and supplementary motor regions (Kawashima et al., 1996; Klingberg and Roland, 1997; Konishi, 1998; Liddle et al., 2001; Menon et al., 2001; Rubia et al., 2000b; Waldvogel, 2000). Studies using the go no-go paradigm in normal adults suggest that the anterior cingulate is not involved directly in response inhibition, but rather in monitoring performance (Braver et al., 2001; Kiehl et al., 2000; Liddle et al., 2001).

Development of attention and inhibition

Research suggests relatively small developmental differences across childhood in visual search. One way to index the effectiveness of visual search in conjunction tasks is to measure the slope of reaction time as a function of the number of distracters—the steeper the slope the less effective the search. Some have reported similar slopes in young children (1- to 3-year-olds) and adults (Gerhardstein and Rovee-Collier, 2002), whereas others have reported significant, but relatively modest, developmental differences in the slope of the search function between preschool children and adults (Thompson and Massaro, 1989). Although some studies with adults have compared visual search and go no-go tasks (Van der Heijden and la Heij, 1983), very few studies have directly compared developmental differences in performance during attention versus inhibition tasks. Tipper et al. (1989) reported a series of studies comparing second graders to adults that suggested the mechanisms of attention were relatively mature by the second grade, whereas inhibitory mechanisms were relatively immature at this age (Tipper et al., 1989).

In contrast to visual search, relatively large developmental differences in accuracy and reaction time have been reported in go no-go tasks in preschool children (Levy, 1980) and in school age children (Becker et al., 1987). Studies using stop tasks have also shown that the speed of suppressing a response becomes faster throughout childhood (Williams et al., 1999). Some have interpreted the late maturation of inhibitory processes as a reflection of the slow maturation of the prefrontal cortex (Bjorklund and Harnishfeger, 1990; Dempster, 1992). Relatively greater changes in the prefrontal cortex compared to other brain regions have been reported for synaptogenesis (Huttenlocher and Dabholkar, 1997), gray matter reduction (Sowell et al., 1999), myelination increases (Giedd et al., 1999) and resting level metabolism (Chugani et al., 1987).

Developmental neuroimaging studies

No neuroimaging studies using positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) have examined developmental differences in spatial selective attention. Although other studies (see discussion) have used stop and anti-saccade tasks to examine response inhibition (Luna et al., 2001; Rubia et al., 2000a), only four

neuroimaging studies have examined developmental differences with a go no-go task. Our discussion of these studies will focus on results regarding the prefrontal cortex and basal ganglia.

Although they only examined the frontal cortex, Casey et al. (1997) reported a greater number of voxels active for children than for adults in the middle and superior frontal gyri (Casey et al., 1997). This study also showed that more activated voxels in orbitofrontal cortex was associated with fewer commission errors, suggesting that this region may be associated with inhibitory processing. Using a go no-go paradigm quite similar to Casey et al. (1997), Tamm et al. (2002) found similar developmental decreases in activation in the left superior frontal gyrus extending into middle frontal gyrus. However, they also reported developmental increases in activation in the left inferior frontal gyrus extending into orbital frontal gyrus (Tamm et al., 2002). The discrepancy between these studies in the inferior frontal gyrus could be accounted by the lower sensitivity of the large regions of interest used by Casey et al. (1997). Durston et al. (2002) included a parametric manipulation in which inhibitory demands were gradually increased by presenting either 1, 3, or 5 go trials before the no-go trials (Durston et al., 2002). They found that children showed greater intensity of activation than adults in bilateral inferior frontal gyrus and right middle frontal gyrus. The finding that adults, but not children, showed a reliable context effect (increasing activation as a function of number of preceding go trials) in the inferior frontal gyrus suggests that the children may have found all no-go trials difficult. Durston et al. (2002) also showed that higher accuracy was correlated with greater intensity of activation in both the left caudate nucleus and in bilateral inferior frontal gyrus. Although there are some inconsistent findings, these three response inhibition studies seem to converge on the finding of greater activation for children than for adults in the middle or superior frontal gyri.

Bunge et al. (2002) also examined developmental differences in activation during a go no-go task (Bunge et al., 2002). They reported greater intensity of activation for children in medial frontal, whereas there was greater intensity of activation for adults in lateral aspects of the inferior, middle and superior frontal gyri. Although the brain behavior correlation was not specific to the basal ganglia, Bunge et al. (2002) also reported that, for the children, greater intensity of activation in the globus pallidus was associated with better performance on the no-go task.

Several important differences may account for the discrepancy between these studies. First, the event-related design in Bunge et al. (2002) and Durston et al. (2002) may not have establish a pre-potent response because the subjects could not plan a response until the stimulus appeared, whereas the block design in Casey et al. (1997) and Tamm et al. (2002) established a strongly pre-potent response in the go blocks. Second, the event-related design in Bunge et al. (2002) and Durston et al. (2002) allowed them to only

examine correct responses, so errors were not included in the group comparisons as in Casey et al. (1997) and Tamm et al. (2002). Third, the event-related design in Bunge et al. (2002) and Durston et al. (2002) may be less sensitive than the block design in Casey et al. (1997) and Tamm et al. (2002) in detecting group differences. Block designs have greater detection power than event-related designs (Bandettini and Cox, 2000; Liu et al., 2001), plus they allow for distributed sampling over the peri-stimulus time (Price et al., 1999). Because we wanted to maximize our detection power, we used a block design that established a strongly pre-potent response in go blocks that then had to be inhibited in no-go blocks.

Current study

The goal of this project was to use fMRI to examine the neural development of both spatial selective attention and response inhibition in healthy children and adults. We decided to examine brain activation in 9- to 12-year-old children because the behavioral literature suggested that at this age, selective attention mechanisms are relatively mature, but response inhibition mechanisms are still immature. The neural substrate of selective attention was evaluated using conjunction visual search tasks, whereas response inhibition was evaluated using go no-go tasks. Both tasks were structured in exactly the same way except that the visual search task required a yes or no response, whereas the no-go task required the inhibition or execution of a response (target present vs absent for both tasks). Based on the developmental research described above, we expected to see relatively smaller age-related differences for spatial selective attention than for response inhibition. Specifically, we expected to find fewer voxels in our regions of interest that exhibited significant differences between children and adults in the magnitude of activation. Our regions of interest were based on neuro-cognitive models of selective attention (Mesulam, 1990) and response inhibition (Casey et al., 2001) as well on the most typically activated regions reported in the neuroimaging studies reviewed above. These regions included the superior parietal lobule and lateral premotor for the visual search task and the basal ganglia and prefrontal cortex for the response inhibition task.

Materials and methods

Participants

Twelve healthy adults ($M = 25.1$; range = 20.6–30.9 years) and twelve healthy children ($M = 10.9$; range = 9.3–11.7 years) participated in the fMRI study. There were 5 males and 7 females in the adult age group and there were 7 males and 5 females in the child age group. Statistical tests of the behavioral performance and brain activation revealed no significant differences between the males and females in

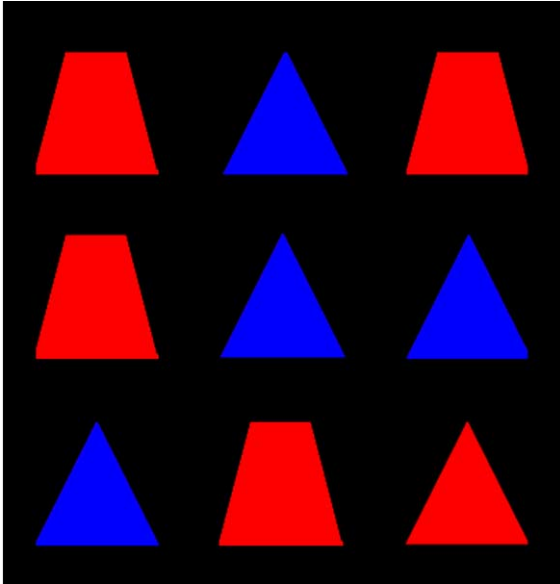


Fig. 1. An example of a trial in the selective attention and response inhibition task in which the target (red triangle) is in a field of eight distracters.

either group; therefore, the results from both genders were pooled for analysis. Adults were undergraduate or graduate students at Northwestern University and children were re-

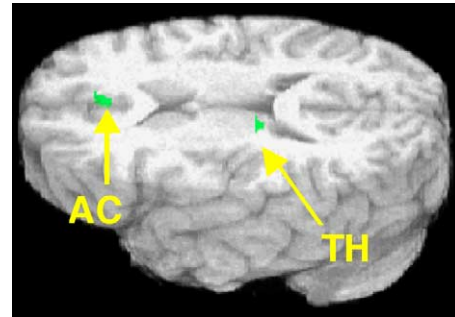


Fig. 5. Significantly greater activation (green) for children than for adults in the selective attention blocks with nine stimuli compared to the go blocks of the response inhibition task with nine stimuli. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (>15 voxels) were labeled. Children showed significantly more activation in anterior cingulate (AC) and thalamus (TH).

