Hemodynamic Differences in Children with Dichotic Listening Deficits: Preliminary Results from an fMRI Study during a Cued Listening Task

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Abstract

Functional magnetic resonance images were acquired while children with and without dyslexia identified incongruous words embedded within fairy tale segments in a quasidichotic listening task. All children produced greater activation in the left hemisphere than in the right hemisphere during the binaural separation listening task. Children with dyslexia, who had a higher incidence of a dichotic left ear deficit from prescanning behavioral tests, produced fewer hits and more misses than control children while monitoring their left ears in the scanner. Control children produced stronger left hemispheric activation for ipsilateral left ear input than right hemispheric activation for ipsilateral right ear input, but ipsilateral activation patterns in children with dyslexia were symmetrical. Children with dyslexia who monitored their right ears first produced the lowest left hemispheric activation overall, suggesting that priming of the right ear may have inhibited the ability of children with a left ear deficit to adequately identify target words presented toward their left ears while in the scanner.

Key Words: Asymmetry, children, dichotic, dyslexia, fMRI, hemodynamic

Abbreviations: CV = consonant-vowel; EPI = echo-planar imaging; fMRI = functional magnetic resonance imaging; FOV = field of view; LE = left ear; LH = left hemisphere; RE = right ear; REA = right ear advantage; RH = right hemisphere; SCAN = Screening Test for Auditory Processing Disorders; SRT = speech reception threshold; TE = time to echo; TR = repetition time

Sumario

Se registraron imágenes de resonancia magnética funcional mientras niños con sin dislexia identificaban palabras incongruentes inmersas en segmentos de un cuento de hadas, durante una tarea de escucha cuasi-dicótica. Todos los niños produjeron una mayor activación en el hemisferio izquierdo que en el derecho durante dicha tarea de separación auditiva binaural. Los niños con dislexia, quienes mostraban una mayor incidencia de deficiencia dicótica en el oído izquierdo demostrada por pruebas conductuales previas al escaneo, lograron menores aciertos y más fallas que los niños del grupo control, mientras se monitoreaban sus oídos izquierdos en el equipo. Los niños controles produjeron una activación más fuerte del hemisferio izquierdo para la estimulación ipsilateral del oído izquierdo que activación del hemisferio

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derecho para la estimulación ipsilateral del oído derecho, pero los patrones de activación ipsilateral en los niños de dislexia fueron simétricos. Los niños con dislexia que monitorearon primero sus oídos derechos produjeron la activación global más baja del hemisferio izquierdo, sugiriendo que poner atención al oído derecho puede haber inhibido la capacidad de los niños con una deficiencia del oído izquierdo para identificar adecuadamente palabras clave presentadas hacia el oído izquierdo mientras eran escaneados.

Palabras Clave: Asimetría, niños, dicótico, dislexia, fMRI, hemodinámico

Abreviaturas: CV = consonante-vocal; EPI = imagen eco-planar; fMRI = imágenes por resonancia magnética funcional; FOV = campo de visión; LE = oído izquierdo; LH = hemisferio izquierdo; RE = oído derecho; REA = ventaja del oído derecho; RH = hemisferio derecho; SCAN = Prueba de Tamizaje para Trastornos de Procesamiento Auditivo; SRT = umbral de recepción del lenguaje; TE = tiempo para el eco; TR = tiempo de repetición

Dichotic listening is a behavioral technique used to reveal important information about auditory lateralization following input of speech. In the assessment of auditory processing disorders (APD), dichotic listening tests have been widely used to reveal deficits in children with listening, language, and learning difficulties (Bellis, 2003; Moncrieff, 2006). A unilateral deficit during dichotic listening is characterized by normal performance in one ear and significantly poorer performance in the other ear. Unilateral deficits on dichotic listening tests have been linked to lesions of the corpus callosum (Musiek et al, 1979: Musiek, 1983; Sugishita et al, 1995) and temporal lobe (Wester et al, 1991; Lee et al, 1994), lending support to a structural model of dichotic listening (Kimura, 1967). The structural model of dichotic listening states that in most listeners, the right ear will have superior performance relative to the left ear because of (1) preferential activation along contralateral auditory pathways that are more densely innervated than ipsilateral pathways, (2) suppression of ipsilateral pathways when the two ears are placed in competition, and (3) greater linguistic representation of verbal material in the left hemisphere of the brain that is preferentially activated by the right ear through the contralateral pathways. A right-ear advantage (REA) occurs in dichotic listening because information from the ipsilateral left ear arrives at the left hemisphere indirectly, having ascended to the right hemisphere and then crossed through the corpus callosum to the homologous region on the left side.

An alternative model for dichotic listening proposes that brain regions responsible for linguistic analysis are primed by presentations of verbal material, thereby pulling the listener's attention toward the stimulus source that is contralateral to the language-dominant hemisphere (Kinsbourne, 1970). This attentional model supports the notion of an REA but acknowledges that some listeners can overcome structural bias and improve performance in the ipsilateral, nondominant ear by directing attention toward it (Bryden et al, 1983; Obrzut et al, 1986; Asbjornsen and Hugdahl, 1995). With or without specific instructions regarding attention, listeners typically produce an REA during dichotic listening tasks with different stimulus types, including consonant vowels (CVs) (Asbjornsen and Hugdahl, 1995), CVCs (Asbjornsen and Bryden, 1996), digits (Strouse and Wilson, 1999), or words (Roup et al, 2006).

