

Larger deficits in brain networks for response inhibition than for visual selective attention in attention deficit hyperactivity disorder (ADHD)

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Background: Brain activation differences between 12 control and 12 attention deficit hyperactivity disorder (ADHD) children (9- to 12-year-olds) were examined on two cognitive tasks during functional magnetic resonance imaging (fMRI). **Method:** Visual selective attention was measured with the visual search of a conjunction target (red triangle) in a field of distracters and response inhibition was measured with a go/no-go task. **Results:** There were limited group differences in the selective attention task, with control children showing significantly greater intensity of activation in a small area of the superior parietal lobule region of interest. There were large group differences in the response inhibition task, with control children showing significantly greater intensity of activation in fronto-striatal regions of interest including the inferior, middle, superior and medial frontal gyri as well as the caudate nucleus and globus pallidus. **Conclusion:** The widespread hypoactivity for the ADHD children on the go/no-go task is consistent with the hypothesis that response inhibition is a specific deficit in attention deficit hyperactivity disorder. **Keywords:** ADD/ADHD, attention, brain development, brain imaging, development, inhibition.

Attention deficit hyperactivity disorder (ADHD) is one of the most common forms of childhood disorder in the United States. The estimates of prevalence are about 5–15% of school-age children (Szatmari, 1992; Wolraich, Hannah, Baumgaertel, & Feurer, 1998). About 50% of these children continue to experience ADHD symptoms when they are adults (Mannuzza, Klein, Bessler, Malloy, & LaPadula, 1993; Weiss & Hechtman, 1979) with about 2–3 times as many males as females affected (Gaub & Carlson, 1997; Wolraich et al., 1996). Two of the central deficits in ADHD are response inhibition and selective attention. Barkley (1997) argues that poor interference control and poor inhibition are the primary deficits in ADHD and that these result in deficits in sustained attention and executive functions (Barkley, 1997).

Over the last several years the neural basis of response inhibition and selective attention has become clearer through the use of neuroimaging technology. Casey, Durston, and Fossella (2001) have argued that the prefrontal cortex is involved in interference control and that the basal ganglia is involved in response inhibition (Casey et al., 2001). The prefrontal region seems to be involved in the supporting representations of relevant information from interference due to competing information (Miller & Cohen, 2001), whereas the basal ganglia seems to be

involved in the inhibition of inappropriate behaviors (Mink, 1996). The visual selective attention network is partially distinct from the response inhibition network. Mesulam (1990, 1999) has proposed that the superior parietal lobule and the lateral premotor cortex form the core of the network for selective attention. The superior parietal lobule appears to be involved in representing extrapersonal space and the lateral pre-motor cortex seems to be involved in orienting and exploratory movements. Many studies have demonstrated that the superior parietal lobule and the lateral premotor cortex are active in both overt and covert selective attention tasks (Corbetta, 1998; Gitelman et al., 1999; Kim et al., 1999; Nobre, Gitelman, Dias, & Mesulam, 2000).

Several lines of behavioral and molecular genetic work show a genetic component for ADHD involving the dopaminergic system (Comings et al., 2000; Cook, Stein, & Krasowski, 1995; Faraone, Doyle, Mick, & Biederman, 2001; Gill, Daly, Heron, Hawi, & Fitzgerald, 1997; LaHoste, Swanson, & Wigal, 1996; Swanson et al., 2000). Furthermore, one of the most common medications for ADHD, methylphenidate, seems to act on the brain by amplifying dopamine signals (Volkow, Fowler, Wang, Ding, & Gatley, 2002; Volkow et al., 2001). These findings suggest that one of the primary brain deficits in ADHD may lie in fronto-striatal brain networks involving the

prefrontal region and the basal ganglia. Indeed, structural and functional neuroimaging research shows differences between control and ADHD subjects in this network. ADHD subjects have smaller prefrontal volumes than controls (Castellanos et al., 1996; Yeo et al., 2003) and studies have documented relations between prefrontal morphology and behavioral characteristics in ADHD subjects (Casey, Castellanos, Giedd, & Marsh, 1997a; Castellanos et al., 2002; Filipek et al., 1997). Functional studies have also generally shown less activation in ADHD subjects compared to controls in frontal and cingulate regions (Amen & Carmichael, 1997; Bush et al., 1999; Ernst, Zametkin, Matochik, Jons, & Cohen, 1998a; Rubia et al., 1999, 2001; Zametkin et al., 1990) and have shown correlations between activation and behavioral characteristics in ADHD subjects (Teicher et al., 2000; Yeo et al., 2003; Zametkin et al., 1993).

Frontal regions are heavily interconnected with striatal regions, and neuroimaging research has shown differences between control and ADHD subjects in these subcortical structures. Although some studies show larger caudate volumes in ADHD subjects (Mataro, Garcia Sanchez, Junque, Estevez, & Pujol, 1997), most studies show that ADHD subjects have smaller caudate and globus pallidus volumes (Aylward et al., 1996; Castellanos et al., 1996, 2002; Filipek et al., 1997; Hynd et al., 1993) and studies have shown that volume and asymmetry of the caudate nucleus are correlated with task performance on response inhibition tasks in ADHD subjects (Casey et al., 1997a; Semrud-Clikeman et al., 2000). Functional neuroimaging studies have also reported differences in the amount of activation in the caudate, putamen and globus pallidus (Durstun et al., 2003; Ernst, Cohen, Liebenauer, Jons, & Zametkin, 1997; Jin, Zang, Zeng, Zhang, & Wang, 2001; Rubia et al., 1999, 2001; Vaidya et al., 1998). In summary, the literature clearly shows that there are pronounced differences between control and ADHD subjects in the network involved in interference control and response inhibition.

In contrast to the extensive work on the fronto-striatal system, comparatively little neuroimaging research has reported brain differences in the selective attention network. Filipek et al. (1997) showed that ADHD subjects have smaller white matter tracts than controls in posterior brain regions and that methylphenidate non-responders had smaller bilateral retrocallosal (parietal) white matter tracts than responders (Filipek et al., 1997). Castellanos et al. (2002) reported that ADHD had smaller parietal as well as fronto-striatal (caudate) volumes, but only the frontal-striatal volumes correlated with clinician and parent ratings of symptom severity. A positron emission tomography (PET) study has supported these structural studies by showing abnormalities in glucose metabolism in posterior parietal regions (Ernst et al., 1997).

Although event-related potential (ERP) studies have also consistently found differences between ADHD and controls, it is difficult to determine the focus of activation due to low spatial resolution. Most ERP studies report smaller amplitude in centro-parietal potentials at around 300 ms after stimulus onset (Brandeis et al., 1998; Karayanidis et al., 2000; Robaey, Breton, Dugas, & Renault, 1992; van Leeuwen et al., 1998) and the amplitude of this component in ADHD subjects can be normalized with methylphenidate treatment (Jonkman et al., 1997; Verbaten et al., 1994; Winsberg, Javitt, & Shanahan/Silipo, 1997).