cruited from the Evanston, Illinois community. Adults and the parents of children were given an interview to insure that they met the following inclusionary criteria: (1) native English speakers, (2) normal hearing and normal or corrected-to-normal vision, (3) free of neurological diseases or psychiatric disorders, (4) not taking medication affecting the central nervous system, (5) no history of intelligence, read-

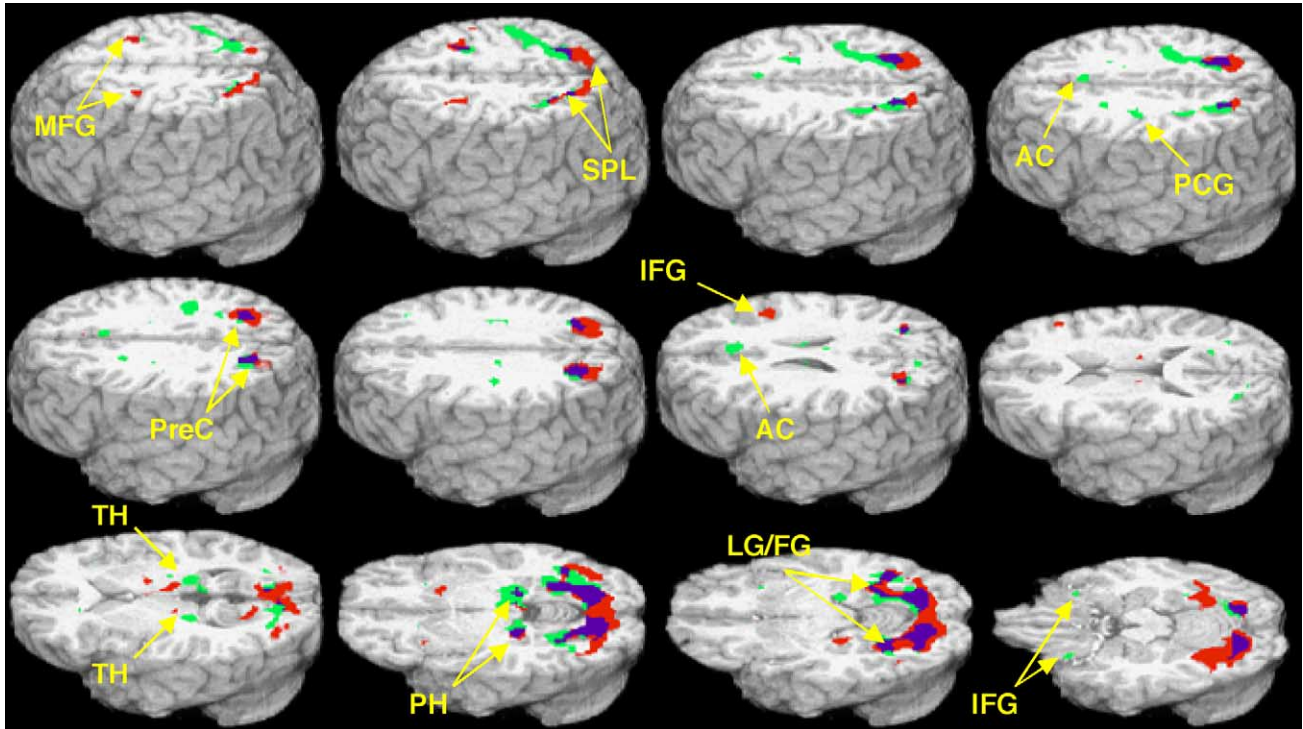


Fig. 2. Significantly greater activation for the selective attention blocks with nine stimuli compared to the blocks with one stimulus. Red indicates activation for the adults, green indicates activation for the children and purple indicates overlap of activation for the adults and children. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (>30 voxels) were labeled. Both adults and children showed clusters of activation in lingual to fusiform gyrus (LG/FG), middle frontal gyrus (MFG), parahippocampus (PH), precuneus (PreC), superior parietal lobule (SPL) and thalamus (TH). Children showed activation in the anterior cingulate (AC), inferior frontal gyrus (IFG), and precentral gyrus (PCG). See Fig. 5 for significant differences between the adults and children.

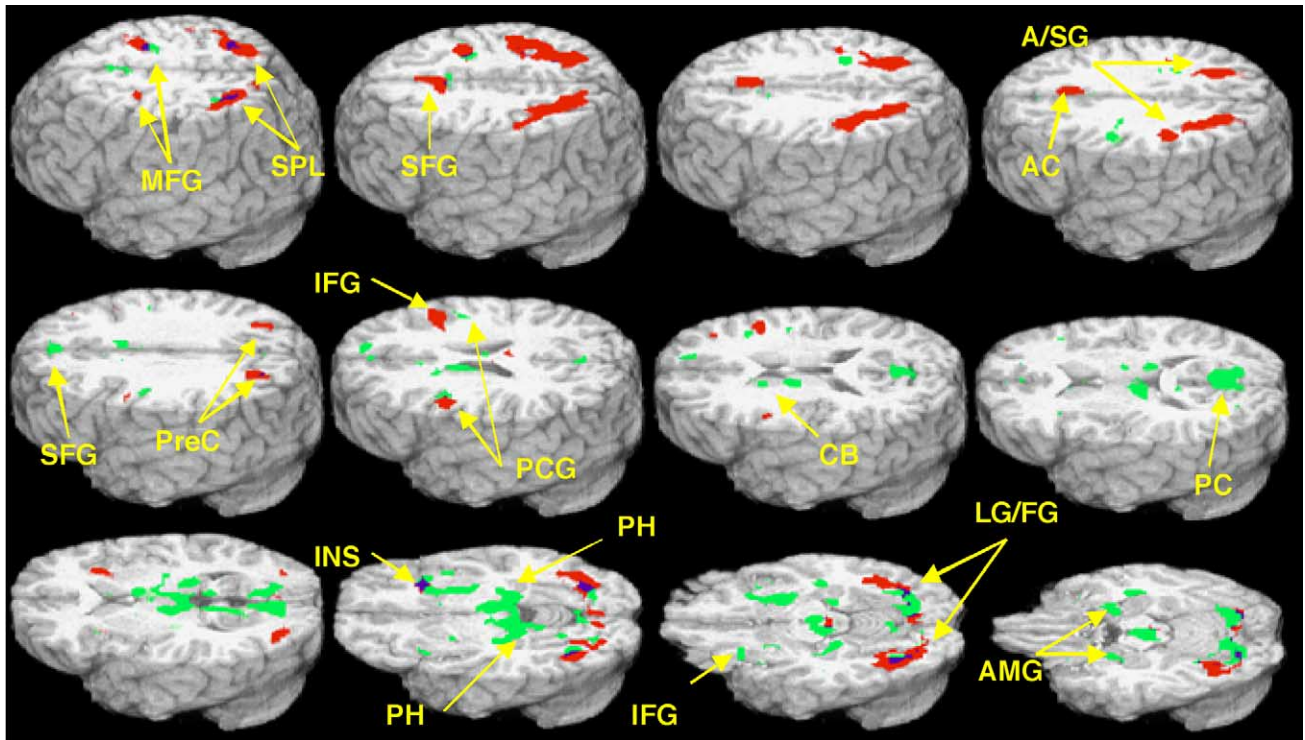


Fig. 3. Significantly greater activation the no-go blocks compared to the go blocks of the response inhibition task. Red indicates activation for the adults, green indicates activation for the children and purple indicates overlap of activation for the adults and children. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (>30 voxels) were labeled. Both adults and children showed clusters of activation in inferior frontal gyrus (IFG), insula (INS), lingual and fusiform gyrus (LG/FG), middle frontal gyrus (MFG), precentral gyrus (PCG), medial aspects of superior frontal gyrus (SFG) and superior parietal lobule (SPL). Adults showed activation in angular/supramarginal gyrus (A/SG), anterior cingulate (AC), and precuneus (PreC). Children showed activation in amygdala (AMG), caudate body (CB), parahippocampus (PH) posterior cingulate (PC), and medial aspects of superior frontal gyrus (SFG). See Fig. 4 for significant differences between the adults and children.

ing, or oral-language deficits, and (6) no learning disability or attention deficit hyperactivity disorder (ADHD). Learning disability and ADHD was assessed by self-report from the adult or the parent of the child.