The REA in normal adults reflects a small interaural asymmetry during dichotic listening tasks. In children, interaural asymmetry varies from 2 to 40%, depending on the age of the child and the verbal demands of the dichotic listening stimuli. By age 11, normal right-handed children typically demonstrate an REA of 2% with digits and 15% with words (Bellis, 2003; Moncrieff, 2006). A binaural integration deficit type of auditory processing disorder is suggested when interaural asymmetry exceeds a child's age-appropriate value in the presence of normal performance in the dominant ear. Larger than normal values for the REA have been reported in dichotic listening studies of children with language and reading disorders when tested with digits and words (Morton and Siegel, 1991; Lamm and Epstein, 1994; Moncrieff and Musiek, 2002). Under the structural model, an abnormally large interaural asymmetry is thought to occur because of poor transmission of auditory information from the left ear through interhemispheric pathways, similar to the results seen in lesion patients (Jerger et al, 1993). Under the attention model, a unilateral deficit could result from insufficient capacity within working memory or attentional networks to correctly identify information arriving through two competing auditory pathways, especially when the dichotic task requires the listener to identify both stimuli. It has long been recognized that factors related to attention and short-term memory interact with distinct acoustic properties of the two competing stimuli and that information is lost in the process, especially information in the nondominant pathway (Studdert-Kennedy and Shankweiler, 1970).

There has been widespread evidence with fMRI (functional magnetic resonance imaging) techniques that auditory verbal stimulation produces a bilateral hemodynamic response with stronger activation in left hemisphere regions in adults (Chee et al, 1999; Benson et al, 2001; Burton et al, 2001; Newman and Twieg, 2001) and in children (Booth et al, 1999). Similar results have occurred in fMRI experiments using dichotic presentations of speech material (Hashimoto et al, 2000), and in some dichotic listening fMRI studies, areas of activation in fronto-temporal networks such as the cingulate gyrus and presupplementary motor area have also been reported (Jäncke and Shah, 2002; Thomsen et al, 2004). Activation in these additional regions is presumed to represent recruitment of additional processing capacity in working memory and attentional networks beyond those required for speech perception. These results suggest that fMRI methods may be useful for characterizing both structural and attentional modulations involved when listeners perform a dichotic listening task.

The purpose of our study was to use fMRI techniques to measure the hemodynamic response in two different groups of children, one with normal dichotic listening abilities and another with unilateral deficits during dichotic listening. We predicted that children with normal dichotic listening results would produce bilateral activation patterns similar to those reported from studies with adults, demonstrating a left-hemisphere advantage consistent with their behavioral REA. We predicted that the hemodynamic response in children with a greater interaural asymmetry during behavioral dichotic listening tasks would demonstrate a larger left-sided hemodynamic response, consistent with their larger than normal REA.

MATERIALS AND METHODS

Subjects

Experimental subjects were selected from a chart review of the outpatient population of the Luke Waites Center for Dyslexia and Learning Disorders at Texas Scottish Rite Hospital for Children in Dallas, Texas. All children who were left-handed were excluded. Children were selected from those who had received a diagnosis of dyslexia provided there was no additional diagnosis of hearing loss, attention deficit disorder with/without hyperactivity, chronic psychological disorder, or neurological impairment. Dyslexia was diagnosed on the basis of parent and school history of reading difficulty and on test results that were consistent with normal intelligence and below-normal results on some or all measures of phonologic awareness and reading skills. Charts were screened to determine that all children selected demonstrated a full scale IQ score above 85 and a Wechsler Individual Achievement Test (WIAT) basic reading standard score less than or equal to 90. Only monolingual native speakers of English were included in the study. Children with dyslexia were chosen for participation because of strong research evidence that dichotic listening asymmetries are common among children with reading disorders. Control subjects and two additional children with reading difficulties were recruited from the community. All control children were confirmed by standardized test scores to be normally achieving in an age-appropriate grade with no known diagnosis of hearing loss, attention deficit disorder with or without hyperactivity, psychiatric disorder, or neurological impairment. There were initially ten children (seven males and three females) in each of the two groups, but one female dyslexic child recruited from the community was removed when the initial report of dyslexia was not confirmed by test results.

Behavioral Measures

Each child's hearing was evaluated for pure tones at frequencies from 500 to 4000 Hz. Middle ear status was evaluated by tympanometry. Speech reception thresholds (SRTs) were established using the Central Institute for the Deaf (CID) W-1 word list. Participation continued only when hearing thresholds were recorded at or below 15 dB HL at all frequencies together with normal acoustic admittance bilaterally. All subjects were in excellent general health, and all met the above selection criteria. Handedness was assessed by questionnaire (Annett, 1970), and all 19 subjects were strongly right-handed. Results of language and reading measures in the children with dyslexia have been previously reported (Moncrieff and Black, 2008).

Three dichotic listening tests were administered to explore hemispheric dominance for language in each subject and to measure degree of laterality: the Dichotic Digits Test (Musiek, 1983), the Competing Words subtest of the Screening Test for Auditory Processing Disorders (SCAN) (Keith, 1986), and the Dichotic Consonant Vowel Test (Berlin et al, 1973). The Dichotic Digits Test is composed of the single-syllable digits from one to ten, naturally spoken by a male voice (Musiek, 1983). The stimuli were recorded so that digits on one channel of the tape recorder are aligned with digits on the other channel by using a timing cue to the talker. The test is composed of 20 single pairs plus 3 practice items, followed by 20 double digit pairs plus 3 practice items. In the double pairs condition, all digits except the number seven were used. The Competing Words subtest of the SCAN consists of 50 pairs of single-syllable words recorded naturally by a male voice and spoken with simultaneous onset times to the two ears (Keith, 1986). The Dichotic Consonant Vowel Test from AUDiTEC is comprised of 30 pairs of simultaneously presented pairs of CVs. The six English stops /p/, /t/, /k/, /b/, /d/, and /g/ were paired with the vowel /a/ and recorded within 100 msec (Berlin et al, 1973). Each possible pair is presented twice so that each token from the pair is presented once to the right ear and once to the left ear.

