



The Development of Specialized Brain Systems in Reading and Oral-Language

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ABSTRACT

Functional magnetic resonance imaging (fMRI) was used to examine differences between children (9–12 years) and adults (21–31 years) in the distribution of brain activation during word processing. Orthographic, phonologic, semantic and syntactic tasks were used in both the auditory and visual modalities. Our two principal results were consistent with the hypothesis that development is characterized by increasing specialization. Our first analysis compared activation in children versus adults separately for each modality. Adults showed more activation than children in the unimodal visual areas of middle temporal gyrus and fusiform gyrus for processing written word forms and in the unimodal auditory areas of superior temporal gyrus for processing spoken word forms. Children showed more activation than adults for written word forms in posterior heteromodal regions (Wernicke's area), presumably for the integration of orthographic and phonologic word forms. Our second analysis compared activation in the visual versus auditory modality separately for children and adults. Children showed primarily overlap of activation in brain regions for the visual and auditory tasks. Adults showed selective activation in the unimodal auditory areas of superior temporal gyrus when processing spoken word forms and selective activation in the unimodal visual areas of middle temporal gyrus and fusiform gyrus when processing written word forms.

INTRODUCTION

Orthographic and Phonologic Processing

Only three published studies of single-word priming have directly examined the relative influences of orthographic and phonologic processes in children's visual word recognition, and two of these studies did not examine developmental differences (Goswami, 1990; Hansen & Bowey, 1992). In a recent investigation of children (2nd through 6th graders), Booth, MacWhinney, et al. (1999) reported that older or high skill readers

exhibit more phonologic and orthographic priming than younger or low skill readers. These readers were presented with three different prime-target trials. All primes were non-words and shared with a target word (e.g., *tomb*) either the same phonology (e.g., *TUME*), a similar orthography (e.g., *TAMS*) or no letters in common (e.g., *USAN*). Because these prime-target pairs were displayed for a brief duration (less than 60 ms) that prevented complete processing, it was concluded that older or high skill readers activated orthographic and phonologic informa-

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tion more quickly and automatically than younger or low skill readers. Booth, Perfetti, MacWhinney, and Hunt (2000) replicated and extended the results of this earlier study in a population of children and adults with learning disorders.

Semantic Processing

A number of studies have shown larger semantic priming effects for younger and poor readers than for older and good readers when reading target words presented after a single-word or sentential priming context (Schwantes, 1985, 1991; Simpson & Lorschach, 1983, 1987; West & Stanovich, 1978). Plaut and Booth (2000) have developed a computational model of developmental and individual differences in semantic processing. They suggest that older or good readers show small semantic priming (e.g., table, chair) effects because their well-developed spelling-sound mapping allows them to decode words rapidly, thereby reducing the effects of semantics on word recognition. Younger or poor readers show more semantic priming because their underdeveloped grapheme-phoneme connections allow semantic information to influence their slow word recognition processes. As reviewed above, Booth et al. (1999) showed that there is a strong positive relation of orthographic and phonologic priming with both naming accuracy and age. Plaut and Booth (2000) suggested that as children learn the statistical regularities between phonology and orthography, they rely less on semantics and more on interactions between orthographic and phonologic representations for rapid word recognition.

Syntactic Processing

Substantial research suggests that the acquisition of noun-based and verb-based morphological forms are important developmental milestones in normally developing children as well as in children with reading disorders and specific language impairments. The general developmental trend in normally developing children is better performance on noun-based morphology like possessive and plural forms than on verb-based morphology like past tense forms (Gleason, 1958). Many reading disabled children also tend to have larger deficits in forming the past tense of verbs than forming the possessive and plural form

of nouns (Vogel, 1983; Wiig, Semel, & Crouse, 1973). Children with specific language impairment also have deficits in the production of verb-based morphology as compared to noun-based morphology (Leonard, 1995; Leonard, Bortolini, Caselli, McGregor et al., 1992; Leonard, Eyer, Bedore, & Grela, 1997; Rice, Wexler, & Redmond, 1999). However, it is unclear whether dyslexic and language impaired children constitute a delayed or immature pattern of development or whether they are qualitatively different from normal populations by making use of compensatory mechanisms involving contextual facilitation provided by morphological information (Bryant, Nunes, & Bindham, 1998; Elbro & Arnbak, 1996).

Neural Basis of Reading and Oral-Language Processing

Oral-language and reading differ at the most basic level in terms of the nature of perceptual input. In oral-language, auditory input is transmitted from the medial geniculate nucleus in the thalamus to both primary cortical areas (Brodmann's area [BA] 41) and secondary areas (BA 42) in the superior temporal gyrus, the latter of which may contain auditory representations of words (Binder et al., 1994). In written language, visual input is transmitted from the lateral geniculate nucleus in the thalamus to primary cortical areas (BA 17) in the striate cortex and to secondary areas (BA 18) in the extrastriate cortex. From here visual information has a dorsal "where" projection and a ventral "what" projection (Mishkin, Ungerleider, & Macko, 1983). The ventral projection includes the unimodal visual area of the fusiform gyrus (BA 37) that may contain orthographic representations of words (Fujimaki et al., 1999; Herbster, Mintun, Nebes, & Becker, 1997; Nobre, Allison, & McCarthy, 1994), whereas the dorsal system includes the superior parietal lobule (BA 7) that may be important for spatial attention aspects of reading. Wernicke's (BA posterior 22) and surrounding areas including the angular gyrus and supramarginal gyrus (BA 39, 40) are heteromodal areas that may be responsible for the integration of spoken and written word forms with arbitrary associations that give rise to meaning or semantics (Mesulam, 1998). Consistent with this

role, Wernicke's area is interconnected to category specific areas in the inferior temporal lobe (BA 20, 37) that appear to contain representations of faces, animals and tools (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Di Virgilio & Clarke, 1997).

Wernicke's area also has massive connections through the arcuate fasciculus with Broca's area (BA 44, 45, 47) that tends to show later peaks of activation in language tasks (Thierry, Boulanouar, Kherif, Ranjeva, & Demonet, 1999). Broca's area includes brain regions for overt (Hagoort, Indefrey, et al., 1999) and covert speech production of articulatory word forms (Friedman et al., 1998) as well as syntactic processing (Caplan, Alpert, & Waters, 1998). The anterior superior temporal gyrus (BA 38) is strongly interconnected with Broca's area through the uncinate fiber tract and is also implicated in syntactic processing (Hagoort, Brown, & Osterhout, 1999; Mazoyer et al., 1993; Vorob'ev et al., 1998). Finally, the prefrontal cortex (BA 10, 46) may be responsible for modulation of processing in posterior regions such as Wernicke's area (Frith, Friston, Liddle, & Frackowiak, 1991; Raichle et al., 1994) and/or for maintaining and manipulating verbal information in memory (Gabrieli, Desmond, Domb, Wagner, & et al., 1996; Jonides et al., 1997). We refer the reader to chapters in a recent edited book on the neural basis of language that presents a critical evaluation of recent brain imaging and lesion research of language processing that is largely consistent to the model outlined above (Hagoort et al., 1999; Price, Indefrey, & van Turenout, 1999).