Functional activation tasks

Both the selective attention and response inhibition task involved red triangle targets that were presented on 50% of

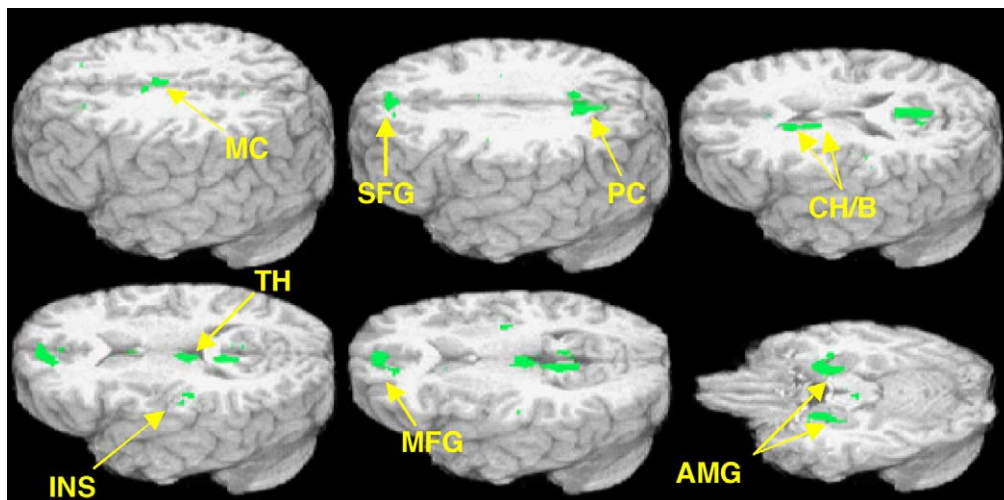


Fig. 4. Significantly greater activation (green) for children than for adults in the no-go compared to the go blocks of the response inhibition task. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (>30 voxels) were labeled. Children showed significantly more activation than adults in amygdala (AMG), caudate body and head (CB/H), insula (INS), middle cingulate (MC), medial frontal gyrus (MFG), posterior cingulate (PC), medial aspects of superior frontal gyrus (SFG), and thalamus (TH).

the trials. The non-target stimuli (distracters) were blue triangles and red trapezoids; therefore, the red triangle target shared either its shape or its color with each of the distracters. Each stimulus was displayed for 1400 ms followed by an interval (blank screen) that was either 450, 600, or 750 ms. The average inter-stimulus interval was 2000 ms. A variable interval was used to limit the participants' ability to pace during the task. Participants were encouraged to respond as quickly as possible. Both tasks consisted of 12 blocks and each block consisted of 18 trials plus a one-word instruction screen presented for 3 sec at the beginning of each block. The selective attention task was always administered before the response inhibition task.

Selective attention task

For the selective attention task, blocks with one and nine stimuli were alternated (6 blocks of each). In the blocks with one stimulus, only one shape was presented at a time and each distracter (a blue triangle or red trapezoid) was presented on 25% of the trials. The display was pseudo-randomized to prevent more than three of the same distracters or targets from appearing in consecutive trials. In the blocks with nine stimuli, nine shapes were presented in a 3×3 matrix including 4 of each distracter (blue triangles and red trapezoids) plus either a target or another distracter. See Fig. 1 for an example of one trial in the nine stimuli condition. The targets were counterbalanced to ensure that each of the nine positions had an equal number of distracters. In order to prevent large regions with similar stimuli, the distracters were also positioned so that there were no more than 3 of the same distracter adjacent on a side. For blocks with one and nine stimuli, the participant pressed his or her index finger if the target was present and the middle finger if the target was absent. An instruction screen was presented for 3 sec at the beginning of each block and displayed "One" for the blocks with one stimulus and "Many" for the blocks with nine stimuli.

Response inhibition task

For the response inhibition task, go and no-go blocks were alternated (6 blocks of each). In both blocks, trials consisted of nine stimuli. In the go blocks, the participants pressed their index finger as soon as the shapes appeared on the screen, regardless of whether or not a target was present. In the no-go blocks, the participants pressed their index finger as quickly as possible once stimuli appeared, withholding their finger press only if the target was present. An instruction screen was presented for 3 sec at the beginning of each block and displayed "Go" for the go blocks and "Stop" for the no-go blocks.

The no-go blocks forced the participants to inhibit the pre-potent response trained during the go blocks. We chose to use a stimulus-controlled task (same number of trials in the go and no-go blocks) rather than a response-controlled task (same number of motor responses in the go and no-go blocks) because previous research has shown that stimulus-

controlled tasks more robustly activate the basal ganglia in children, and therefore, these may be more sensitive to response inhibition (Vaidya et al., 1998).

Experimental procedure

After informed consent was obtained, participants were administered the interview (see above) and the practice session (see below). Within three days, the participant was administered the fMRI session. The Institutional Review Board at Northwestern University and Evanston Northwestern Healthcare Research Institute approved the consent procedures.

fMRI practice session

The participant was acclimated to the scanner environment in a simulator (Rosenberg et al., 1997). From the tube-like structure, the participant was able to view a computer monitor about 40 cm directly above. The participant put on headphones and grasped a button box in his/her right hand. The experimenter played digitized sounds to familiarize the participant with the loud banging noise made by the MRI machine. After the participant seemed comfortable with the loud sounds in the simulator, the participant practiced a full-length version of each experimental task. (See Table 2 for error rates and reaction time during the practice session.)

fMRI data acquisition

After screening, the participant was asked to lie down on the scanner bed. The head position was secured with a specially designed vacuum pillow (Bionix, Toledo, OH, USA). An optical response box (Lightwave Medical, Burnaby, Canada) was placed in the participant's right hand and a squish ball was placed in the left hand. The squish ball was used to signal the operator to terminate the scan if the participant felt that this was necessary for any reason. The head coil was positioned over the participant's head and a goggle system for the visual presentation of stimuli (Avotec, Jensen Beach, FL, USA) was secured to the head coil. Each imaging session took less than one hour.

All images were acquired using a 1.5 Tesla General Electric scanner. Gradient echo localizer images were acquired to determine the placement of the functional slices. For the functional imaging studies, a susceptibility weighted single-shot EPI (echo planar imaging) method with BOLD (blood oxygenation level-dependent) was used. The following scan parameters were used: TE = 40 ms, flip angle = 90° , matrix size = 64×64 , field of view = 22 cm, slice thickness = 4 mm (no gap), number of slices = 32. These scanning parameters resulted in a $3.437 \times 3.437 \times 4$ mm voxel size. The acquisition of a volume (32 slices) of data was repeated every 3 sec (TR = 3000 ms) for a total of 7.8 minutes per run. This amounted to 156 images obtained per slice each for the selective attention task and for the response inhibition task.

Table 1

Means (and ranges) in millimeters for adult and child movement in the X, Y and Z directions for the selective attention blocks with nine stimuli (Nine) and with one stimulus (One) and for the no-go and go response inhibition blocks with nine stimuli

	X	Y	Z
ADULT			
Attention Nine	0.11 (0.03–0.28)	0.21 (0.05–0.53)	0.36 (0.11–0.87)
Attention One	0.12 (0.03–0.31)	0.22 (0.06–0.63)	0.41 (0.12–0.97)
No-Go Nine	0.15 (0.04–0.37)	0.25 (0.07–0.55)	0.49 (0.09–1.33)
Go Nine	0.18 (0.05–0.37)	0.25 (0.07–0.48)	0.51 (0.10–1.51)
CHILD			
Attention Nine	0.10 (0.05–0.20)	0.23 (0.10–0.63)	0.29 (0.08–0.59)
Attention One	0.10 (0.03–0.25)	0.23 (0.12–0.69)	0.30 (0.11–0.84)
No-Go Nine	0.10 (0.03–0.24)	0.33 (0.16–0.83)	0.49 (0.07–1.17)
Go Nine	0.11 (0.04–0.28)	0.33 (0.15–0.86)	0.53 (0.08–1.85)

At the end of the functional imaging session, a high resolution, T1 weighted 3D image was acquired (SPGR, TR = 21 ms, TE = 8 ms, flip angle = 20°, matrix size = 256 × 256, field of view = 22 cm, slice thickness = 1 mm). These scanning parameters resulted in a .86 × .86 × 1 mm voxel size. The acquisition of the anatomical scan took 8.6 minutes. The orientation of this 3D volume was identical to the functional slices.

Image data analysis

Most of the analysis of the data was performed using SPM-99 (Friston et al., 1995a; Friston et al., 1995b; Friston et al., 1994). Personalized software with modules in AVS (Advanced Visual Systems, Waltham, MA, USA) was used for visualization.

The functional images were realigned (3D) to the last functional volume in the scanning session using affine transformations. No individual runs had more than 2.0 mm movement (less than 1/2 the voxel size) from the beginning to the end of the run in the x-plane, y-plane, or z-plane (see Table 1 for estimates of movement). No subjects were excluded due to excess movement. The small amount of movement confirmed that the vacuum pillow satisfactorily kept the heads of our participants still. All statistical analyses were conducted on these movement-corrected images.