Tests with digits and words were presented in a directed response format during which the subject was instructed to repeat both stimuli but to repeat the stimulus heard in the right ear first during one-half of the test and the stimulus heard in the left ear first in the other half of the test. Throughout dichotic listening testing, earphones were reversed and test order was pseudorandomized across all subjects. Each time test material was changed, the audiometer was recalibrated to the test tone provided with the test. Dichotic material was presented to each subject at 50 dB SL relative to the subject's SRT. Correct responses were recorded and converted to percent correct for each ear. Results from the left ear were subtracted from results from the right ear to determine laterality and degree of interaural asymmetry.

Image Acquisition

While each subject attended to a cued listening paradigm as previously described, fMRI was performed (Moncrieff et al, 2004). The task consisted of dichotic presentations of eight sentences of the fairy tales *Cinderella* and *Snow White*, followed by eight silent intervals, repeated four times, for 64 acquisitions per functional run. Sentences were recorded onto compact disc in four separate tracks for delivery via compact disc player attached to a portable Qualitone two-channel audiometer. The level at which the segments were presented was always 80 dB SPL (SPL of [1] a broadband noise signal presented through the portable audiometer and calibrated at the insert earphones used for testing and [2] the average for representative speech segments played from the CD and presented through the portable audiometer and calibrated at the insert earphones used for testing). Etymotic Research ER-30 insert earphones were connected from the audiometer to 20' of 4 mm internal diameter, 2.5 mm wall medical grade silicone tubing, which was connected to Libby Horn tubing and to ER3-14 foam ear tips with horn tubing. Following placement of the foam ear tips into subjects' ears, Silicast™ (Westone Corp., Colorado Springs, CO) earmold impression material was used to fill the bowl of each ear and extend down the length of the Libby Horn tubing in order to attenuate the background noise of the scanner. The presentation level was calibrated to each subject so that a calibration tone at 1000 Hz sounded equally loud in both ears.

Within each group of eight sentences, between three and five sentences contained one incongruous word (Figure 1). At the onset of each block, the subject was cued to ignore the segments presented in one ear, pay attention to sentences in the other ear, and wiggle a foot when an incongruous word was detected. Figure 1 displays a sequence of eight dichotically presented fairy tale segments, each followed by a scan. After the eight scans during presentations of segments, an equivalent period of time followed during which no fairy tales were presented and baseline scans were made. Behavioral responses were monitored and recorded in four ways: number of hits (correctly identified target in the cued ear), number of misses (no response when a target was presented to the cued ear), number of false alarms (response when no target was presented in either ear), and number of laterality errors (identified target presented toward the noncued ear when no target was presented in the cued ear). Four functional runs were performed: prior to the first run, the subject was cued to attend to left or right ear only for that entire run. For the next three runs, the cued ear alternated, so that at the completion of data acquisition, the subject had been cued to attend to each ear twice. Earphones were reversed, and initial ear for attending and reporting were alternated across subjects throughout the study.

All images were acquired from a 1.5 Tesla Philips ACS-NT MRI scanner, equipped with PowerTrak gradients capable of echo-planar imaging (EPI). The patient's head was secured by velcro strapping to the support base of the head coil to minimize motion. Following patient positioning in the scanner, a three plane localizer was obtained. From this, 12 axial T1 slices were planned (256X256 matrix, FOV [field of view] = 240 mm, 7 mm slice, 0.5 mm gap TE [time to echo]/TR [repetition time] = 15/300 msec) to completely cover the temporal lobe. For the functional imaging, a time course of 66 acquisitions was planned at the same slice locations as the T1 slices (64X64 matrix, FOV = 240 mm, 7 mm slice, 0.5 mm gap, TE/TR = 40/10150 msec, 90 tip angle) and were manually synchronized to follow closely behind the presentation of each sentence of the fairy tale on the CD. The TR = 10150 msec was chosen to allow time for each sentence to be presented in an automated fashion and leave enough temporal space for the data to be collected, without the gradient noise intruding on the presented sentence.

All images were transferred via ethernet

LEFT EAR			RIGHT EAR		
NT	Once upon a time	SCAN	T	Be allowed to go to the **hair**	SCAN
NT	There was a beautiful girl	SCAN	NT	But the ugly nasty sisters	SCAN
NT	Who was called Cinderella	SCAN	T	Oh they were **tree**	SCAN
T	She had two ugly **windy**	SCAN	NT	They couldn't think about anything else	SCAN
NT	Who were very unkind to her	SCAN	T	When the day of the **floor** came	SCAN
NT	And made her do all the hard work	SCAN	NT	They made such a great fuss	SCAN
T	She had to sweep the **sky**	SCAN	T	Poor Cinderella **boat** to rush about	SCAN
T	She had to cook the **car**	SCAN	T	Upstairs and down **blue**	SCAN
		SCAN			SCAN
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		SCAN			SCAN
		SCAN			SCAN
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Figure 1. One of four listening blocks in the cued listening task with fairy tale segments that were delivered to each of the two ears. Target words (T) are in bold letters. Segments without target words are designed as nontarget (NT).