This review of the literature suggests that ADHD subjects tend to have larger abnormalities in the response inhibition network (including prefrontal cortex and basal ganglia) than in the selective attention network (including superior parietal lobule and lateral premotor cortex). Behavioral research also seems to suggest that there are larger deficits for ADHD subjects in response inhibition than in selective attention. Several studies have consistently shown that ADHD subjects are slower and exhibit more errors on go/no-go tasks (Castellanos et al., 2000; Hartung, Milich, Lynam, & Martin, 2002; Iaboni, Douglas, & Baker, 1995; Itami & Uno, 2002; Vaidya et al., 1998; Yong-Liang et al., 2000). In contrast, studies have inconsistently shown differences between ADHD and controls on tasks tapping into selective attention. Two studies have shown that the slope of reaction time as function of number of stimuli in a memory search task was the same for ADHD and controls (Klorman, Brumaghim, Fitzpatrick, & Borgstedt, 1992; Sergeant & Scholten, 1983) and another study showed no group differences with respect to task efficiency in a distraction condition during a focused attention task that required ignoring irrelevant information in favor of relevant information (van der Meere & Sergeant, 1988). Furthermore, no difference between ADHD and controls were found in latency or accuracy of visuo-spatial memory in a task that required subjects to delay their saccadic eye movement to a visually presented cue (Ross, Hommer, Breiger, Varley, & Radant, 1994). Other studies have shown reliable differences between ADHD and controls in the initiation of visual search and the slope of the visual search function (Karatekin & Asarnow, 1998). Although Leung and Connolly (1994) also showed deficits in a visual search task, they showed that the performance decrement over time was similar in ADHD and controls (Leung & Connolly, 1994). One study has directly compared deficits in response inhibition to selective attention (Aman, Roberts, & Pennington, 1998). They found that ADHD children had larger deficits on 'frontal lobe' tasks (i.e., Stopping Task, Anti-saccade Task, Tower of Hanoi) than parietal tasks (i.e., Visual-Spatial Cuing Task, Turning Task, Spatial Relations). More studies are needed that directly compare response inhibition

and selective attention within the same population of ADHD children, preferably with experimental tasks that are equated in stimulus characteristics so that observed differences can be attributed clearly to one construct.

The goal of this project was to use fMRI to examine brain activation differences between control and ADHD children (9- and 12-year-olds) in both visual selective attention and response inhibition. No neuroimaging studies have directly compared both selective attention and response inhibition in the same population, so we cannot make statements about the relative role of each of these networks in the disorder. It is important to compare population differences on selective attention and response inhibition tasks in order to examine the hypothesis that response inhibition is the primary deficit in ADHD (Barkley, 1997). In our study, the neural substrate of selective attention was measured by a conjunction visual search task (Treisman, 1990, 1992; Treisman & Gelade, 1980) that has been shown to activate the superior parietal lobule and lateral premotor cortex (Ashbridge, Walsh, & Cowey, 1997; Corbetta, Shulman, Miezin, & Petersen, 1995; Donner et al., 2000; Walsh, Ellison, Ashbridge, & Cowey, 1999). Response inhibition was measured by a go/no-go task that has been shown to activate the basal ganglia and prefrontal cortex (Kawashima et al., 1996; Konishi, 1998; Liddle, Kiehl, & Smith, 2001; Menon, Adleman, White, Glover, & Reiss, 2001; Rubia et al., 2000b; Waldevogel, 2000). Both tasks were structured in exactly the same way so as to equate perceptual demands of the tasks 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 versus absent for both tasks). Based on the genetic, brain imaging and behavioral research reviewed above, we expected smaller differences between control and ADHD children for selective attention than for response inhibition. Specifically, we expected to find fewer voxels in our regions of interest to exhibit significant differences in intensity of activation between control and ADHD children. 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 control children ($M = 10.9$; range = 9.3–11.7 years) and twelve ADHD children ($M = 11.0$; range = 9.4–11.9 years) participated in the study. There were 7 males and 5 females in the control group and there were 8 males and 4 females in the ADHD group. Control children were recruited from the Evanston, Illinois community. ADHD children were recruited from pediatric or neurology practices in the Chicago metropolitan area. All ADHD children had been given

the ADHD diagnosis by a medical professional and were currently taking medication (5 Ritalin, 5 Concerta, 1 Adderall and 1 Dexedrine). ADHD children had been on medication between 1 and 3 years. All ADHD children were free from medication for at least 48 hours at the time of the behavioral testing or the MRI scan.

In order to independently confirm the diagnosis of ADHD, the parents of children were administered the Disruptive Behavior Rating Scale (Barkley & Murphy, 1998), which includes modified inattentive and hyperactive-impulsive symptoms from the *Diagnostic Statistical Manual – IV* (American Psychiatric Association, 1994). According to the DSM-IV, a child must have 6 or more symptoms from either scale to qualify for the diagnosis of ADHD. The Disruptive Behavior Rating Scale allows for a graded response on a 4-point Likert scale including the labels ‘never or rarely’, ‘sometimes’, ‘often’ and ‘very often’. In order to compare the Disruptive Behavioral Rating Scale to the DSM-IV, we considered only ‘often’ or ‘very often’ to indicate the presence of that symptom. According to this criterion, all of the ADHD children had at least 6 symptoms on one of the scales: 8 children for both the inattentive and hyperactive-impulsive scales and 4 children for just the inattentive scale. No control children had more than two of the inattentive or hyperactive-impulsive items endorsed ‘often’ or ‘very often’ by their parents.

Parents of children were given an informal interview to insure that they did not meet the following exclusionary criteria: (1) non-English or bilingual backgrounds, (2) uncorrected visual impairment or significant hearing impairment, (3) DSM Axis I or II psychiatric disorders, (4) oppositional defiant disorder or conduct disorder, (5) neurological disease or seizures, (6) severe pregnancy or birth complications, (7) significant head injury with loss of consciousness, (8) chronic substance abuse, and (9) for the control children, not taking medication affecting the central nervous system and no attention deficit hyperactivity disorder.

Standardized testing

All participants were administered an extensive battery of standardized tests including the full version of the Wechsler Intelligence Scale for Children-III (Wechsler, 1991), Peabody Picture Vocabulary Test-III (Dunn & Dunn, 1997), Woodcock Johnson Picture Vocabulary and Word Attack (Woodcock, 1997), Comprehensive Test of Phonological Processes (Wagner, Torgesen, & Rashotte, 1999), and Wide Range Achievement Test-III (Wilkinson, 1993). The purpose of this battery was to establish that the control and ADHD children were not significantly different on measures of cognitive functioning.