Realigned images were segmented (gray matter, white matter, cerebrospinal fluid and scalp), and the gray-white matter information was used to co-register the structural and functional images. The co-registered images were normalized to the Montreal Neurological Institute (MNI) stereotaxic template (12 linear affine parameters for brain size and position, 8 non-linear iterations and 2 × 2 × 2 nonlinear basis functions for subtle morphological differences). The MNI template is similar to the Talairach and Tournoux (1998) stereotaxic atlas (Talairach and Tournoux, 1988) and there are algorithms to convert between coordinate spaces (Calder et al., 2001; Duncan et al., 2000). Considering the age of our participants and our voxel size, it is reasonable to normalize all participants into the standard MNI template

(Burgund et al., 2002; Kang et al., 2003; Muzik et al., 2000; Wilke et al., 2002).

Statistical analyses were calculated on the smoothed data (7 mm isotropic Gaussian kernel) using a delayed boxcar design with a 6 sec delay from onset of block in order to account for the lag in hemodynamic response. Preprocessing of the data also included the use of a high pass filter equal to 2 cycles of the experimental and control conditions (156 sec) in order to remove signal drift, cardiac and respiratory effects, and other low frequency artifacts.

Random effect statistics allowed generalization to the population and required a first and second level of analysis. In the first level analysis, we calculated parameter estimate images for individual subjects across the entire brain. For each individual, we calculated 3 contrasts: selective attention blocks with nine stimuli minus selective attention blocks with one stimulus, response inhibition no-go blocks with nine stimuli minus go blocks with nine stimuli, and selective attention blocks with nine stimuli minus go blocks with nine stimuli. Using the go blocks as the baseline for both the selective attention and response inhibition paradigms meant that the experimental and control blocks were equated in terms of visual information. However, because we were interested in the interaction between group (children and adults) and block, the comparison of blocks with nine stimuli to those with one stimulus is valid.

In the second level analysis, the parameter estimate images for each contrast were entered into statistical analyses. One and two-sample Z-tests were used for comparisons. All reported areas of activation are significant using $p < .001$ uncorrected at the voxel level and contain a cluster size greater than or equal to 10 voxels.

Results

Behavioral performance

Table 2 presents error rates and reaction times on the selective attention task and the response inhibition task. In order to examine developmental differences on the selective attention task, we calculated a 2 age (adults, children) × 2 session (practice, test) × 2 block (nine, one) ANOVA separately on error rates and reaction times. This analysis showed that children had more errors, $F(1, 95) = 22.12$, $p < .001$, and slower reaction times, $F(1, 95) = 52.40$, $p < .001$, compared to adults. This analysis also showed that the blocks with nine stimuli had slower reaction times than the blocks with one stimulus, $F(1, 95) = 79.58$, $p < .001$.

In order to examine developmental differences on the response inhibition task, we calculated a 2 age (adults, children) × 2 session (practice, test) × 2 block (no-go, go) ANOVA separately on error rates and reaction times. Error rates for the go blocks include only omissions (misses) because participants were supposed to press the button for every stimulus, whereas error rates for the no-go blocks

Table 2

Means (*M*) and standard errors (*SE*) for error rates (%) and reaction time (RT in ms) for the practice and fMRI sessions for the selective attention blocks with nine stimuli (Nine) and with one stimulus (One) and for the no-go and go response inhibition blocks with nine stimuli

	Practice				fMRI			
	Error rates		RT		Error rates		RT	
	M	SE	M	SE	M	SE	M	SE
ADULT								
Attention Nine	2.9	0.6	700	41	1.9	0.5	713	35
Attention One	2.2	0.5	497	26	2.7	0.7	528	23
No-Go Nine	2.9	0.6	679	34	2.8	0.7	681	34
Go Nine	1.1	0.4	315	14	2.3	1.0	356	18
CHILD								
Attention Nine	8.6	1.7	891	32	5.7	1.3	853	39
Attention One	4.8	1.4	666	30	4.6	0.8	673	34
No-Go Nine	5.8	1.2	835	38	6.4	1.1	813	32
Go Nine	5.1	1.3	509	45	2.9	1.0	492	49

include omissions as well as commissions (false alarms) because participants were asked to withhold a response when the target was present. This analysis showed that children had more errors, $F(1, 95) = 18.16, p < .001$, and slower reaction times, $F(1, 95) = 43.47, p < .001$, compared to adults. This analysis also showed that the no-go blocks had more errors, $F(1, 95) = 6.39, p < .05$, and slower reaction times, $F(1, 95) = 204.23, p < .001$, compared to the go blocks. We calculated an additional 2 age (adults, children) \times 2 session (practice, test) ANOVA to examine developmental differences in commissions. Block could not be used as an independent variable in this analysis because commissions were not possible in the go blocks. This analysis revealed that children ($M = 5.3; SE = 0.9$) showed significantly more commissions than adults ($M = 2.6; SE = 0.6$), $F(1, 47) = 18.89, p < .001$.

The lack of significant main effects or interactions involving session ($ps > .15$) for the selective attention and response inhibition tasks indicates that the environment of the scanner did not negatively affect performance for either group. There were also no significant interactions between age and block for the selective attention or response inhibition task ($ps > .40$, except for errors on the selective attention task, $t = 2.93, p = .09$). This indicates that any age-by-block differences in patterns of brain activation may not be associated with performance differences because, like the behavioral analyses, our fMRI analysis examined developmental differences in the nine versus one blocks for selective attention and in the no-go versus go blocks for response inhibition. We also calculated a 2 age (adults, children) \times 2 session (practice, test) \times 2 block (no-go, go or nine, one) \times 2 task (selective attention, response inhibition) ANOVA. This analysis revealed no significant age-by-task interactions or age-by-block-by-task interactions for either error rates or reaction times. This indicates different age-related patterns in activation for the selective attention and response inhibition tasks may not be accounted for by performance differences.

Comparison of accuracy and reaction time across blocks

or tasks is difficult to interpret because the nature of the measures in these comparisons differ. For example, because children made more errors than adults and the types of errors in the selective attention task (omissions and commissions) were not precisely of the same nature as the errors in the response inhibition task (only omissions for the go blocks, both omissions and commissions for the no-go blocks), a lack of interaction does not preclude the possibility that age-related differences in brain activation are due to the differences in the type of error produced more frequently by children in a particular block type. Similarly, comparing reaction time across the selective attention task and the response inhibition task is not ideal because we do not have a measure of the amount of time required for response inhibition in the no-go blocks. Reaction time for the no-go blocks instead reflects the amount of time required to determine that the target is absent before making a response.

Brain activation for selective attention

Table 3 and Fig. 2 identify regions with significantly greater activation in the selective attention blocks with nine stimuli compared to the blocks with one stimulus, separately for the adults and for the children. In general, the patterns of activation for the adults and children were quite similar. Both groups exhibited a large amount of bilateral activation in precuneus, superior parietal lobule, lingual gyrus, and fusiform gyrus. Both groups also showed bilateral activation in parahippocampal areas and greater activation in right than in left thalamus. Both groups also exhibited activation in middle frontal gyrus, but this activation was confined to the right hemisphere for children. Both groups also showed activation in the inferior frontal gyrus, but this activation was bilateral for children and confined to the right hemisphere for adults. The major developmental difference between these activation maps was that only the children showed areas of reliable activation in the left and right anterior cingulate. However, the data presented in Fig.

Table 3

Significantly greater activation in the selective attention blocks with nine stimuli compared to the blocks with one stimulus. Results are presented separately for the adults and children

Group	Location		Significance		Coordinate		
	Area	BA	z-test	voxels	X	Y	Z
ADULT	Superior parietal lobule precuneus	7/19	5.43	399	30	-66	39
		7/19	5.67	346	-24	-72	33
	Lingual/fusiform gyrus	18/19/37	5.33	1781	-30	-54	-18
	Middle frontal gyrus	6	4.68	72	33	3	45
		46	4.61	24	54	33	15
		6	4.12	29	-27	3	48
	Inferior frontal gyrus	44	3.81	26	48	12	21
	Thalamus	*	5.46	108	18	-3	3
		*	4.01	34	-15	-15	12
	Parahippocampus	35	3.61	11	24	-27	-9
		27	4.35	43	-24	-33	-6
	Medial frontal gyrus	6	3.99	11	6	33	36
	Subcallosal gyrus	25	3.86	22	21	18	-9
	Cerebellum	*	3.96	18	-3	-30	-9
		*	4.96	25	-9	-30	-30
CHILD	Superior parietal lobule/precuneus	7/19	5.36	1861	27	-57	48
	Lingual/fusiform	18/37					
	Middle frontal gyrus	6	4.14	64	27	0	45
	Inferior frontal gyrus	47	3.92	32	30	27	-3
		47	3.96	30	-30	24	-18
	Thalamus/parahippocampus	*/27	5.31	200	24	-30	-3
		*/27	5.13	102	-21	-30	0
	Precentral gyrus	6	4.28	38	-33	-18	30
	Anterior cingulate	32	4.68	26	9	21	36
		32	4.52	39	12	33	21
		32	4.38	16	-18	9	36
		32	3.94	25	-12	30	15
		32	3.94	25	-12	30	15
	Posterior cingulate	31	4.25	20	24	-60	15
	Medial globus pallidus	*	3.68	19	12	-6	-3

Note. BA: Brodmann's area of peak activation as determined by z-test ($p < .001$ uncorrected at the voxel level). Voxels: number of voxels in cluster including this peak, only clusters 10 or greater are presented. Coordinates: -X left hemisphere, +X right hemisphere, -Y behind anterior commissure, +Y in front of anterior commissure, -Z below anterior-posterior commissure plane, +Z above anterior-posterior commissure plane. Regions activated in both groups (adults and children) are listed first. Some of the regions contained multiple clusters—right hemisphere clusters are always listed first.