to an analysis workstation. For the echo-planar images, the first two volumes were discarded to allow for steady-state and because these were needed to cue the start of the appropriate track on the CD. All volumes were coregistered to the first volume of the remaining 64 volumes, using the AIR program (Woods et al, 1992). The T1 image volume was coregistered to the first EPI volume interactively (McColl et al, 1996). Statistical analysis of each time course involved correlation analysis (Bandettini et al, 1993) using square waves as ideal correlators, with first-order detrending and a three-pixel Gaussian filter. Groups of fewer than three pixels were rejected, at a correlation threshold of $p > 0.30$. Both positive and negative correlations were retained. Activated groups were superimposed on the T1 images using a rainbow color scheme.

Following correlation analysis, hemispheric activation statistics were obtained via an interactive program that allowed the user to work with the colorized images obtained from the statistical analysis. Those slices that covered the temporal lobe were identified, and a band was identified at the midline in order to reject medial activation patterns. The program was then run via a command line interface, and activated pixels for all slices were summed for left and right hemispheres. Positive correlations only, or positive and negative correlations, were separately counted.

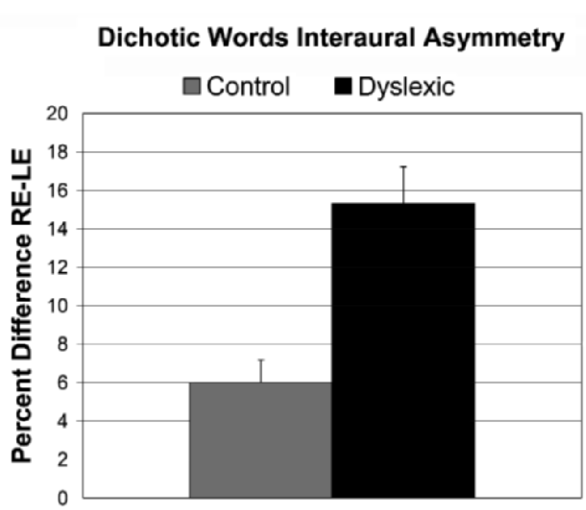

Figure 2. Average interaural asymmetry during the Competing Words subtest of the SCAN measured as the percent correct difference in performance between the two ears (right minus left) for children in the two groups.

STATISTICAL ANALYSES

Within subject effects were analyzed by repeated measures analysis of variance (ANOVA). Between group effects were analyzed by multivariate ANOVA or by use of paired samples t-tests. Correlations were obtained with bivariate Pearson product analysis procedures. Significance was measured at $p < .05$ and $p < .01$.

RESULTS

Dichotic Listening

As previously reported (Moncrieff and Black, 2008), children with dyslexia performed more poorly than controls from their left ears when listening to digits and words and from their right ears when listening to CVs. In the directed response format, degree of ear advantage differed significantly between groups with both words and digits. A greater number of dyslexic children demonstrated clinically significant difficulties in dichotic listening performance, and interaural asymmetries were larger among dyslexic children, especially for the dichotic test with single-syllable words (Figure 2). These results, however, were not uniform across all of the dyslexic children. Individual measures of interaural asymmetry on the test with single-syllable words varied from 2 to 14% in the control children and from 4 to 28% in the dyslexic children. There were four dyslexic children with REAs that were greater than 15% and five with REAs ranging from 4 to 14% (Figure 3).

Behavioral Measures during Acquisition

Each child's acknowledgement of a target anomalous word was recorded during acquisition of the fMRI scans. The number of hits, false alarms, misses, and laterality errors were calculated and converted to percent correct. When analyzed by multivariate ANOVA, there was no difference in performance between the two groups of children when they were monitoring the segments presented toward their right ears, but there was a significant effect of group for responses while monitoring the left ear that occurred across all measures:

for hits, $F(1, 18) = 14.721$, $p < .01$; for false alarms, $F(1, 18) = 4.996$, $p < .05$; for misses, $F(1, 18) = 11.068$, $p < .01$; and for laterality errors, $F(1, 18) = 10.451$, $p < .01$. Scores across the two ears were subjected to a paired samples t-test, and no differences were found for the control children, but results for children with dyslexia were significantly different for hits, t = 3.90, df = 8, $p < .01$, and misses, t = -3.847, df = 8, $p < .01$. These effects were due to significantly fewer hits and more misses when children with dyslexia were monitoring their left ears, but the number of laterality errors due to intrusions from the right ear was no different than for intrusions from the left ear in children with dyslexia. A correlational analysis was performed on the results from the prescanning dichotic listening tests and the behavioral measures obtained while the children were being scanned, and significant negative correlations occurred between the REA score from the dichotic words test and the number of hits obtained during the left ear monitoring condition (R = -701, $p < .01$).

Results were converted to d' score for each subject during the two listening conditions (right and left ear monitoring) by signal detection theory methods (Figure 4). Again, a multivariate ANOVA revealed a significant difference between groups only for the d' score for the left ear monitoring condition, $F(1, 18) = 18.371$, $p < .01$. This difference was due to significantly poorer d' scores among children with dyslexia in the left ear monitoring condition, which was also revealed by a paired samples t-test that showed a significant difference between the d' scores obtained for the two listening conditions, t = 3.128, df = 8, $p < .05$. A correlational analysis between the REA score from the dichotic words test and the d' scores for the left and right ear monitoring conditions in the scanner revealed a significant correlation only for the d' score in the left ear monitoring condition (R = -.471, $P < .05$).