Goals and Hypotheses of Current Study

There is an increasing number of fMRI studies examining cognitive processing in normal developmental populations including passive tasks (Souweidane et al., 1999), visual stimulation (Born et al., 1998; Martin et al., 1999; Yamada et al., 1997), auditory stimulation (Ulualp, Biswal, Yetkin, & Kidder, 1998, 2000), facial affect recognition (Baird et al., 1999), response inhibition (Casey et al., 1997; Rubia et al., 2000), spatial working memory (Nelson et al., 2000; Thomas et al., 1999), non-spatial working memory (Casey et al., 1995), verbal fluency (Gaillard

et al., 2000), silent word spelling (Lee et al., 1999), mental rotation and sentence processing (Booth, MacWhinney, et al., 1999; Booth et al., 2001). To our knowledge, no published fMRI research has addressed developmental differences in patterns of brain activation in a normal population during both reading and oral-language processing. The goal of this project was to examine developmental changes common to four types of word judgment tasks and to compare results in the visual and auditory modalities. These four tasks separately emphasized orthographic, phonologic, semantic and syntactic processing. The use of two modalities allowed us to determine whether these processes utilized the same brain structures in reading and oral-language.

Our general hypothesis was that developmental changes in the neural substrate of auditory and visual word recognition should be associated with increasing specialization. Our first assumption was that specialized processing should be performed in secondary brain regions where neural assemblies encode *unimodal* word forms in the visual modality (BA 18, 19, and posterior 37) and in the auditory modality (BA 42 and surrounding 22). We did not expect word forms to be represented in the primary sensory areas (BA 17 for the visual modality and BA 41 for the auditory modality) because these areas are responsible for the encoding of low-level information. Our second assumption was that brain regions responsible for specialized processing should show little overlap in activity with other distinct processes such as processing written versus spoken word forms. We did not expect specialized processes in tertiary areas, because these areas have many overlapping anatomical projections from different brain regions (Kolb & Wishaw, 1996) and are *heteromodal* areas responsible for the integration of multiple sources of information (Mesulam, 1998). These heteromodal areas include brain regions in Wernicke's area (BA posterior 22), in the angular and supramarginal gyrus (BA 39, 40), and along the inferior frontal gyrus (BA 9, 46) including Broca's area (BA 44, 45, 47).

Our first goal was to examine developmental differences in the patterns of brain activation during oral-language and reading. In the visual

modality, we expected adults to show more activation in the unimodal visual areas of fusiform gyrus (BA 19, 37) that are responsible for processing written word forms. In the auditory modality, we expected adults to show more activation in the unimodal auditory areas of superior temporal gyrus (BA 22), because this area has been implicated in processing spoken word forms. For the visual modality, we expected children to show more activation in heteromodal regions of Wernicke's area (BA posterior 22) that are hypothesized to function in the integration of visual and auditory forms. However, we expected to find fewer developmental differences centered about Wernicke's area in the auditory modality because oral-language is acquired earlier than reading. Our second goal was to examine the overlap in activation between reading and oral-language in children and adults. We expected children to have substantial overlap between the visual and auditory language tasks because children have not fully developed specialized networks for reading. In contrast, we expected adults to show selective activation in the unimodal auditory areas of superior temporal gyrus (BA 22, 42) when processing spoken word forms and selective activation in the unimodal visual areas of fusiform gyrus (BA 19, 37) when processing written word forms.

METHOD

Subjects

There were two subject groups: four ($N = 4$) male right-handed adults ($M = 25.5$, range = 22–31 years) and five ($N = 5$) male right-handed children ($M = 11.1$, range = 9.8–12.6 years). The children were recruited from private and public schools in the metropolitan Chicago area. The adults were undergraduate or graduate students at Northwestern University.

Standardized Measures

All children were administered a battery of standardized intelligence (Wechsler, 1991), oral-language (Dunn & Dunn, 1981; Semel & Wiig, 1994) and reading tests (Wiederholt & Bryant, 1967; Wilkinson, 1993; Woodcock, 1987). All children had normal intelligence, reading achievement and oral-language

processing. We defined normal range as within 1 *SD* below or 2 *SD* above the average standard-score of 100. Adults were also given an informal interview to ensure that they did not have a history of intelligence, reading, or oral-language deficits.

Questionnaires and interviews were also given to the adults and the parents of children to determine developmental and medical history. The following exclusionary criteria were used: (1) poor educational opportunities; (2) non-English or bilingual backgrounds; (3) neurological disease or seizures; (4) severe pregnancy or birth complications; (4) significant head injury – head trauma with loss of consciousness; (5) DSM-IV Axis I or II psychiatric disorders (American Psychiatric Association, 1994); (6) Attention Deficit Hyperactivity Disorder (Barkley & Murphy, 1998); (7) chronic substance abuse; (8) speech articulation problems; (9) uncorrected visual impairment or significant hearing impairment; (10) left-handedness (Denckla, 1985; Olfield, 1971); and (11) medication affecting central nervous system processing.

Functional Activation Tasks

Orthographic and Phonologic Tasks

In the orthographic task, subjects determined whether the final word had the same *rime* spelling as either of the first two words. The rime included all letters after the first consonant or consonant cluster (Bowey, 1990). In the phonologic task, subjects determined whether the final word *rhymed* with either of the first two words. For both the orthographic and phonologic task, half of the target trials contained two words that rhymed and were orthographically similar (i.e., had the same rime). The other half consisted of words that rhymed but were orthographically dissimilar (see Table 1). Note that for the dissimilar pairs in the orthographic task subjects had to determine that two words were spelled differently despite their sounding the same. The orthographic task in the auditory modality required access of orthographic forms and the phonologic task in the visual modality required the access of phonologic forms. The orthographic task in the visual modality and the phonologic task in the auditory modality did not require access to the phonologic and orthographic forms, respectively.

Semantic Task

Subjects determined whether a final word was associated in meaning with one of two preceding words. Half of the related pairs had a high association and half of the pairs had a low association (Nelson, McEvoy, & Schreiber, 1994). The mean free association value for the high associates ($M = 0.59$) was greater than the value for the low associates ($M = 0.27$).

Table 1. Examples of Stimuli For the Word Judgment Tasks.