2 and Table 3 does not involve a direct statistical comparison between adults and children. A direct statistical comparison of the selective attention task (nine vs one stimuli) revealed no significant developmental differences in any region. Statistical comparisons are necessary to determine reliable differences between the groups. Adults may show activation in an area because it is just over threshold, whereas children may show no activation in this area because it is just under threshold. In this case, a direct statistical test would yield no significant group differences.

Brain activation for response inhibition

Table 4 and Figure 3 present significantly greater activation in the no-go blocks compared to the go blocks of the response inhibition task, separately for the adults and for the children. The patterns of activation for the adults and children showed some similarities. Both groups showed bilateral activation in the lingual and fusiform gyrus. Both also showed bilateral activation in the superior parietal lobule,

although this activation was larger for the adults and extended into bilateral precuneus and into the inferior portion of the parietal lobe including the supramarginal and angular gyrus. Both groups also exhibited activation in the middle frontal gyrus, but this activation was confined to one region in the right hemisphere for the children, whereas adults showed several areas of activation in the right hemisphere and one region in the left. Both groups also showed activation in the inferior frontal gyrus/insula and precentral gyrus, but this activation was bilateral for the children and confined to one hemisphere for the adults.

The data presented in Fig. 3 and Table 4 also suggested several developmental differences on the response inhibition task. The adults showed large clusters of activation in bilateral anterior cingulate. Both adults and children showed activation in the medial aspects of the superior frontal gyrus, but the adults only showed one cluster whereas the children showed two clusters. Children also showed activation in left caudate body, bilateral posterior cingulate, and bilateral hippocampus-amygdaloid region. However, a direct statisti-

Table 4

Significantly greater activation in the no-go blocks compared to the go blocks of the response inhibition task. Results are presented separately for the adults and children

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
ADULT	Superior parietal lobule/precuneus	7/19	4.95	648	30	-63	36
		Angular/supramarginal gyrus	39/40				
	Middle frontal gyrus	7/19	4.55	633	-30	-51	48
		39/40					
		6	4.47	151	39	3	45
	Inferior frontal gyrus	10	3.90	21	39	42	15
		10	3.82	11	33	60	15
		6	4.14	30	-24	3	48
		45	4.62	116	48	15	21
		13	4.85	77	30	27	0
	Precentral gyrus	6	3.85	66	-48	6	24
	Posterior cingulate	23	3.97	11	9	-27	24
	Lingual/fusiform gyrus	18/19/37	5.24	815	-39	-81	3
	Anterior cingulate/superior frontal gyrus	32/8	4.56	173	9	30	33
	Red nucleus	*	4.06	23	6	-24	-12
CHILD	Superior parietal lobule	7	3.73	45	30	-54	57
		7	3.85	64	33	-33	36
		7	4.20	104	-30	-45	57
	Middle frontal gyrus	6	3.90	77	27	0	42
		44/13	4.60	40	42	24	15
	Inferior frontal gyrus	47	3.68	49	-30	27	-12
	Insula	13	3.76	22	-42	-30	0
	Precentral gyrus	6	3.79	51	48	-3	27
		6	4.14	106	-42	0	33
	Posterior cingulate	31	3.70	10	-24	-78	12
	Superior frontal gyrus	8	3.83	89	3	18	54
		10	5.02	106	15	57	21
		*	4.21	212	-12	-3	18
	Parahippocampus/posterior	35/27/29	5.34	2296	-30	-24	-9
	Cingulate/lingual/fusiform gyrus	18/19/37					
Amygdala	*	4.50	44	45	-12	-18	
Amygdala	*	3.57	40	-21	-3	-18	

Note. See Table 3 note.

cal comparison between adults and children is necessary to determine whether any of these potential developmental differences were reliable. This analysis revealed that children exhibited significantly more activation than adults in medial aspects of the bilateral superior frontal gyrus, left caudate head and body, bilateral posterior cingulate, and bilateral hippocampo-amygdaloid region. Children also showed significantly greater activation than adults in bilateral regions of the middle cingulate, insula, medial frontal gyrus, and thalamus. Fig. 4 and Table 5 (top) identify regions with significantly greater activation for children than for adults in the no-go vs go blocks of the response inhibition task. Adults did not show significantly greater activation than children in any brain region in this comparison.

Re-examination of selective attention

To further examine developmental differences in selective attention, we compared the selective attention blocks

with nine stimuli to the go blocks of the response inhibition task with nine stimuli. The rationale for this was that both blocks would be equated for stimulus characteristics, and therefore, this contrast may be more sensitive to developmental differences in selective attention. Fig. 5 and Table 5 (bottom) identify regions with significantly greater activation for children than for adults on this contrast. Although the clusters were small, this analysis revealed significantly greater activation for children than for adults in left thalamus and right anterior cingulate. Adults did not show significantly greater activation than children in any brain region in this comparison.

Discussion

Selective attention

Both the adults and children showed activation during our spatial selective attention task in a neuro-cognitive net-

Table 5

Significantly greater activation for children than for adults in the no-go compared to the go blocks of the response inhibition task (INH) and significantly greater activation for children than for adults in the selective attention blocks with nine stimuli compared to the go blocks of the response inhibition task with nine stimuli (ATT)

Group	Location		Significance		Coordinate		
	Area	BA	z-test	voxels	X	Y	Z
INH	Superior frontal gyrus	9	3.89	12	21	39	39
		9	4.21	115	3	54	30
	Medial frontal gyrus	10	5.12	152	3	60	0
	Insula	13	4.03	10	45	0	12
	Insula/superior temporal gyrus	13/22	3.70	52	-42	-30	15
	Caudate head/body	*	4.35	67	-12	15	18
	Middle cingulate	24	3.90	62	6	-9	36
	Posterior cingulate/thalamus	29	5.35	405	-6	-42	9
	Amygdala/hippocampus	*	5.01	92	24	-3	-15
	Amygdala/hippocampus	*	4.14	46	-27	-9	-21
	Substantia nigra	*	4.00	12	12	-27	-9
	Pons	*	4.12	13	-3	-24	-21
	ATT	Anterior cingulate	32	4.06	17	6	42
Thalamus		*	3.80	17	-12	-27	12

Note. See Table 3 note.

work involving the thalamus, the superior parietal lobule and the middle frontal gyrus (premotor cortex). Our results are generally consistent with past neuroimaging studies in adults that have examined spatial selective attention (Gitelman et al., 1999; Kim et al., 1999; LaBar et al., 1999; Mesulam et al., 2001; Nobre et al., 1999; Nobre et al., 2000; Nobre et al., 1997) and conjunction search in particular (Corbetta et al., 1995; Coull and Nobre, 1998; Donner et al., 2000). Because the analysis of our selective attention task within age groups involved a comparison between blocks with nine stimuli and blocks with one stimulus, the differences reflect a combination of selective attention, eye movement and sensory effects. However, we were primarily interested in testing whether there were developmental differences in the selective attention task.

Our study revealed relatively small developmental differences on the selective attention task and none of these differences were in our a priori regions of interest (superior parietal lobule and lateral premotor cortex). Children showed significantly greater intensity of activation than adults in a small number of voxels in only two regions: anterior cingulate (17 voxels) and thalamus (17 voxels). These developmental differences only emerged when comparing the selective attention blocks with nine stimuli to the go blocks with nine stimuli. Note that the go blocks required minimal involvement of attentional resources since a quick response was required at stimulus onset regardless of stimulus configuration; thus, using go blocks as a baseline should provide maximal sensitivity for demonstrating attentional effects. No significant group differences between the adults and children were found when comparing the selective attention blocks with nine stimuli to the selective attention blocks with one stimulus. Although there were several significant developmental differences for the response inhibition task in the frontal lobe (see below), these areas

tended to be in prefrontal regions that have a delayed maturational course (Chugani et al., 1987; Giedd et al., 1999; Huttenlocher and Dabholkar, 1997; Sowell et al., 1999). The lack of a significant developmental difference in the lateral premotor cortex (frontal eye fields) for the selective attention task is not necessarily inconsistent with the findings for response inhibition because in addition to its role in selective attention, the frontal eye fields is a motor control region which shows earlier maturational time tables than anterior prefrontal regions (Sowell et al., 1999).