Activation Results

All subjects were scanned by functional magnetic resonance imaging, but data from two subjects in each group were excluded because they had orthodontic braces that interfered with the signal and caused an excessive amount of spurious activation across brain slices. Analysis of functional imaging activation is therefore based on eight children in the control group and seven children with dyslexia.

Functional magnetic resonance images were compared to axial slices parallel to the anterior commissure-posterior commissure (CA-CP) line according to Talairach and Tournoux (1988). For each subject, two columns of slices were selected, representing the images collected as close to the anterior commissure as possible and the images collected approximately 7–8 mm superior to them. All activation data are for those columns of slices with each column

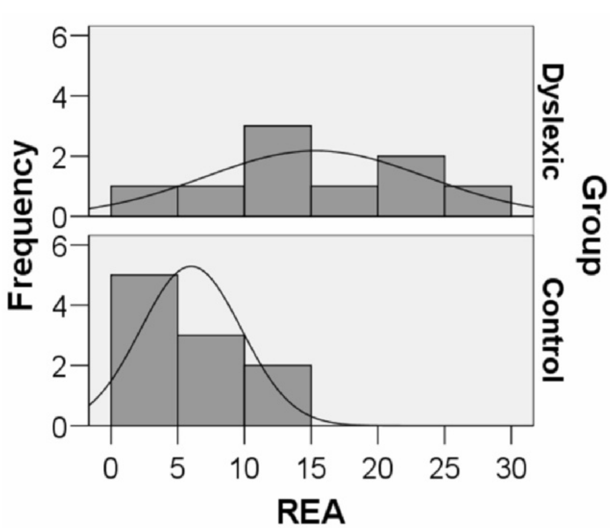

Figure 3. Distribution of the REA magnitude from the Competing Words subtest across the two groups of children.

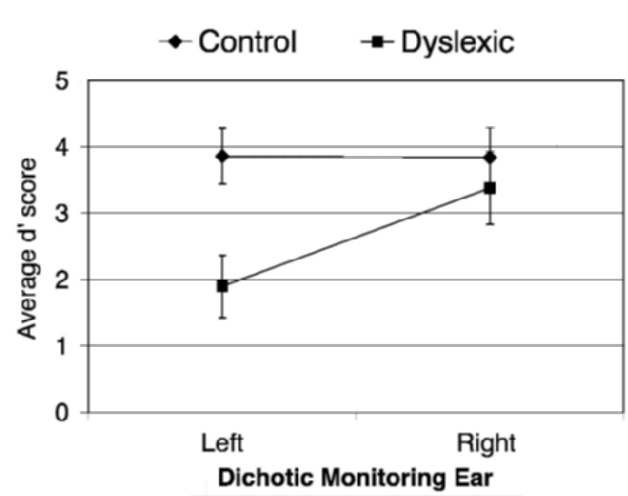

Figure 4. Results from analysis by signal detection theory methods reported as the d' score for monitoring targets in the left ear and right ear while inside the scanner.

representing the activation pattern following two presentations of 32 fairy tale segments to each ear. The total number of pixels demonstrating both positive and negative activation, excluding the midline 20% of each slice, were counted and recorded for each subject. Activations in the negative direction were excluded from analysis. The number of pixels activated for each hemisphere by each ear of input is recorded for each subject in Table 1.

Activation occurred primarily in the superior temporal gyrus across all subjects in primary auditory cortex and in Wernicke's area, but there was a lot of variability in responses across the subjects scanned. The total number of pixels were subjected to a two condition (monitor right and monitor left) by two hemisphere (right hemisphere and left hemisphere) repeated measures ANOVA with group as a between subjects factor, and there was a significant effect only for hemisphere, $F(1, 13) = 5.291$, $p < .05$, which was due to greater left hemisphere activation across all subjects. One potential problem with comparing the two groups is the presence of one significant outlier in the control group (JS) who produced a total number of pixels across conditions that was significantly greater than any other subject (Figure 5). Paired samples t tests were performed separately on the total number of voxels across both hemispheres (LH [left hemisphere] - Total and RH [right hemisphere] - Total) and for input from the two ears (LE [left ear] - Total and RE [right ear] - Total) for children in each of the two groups. None of the paired samples achieved significance at the $p < .05$ level, but for children in the dyslexic subgroup, the pairing of LH-Total and RH-Total activation approached significance, $t = 2.103$, $p = .07$, because more voxels were observed in the left hemisphere than in the right hemisphere of children with dyslexia. Paired samples t tests were also performed on the total number of voxels produced in ipsilateral hemispheres (LH-LE and RH-RE) and contralateral hemispheres (LH-RE and RH-LE). Among children in the control subgroup, the pairing of ipsilateral activations approached significance, $t = 2.160$, $p = .07$, because these children produced greater activation in the left hemisphere following left ear input than in the right hemisphere following right ear input (Figure 6).