Functional activation tasks

Both the selective attention and response inhibition task involved red triangle targets that were presented on 50% of 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 seconds 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 Figure 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 seconds 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 seconds at the beginning of each block and displayed 'Go' for the go blocks and 'Stop' for the no-go blocks.

Because the same stimuli were used in the selective attention and response inhibition tasks, there was exactly the same amount of search in both tasks. When the target was absent, both tasks required exhaustive search and when the target was present both tasks required search until the target was identified. On average, target identification probably occurred on the middle stimulus in the nine-stimuli array because the targets were equally distributed in the nine positions (assuming a serial left to right and up to down search strategy).

Experimental procedure

After informed consent was obtained, participants were administered the informal 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.

MRI 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.

MRI 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). 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) 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 seconds (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.

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 $.86 \times .86 \times 1$ 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, 1995b; Friston, Jezzard, & Turner, 1994). Personalized software with modules in AVS (Advanced Visual Systems, Waltham, MA) 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,

Table 1 Means (and ranges) in millimeters for control and ADHD children 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

Group	Coordinates		
	X	Y	Z
Control			
Attention Nine	.10(.05–.20)	.23(.10–.63)	.29(.08–.59)
Attention One	.10(.03–.25)	.23(.12–.69)	.30(.11–.84)
No-Go Nine	.10(.03–.24)	.33(.16–.83)	.49(.07–1.17)
Go Nine	.11(.04–.28)	.33(.15–.86)	.53(.08–1.85)
ADHD			
Attention Nine	.14(.05–.39)	.28(.04–.94)	.56(.11–1.48)
Attention One	.13(.07–.29)	.25(.04–.69)	.48(.11–1.10)
No-Go Nine	.18(.03–.47)	.49(.05–1.35)	.85(.27–1.67)
Go Nine	.14(.03–.27)	.40(.04–.72)	1.03(.25–1.90)

y-plane, or z-plane (see Table 1 for estimates of movement). There were no significant group differences in the amount of movement except for ADHD children moving more than control children on the response inhibition task in the z-plane. If the three ADHD children with the most movement were removed from the analyses, then there was no longer a significant difference between groups. For this reason, we compared activation within and between groups for the response inhibition task with and without these three subjects. 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 $2 \times 2 \times 2$ nonlinear basis functions for subtle morphological differences). The MNI template is similar to the Talairach and Tournoux (1998) stereotaxic atlas (Talairach & Tournoux, 1988) and there are algorithms to convert between coordinate spaces (Calder, Lawrence, & Young, 2001; Duncan et al., 2000). Previous studies have shown that normalization to a standard template is appropriate for children older than 8 years of age and for voxel sizes greater than about 3.5 mm (Burgund et al., 2002; Kang, Burgund, Lugar, Petersen, & Schlaggar, 2003; Muzik, Chugani, Juhász, Shen, & Chugani, 2000; Wilke, Schmithorst, & Holland, 2002).

Statistical analyses were calculated on the smoothed data (7 mm isotropic Gaussian kernel) using a delayed boxcar design with a 6-second 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 seconds) 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. 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. Unless otherwise noted, 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

Standardized testing

Table 2 presents means on the standardized measures and the behavioral rating scales for control and ADHD children. Standardized measures for all children were within the normal range (80–130 scaled scores). There were no significant group differences for verbal or performance IQ (Wechsler, 1991), vocabulary measures (Dunn & Dunn, 1997; Woodcock, 1997), non-word reading (Woodcock, 1997), phonological awareness (Wagner et al., 1999), or mathematics achievement (Wilkinson, 1993). This suggests that the control and ADHD group were well matched on their cognitive functioning ability. Although the control children scored significantly higher than the ADHD children on reading and spelling achievement (Wilkinson, 1993), all scores were within the normal range. Most importantly, the ADHD children scored significantly higher than the control children on parental ratings of inattentiveness $F(1, 23) = 10.93, p < .001$, and hyperactivity-impulsivity, $F(1, 23) = 6.68, p < .001$.

Behavioral performance

Table 3 presents error rates and reaction times on the selective attention task and the response inhibition task. In order to examine population differences on the selective attention task, we calculated a 2 group (control, ADHD) \times 2 session (practice, test) \times 2 block (nine, one) ANOVA separately on error rates and reaction time. This analysis showed that ADHD children had more errors, $F(1, 95) = 20.27, p < .001$, and slower reaction times, $F(1, 95) = 21.46, p < .001$, compared to control children. This analysis also showed that the blocks with nine stimuli elicited slower reaction times than the blocks with one stimulus, $F(1, 95) = 64.75, p < .001$.

In order to examine population differences on the response inhibition task, we calculated a 2 group (control, ADHD) \times 2 session (practice, test) \times 2 block

Table 2 Means (*M*) and standard deviations (*SD*) for control and ADHD children on the standardized measures and the behavioral rating scales

Measure	Control		ADHD		<i>p</i> -value
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
WISC-III Verbal IQ (Wechsler, 1991)	113.6	10.0	112.4	12.6	.801
WISC-III Performance IQ (Wechsler, 1991)	101.0	12.7	109.2	16.5	.191
PPVT-III (Dunn & Dunn, 1997)	115.3	10.4	118.3	8.8	.464
WJ-III Picture Vocabulary (Woodcock, 1997)	104.7	11.8	110.7	8.1	.177
WJ-III Word Attack (Woodcock, 1997)	105.5	8.3	101.0	10.0	.245
CTOPP Phonological Awareness (Wagner et al., 1999)	97.5	12.7	98.3	11.6	.869
WRAT-3 Reading (Wilkinson, 1993)	112.1	8.7	101.3	9.6	.010
WRAT-3 Spelling (Wilkinson, 1993)	112.4	11.0	96.0	11.4	.002
WRAT-3 Math (Wilkinson, 1993)	109.8	15.9	99.2	12.5	.094
DBRS Hyperactive-Impulsive (Barkley & Murphy, 1998)	.32	.42	1.62	.57	.000
DBRS Inattentive (Barkley & Murphy, 1998)	.50	.42	2.34	.39	.000

Note: All standardized measures are standard scores with a mean of 100 and a standard deviation of 15 on the normative sample. The DBRS rating scales are on a 3-point scale. The right column indicates the *p*-value based on a *t*-test between groups.