Our developmental results are consistent with previous ERP studies that have found age-related decreases across childhood in the amplitude of the P2 component and latency of the P3 component during search tasks (Taylor and Khan, 2000; Taylor et al., 1999; Taylor et al., 1997). Although the spatial resolution of ERP studies is limited, these studies show that developmental differences are not specific to conjunction visual search. Similar age-related differences are found on tasks that require the search of a single feature. In other words, there appears to be no interaction between the type of search (conjunction and feature) and the developmental period examined in these ERP studies. The lack of specificity of these ERP results is consistent with our demonstration of little or no developmental difference between children and adults when comparing the harder blocks involving conjunction search in a field of eight distracters to the easier blocks.

The small developmental differences in brain activation for our selective attention task is also consistent with previous behavioral performance studies which have shown relatively rapid maturation on visual search tasks in early childhood (Gerhardstein and Rovee-Collier, 2002; Thompson and Massaro, 1989). Although our study had only two distracter conditions (one versus nine stimuli), our behavioral performance analyses showed that there was no age-

related difference in the slope function of visual search as evidenced by the lack of a significant interaction between age and number of distracters. The lack of large age differences for brain activation on our selective attention task may be attributed to the relatively small differences in the neural network involved in simple search tasks during development from the middle childhood to adult age period.

Response inhibition

The response inhibition task also required visual search in order to detect the presence or absence of a target in a field of distracters, so not surprisingly the no-go task produced activation in the selective attention network. Both the adults and children showed activation in bilateral superior parietal lobule and in predominantly right middle frontal gyrus. Because the analysis of our response inhibition task within age groups involved a comparison between go blocks with a motor response to every trial and no-go blocks with a response to only half of the trials, any differences reflect a combination of motor and response inhibition effects. However, we were primarily interested in developmental differences during the go no-go task in brain regions implicated in response inhibition. We will first consider age-related changes in our regions of interest that included medial frontal regions and the basal ganglia.

Our response inhibition task produced extensive developmental differences with children showing significantly greater intensity of activation than adults in frontal lobe regions including bilateral medial frontal gyrus (152 voxels) and medial aspects of bilateral superior frontal gyrus (127 voxels). These large developmental differences for our response inhibition task are consistent with research that has shown age-related differences in accuracy and reaction time on go no-go tasks across childhood (Becker et al., 1987; Levy, 1980). These prominent developmental differences could reflect slower maturational processes in the prefrontal cortex (Chugani et al., 1987; Giedd et al., 1999; Huttenlocher and Dabholkar, 1997; Sowell et al., 1999). Some have argued that prefrontal regions are involved in protecting representations of relevant information from interference due to competing information (Casey et al., 2001). Immature prefrontal networks in the children in our study may have resulted in more activation because of the increased effort in maintaining a no-go response to a red triangle in the face of interference from earlier conditioning to pre-potently respond to this stimulus.

Our demonstration of developmental differences in activation in the frontal cortex is consistent with studies which have shown that younger subjects exhibited greater activation than older subjects in the middle and superior frontal gyrus during a go no-go task (Casey et al., 1997; Tamm et al., 2002). However, Casey et al. (1997) reported results in five regions of interest including the anterior cingulate, inferior frontal, middle frontal, orbital frontal, and superior frontal. Activation maps or stereotaxic coordinates were not

provided, so it is not clear from the report whether activation was medial or lateral within these regions. Because of this, it is difficult to directly compare our results of developmental differences in medial frontal regions with their results.

Our frontal cortex results are somewhat inconsistent with the results of Rubia et al. (2000b) who reported developmental differences during a stop task (Rubia et al., 2000a). The stop task requires the retraction of a response that has already been triggered by a go signal. This is different than our go no-go tasks, which involved the creation of a pre-potent response in the go blocks and the inhibition of that pre-potent response in the no-go blocks. Rubia et al. (2000b) reported age-related increases in activation in lateral aspects of left middle frontal gyrus and the opercular part of left inferior frontal gyrus that extended medially into the insula. However, they reported age-related decreases in activation in right caudate nucleus and in lateral aspects of right inferior frontal gyrus. The discrepancy between our results and Rubia et al. (2000b) study could be accounted for by task differences. In a different study with adults only, Rubia et al. (2000b) reported that stop and go no-go tasks shared some network components, but that the go no-go task produced more activation in the medial frontal gyrus and the lateral aspects of the middle frontal gyrus (Rubia et al., 2000b).

Our study also showed significantly greater intensity of activation for children than for adults in the body and head of the left caudate nucleus (67 voxels). This result is consistent with the Rubia et al. (2000b) study that reported age-related decreases in activation in the right caudate nucleus during a stop task (Rubia et al., 2000a). Our finding of greater caudate activation in children is also consistent with other studies that reported younger children have larger caudate volumes than older children (Castellanos et al., 1996). Thompson et al. (2000) estimated that there is about a 50% reduction the size of the caudate head but that the caudate tail remains stable with development (Thompson et al., 2000). Whereas prefrontal networks have been proposed to be involved in maintaining representations in the face of competing interference, the basal ganglia has been proposed to be involved in the inhibition of inappropriate behaviors (Casey et al., 2001). The immature basal ganglia in the children in our study may have resulted in more activation because they were inefficient at generating an inhibitory signal in response to the red triangles in the no-go blocks.

Our finding of increased caudate activation in children appears to be inconsistent with Luna et al. (2001), who examined developmental differences in an anti-saccade task. This task requires that subjects voluntarily stop reflexive eye movements to a pre-potent visual stimulus and instead move their eyes in the opposite direction. They found that children (8- to 13-years-old) showed little activation, adolescents (14- to 17-year-olds) showed the most activation, and adults (18- to 30-years-old) showed moderate activation in the prefrontal cortex and basal ganglia.

Only the cerebellum, however, showed significant developmental differences that were specific to the anti-saccade task. Differences between our results and those of Luna et al. (2001) may be due to different developmental trajectories for the go no-go and anti-saccade tasks. Although both tasks require inhibition, performance on the go no-go task appears to mature earlier at about 12 years of age (Levin et al., 1991), whereas performance on the anti-saccade task appears to mature later at about 15–20 years of age (Munoz et al., 1998). The incomplete and partial maturation of the go no-go performance of the 9- to 12-year-old children in our study may account for the developmental differences in brain activation we observed for the caudate nucleus. The lack of activation for the youngest age group in the Luna et al. (2001) study may have resulted from their inability to effectively recruit the basal ganglia for performance on their anti-saccade task.

There were several other developmental differences outside our regions of interest during the response inhibition task. It is interesting to note that the areas of greater activation for children during the go no-go task were located predominantly within the limbic and paralimbic areas, including bilateral hippocampo-amygdaloid regions. The reason for activation of this region in the go no-go task is not clear, and none of the other developmental studies examining response inhibition reported age-related differences in this region (Bunge et al., 2002; Casey et al., 1997; Durston et al., 2002; Luna et al., 2001; Rubia et al., 2000a; Tamm et al., 2002). Studies have shown activation in the amygdala during positive and negative feedback (Zalla et al., 2000), positive and negative emotions (Iidaka et al., 2001; Sander and Scheich, 2001), as well as concrete and abstract fear conditioning (Morris et al., 2001; Phelps et al., 2001). The medial prefrontal cortex has been postulated to play a role in emotion through inhibition of amygdala responsiveness (Bremner et al., 1999). Perhaps, the children in our study devoted more prefrontal brain resources for motor response inhibition, and therefore, could less effectively inhibit affective responses in the amygdala. The affective component in our study cannot, however, be associated with the general MRI environment, because there were no group differences in activation within the hippocampo-amygdaloid regions during the selective attention task.

Conclusion

This study found significant developmental differences (9- to 12-year-olds vs adults) in the intensity of activation in only two small brain areas (neither point in our regions of interest) during selective attention as measured by a visual search task. These relatively small differences may reflect earlier maturation of brain networks subserving selective attention. In contrast, there were significant developmental differences in the intensity of activation encompassing large areas in both of our regions of interest (medial frontal and

basal ganglia) during response inhibition as measured by a go no-go task. The different developmental trajectories of activation for the two tasks may reflect the relatively prolonged development of fronto-striatal networks. The characterization of developmental differences in response inhibition is important because theorists argue that an increase in the efficiency of inhibitory processing is a maturational process that impacts many cognitive domains.