Effects of Monitoring Order

Some of the children monitored for targets in their right ear first, and others monitored for targets in their left ear first. The total number of voxels activated by either the

Table 1. Number of Voxels Representing Significant Activation within the Region of Interest

Subject	Subgroup	Order	LH-LE	LH-RE	RH-LE	RH-RE	Total LH	Total RH	Total LE	Total RE
CL	Dyslexic	R	12	5	0	8	17	8	12	13
ML	Dyslexic	R	16	56	11	35	72	46	27	91
VK	Dyslexic	R	11	2	0	6	13	6	11	8
JM	Dyslexic	R	0	0	0	0	0	0	0	0
RL	Dyslexic	L	16	30	29	0	46	29	45	30
CC	Dyslexic	L	25	17	25	14	42	39	50	31
SS	Dyslexic	L	12	8	20	10	20	30	32	18
JW	Dyslexic	L	0	42	0	6	42	6	0	48
AB	Control	R	40	10	38	17	50	55	78	27
HS	Control	R	9	15	1	7	24	8	10	22
JS	Control	R	45	60	115	4	105	119	160	64
CS	Control	L	7	33	10	5	40	15	17	38
KB	Control	L	27	0	11	0	27	11	38	0
BF	Control	L	0	4	0	12	4	12	0	16
JM	Control	L	21	8	10	0	29	10	31	8

Note: LH = left hemisphere; RH = right hemisphere; LE = left ear; RE = right ear

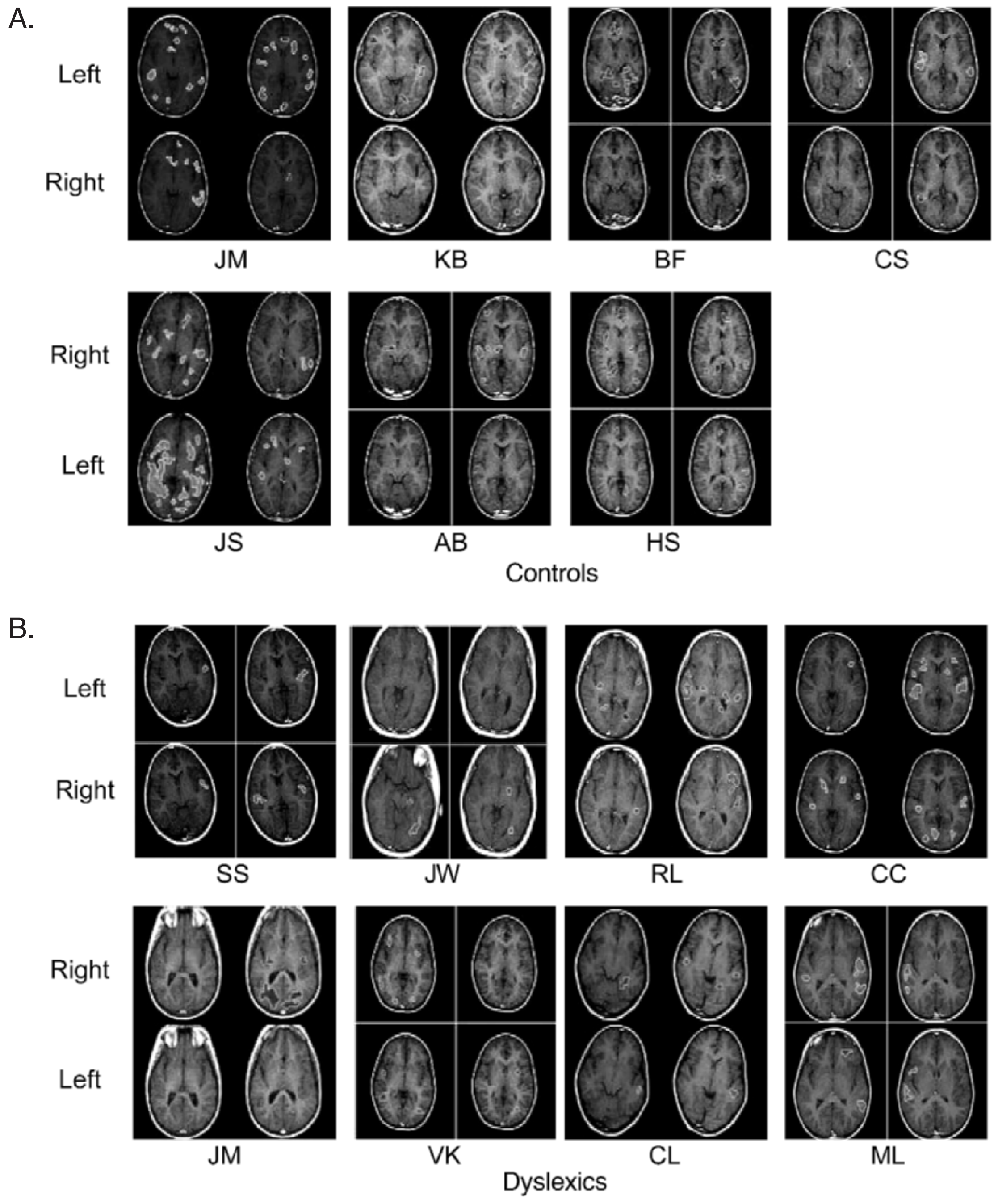

Figure 5. Voxels indicating significant activation within the region of interest in the temporal lobe for each of the children in the study. Control children are displayed in *A*, and dyslexic children are displayed in *B*. Within each group, children are divided between those who listened with their right ears first and those who listened with their left ears first while inside the scanner. For each image, the left hemisphere of the brain is shown on the right side of the image, and the right hemisphere is shown on the left side of the image.