	Type	
<i>Orthographic</i>	Similar orthography	Dissimilar orthography
First match	hold – plant – cold	hope – colt – soap
Second match	built – vote – note	boil – nest – blessed
<i>Phonologic</i>	Similar orthography	Dissimilar orthography
First match	seat – fresh – heat	jazz – last – has
Second match	wish – fall – wall	myth – home – foam
<i>Semantic</i>	High association	Low association
First match	frame – gain – picture	hate – wire – like
Second match	got – left – right	input – boots – cowboy
<i>Syntactic</i>	First-second violation	Second-third violation
	girls – was – swimming	boys – could – running
	student – have – jumped	mother – had – clever

Syntax Task

Subjects determined whether the combination of the second word with the third word was grammatically correct in relation to an animate noun (first word). Half of the animate nouns were plural and half were singular. Both auxiliary verbs (*is, are, was, were, has, have, had*) and modal auxiliaries (*can, could*) were included in the second word position. The following verb tense forms were used for the third word: regular past tense *-ed*, third person plural *s* and progressive *-ing*. In addition, 25% of the third words were adjectives. In order for these to be grammatical they must be paired with the copula forms of *be*. Adjectives were included to make the syntactic task comparable to the other word level tasks, that is so that they had the same percentage of nouns, verbs and adjectives.

Response Characteristics

For the orthographic, phonologic and semantic tasks, half of the correct trials involved a match to the first stimulus (first match) and half involved a match to the second stimulus (second match). If there was a match, they pressed a button with their index finger. If there was no match, they pressed a different button with their middle finger. The non-matching trials (40%) involved three orthographically different words that were non-rhyming and semantically unrelated. The syntactic task was structured in a slightly different manner. For the 40% ungrammatical trials, one third of these trials involved an error in grammar between the first and second words (“noun-based morphology”) and two-third involved an error in grammar between the second and third words (“verb-based morphology”). They pressed one button with their index finger if the phrase was grammatical and a different button with their middle finger if the phrase was ungrammatical. We realize that the grammaticality judgment required a

decision based on the combination of words and therefore noun- and verb-based morphology were not clearly separated.

Stimulus Characteristics

The word judgment tasks controlled for several characteristics. First, the different tasks consisted of words with similar frequency (Kucera & Francis, 1967). Second, no homophones were included in the experimental lists. Third, the word judgment tasks contained about the same number of nouns (55–65%), verbs (25–35%) and adjectives (10–20%) based on their most frequent usage in the Oxford English Dictionary. This was important to control because nouns and verbs may be associated with distinct neural systems (Daniele, Giustolisi, Silveri, Colosimo, & et al., 1994).

Visual Word Judgment Tasks

Each word reading task lasted 9 min consisting of 10 blocks of 54 s (including a 4-s single-word introduction screen to each block). The 5 experimental blocks alternated with the 5 control blocks. In each trial, three consecutive words were presented in lowercase letters with each word presented for 800 ms followed by a 200 ms blank interval. A yellow fixation cross (+) appeared on the screen after the third stimulus was removed, indicating the need to make a response during the subsequent 2000 ms interval. Subjects were told that they could respond before the yellow cross (+) appears on the screen. Each trial lasted a total of 5000 ms and there were 10 trials in each block.

Auditory Word Judgment Tasks

The auditory tasks involved a different list of stimuli, but were matched to the visual tasks in stimulus characteristics (see above). All stimuli for the auditory tasks were recorded in a soundproof booth using a

digital recorder and a high quality stereo microphone. A native Chicagoan female speaker read all words. Each word was read in isolation so that there were no contextual effects. Each word was digitized to 8-bits at a rate of 22.050 kHz. Individual files were created for each word and a 1 ms silence was added to the beginning and end of each word. All words longer than 800 ms were shortened to this duration (less than 1% of the words). All words were then normalized so that they were of equal amplitude. The stimuli were easily heard through the headphones in the 1.5 Tesla scanner.

During the auditory tasks, a white fixation cross (+) was presented during the experimental and control blocks (see below). As in the word reading task, a yellow fixation cross (+) appeared on the screen after the third stimulus was presented, indicating the need to make a response. Subjects were asked to fixate on the cross during the entire trial. This was done to prevent subjects from making large eye movements and therefore made the auditory data more comparable to the visual data. It is important to control for eye movement because studies show that eye movement control involves a distributed network in the brain (Sweeney et al., 1996).

Control Conditions

The control blocks for the visual and auditory tasks were designed to equate the experimental and control blocks in terms of their memory demands and response characteristics. The set-up and timing for the control blocks was exactly the same as for the word blocks.

For control blocks in the visual tasks, the three stimuli were abstract, *non-linguistic* symbols consisting of straight lines (see Table 2). Subjects determined whether the third stimulus was the same as one of the first two stimuli. Half of the correct trials involved a match to the first stimulus (first match) and half involved a match to the second stimulus (second match). The non-matching trials involved three different stimuli. All possible combinations were included in the matching and non-matching trials. As with the experimental blocks, 60% of the trials involved a match and 40% involve a non-match.

For control blocks in the auditory tasks, the three stimuli were high (700 Hz), medium (500 Hz) and low

frequency (300 Hz) *non-linguistic* pure tones. The tones were 600 ms in duration and contained a 100 ms linear fade in and a 100 ms linear fade out. Otherwise, the auditory control task was structured exactly like the visual control.

For all visual and auditory tasks, the presentation of trials in the experimental and control conditions that required 'yes' responses and those that required 'no' responses were randomized within a block. This was done with the constraint that no more than two 'no' responses occurred in a row and no more than two of each stimulus type within each task (orthographic similarity, semantic association and morphology) occurred in a row. The same pseudo-random order of presentation was used for each subject.

Experimental Procedure

After informed consent was obtained, participants were administered the battery of standardized measures (see above).

MRI Practice Session

The subject was acclimated to the scanner environment in a simulator (Rosenberg et al., 1997). The subject was slid on a mat into the open tube-like structure of the simulator. From this position, the subject was able to view a computer monitor about 40 cm directly above them. The subject then put on headphones and grasped a button box in their right hand. The experimenter played digitized sounds to familiarize the subject with the loud banging noise made by the MRI machine. After the subject seemed to be comfortable, the subject practiced a full-length version of each experimental task. Different stimuli were used in the practice and fMRI sessions.

MRI Data Acquisition

Head placement was secured with a specially designed vacuum pillow that allowed for the insertion of two earphones. An optical response button was placed in the subject's right hand and a compression ball was placed in the left hand. This ball was used to signal the operator to terminate the scan if the subject felt that this was necessary for any reason. The head coil was positioned over the subject's head and a mirror system for the visual presentation of stimuli was secured to the head coil. Each imaging session took less than 1 hr.

All images were acquired using a 1.5 Tesla scanner. The orientation of all images was transaxial angled to incorporate the anterior commissure and the posterior commissure (AC-PC line). For the functional imaging studies, a susceptibility weighted single-shot EPI (echo planar imaging) method sensitive to BOLD (blood oxygenation level-dependent) contrast was used. The following scan parameters were used: TE = 40, flip

Table 2. Examples of Stimuli for Control Tasks in the Visual and Auditory Modality.