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References

- Alexander, G.E., DeLong, M.R., Strick, P.L., 1986. Parallel organization of functionally segregated circuits linking basal ganglia and cortex. *Annual Review of Neuroscience* 9, 357–381.
- Ashbridge, E., Walsh, V., Cowey, A., 1997. Temporal aspects of visual search studied by transcranial magnetic stimulation. *Neuropsychologia* 35 (8), 1121–1131.
- Bandettini, P.A., Cox, R.W., 2000. Event-related fMRI contrast when using constant interstimulus interval: theory and experiment. *Magnetic Resonance in Medicine* 43 (4), 540–548.
- Barkley, R.A., 1997. Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychological Bulletin* 121, 65–94.
- Becker, M.G., Isaac, W., Hynd, G.W., 1987. Neuropsychological development of nonverbal behaviors attributed to “frontal lobe” functioning. *Developmental Neuropsychology* 3, 275–298.
- Bjorklund, D.F., Harmishfeger, K.K., 1990. The resources construct in cognitive development: diverse sources of evidence and a theory of inefficient inhibition. *Developmental Review* 10, 48–71.
- Botvinick, M., Nystrom, L.E., Fissell, K., Carter, C.S., Cohen, J.D., 1999. Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature* 402 (6758), 179–181.
- Braver, T.S., Barch, D.M., Gray, J.R., Molfese, D.L., Snyder, A., 2001. Anterior cingulate cortex and response conflict: effects of frequency, inhibition and errors. *Cerebral Cortex* 11 (9), 825–836.
- Bremner, J.D., Staib, L.H., Kaloupek, D., Southwick, S.M., Soufer, R., Charney, D.S., 1999. Neural correlates of exposure to traumatic pictures and sound in Vietnam combat veterans with and without post-traumatic stress disorder: a positron emission tomography study. *Biological Psychiatry* 45 (7), 806–816.
- Bunge, S.A., Dudukovic, N.M., Thomason, M.E., Vaidya, C.J., Gabrieli, J.D., 2002. Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron* 33, 301–311.
- Burgund, E.D., Kang, H.C., Kelly, J.E., Buckner, R.L., Snyder, A.Z., Petersen, S.E., Schlaggar, B.L., 2002. The feasibility of a common stereotactic space for children and adults in fMRI studies of development. *Neuroimage* 17 (1), 184–200.
- Calder, A.J., Lawrence, A.D., Young, A.W., 2001. Neuropsychology of fear and loathing. *Nature Reviews Neuroscience* 2, 352–363.

- Casey, B.J., Durston, S., Fossella, J.A., 2001. Evidence for a mechanistic model of cognitive control. *Clinical Neuroscience Research* 1, 267–282.
- Casey, B.J., Trainor, R.J., Orendi, J.L., Schubert, A.B., Nystrom, L.E., Giedd, J.N., Castellanos, F.X., Haxby, J.V., Noll, D.C., Cohen, J.D., Forman, S.D., Dahl, R.E., Rapoport, J.L., 1997. A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *Journal of Cognitive Neuroscience* 9, 835–847.
- Castellanos, F.X., Giedd, J.N., Marsh, W.L., Hamburger, S.D., et al., 1996. Quantitative brain magnetic resonance imaging in attention-deficit hyperactivity disorder. *Archives of General Psychiatry* 53 (7), 607–616.
- Chugani, H.T., Phelps, M.E., Mazziotta, J.C., 1987. Positron emission tomography of human brain functional development. *Annals of Neurology* 22, 487–497.
- Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual locations: identical, independent, or overlapping neural systems? *Proceedings of the National Academy of Sciences of the United States of America*, 95(3), 831–838.
- Corbetta, M., Shulman, G.L., Miezin, F.M., Petersen, S.E., 1995. Superior parietal cortex activation during spatial attention shifts and visual feature conjunction. *Science* 270 (5237), 802–805.
- Coull, J.T., Nobre, A.C., 1998. Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience* 18 (18), 7426–7435.
- Deiber, M.-P., Honda, M., Ibanez, V., Sadato, N., Hallett, M., 1999. Mesial motor areas in self-initiated versus externally triggered movements examined with fMRI: effect of movement type and rate. *Journal of Neurophysiology* 81 (6), 3065–3077.
- Dempster, F.N., 1992. The rise and fall of inhibitory mechanism: Toward a unified theory of cognitive developmental and aging. *Developmental Review* 12, 45–75.
- Donner, T., Kettermann, A., Diesch, E., Ostendorf, F., Villringer, A., Brandt, S.A., 2000. Involvement of the human frontal eye field and multiple parietal areas in covert visual selection during conjunction search. *European Journal of Neuroscience* 12 (9), 3407–3414.
- Duncan, J., Seitz, R.J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., Newell, F.N., Emslie, H., 2000. A neural basis for general intelligence. *Science* 289, 457–460.
- Durston, S., Thomas, K.M., Yang, Y., Ulug, A.M., Zimmerman, R.D., Casey, B.J., 2002. A neural basis for the development of inhibitory control. *Developmental Science* 5 (4), F9–F16.
- Friston, K.J., Ashburner, J., Frith, C.D., Poline, J.B., Heather, J.D., Frackowiak, R.S.J., 1995a. Spatial registration and normalization of images. *Human Brain Mapping* 2, 1–25.
- Friston, K.J., Holmes, A.P., Poline, J.B., Grasby, P.J., Williams, S.C.R., Frackowiak, R.S.J., Turner, R., 1995b. Statistical parametric maps in functional imaging: a general linear approach. *Human Brain Mapping* 2, 189–210.
- Friston, K.J., Jezzard, P., Turner, R., 1994. Analysis of functional MRI times-series. *Human Brain Mapping* 1, 153–171.
- Gerhardstein, P., Rovee-Collier, C., 2002. The development of visual search in infants and very young children. *Journal of Experimental Child Psychology* 81 (2), 194–215.
- Giedd, J.N., Blumenthal, J., Jeffries, N.O., Castellanos, F.X., Liu, H., Zijdenbos, A., Paus, T., Evans, A.C., Rapoport, J.L., 1999. Brain development during childhood and adolescence: a longitudinal MRI study [letter]. *Nature Neuroscience* 2 (10), 861–863.
- Gitelman, D.R., Nobre, A.C., Parrish, T.B., LaBar, K.S., Kim, Y.H., Meyer, J.R., Mesulam, M.M., 1999. A large-scale distributed network for covert spatial attention: further anatomical delineation based on stringent behavioral and cognitive controls. *Brain* 122, 1093–1106.
- Goldman-Rakic, P.S., 1987. Development of cortical circuitry and cognitive function. *Child Development* 58 (3), 601–622.
- Huttenlocher, P.R., Dabholkar, A.S., 1997. Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology* 387, 167–178.
- Iidaka, T., Omori, M., Murata, T., Kosaka, H., Yonekura, Y., Okada, T., Sadato, N., 2001. Neural interaction of the amygdala with the prefrontal and temporal cortices in the processing of facial expressions as revealed by fMRI. *Journal of Cognitive Neuroscience* 13 (8), 1035–1047.
- Jenkins, I.H., Brooks, D.J., Nixon, P.D., Frackowiak, R.S.J., Passingham, R.E., 1994. Motor sequence learning: A study with positron emission tomography. *Journal of Neuroscience* 14, 3775–3790.
- Kang, H.C., Burgund, E.D., Lugar, H.M., Petersen, S.E., Schlaggar, B.L., 2003. Comparison of functional activation foci in children and adults using a common stereotaxic space. *Neuroimage*.
- Kawashima, R., Satoh, K., Itoh, H., Ono, S., Furumoto, S., Gotoh, R., Koyama, M., Yoshioka, S., Takahashi, T., Takahashi, K., Yanagisawa, T., Fukuda, H., 1996. Functional anatomy of GO/NO-GO discrimination and response selection—a PET study in man. *Brain Research* 728 (1), 79–89.
- Kiehl, K.A., Liddle, P.F., Hopfinger, J.B., 2000. Error processing and the rostral anterior cingulate: an event-related fMRI study. *Psychophysiology* 37 (2), 216–223.
- Kim, Y.H., Gitelman, D.R., Nobre, A.C., Parrish, T.B., LaBar, K.S., Mesulam, M.M., 1999. The large scale neural network for spatial attention displays multi-functional overlap but differential asymmetry. *NeuroImage* 9 (3), 269–277.
- Klingberg, T., Roland, P.E., 1997. Interference between two concurrent tasks is associated with activation of overlapping fields in the cortex. *Cognitive Brain Research* 6 (1), 1–8.
- Konishi, S., 1998. No-go dominant brain activity in human inferior prefrontal cortex revealed by functional magnetic resonance imaging. *European Journal of Neuroscience* 10 (3), 1209–1213.
- LaBar, K.S., Gitelman, D.R., Parrish, T.B., Mesulam, M.M., 1999. Neuroanatomic overlap of working memory and spatial attention networks: a functional MRI comparison within subjects. *Neuroimage* 10, 695–704.
- Leonards, U., Sunaert, S., Van Hecke, P., Orban, G.A., 2000. Attention mechanisms in visual search: an fMRI study. *Journal of Cognitive Neuroscience* 12 (Suppl 2), 61–75.
- Levin, H.S., Culhane, K.A., Hartmann, J., Evankovich, K., 1991. Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology* 7, 377–395.
- Levy, F., 1980. The development of sustained attention (vigilance) in children: some normative data. *Journal of Child Psychology & Psychiatry & Allied Disciplines* 21 (1), 77–84.
- Liddle, P.F., Kiehl, K.A., Smith, A.M., 2001. Event-related fMRI study of response inhibition. *Human Brain Mapping* 12 (2), 100–109.
- Liu, T.T., Frank, L.R., Wong, E.C., Buxton, R.B., 2001. Detection power, estimation efficiency, and predictability in event-related fMRI. *Neuroimage* 13 (4), 759–773.
- Luna, B., Thulborn, K.R., Munoz, D.P., Merriam, E.P., Garver, K.E., Minshew, N.J., Keshavan, M.S., Genovese, C.R., Eddy, W.F., Sweeney, J.A., 2001. Maturation of widely distributed brain function subserves cognitive development. *Neuroimage*, 1–8.
- Menon, V., Adelman, N.E., White, C.D., Glover, G.H., Reiss, A.L., 2001. Error-related brain activation during a Go/NoGo response inhibition task. *Human Brain Mapping* 12 (3), 131–143.
- Mesulam, M.-M., 1999. Spatial attention and neglect: parietal, frontal and cingulate contributions to the mental representation and attentional targeting of salient extrapersonal events. *Phil. Trans. R. Soc. Lond. B.* 354, 1325–1346.
- Mesulam, M.M., 1990. Large-scale neurocognitive networks and distributed processing for attention, memory, and language. *Annals of Neurology* 28, 597–613.
- Mesulam, M.M., Nobre, A.C., Kim, Y.H., Parrish, T.B., Gitelman, D.R., 2001. Heterogeneity of cingulate contributions to spatial attention. *NeuroImage* 13, 1065–1072.
- Miller, E.K., Cohen, J.D., 2001. An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience* 24, 167–202.