Table 3 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

Group	Practice				fMRI			
	Error rates		RT		Error rates		RT	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Control								
Attention Nine	8.6	1.7	891	32	5.7	1.3	853	39
Attention One	4.8	1.4	666	30	4.6	.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
ADHD								
Attention Nine	15.6	2.9	981	37	16.8	4.7	976	35
Attention One	10.8	2.7	779	35	13.9	3.2	799	37
No-Go Nine	14.4	2.6	944	36	16.0	3.4	930	46
Go Nine	7.2	2.3	628	40	12.5	5.0	644	52

(no-go, go) ANOVA separately on error rates and reaction time. 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 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 ADHD children had more errors, $F(1, 95) = 17.41$, $p < .001$, and slower reaction times, $F(1, 95) = 16.93$, $p < .001$, compared to control children. This analysis also showed that the no-go blocks had more errors, $F(1, 95) = 4.09$, $p < .05$, and slower reaction times, $F(1, 95) = 107.82$, $p < .001$, compared to the go blocks. We calculated an additional 2 group (control, ADHD) \times 2 session (practice, test) ANOVA to examine group 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 ADHD children ($M = 10.3$; $SE = 2.2$) showed significantly more commissions than control children ($M = 5.3$; $SE = .9$), $F(1, 47) = 8.62$, $p < .01$.

The lack of significant main effects or interactions involving session ($ps > .25$) for the selective attention and response inhibition tasks indicates that the environment of the scanner may not have affected the performance for either group. There were also no significant interactions between group and block for the selective attention or response inhibition task ($ps > .35$). In other words, the difference between the no-go and go blocks for the response inhibition task and the differences between the nine stimuli and one stimulus for the selective attention task were similar for the control and ADHD children. This indicates that any group-by-block differences in patterns of brain activation may not be associated with performance differences because, like the behavioral analyses, our fMRI analysis examined group differences in the nine stimuli versus one stimulus blocks for selective attention and in the no-go versus go blocks for response inhibition. We also calculated a 2 group (control, ADHD) \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 group-by-task interactions or group-by-block-by-task interactions ($ps > .70$) for either error rates or reaction times. This indicates that different group differences in activation for the selective attention and response inhibition tasks may not be accounted for by performance differences.

Brain activation for selective attention

Figure 2 (see Table 4 for numerical data) presents significantly greater activation for the selective attention blocks with nine stimuli compared to the blocks with one stimulus ($p < .001$) for control children (red), for ADHD children (green) and for the

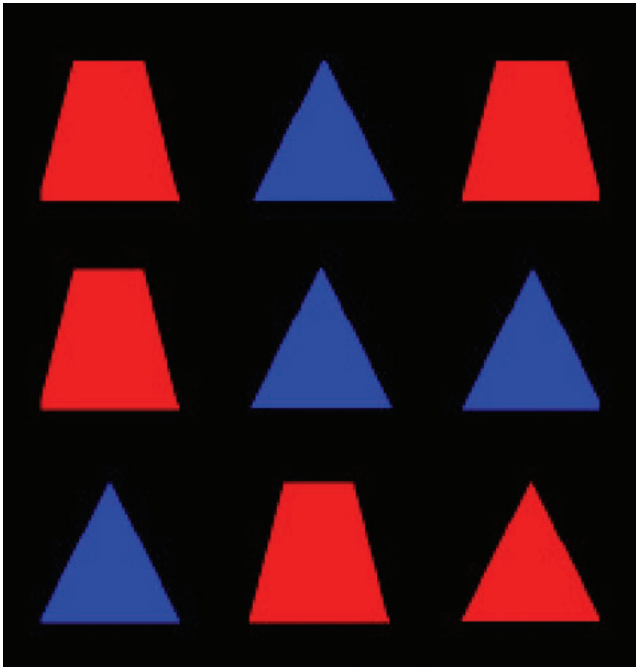


Figure 1 An example of a trial in the selective attention and response inhibition task in which the target (red triangle) is in a field of eight distracters

overlap between control and ADHD children (purple). In general, the patterns of activation for the control and ADHD children were similar. Both groups

Figure 3 Significantly greater activation for the no-go blocks compared to the go blocks of the response inhibition task. Red indicates activation for control children ($p < .001$), green indicates activation for ADHD children ($p < .05$) and purple indicates activation that overlaps for control and ADHD children. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (≥ 30) were labeled (AMG: amygdala; CB: caudate body; CH: caudate head; IFG: inferior frontal gyrus; LG/FG: lingual and fusiform gyrus; MFG: middle frontal gyrus; PH: parahippocampus; PC: posterior cingulate; PCG: precentral gyrus; SFG: superior frontal gyrus; SPL: superior parietal lobule; TH: thalamus)

Figure 4 Significantly greater activation (red) for control than ADHD children in the no-go blocks compared to the go blocks of the response inhibition task ($p < .001$). Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (> 10) were labeled (CB: caudate body; CH: caudate head; C: cuneus; IFG: inferior frontal gyrus; FG: fusiform gyrus; MedFG: medial frontal gyrus; MFG: middle frontal gyrus; PCG: precentral gyrus; SFG: superior frontal gyrus; TH: thalamus)