	Modality	
	Visual	Auditory (Hz)
First match	/\ - \ \ - / \	300-500-300
Second match	// - \ \ - \ \	500-700-700

angle = 90°, matrix size = 64×64, field of view = 22 cm, slice thickness = 4 mm, number of slices = 32. The signal was allowed to equilibrate over five initial volumes that were excluded from the analyses. These scanning parameters resulted in a 3.437×3.437×4 mm voxel size. The acquisition of this volume was repeated every 3 s (TR = 3000 ms) for a total of 9 min per run. At the end of the functional imaging session, a high resolution, T1 weighted 3D image was acquired (3D FLASH, TR = 15 ms, TE = 6 ms, flip angle = 20°, matrix size = 256×256, field of view = 22 cm). One hundred sixty 1 mm 3D partitions were acquired in the slice direction. These scanning parameters resulted in a .86×.86 1 mm voxel size. The acquisition of the anatomical scan took 7 min.

Image Data Analysis

Data analysis was performed using SPM-96 (Statistical Parametric Mapping) for motion correction and statistical inference (Friston, Ashburner, et al., 1995; Friston, Holmes, et al., 1995; Friston, Jezzard, & Turner, 1994).

The functional images were realigned to the last functional volume in the scanning session using sinc interpolation. No individual runs (orthographic, phonologic, semantic or syntactic) had more than 4 mm maximum displacement (less than the voxel size) for any subject in the *x*-plane ($M = 0.27$, range = .00–1.52), *y*-plane ($M = 0.65$, range = .00–1.29), or *z*-plane ($M = 0.94$, range = .00–3.85). Furthermore, no individual runs had more than 4.5° of maximum displacement in rotation for pitch ($M = 1.2$, range = 0.1–4.4), yaw ($M = 0.5$, range = 0.1–3.3), or roll ($M = 0.7$, range = 0.1–2.9). All statistical analyses were conducted on these movement-corrected images.

Images were normalized to the SPM stereotaxic template (12 linear affine parameters for brain size and position, 8 non-linear iterations and 2×2×2 nonlinear basis functions for subtle morphological differences). The normalization of children's brain to an adult template was justified because, in 9-year-old children, the cerebrum is 95% of adult size, the neocortex is 102% of adult size with established sulcal and gyral patterns, and white matter is 85% of adult size (Caviness, Kennedy, Bates, & Makris, 1997). The normalization of children and adult brains to the same template was necessary in order to conduct the statistical analyses between these groups. In addition, the normalization process simplifies reporting anatomic locations by using a standardized coordinate system. Each normalization procedure was examined to make sure that the subject's brain was not distorted due to the procedure. The normalized data were then spatially smoothed (7 mm isotropic Gaussian kernel). Data were also temporally smoothed with a 4 s Gaussian kernel (Worsley & Friston, 1995). Temporal smoothing was used in SPM96 to impose a known autocorrelation on

the time series data allowing for estimation of the degrees of freedom and statistical inference (Bullmore et al., 1996; Friston et al., 2000).

Statistical analyses were calculated on the smoothed data using a delayed boxcar design with a 6-s delay from onset of block in order to account for the lag in hemo-dynamic response. Statistics were also calculated with a high pass filter equal to 2 cycles of the experimental and control conditions (216 s) in order to remove signal drift, cardiac and respiratory effects, and other low frequency artifacts. We used global normalization to scale the mean of each scan to a common value in order to correct for whole brain differences over time.

All statistics were done through the use of contrasts. The significance of all contrasts was tested using a *t*-statistic for each voxel. The *t*-statistic was transformed to the unit normal distribution to give a Gaussian Field or *z*-statistic. All areas of activation reported in the manuscript were significant using $p < .001$ uncorrected. Furthermore, all voxels were contained in a cluster size of greater than 12 voxels in order to be considered significant. These significance criteria adequately controlled for Type I error because we hypothesized a priori regions of interest. These regions included the inferior frontal gyrus (Broca's area), the posterior superior to middle temporal gyrus (Wernicke's area) as well as the unimodal visual area of fusiform gyrus and the unimodal auditory area of superior temporal gyrus.

For the statistical analyses, data was first analyzed from individual subjects, and then analyzed for groups of subjects (children and adults). For individual subjects, the whole-brain volumes from all 5 experimental blocks in a task were contrasted with the 5 interleaved blocks of control trials. With 18 whole-brain volumes per block (each volume derived from 32 slices), this provided 90 experimental images to be compared with an equal number of control images for each subject. For individual subject analyses, we calculated 8 contrasts [experimental-control] for analysis of the four word judgment tasks (orthographic, phonologic, semantic and syntactic) in the 2 modalities (visual and auditory). For each individual, we examined the activation patterns superimposed on the subject's normalized as well as actual brain to make sure that the normalization process, particularly in children, did not distort the statistics.

A fixed effect model was used to examine group differences between the children and adults and task differences between the visual and auditory modality. For the child versus adult comparison, we calculated children [experimental-control] minus adults [experimental-control] activation maps for each word judgment task. This contrast produced a map showing those regions activated significantly more in children than adults. We

then calculated the opposite analysis for adults [experimental-control] minus children [experimental-control]. Finally, we compared overlap in activation between adults and children by calculating a conjunction analysis on children [experimental-control] and adults [experimental-control]. This analysis produced a map of areas that are significantly activated to the same degree in adults and children. When comparing activation between adults and children, the activation of each group was weighted to compensate for unequal numbers of participants between groups. For the visual versus auditory comparison, we calculated visual [experimental-control] minus auditory [experimental-control] activation maps for each word judgment task separately for the children and adults. We then calculated the opposite analysis for auditory [experimental-control] minus visual [experimental-control]. Finally, we compared overlap in activation between visual and auditory by calculating a conjunction analysis on visual [experimental-control] and auditory [experimental-control].

RESULTS

Behavioral Performance in Visual and Auditory Word Processing

Table 3 presents accuracy and reaction time data for adults and children on the experimental tasks. Accuracy and reaction time were collapsed across the practice and test sessions because there were no significant differences and because this allowed for a more reliable measure of each subject's performance. We calculated an age (children, adults) by

task (orthographic, phonologic, semantic, syntactic) ANOVA separately for the visual and auditory modalities. Overall, children had significantly lower accuracy levels than adults in the visual, $F(1, 7) = 23.54, p < .001$, and auditory modalities, $F(1, 7) = 6.26, p < .05$, but reaction times were not significantly different between adults and children. There was no effect for task or interaction between age and task for accuracy or reaction time in either the visual or auditory modality.

There were no significant age differences in accuracy or reaction time for the visual control tasks; however, children had significantly lower accuracy levels than adults on the auditory control task, $F(1, 7) = 14.82, p < .001$. Furthermore, there were no significant differences in performance between the word judgment tasks and the control tasks. This is important because the activation patterns during the word judgment tasks cannot be attributed to a general difficulty difference between the experimental and control tasks.