- Mink, J.W., 1996. The basal ganglia: focused selection and inhibition of competing motor programs. *Progress in Neurobiology* 50 (4), 381–425.
- Morris, J.S., Buchel, C., Dolan, R.J., 2001. Parallel neural responses in amygdala subregions and sensory cortex during implicit fear conditioning. [erratum appears in *Neuroimage* 2001 Aug; 14(2): 529.]. *Neuroimage* 13 (6 Pt 1), 1044–1052.
- Munoz, D.P., Broughton, J.R., Goldring, J.E., Armstrong, I.T., 1998. Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research* 121 (4), 391–400.
- Mushiaki, H., Masahiko, I., Tanji, I., 1991. Neuronal activity in the primate premotor, supplementary, and precentral motor cortex during visually guided and internally determined sequenced movements. *Journal of Neurophysiology* 66, 705–718.
- Muzik, O., Chugani, D.C., Juhasz, C., Shen, C., Chugani, H.T., 2000. Statistical parametric mapping: assessment of application in children. *Neuroimage* 12 (5), 538–549.
- Nobre, A.C., Coull, J.T., Frith, C.D., Mesulam, M.M., 1999. Orbitofrontal cortex is activated during breaches of expectation in tasks of visual attention. *Nature Neuroscience* 2 (1), 11–12.
- Nobre, A.C., Gitelman, D.R., Dias, E.C., Mesulam, M.M., 2000. Covert visual spatial orienting and saccades: overlapping neural systems. *Neuroimage* 11 (3), 210–216.
- Nobre, A.C., Sebestyen, G.N., Gitelman, D.R., Mesulam, M.M., Frackowiak, R.S.J., Frith, C.D., 1997. Functional localization of the system for visuospatial attention using positron emission tomography. *Brain* 120, 515–533.
- Phelps, E.A., O'Connor, K.J., Gatenby, J.C., Gore, J.C., Grillon, C., Davis, M., 2001. Activation of the left amygdala to a cognitive representation of fear. *Nature Neuroscience* 4 (4), 437–441.
- Price, C.J., Veltman, D.J., Ashburner, J., Josephs, O., Friston, K.J., 1999. The critical relationship between the timing of stimulus presentation and data acquisition in blocked designs with fMRI. *Neuroimage* 10 (1), 36–44.
- Rosenberg, D.R., Sweeney, J.A., Gillen, J.S., Chang, S.Y., Varanelli, M.J., O'Hearn, K., Erb, P.A., Davis, D., Thulborn, K.R., 1997. Magnetic resonance imaging of children without sedation: preparation with simulation. *Journal of the American Academy of Child Adolescent Psychiatry* 36, 853–859.
- Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S.C.R., Simmons, A., Andrew, C., Bullmore, E.T., 2000a. Functional frontalisation with age: mapping neurodevelopmental trajectories with fMRI. *Neuroscience & Biobehavioral Reviews* 24 (1), 13–19.
- Rubia, K., Russell, T., Overmeyer, S., Brammer, M., Bullmore, E.T., Sharma, T., Simmons, A., Williams, S.C., Giampietro, V., Andrew, C.M., Taylor, E., 2000b. Mapping motor inhibition: conjunctive brain activations across different versions of Go/No-Go and Stop tasks. *Neuroimage*, 1–12.
- Sander, K., Scheich, H., 2001. Auditory perception of laughing and crying activates human amygdala regardless of attentional state. *Cognitive Brain Research* 12 (2), 181–198.
- Sowell, E.R., Thompson, P.M., Holmes, C.J., Jernigan, T.L., Toga, A.W., 1999. In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. *Nature Neuroscience* 2 (10), 859–861.
- Talairach, J., Tournoux, P., 1988. *Co-Planar Stereotaxic Atlas of the Human Brain*. Thieme, New York.
- Tamm, L., Menon, V., Reiss, A.L., 2002. Maturation of brain function associated with response inhibition. *Journal of the American Academy of Child & Adolescent Psychiatry* 41 (10), 1231–1238.
- Taylor, M.J., Khan, S.C., 2000. Top-down modulation of early selective attention processes in children. *International Journal of Psychophysiology* 37, 135–147.
- Taylor, M.J., Shakeela, C.K., Malone, M.A., 1999. Parallel and serial attentional processes: a developmental ERP study. *Developmental Neuropsychology* 15 (3), 351–358.
- Taylor, M.J., Sunohara, G.A., Khan, S.C., Malone, M.A., 1997. Parallel and serial attentional processes in ADHD: ERP evidence. *Developmental Neuropsychology* 13 (4), 531–539.
- Thompson, L.A., Massaro, D.W., 1989. Before you see it, you see its parts: evidence for feature encoding and integration in preschool children and adults. *Cognitive Psychology* 21, 334–362.
- Thompson, P.M., Giedd, J.N., Woods, R.P., MacDonald, D., Evans, A.C., Toga, A.W., 2000. Growth patterns in the developing brain detected by using continuum mechanical tensor maps. *Nature* 404 (6774), 190–193.
- Tipper, S.P., Bourque, T.A., Anderson, S.H., Brehaut, J.C., 1989. Mechanisms of attention: a developmental study. *Journal of Experimental Child Psychology* 48 (3), 353–378.
- Treisman, A., 1990. Variations on the theme of feature integration: Reply to Navon (1990). *Psychological Review* 97 (3), 460–463.
- Treisman, A., 1992. Spreading suppression or feature integration? A reply to Duncan and Humphreys (1992). *Journal of Experimental Psychology: Human Perception & Performance* 18 (2), 589–593.
- Treisman, A.M., Gelade, G., 1980. A feature-integration theory of attention. *Cognitive Psychology* 12, 97–136.
- Vaidya, C.J., Austin, G., Kirkorian, G., Ridlehuber, H.W., Desmond, J.E., Glover, G.H., Gabrieli, J.D.E., 1998. Selective effects of methylphenidate in attention deficit hyperactivity disorder: a functional magnetic resonance imaging study. *Proceedings of the National Academy of Sciences* 95, 14494–14499.
- Van der Heijden, A.H., IJzerman, W., 1983. The array-size function in simple visual search tasks: a comparison between a “goo go” and a “detection” task under conditions of low target-noise similarity. *Psychological Research* 45 (3), 221–234.
- Waldvogel, D., 2000. The relative metabolic demand of inhibition and excitation. *Nature* 406 (6799), 995–998.
- Walsh, V., Ellison, A., Ashbridge, E., Cowey, A., 1999. The role of the parietal cortex in visual attention-hemispheric asymmetries and the effects of learning: a magnetic stimulation study. *Neuropsychologia* 37 (2), 245–251.
- Wilke, M., Schmithorst, V.J., Holland, S.K., 2002. Assessment of spatial normalization of whole-brain magnetic resonance images in children. *Human Brain Mapping* 17 (1), 48–60.
- Williams, B.R., Ponesse, J.S., Schachar, R.J., Logan, G.D., Tannock, R., 1999. Development of inhibitory control across the life span. *Developmental Psychology* 35 (1), 205–213.
- Zalla, T., Koechlin, E., Pietrini, P., Basso, G., Aquino, P., Sirigu, A., Grafman, J., 2000. Differential amygdala responses to winning and losing: a functional magnetic resonance imaging study in humans. *European Journal of Neuroscience* 12 (5), 1764–1770.