right or the left ear was also analyzed by multivariate ANOVA with factors of monitoring order (left first or right first) and subgroup as between subjects variables. A significant interaction occurred between subgroup and test order for the total number of voxels activated while monitoring for targets presented toward the left ear, F (1, 15) = 4.686, $p < .05$. This appears to be due to a larger number of voxels within both hemispheres for left ear input among children in the dyslexic subgroup who monitored their left ears first and the opposite result for children in the control subgroup who demonstrated more activated voxels from their left ears if they monitored their right ear first (Figure 7). Even with the one outlier control subject, JS, removed from

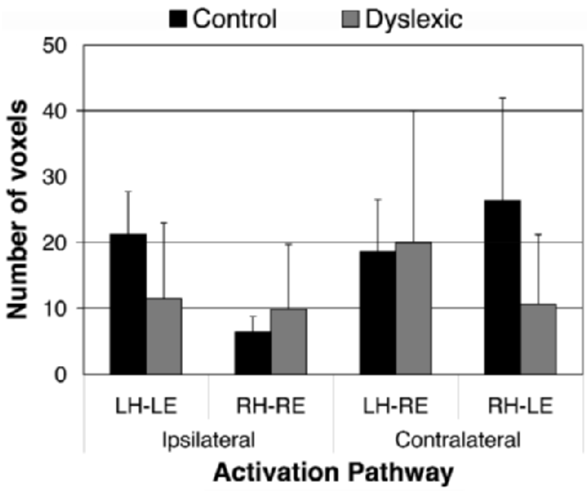

Figure 6. Average number of voxels indicating significant activation for inputs arriving in the left or right hemisphere via the ipsilateral or contralateral pathways for children in each of the two groups.

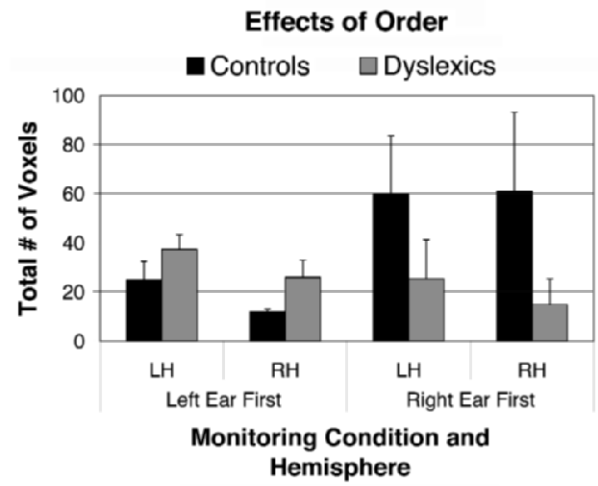

Figure 7. Average number of voxels indicating significant activation within the left and right hemispheres for children in each of the two groups, divided between those who listened with their left ears first and those who listened with their right ears first.

the data, the average number of voxels produced for left ear monitoring by control children who listened to their right ears first was larger than for the other control children (44 versus 21.50). For children in the dyslexic subgroup, those who monitored their left ears first produced identical activations for both ears (31.75) whereas those who monitored their right ears first produced greater activation for right ear input than for left ear input (28 versus 12.5). Within hemispheres, a follow-up multivariate ANOVA performed on the results within each subgroup produced a nearly significant (p = .06) effect of monitoring the left ear first among children in the dyslexic group that resulted in greater right hemisphere activation for left ear inputs. The four children with dyslexia who listened to their left ears first produced a larger number of voxels in their right hemisphere with left ear targets than those who listened to their right ears first. Among the four children with dyslexia who listened to their right ears first, three of them produced no voxels in the right hemisphere during presentations to their left ears.

DISCUSSION

Children in both subgroups produced bilateral activation in regions of the temporal lobe as expected during a speech-based listening task (Ulualp et al, 1998) with stronger activation in the left hemisphere (Booth et al, 1999). Based on the number of activated voxels within a predefined region of interest, the REA children in this study produced a greater number of activated voxels in the left temporal lobe while monitoring target words, similar to results obtained in another study from REA adults as they listened to words in the scanner (Rimol et al, 2006). As predicted, children in the dyslexic subgroup produced more asymmetric activation with a larger number of voxels in the left hemisphere relative to the right hemisphere, similar to results obtained in a study indicating stronger left hemisphere fMRI activation among dyslexic boys during a rhyming task (Corina et al, 2001). The structural model of dichotic listening proposes stronger left than right hemisphere activation among all right-handed listeners because of preferential activation along contralateral pathways ascending from the right ear. This model is supported by the results obtained from all of the children in this study, but the greater asymmetry observed in the activation patterns among the children with dyslexia suggests a lesser degree of bilaterality in activation among children with a dichotic listening left ear deficit. One model of abnormal lateralization among dyslexic individuals has proposed that the larger than normal REA observed during behavioral dichotic testing occurs because of excessive activation in the left hemisphere (Kershner and Morton, 1990). This model is supported by the evidence in this study that compared to the control children, the children with dyslexia produced a larger degree of asymmetry between the hemispheres, but there was very little evidence that the degree of left hemispheric activation observed in the children with dyslexia was excessive. The results from this study support an ear-specific pattern of activation differences rather than one related to the cortical hemispheres. Compared to the control children, the children with dyslexia produced greater activation in both the right and left hemispheres while monitoring their right ears but produced lower activation in both the right and left hemispheres while monitoring their left ears.