Developmental Differences in Visual Word Processing

Although there were some significant differences, the four visual word judgment tasks produced a similar overall pattern of results, suggesting that the reported developmental differences were general aspects of language processing. Figure 1 presents maps showing significantly more activa-

Table 3. Means (*M*) and Standard Errors (*SE*) for Accuracy (%) and Reaction Time (RT in ms) for Children and Adults in the Four Word Judgment Tasks (and Control Tasks) in the Visual and Auditory Modality.

	Children				Adults			
	Accuracy		RT		Accuracy		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>
<i>Visual</i>								
Orthographic	82.8	3.8	1683	103	92.7	3.3	1440	108
Phonologic	90.3	3.3	1625	135	95.2	1.0	1451	147
Semantic	89.9	2.7	1727	87	90.9	3.3	1666	126
Syntactic	89.4	3.1	1609	89	95.9	1.5	1429	150
Control	88.3	2.3	1356	113	89.1	5.4	1450	159
<i>Auditory</i>								
Orthographic	74.8	5.9	1715	76	93.6	1.0	1694	32
Phonologic	85.4	5.3	1601	85	95.0	2.5	1507	92
Semantic	83.1	4.0	1663	43	97.3	0.9	1683	48
Syntactic	82.6	3.6	1499	86	95.8	2.6	1526	69
Control	81.9	5.4	1541	93	95.4	2.2	1443	95

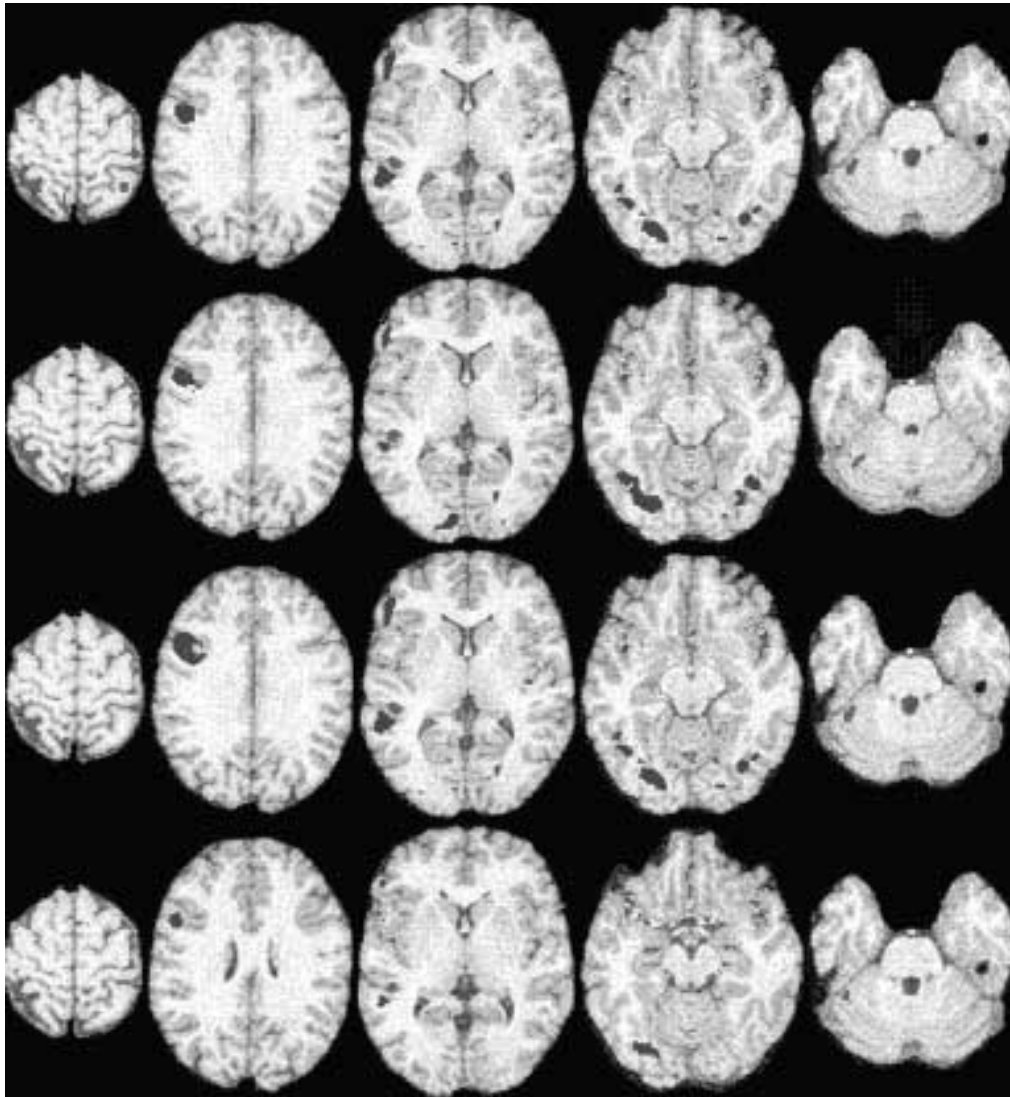


Fig. 1. Activation maps for developmental differences in the orthographic (1st row), phonologic (2nd row), semantic (3rd row) and syntactic tasks (4th row) for the visual modality. The columns from left to right correspond to Z coordinates +60, +28, +4, -8 and -32. Representative slices were chosen to show maximal activation for both the children and the adults. Green indicates significantly more activation in children, red indicates significantly more activation in adults and purple indicates equal activation in children and adults. The left side of the brain is on the left.

tion for children, significantly more activation for adults, and overlap of significant activation for children and adults. See Appendix A for a full listing of the significant activation sites for the four visual tasks for the adults and children. The Appendix presents both number of voxels and z-score for each area of activation because number

of voxels is highly dependent on the significance threshold.

Adults and children activated a similar network involving the inferior frontal gyrus (BA 45, 9) and the middle temporal gyrus (BA 22) in the left hemisphere. Both groups also bilaterally activated the middle occipital gyrus and the lingual

gyrus (BA 18, 19). However, the adults showed statistically more activation in the middle temporal and fusiform gyri (BA 19, 37), primarily in the left hemisphere. In contrast, children showed statistically more activation in the posterior superior temporal gyrus in the left hemisphere (BA 22), in the superior parietal lobule (BA 7), in the post-central gyrus (BA 5) in both hemispheres and in the cerebellar tonsil of the posterior lobe of the cerebellum.