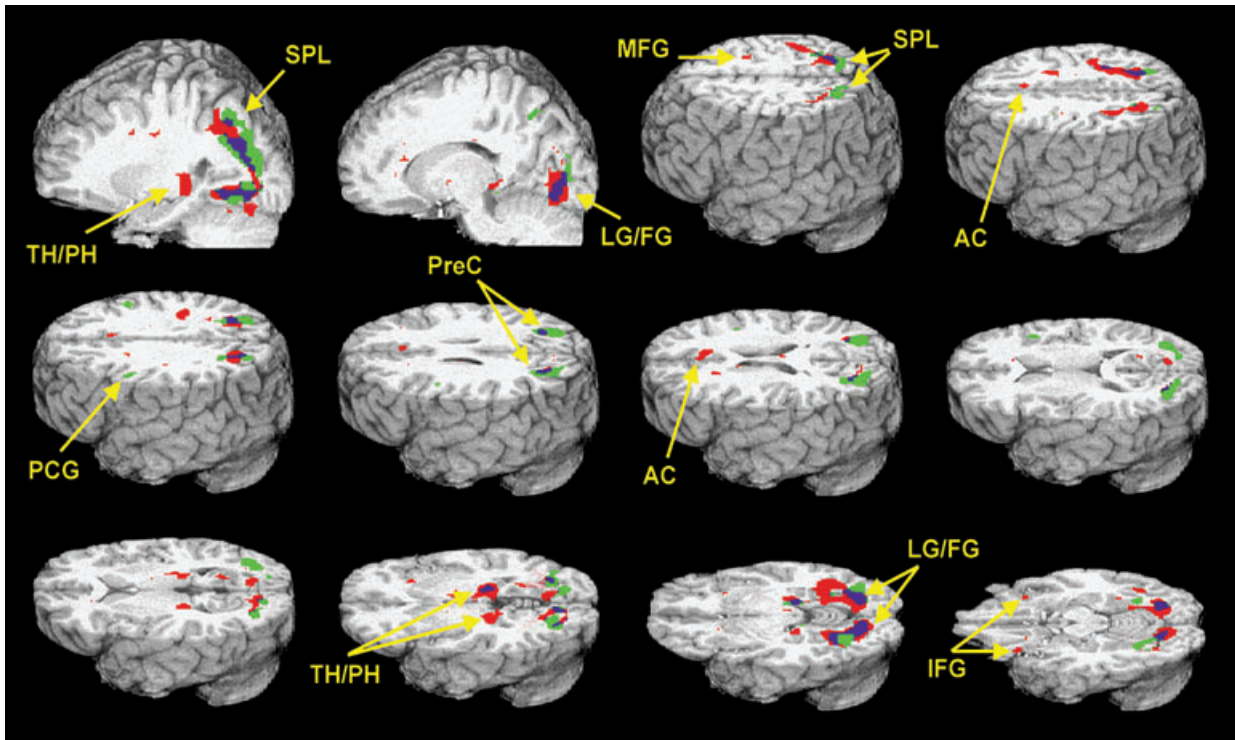
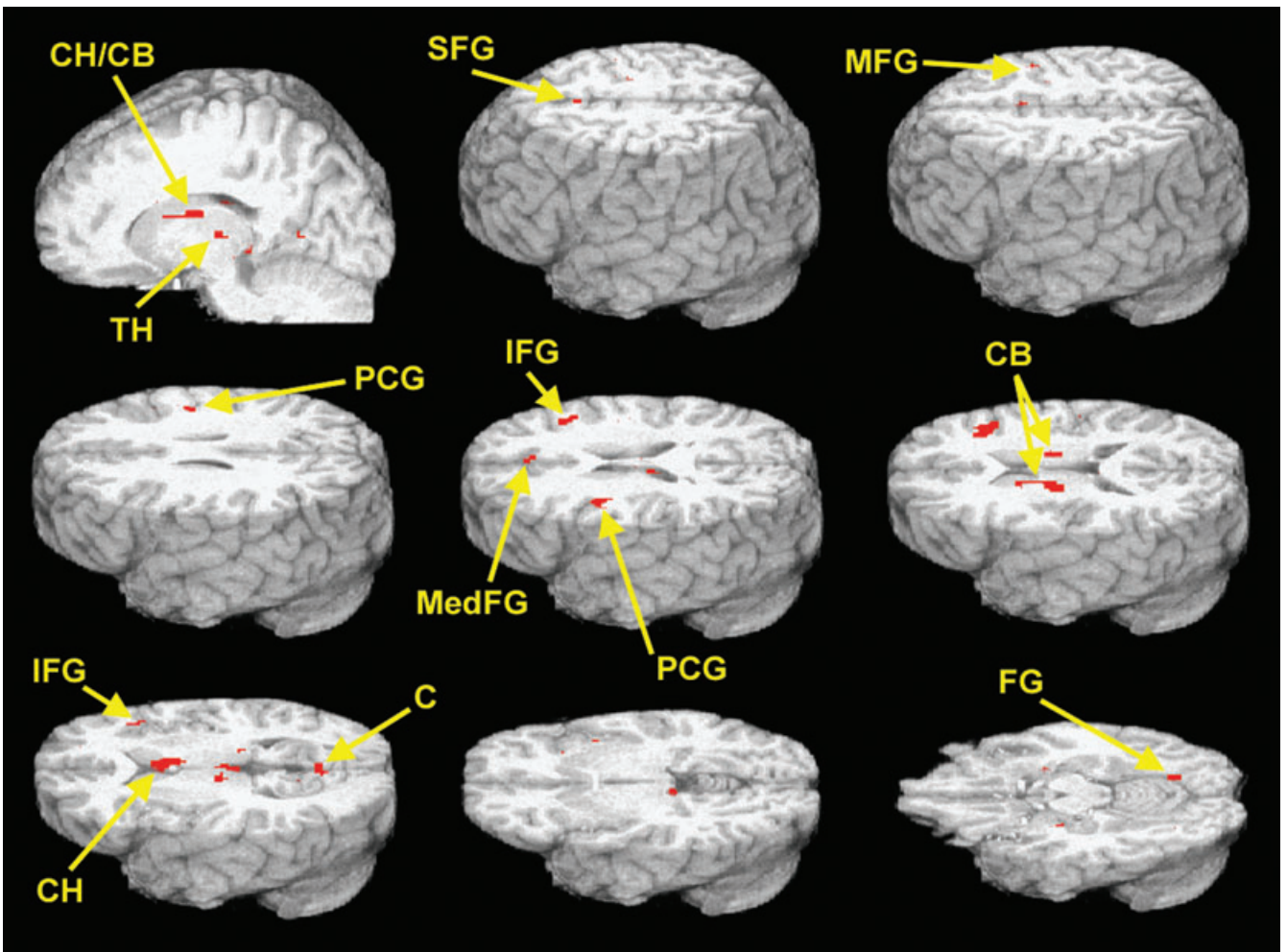
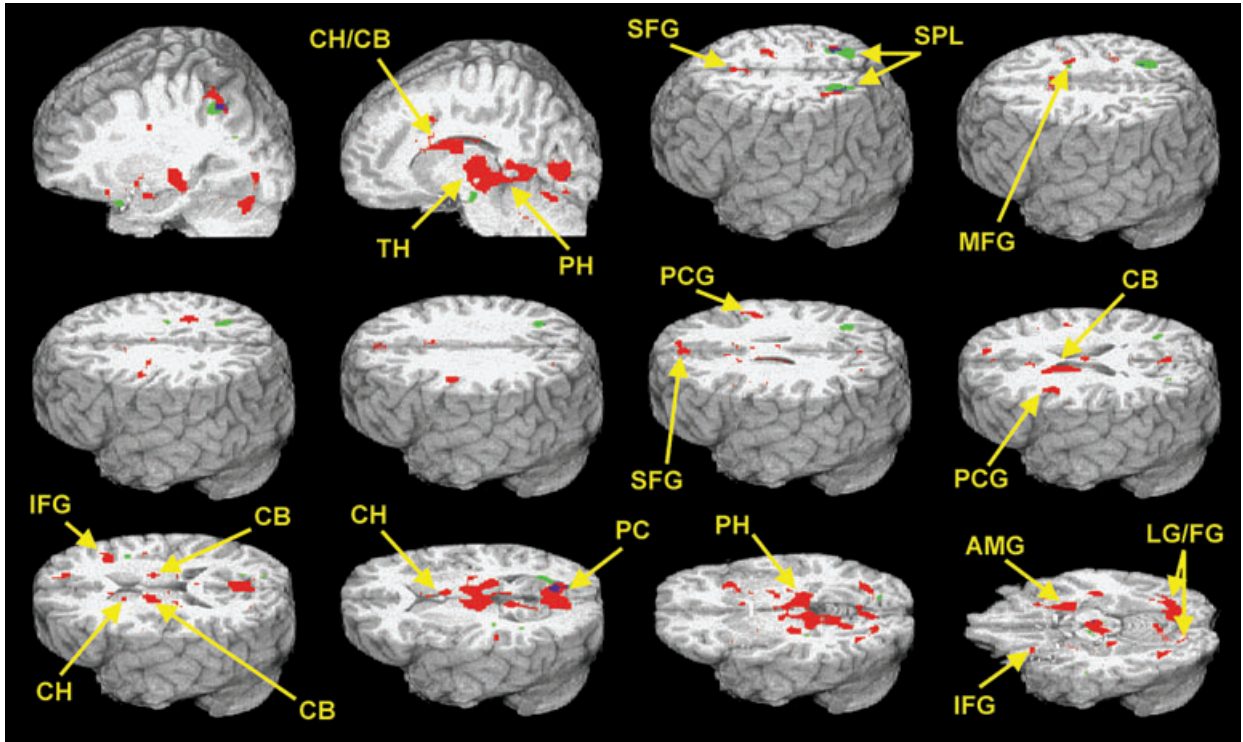