The behavioral responses obtained from the children with dyslexia while listening in the scanner similarly support this ear-specific model. The significantly poorer d' score among them while monitoring left ear presentations suggests that these children had greater difficulty responding to information presented to their left ears while competing information was simultaneously presented to their right ears. While monitoring their right ears, they were able to perform at levels that were similar to the control children, suggesting that noise or other factors related to being inside the scanner had limited effect on their performance. The strong negative correlation between the number of hits while monitoring their left ears and the magnitude of their REA on standard tests of dichotic listening suggests that these children were producing performance patterns while being scanned that were similar to those obtained in quiet during behavioral dichotic testing.

As previously reported from an ERP study using the same quasidichotic speech stimuli from the fairy tale *Cinderella* as used during scanning, the children with dyslexia in this study with larger than normal REAs also demonstrated significantly longer latencies and reduced responses to information presented toward their left ears (Moncrieff et al, 2004). This result was similar to measures obtained in a case study of a child with an abnormally large interaural asymmetry on behavioral dichotic listening tests whose ERP responses suggested a deficit in the efficiency of interhemispheric transfer of auditory information during dichotic tasks (Jerger et al, 2002). Results from these electrophysiologic studies suggest that neural timing for input to the left ear during a dichotic listening task may be slower in children with a larger than normal REA. One explanation for the delay is that information arriving from the left ear must cross through the corpus callosum to arrive at the left hemisphere for linguistic processing. A delay in transmission to the left hemisphere for input from the left ear among individuals with a left ear deficit is tentatively supported by the difference between subgroups for ipsilateral input to the left hemisphere. The control children produced almost twice as many voxels for this type of input relative to the children with dyslexia (21.3 versus 11.5), but the differences did not achieve significance in this study. It seems plausible that significant differences for this type of activation pattern might emerge in a larger study exploring this effect. Another possibility is that the delay in transmission may have occurred within the ascending auditory pathways from the left ear to the right hemisphere. In this contralateral condition, the control children produced more than twice as many voxels as the children with dyslexia (26.4 versus 10.6). This between group difference failed to achieve statistical significance in this study, possibly because of the limited number of individuals involved in the analysis, but a larger study may be warranted to explore whether this ear-specific deficit in contralateral activation is present among children with dichotic listening deficits.

The attention model of dichotic listening predicts that priming of the left hemisphere will occur with verbal listening tasks, drawing a listener's attention toward the contralateral auditory space at the right ear. Priming effects involving enhancement of dichotic listening right ear performance have been reported in monaural or binaural listening tasks (Jäncke, 1994) and in dichotic listening tasks (Morton and Kershner, 1993). In order to switch from monitoring the right ear to monitoring the left ear, the listener must use top-down resources to overcome this bias toward the right ear and redirect attention toward the left auditory space, a task that is reportedly more difficult among children and older adults during dichotic listening tasks (Hugdahl et al, 1990). In this study, control children who monitored their right ears first produced more activation in both hemispheres, with greater activation in the left hemisphere during left ear presentations than during right ear presentations. Part of this effect occurred because of one particular subject who produced a large number of voxels in all conditions, but even with that subject removed, the control subjects who monitored their right ears first demonstrated the greatest activation overall, especially in the left hemisphere. This suggests that these control children had no difficulty switching attention from the right to the left ear when directed to do so during the listening tasks inside the scanner. Alternatively, children with dyslexia who monitored their right ears first had less activation overall and produced the lowest levels of activation during left ear monitoring conditions, suggesting that they may have had greater difficulty switching to their left ears after priming of their right ear in the initial listening task in the scanner. Since children with dyslexia together with a comorbid diagnosis of attention deficit disorder were excluded from participating in this study, it seems unlikely that these children had greater difficulty with attention in general, however. It is possible that the interaural asymmetry between the two ears during behavioral testing with dichotic stimuli may reflect a strong bias in these children toward the right auditory space that is very difficult for them to overcome when input toward the left ear is of interest. One way to avoid this bias in future studies of hemispheric activation during dichotic listening tasks would be to replace the event-related block design of stimulus presentation utilized in this study with a randomized presentation of dichotic material. Randomly presented dichotic stimuli, especially if interleaved with monaural and binaural stimuli, would produce less of a priming effect on listeners. Alternatively, studies that proposed to investigate the priming effect in children with dichotic listening deficits would benefit from the block design used here but should address this important question in a larger study.

Control children, regardless of which ear they monitored first, and children with dyslexia who monitored their left ears first appeared to be better at allocating attentional resources toward the weaker, less dominant auditory space if the number of activated voxels produced by left ear monitoring can be taken as indication of successful monitoring. The strong correlation observed between total activation for left ear monitoring and the right ear d' score in the control children who monitored their right ears first suggests the possibility that monitoring the right ear first may have enhanced overall performance for children who can perform normally on dichotic listening tests. In the children with dyslexia, however, priming with input to their right ears first may have made it more difficult for them to switch to listening with their left ears as suggested by earlier behavioral results (Hugdahl et al, 1990) and thereby resulted in a lower level of activation during their time in the scanner.

The small number of subjects involved in this study makes results very speculative, especially with activation patterns dependent on the number of activated voxels within a specific region of interest. Newer methods of acquiring whole brain images in a study of this kind could provide information about all regions that are specifically activated during a dichotic monitoring task and also display patterns of activation in fronto-temporal networks that may be related to effects of attention and priming. More elaborate statistical analyses of activation patterns would also potentially yield a clearer picture of the effects that are suggested in this study.

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