Developmental Differences in Auditory Word Processing

Although there were some significant differences, all auditory tasks activated a similar network of brain regions (see Fig. 2 and Appendix B). The activation patterns were similar for children and adults, with activation for both groups involving the inferior frontal gyrus (BA 45, 9), the superior temporal gyrus (BA 22) and the middle temporal gyrus (BA 21, 39), all in the left hemisphere. However, one developmental difference was consistent across all four oral-language tasks. Adults showed significantly more activation in the superior temporal gyrus (BA 22, 42).

Modality Differences in Word Processing for Children

Figure 3 displays activation maps for modality differences among children, distinguishing areas with significantly more activation for the visual modality, significantly more activation for the auditory modality and statistically equal activation for the visual and auditory modalities. The children showed equal activation across modalities in the inferior frontal gyrus (BA 44, 45, 47, 9), the superior temporal gyrus (BA 22, 38), the middle temporal gyrus (BA 22, 39), the supramarginal gyrus (BA 40), the middle occipital and lingual gyri (BA 18, 19), and the middle temporal and fusiform gyri (BA 19, 37). The selective activation of unimodal areas among children was limited to a small portion of the superior temporal gyrus (BA 22) for the auditory modality.

Modality Differences in Word Processing for Adults

In contrast to the children, the adults showed selective activation of unimodal areas for spoken

word forms and for written word forms across all word judgment tasks (see Fig. 4). The adults showed significantly more activation for the visual modality in the middle occipital and lingual gyri (BA 18, 19) and the middle temporal and fusiform gyri (BA 19, 37). The adults also showed significantly more activation for the auditory modality in the superior temporal gyrus (BA 22, 42). The adults showed overlap between the modalities in the inferior frontal gyrus (BA 45, 46, 9), the superior temporal gyrus (BA 22), the middle temporal gyrus (BA 21, 22, 39) and the supramarginal gyrus (BA 40).

Individual Variance in Patterns of Activation

To examine individual differences, we defined regions of interest in the left hemisphere in which there was a significant developmental or modality difference. These regions of interest included the following center points: fusiform gyrus ($x = -44$, $y = -56$, $z = -8$), heteromodal superior temporal gyrus ($x = -52$, $y = -29$, $z = 4$) and unimodal superior temporal gyrus ($x = -64$, $y = -22$, $z = 12$). The mean and standard error were calculated for number of voxels and for intensity of the activation (z -score) in each region of interest separately for children and adults and separately for the visual and auditory modality. We also calculated the percentage of participants that showed reliable activation and the percentage of paradigms across subjects that showed reliable activation in each region of interest (see Table 4). All calculations were done separately for each task (orthographic, phonologic, semantic and syntactic). All tasks showed similar effects, and therefore, the data is only presented for age and modality. We had 16 (4 participants in 4 tasks) data points for each modality for the adults and 20 (5 participants in 4 tasks) data points for each modality for the children. Activation was included in the region of interest calculation if the area of activation lay within 2 voxels (12 mm) from the center points defined above.

Differences in activation patterns among individual children or adults did not affect the general conclusions reported on developmental differences. First, a larger percentage of visual paradigms in children showed a larger area of more intense activation in heteromodal superior tem-

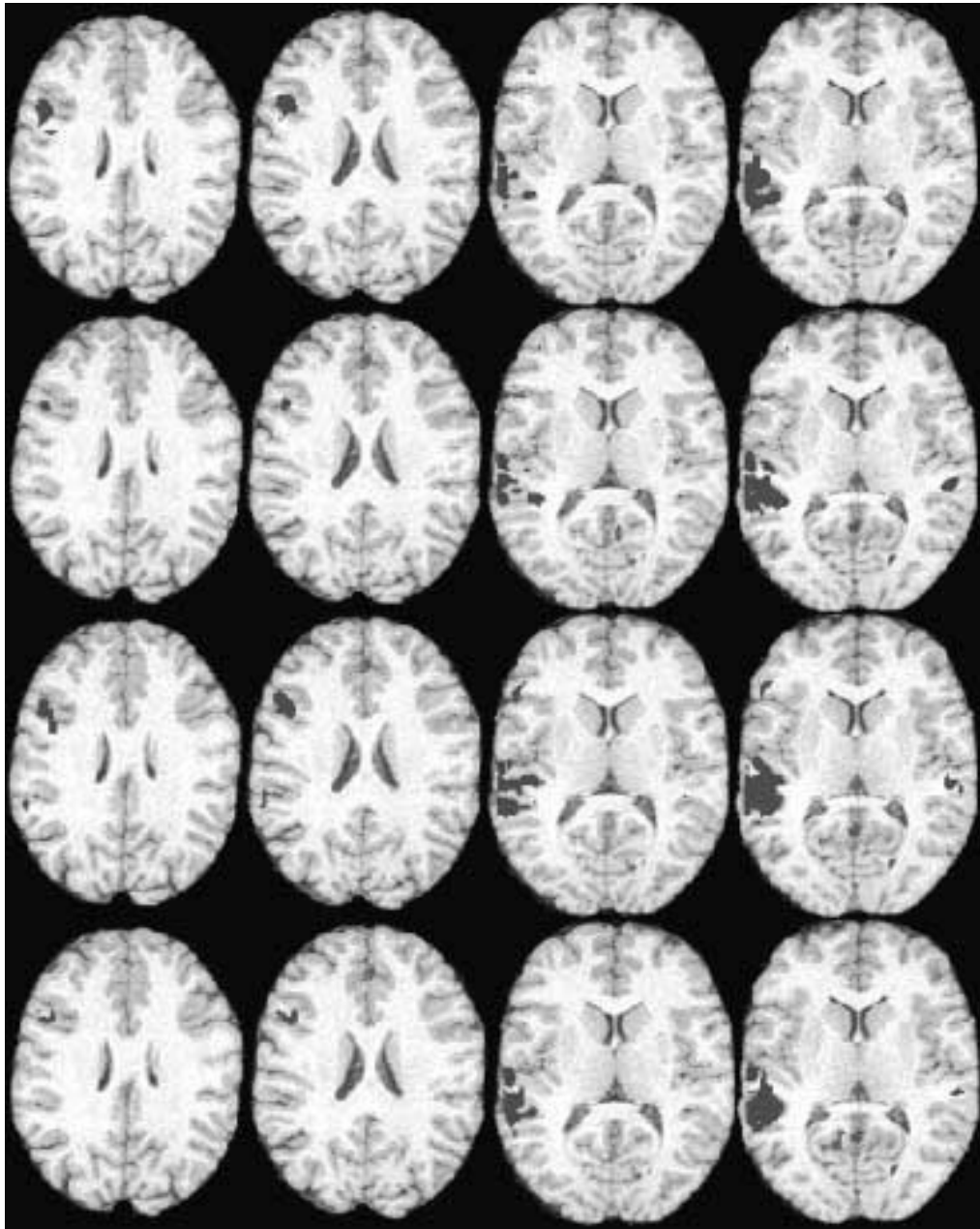


Fig. 2. Activation maps for developmental differences in the orthographic (1st row), phonologic (2nd row), semantic (3rd row) and syntactic tasks (4th row) for the auditory modality. The columns from left to right correspond to Z coordinates +24, +20, +12 and +8. Green indicates significantly more activation in children, red indicates significantly more activation in adults and purple indicates equal activation in children and adults. The left side of the brain is on the left.