Figure 2 Significantly greater activation for the selective attention blocks with nine stimuli compared to the blocks with one stimulus ($p < .001$). Red indicates activation for control children, green indicates activation for ADHD children and purple indicates activation that overlaps for control and ADHD children. Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (≥ 30) were labeled (AC: anterior cingulate; IFG: inferior frontal gyrus; LG/FG: lingual to fusiform gyrus; MFG: middle frontal gyrus; PreC: precuneus; PCG: precentral gyrus; SPL: superior parietal lobule; TH/PH: thalamus and parahippocampus)



exhibited a large amount of bilateral activation in precuneus to superior parietal lobule and from lingual to fusiform gyrus. Both groups also showed activation in the hippocampal area and thalamus, but this was bilateral for control children and confined to the right hemisphere for ADHD children. Both groups also showed activation in the inferior frontal gyrus, but this activation was bilateral for control children and confined to the right hemisphere for ADHD children. Both groups also showed activation in the precentral gyrus, but this activation was bilateral for ADHD children and confined to the left hemisphere for control children. The major difference in the control versus ADHD activation maps was that only the control children showed areas of activation in the right middle frontal gyrus and in the left and right anterior cingulate. However, the data presented in Figure 2 and Table 4 does not involve a direct statistical comparison between control and ADHD children. A direct statistical comparison of the selective attention task (nine stimuli versus one stimulus) revealed no significant group differences (ADHD > control or control > ADHD) in any region. Statistical comparisons are necessary to determine reliable differences between the groups. For example, control children may show activation in an area because it is just over threshold, whereas ADHD children may show no activation in this area because it is just under threshold. In this case, a direct statistical test may yield no significant group differences.

Brain activation for response inhibition

Figure 3 (see Table 5 for numerical data) presents significantly greater activation in the no-go blocks compared to the go blocks of the response inhibition task for control children (red), for ADHD children (green) and for the overlap between control and ADHD children (purple). The control children showed several clusters of activation ($p < .001$) including bilateral superior parietal lobule, bilateral superior frontal gyrus, right middle frontal gyrus, bilateral inferior frontal and precentral gyri, left caudate body, bilateral cuneus to the hippocampal region, and bilateral amygdala. ADHD children did not show any significant clusters of activation at the $p < .001$, so the data presented is at the $p < .05$ level of significance. At this significance level, ADHD children showed clusters of activation in bilateral superior parietal lobule, right precuneus, bilateral posterior cingulate/parahippocampus and brain stem. We also calculated these analyses without the 3 ADHD children who showed the most movement and these 4 regions were still significantly activated at $p < .05$, but with a fewer number of voxels.

Figure 4 (see Table 6 top for numerical data) shows significantly greater activation (red) for the control children compared to the ADHD children in the no-go blocks compared to the go blocks of the response inhibition task. As reviewed above, a direct

comparison between control and ADHD children is necessary to make conclusive statements about group differences. A direct statistical comparison revealed that control children exhibited significantly greater activation than ADHD children in several brain regions. The largest clusters included bilateral precentral gyrus, bilateral caudate body, right caudate head, right inferior frontal gyrus and bilateral thalamus. A direct comparison between the ADHD and control children did not show significantly greater brain activation in any brain region for the ADHD children for the whole data set and for the data set without the 3 ADHD subjects who showed the most movement in the z direction. Although statistical power is reduced due to fewer subjects, after removing these 3 subjects there was no longer a statistical difference in the amount of movement between the control and ADHD children.

Brain activation for selective attention revisited

To further examine group 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 group differences in selective attention. The results for the control and ADHD separately in this analysis were similar to the results reported in Figure 2 and Table 4 that compared selective attention blocks with nine stimuli to the blocks with one stimulus, so we do not present the within-group analysis here. Figure 5 (see Table 6 bottom for numerical data) presents significantly greater activation for control children than for ADHD children on selective attention blocks with nine stimuli to the go blocks of the response inhibition task with nine stimuli. Although the clusters were small, this analysis revealed significantly greater activation for control children in right superior parietal lobule, right cuneus to middle temporal gyrus and left fusiform gyrus. ADHD children did not exhibit significantly greater activation than control children for this comparison in any region.

Discussion

Both control and ADHD children showed activation in our regions of interest for the visual selective attention task that required visual search of a conjunction of features. Our finding of activation in the superior parietal lobule for both groups is generally consistent with past neuroimaging studies with adults that have examined visual selective attention and conjunction search (Corbetta et al., 1995; Donner et al., 2000; Gitelman et al., 1999; Kim et al., 1999; Nobre et al., 2000). We also measured brain activation during a task that required the inhibition of a response during no-go blocks that was

Table 4 Significantly greater activation for control or for ADHD children in the selective attention blocks with nine stimuli compared to the blocks with one stimulus

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
Control	Superior Parietal Lobule/Precuneus/ Lingual Gyrus/Fusiform Gyrus	7/19/18/37	5.36	1861	27	-57	48
	Precentral Gyrus	6	4.28	38	-33	-18	30
	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
	Middle Frontal Gyrus	6	4.14	64	27	0	45
	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
	Posterior Cingulate	31	4.25	20	24	-60	15
	Medial Globus Pallidus	*	3.68	19	12	-6	-3
	ADHD	Superior Parietal Lobule/Precuneus	19/7	5.12	838	27	-60
Lingual Gyrus/Fusiform Gyrus		18/19/37	5.76	759	-27	-81	12
Precentral Gyrus		6	3.68	15	48	9	33
		6	3.88	34	-45	6	27
Inferior Frontal Gyrus		44	3.89	17	51	15	9
Thalamus/Parahippocampus		27	4.5	56	21	-30	-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 (control and ADHD) are listed first. Some of the regions contained multiple clusters - right hemisphere clusters are always listed first.

trained during go blocks. Only control children produced activation in our fronto-striatal regions of interest including the caudate head/body and the inferior, middle, superior and medial frontal gyri. Our results for the control children are consistent with developmental response inhibition studies that have reported fronto-striatal activation during go/no-go tasks (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey et al., 1997b; Durston et al., 2002), stop tasks (Rubia et al., 2000a), delay tasks (Rubia et al., 2000a) and anti-saccade tasks (Luna et al., 2001).