poral gyrus as compared to adults. Second, a larger percentage of visual paradigms in adults showed a larger area of more intense activation in

the fusiform gyrus as compared to children. Third, a larger percentage of visual paradigms in children showed a larger area of more intense

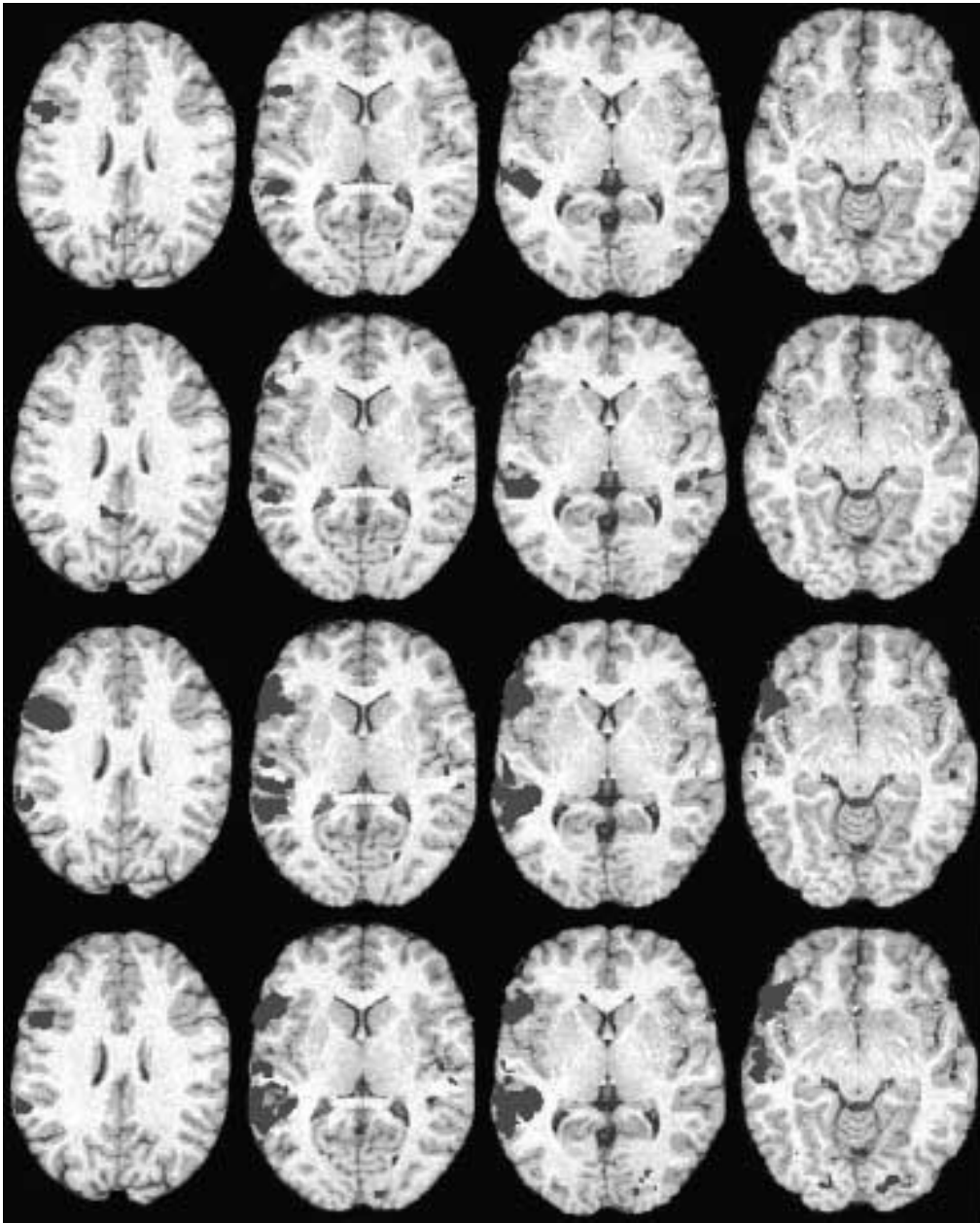


Fig. 3. Activation maps for modality differences for children in the orthographic (1st row), phonologic (2nd row), semantic (3rd row) and syntactic tasks (4th row). The columns from left to right correspond to Z coordinates +24, +12, +4 and -8. Green indicates significantly more activation in the visual modality, red indicates significantly more activation in the auditory modality and purple indicates equal activation in the visual and auditory modality. The left side of the brain is on the left.

activation in unimodal superior temporal gyrus as compared to adults. Overall, these results show that the developmental differences reported above

are not due to single individuals and that the results are representative of the children and adults as a whole.