Our study showed small differences in activation between the ADHD and controls during the selective attention task. These group differences for our regions of interest 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. Our finding of significantly lower intensity of activation for ADHD children than for control children in the superior parietal lobule (10 voxels) is consistent with structural studies that show ADHD children have smaller volume (Castellanos et al., 2002; Filipek et al., 1997) and lower metabolism in

the parietal region (Ernst et al., 1997). Although ERP studies have limited spatial resolution, our finding of lower intensity of activation for ADHD children in the parietal region is also consistent with evoked potential studies (Brandeis et al., 1998; Karayanidis et al., 2000; Robaey et al., 1992; van Leeuwen et al., 1998). The hypoactivity in the superior parietal lobule for the ADHD children in our study could reflect their lack of engagement of this system for representing extrapersonal space. It is essential to have a complete and accurate representation of the visual array in order to efficiently search this array for the target in a field of distracters.

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 control ($p < .001$) and ADHD children ($p < .05$) showed activation in bilateral superior parietal lobule and in predominantly right middle frontal gyrus. In contrast to the small group differences in selective attention, however, our study found large group differences between ADHD and control children for the response inhibition task. ADHD children showed significantly lower intensity of activation than control children in our regions of interest including the right inferior frontal gyrus (68 voxels) and bilateral caudate nucleus (155 voxels). The hypoactivity for

Table 5 Significantly greater activation for control or for ADHD children in the no-go blocks compared to the go blocks of the response inhibition task

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
Control	Superior Frontal Gyrus	8	3.83	89	3	18	54
		10	5.02	106	15	57	21
	Middle Frontal Gyrus	6	3.90	77	27	0	42
	Inferior Frontal Gyrus	44	4.60	40	42	24	15
	Inferior Frontal Gyrus	47	3.68	49	-30	27	-12
	Precentral Gyrus	6	3.79	51	48	-3	27
		6	4.14	106	-42	0	33
	Caudate Head/Body	*	4.21	212	-12	-3	18
	Insula	13	3.76	22	-42	-30	0
	Posterior Cingulate	31	3.70	10	-24	-78	12
	Parahippocampus/Posterior Cingulate/Lingual Gyrus/Fusiform Gyrus	35/27/29/ 18/19/37	5.34	2296	-30	-24	-9
	Superior Parietal Lobule	7	3.73	45	30	-54	57
		7	3.85	64	33	-33	36
	Amygdala	7	4.20	104	-30	-45	57
		*	4.50	44	45	-12	-18
		*	3.57	40	-21	-3	-18
ADHD	Insula	13	2.07	16	42	9	15
		7	2.60 ^a	82	-24	-51	51
	Posterior Cingulate/ Parahippocampus	30/36	2.73 ^a	117	30	-60	3
	Superior Parietal Lobule/ Precuneus	7	2.75 ^a	230	21	-60	48
	Brainstem	*	2.76 ^a	98	-3	-15	-21
	Superior Temporal Gyrus	42	2.38	16	-33	-30	6
	Middle Temporal Gyrus	21	2.59	14	-39	-48	3
	Inferior Temporal Gyrus	20	2.58	17	48	-9	-24

Note: See Table 4 note. Brain areas in our regions of interest (fronto-striatal) are listed first and then areas outside of these regions that are activated in both groups are listed next. For the ADHD only, $p < .05$ uncorrected at the voxel level. ^aindicates that this region was also significant at the $p < .05$ level when excluding the 3 ADHD subjects with the most movement.

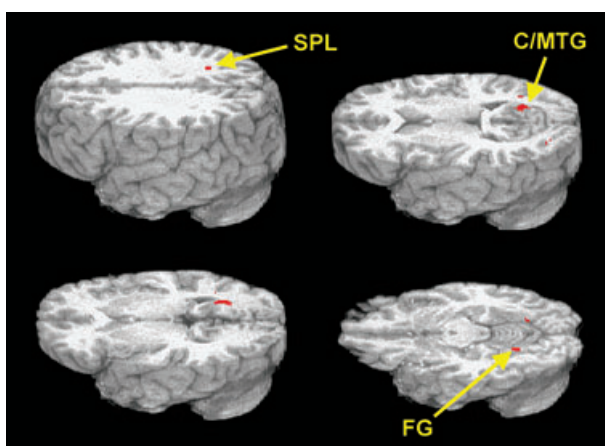


Figure 5 Significantly greater activation (red) for control than ADHD children in the selective attention blocks with nine stimuli compared to the go blocks of the response inhibition task with nine stimuli ($p < .001$). Perspectives were chosen to reveal the greatest extent of activation and regions with the greatest number of significant voxels (≥ 10) were labeled (C/MTG: cuneus and middle temporal gyrus; FG: fusiform gyrus; SPL: superior parietal lobule)

ADHD children in fronto-striatal regions is consistent with structural neuroimaging research that shows ADHD subjects have smaller frontal and basal ganglia volumes (Aylward et al., 1996; Casey et al., 1997a; Castellanos et al., 1996, 2002; Filipek et al., 1997; Hynd et al., 1993; Yeo et al., 2003). This hypoactivity is also consistent with functional neuroimaging research that shows less activation in ADHD subjects than controls in frontal and basal ganglia regions (Amen & Carmichael, 1997; Bush et al., 1999; Ernst et al., 1997, 1998a; Jin et al., 2001; Rubia et al., 1999, 2001; Zametkin et al., 1990).

As reviewed in the introduction, Casey et al. (2001) have proposed that the prefrontal region is involved in interference control from competing representations and the basal ganglia is involved in the inhibition of inappropriate behaviors (Casey et al., 2001). Our results suggest that ADHD children have deficits in both components of the fronto-striatal network. These children are not able to effectively engage this network to maintain appropriate behaviors or inhibit inappropriate behaviors.

Table 6 Significantly greater activation for control than for the ADHD children in the no-go compared to the go blocks of the response inhibition task and in the selective attention blocks with nine stimuli compared to the go blocks of the response inhibition task with nine stimuli

Group	Location Area	BA	Significance		Coordinate		
			z-test	voxels	X	Y	Z
No-go	Superior Frontal Gyrus	8	3.52	13	0	15	54
	Middle Frontal Gyrus	6	3.4	19	24	-9	48
		6	3.68	16	45	3	45
		11	3.59	10	-21	30	-12
	Inferior Frontal Gyrus	44	4.22	68	42	27	15
	Medial Frontal Gyrus	10	4.15	17	21	51	9
	Anterior Cingulate	32	3.32	10	9	42	6
	Precentral Gyrus	6	4.01	31	45	-6	24
		6	4.2	31	-36	9	21
	Caudate Head	*	4.17	53	6	12	3
	Caudate Body	*	3.73	46	12	-9	18
		*	4.19	56	-12	-3	18
	Globus Pallidus	*	3.49	10	-9	-33	-6
	Amygdala	*	3.94	13	30	-3	-15
	Cuneus	30	3.93	28	-3	-72	3
	Fusiform Gyrus	19/37	3.49	23	27	-63	-21
	Thalamus	*	3.5	38	3	-24	3
SEL ATT	Cuneus/Middle Temporal Gyrus	30/37	4.01	81	39	-57	3
	Fusiform Gyrus	19/37	3.67	10	-24	-57	-12
	Superior Parietal Lobule	7	3.9	10	27	-51	36

Note: See Table 4 note.

Less activation in this network could result for a variety of reasons. As reviewed above, quite a bit of evidence suggests that the fronto-striatal networks are underdeveloped in ADHD subjects by showing decreased volumes in these regions. However, our findings could also be explained by differences in functional or effective connectivity (McIntosh, Nyberg, Bookstein, & Tulving, 1997; Pugh et al., 2000).

Although Vaidya et al. (1998) did not investigate selective attention, they used a stimulus-controlled go/no-go task similar to ours and also found less activation in ADHD subjects compared to controls in the basal ganglia (Vaidya et al., 1998). Stimulus-controlled refers to paradigms that have an equal number of items in the go and no-go blocks. However, Vaidya et al. (1998) also reported that ADHD children showed more activation than controls in the caudate nucleus during a response-controlled go/no-go task. Response-controlled paradigms equate the number of motor responses made in the go and no-go blocks, and therefore there are 50% fewer stimuli in the go than in the no-go blocks. The stimulus- and response-controlled tasks may have created different inhibitory demands. There were 50% fewer trials in go blocks for the response-controlled task, and therefore, the establishment of a pre-potent response requiring inhibition may have been stronger in the stimulus-controlled task. The greater inhibitory demands of the stimuli-controlled paradigms may be more sensitive to the hypoactivity of ADHD children.

The results for our behavioral data suggest that group differences in performance may not account for brain activation differences between the control and ADHD children. The behavioral data showed that ADHD children perform more poorly (higher reaction times and lower accuracy) on all blocks. In other words, the difference between the no-go and go blocks for the response inhibition task and the difference between the nine stimuli and one stimulus blocks for the selective attention task were statistically the same for the control and ADHD children. Furthermore, the group differences between these blocks in behavioral performance were similar for the selective attention and response inhibition task. In contrast to the behavioral data, when comparing no-go versus go blocks, there was widespread hypoactivity for the ADHD children, but when comparing nine stimulus blocks to one stimulus blocks, there were no significant group differences in activation. The mismatch between the performance and activation results could suggest that brain differences are not related to any meaningful performance difference between groups. However, future research should use parametric manipulations and event-related designs to more clearly specify the association between behavioral performance and brain activation in these two groups. For example, using an event-related design, Durston et al. (2002, 2003) have varied the number of go trials preceding no-go trials in order to parametrically increase the inhibitory demands (Durston et al., 2002, 2003). In our study, comparison of accuracy and reaction time

across blocks or tasks is also difficult to interpret because the measures in these comparisons differ. For example, because ADHD children made more errors than control children 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 group differences in brain activation are due to the differences in the type of error produced more frequently by ADHD 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.

The DSM-IV (American Psychiatric Association, 1994) now makes the distinction between Predominately Hyperactive-Impulsive (ADHD/H), Predominately Inattentive (ADHD/I), and Combined Type (ADHD/C). Milich, Balentine, and Lynam (2001) have argued that ADHD/C is a distinct and unrelated disorder from ADHD/I (Milich et al., 2001). The results from behavioral studies using carefully designed experimental tasks suggest that inhibition deficits in ADHD/C subjects may be associated with executive functioning (Gansler et al., 1998; Houghton et al., 1999; Klorman et al., 1999; Lockwood, Marcotte, & Stern, 2001; Nigg, Butler, Huang-Pollock, & Henderson, 2002; Trommer, Hoepfner, Lorber, & Armstrong, 1988), whereas attention deficits in ADHD/I subjects may be associated with processing speed (Hynd et al., 1991). ERP and electroencephalography studies have reported some differences between the ADHD subtypes, but these studies cannot pinpoint the location due to limited spatial resolution (Clarke, Barry, McCarthy, & Selikowitz, 2001; Defrance, Smith, Schweitzer, Ginsberg, & Sands, 1996; Johnstone, Barry, & Anderson, 2001). Hesslinger et al. (2001) recently showed that ADHD/C adults showed less N-acetylaspartate concentration than ADHD/I adults in left dorso-lateral prefrontal cortex and that there was no difference between these groups in left striatum (Hesslinger, 2001). Our study included mainly ADHD/C children, so we could not reliably examine subtypes. All ADHD children in our study had 6 or more symptoms of inattention and 8 of 12 ADHD children had 6 or more symptoms on the hyperactive-impulsive scale. Only two children in our study had two or fewer symptoms of hyperactivity-impulsivity, so only these two children were at levels of hyperactivity-impulsivity comparable to our control children. Because our population included mostly children with hyperactive-impulsive symptoms, our results

cannot be generalized to the entire ADHD population. Perhaps a population of children with predominantly inattentive symptoms would reveal brain activation differences in the selective attention network during our visual search task.

Another limitation of our study was that we did not have enough subjects to examine sex differences in the neural profiles of ADHD. Two recent meta-analyses of the literature have shown that boys tend to have more hyperactivity and externalizing problems, whereas girls have greater intellectual impairments (Gaub & Carlson, 1997; Gershon, 2002). These behavioral differences seem to have an underlying neurological component. Animal studies have shown that dopamine transmitters rapidly increase during development and then are pruned to a greater extent in males than females (Andersen & Teicher, 2000), and human neuroimaging studies have also suggested some difference between males and females (Ernst et al., 1994; Ernst, Zametkin, Phillips, & Cohen, 1998b; Yeo et al., 2003).

Conclusion

This study reported small group differences between control and ADHD children in brain activation during selective attention as measured by a visual search task. This small difference may indicate little involvement of the superior parietal lobule and lateral premotor network in our ADHD population. In contrast, there was widespread hypoactivity in the ADHD children during response inhibition as measured by a go/no-go task. The larger population difference for the go/no-go task in the fronto-striatal network is consistent with response inhibition being the primary deficit in ADHD as suggested by previous genetic, brain imaging and behavioral research. More neuroimaging research directly comparing different response inhibition tasks with selective attention tasks is needed in order to determine whether our results are task specific or generalizable.

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