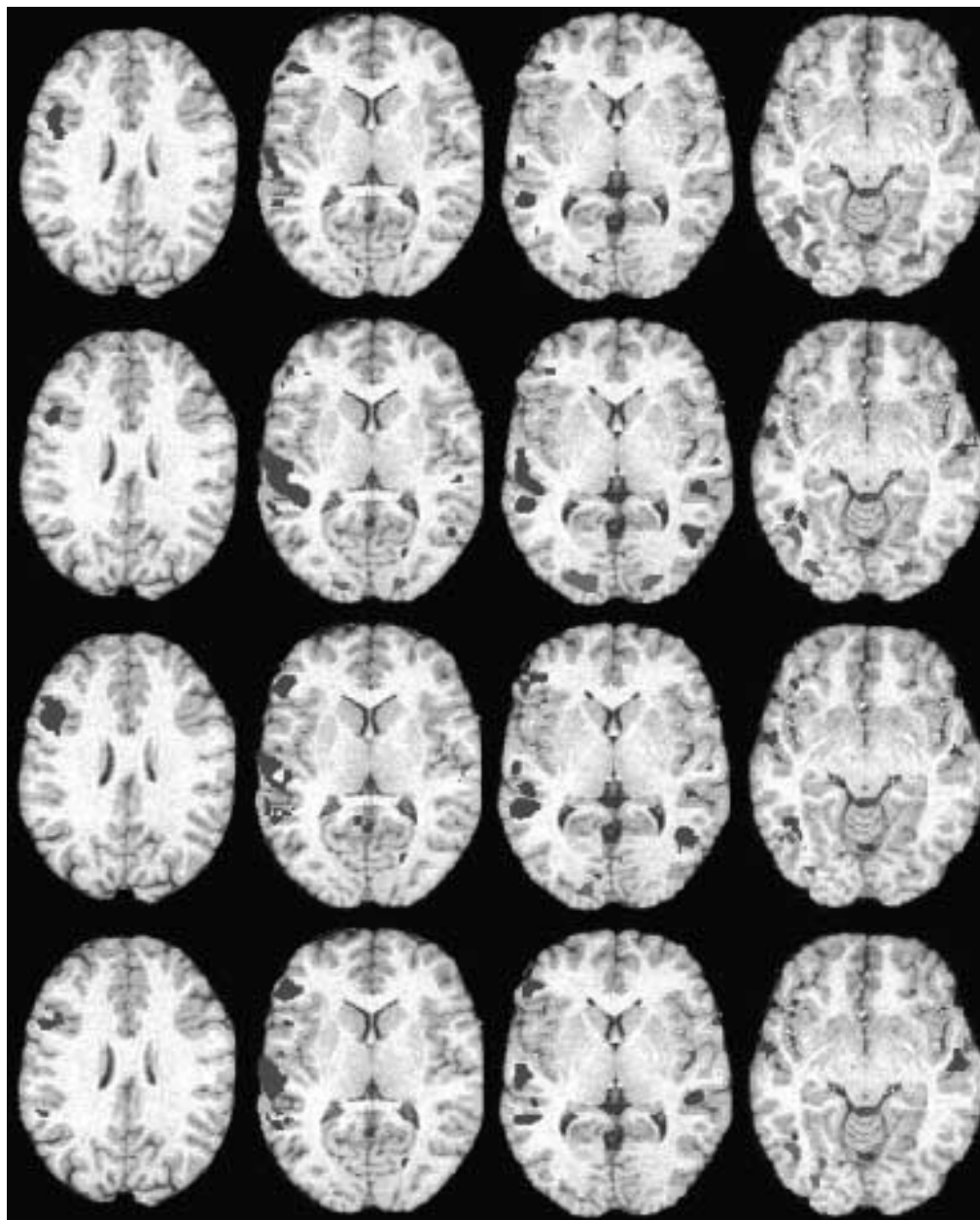


Fig. 4. Activation maps for modality differences for adults in the orthographic (1st row), phonologic (2nd row), semantic (3rd row) and syntactic tasks (4th row). The columns from left to right correspond to Z coordinates +24, +12, +4 and -8. Green indicates significantly more activation in the visual modality, red indicates significantly more activation in the auditory modality and purple indicates equal activation in the visual and auditory modality. The left side of the brain is on the left.

Table 4. Means (*M*) and Standard Errors (*SE*) for Total Number of Voxels and Maximum *z*-Score, and Number of Participants (*N*) Showing Activation in At Least One Paradigm (Orthographic, Phonologic, Semantic or Syntactic), and Total Percentage (%) of Paradigms Across Participants Showing Activation. Data are Presented Separately for Children and Adults and for the Visual and Auditory Modality. All Regions of Interest are in the Left Hemisphere (Fusiform Gyrus, Heteromodal Superior Temporal and Unimodal Superior Temporal).

	Children						Adults					
	Visual			Auditory			Visual			Auditory		
	<i>M</i>	<i>SE</i>	<i>N</i> /%	<i>M</i>	<i>SE</i>	<i>N</i> /%	<i>M</i>	<i>SE</i>	<i>N</i> /%	<i>M</i>	<i>SE</i>	<i>N</i> /%
<i>Voxels</i>												
Fusiform	276	109	4/45	118	58	3/40	560	119	4/87	159	57	3/56
Hetero Temp	179	27	5/85	547	37	5/95	16	6	3/37	179	71	4/93
Uni Temp	147	36	4/50	545	38	5/95	2	2	1/12	361	83	4/75
<i>z-Score</i>												
Fusiform	3.28	0.83	–	2.45	0.71	–	6.08	0.63	–	3.58	0.85	–
Hetero Temp	5.52	0.58	–	7.74	0.16	–	1.77	0.60	–	6.94	0.47	–
Uni Temp	3.53	0.81	–	7.80	0.12	–	0.47	0.32	–	5.57	0.83	–

DISCUSSION

Summary of Results

Among adults, the visual word tasks in our study produced significantly more activation in unimodal visual areas, whereas the auditory word tasks produced significantly more activation in unimodal auditory areas. This result is consistent with other studies that suggest a different neural focus for the orthographic and phonologic lexicons in adults (Demonet, Wise, & Frackowiak, 1993; Howard et al., 1992; Petersen & Fiez, 1993; Zurif & Swinney, 1994). Our main hypothesis was that reading and oral-language processing become more specialized with development such that unimodal visual areas are more prominently activated when processing written word forms and unimodal auditory areas are more prominently activated when processing spoken word forms. Our results illustrated developmental differences consistent with this developmental hypothesis. Adults showed significantly more activation in the middle temporal and fusiform gyri during the reading tasks and more activation in the superior temporal gyrus during the oral-language tasks. The heavier reliance on these unimodal areas in adults suggests that they are more specialized at visual and auditory word recognition. Indeed, cognitive developmental research shows increasing automaticity in the processing of written word forms (Booth, Perfetti,

& MacWhinney, 1999). In addition, developmental differences tended to be smaller for the auditory than for the visual tasks. The more similar patterns of activation for children and adults in the auditory tasks may have resulted from children's relative proficiency in early-acquired oral-language. The more discrepant patterns of activation for children and adults in the visual modality may have resulted from children's relative lack of proficiency in reading.

Our results also showed that children exhibited significantly more activation during the processing of written word forms in the posterior heteromodal language region including Wernicke's area. This region is involved in integrating different sources of information and our assumption is that integrating different sources of information is a less specialized process. The posterior heteromodal region may be responsible for the integration of spoken and written word forms with arbitrary associations that give rise to meaning or semantics (Mesulam, 1998). The greater activation in this region is consistent with behavioral findings and computational models that show greater reliance on semantics in younger children (Plaut & Booth, 2000). Our hypothesis that children are less specialized than adults at processing reading and oral-language is further supported by the finding that children showed mostly overlap between the visual and auditory word judgment

tasks. In contrast, adults showed selective activation in the unimodal auditory areas of superior temporal gyrus when processing spoken word forms and selective activation in the unimodal visual areas of middle temporal and fusiform gyrus when processing written word forms.

Although these areas were not included in our regions of interest, our results also showed that children exhibited significantly more activation during the processing of written word forms in the superior parietal lobule and in the posterior cerebellum. The activation for children in the superior parietal lobe is consistent with the hypothesis that there may be a greater role for spatial attention in less skilled reading (Mesulam, 1990). The activation in cerebellum for children may be associated with the less automatic performance. Brain imaging studies with adults show either a reduction or shift in the focus of activation with increasing practice on verbal response selection and motor learning tasks (Raichle et al., 1994; van Mier, Tempel, Perlmutter, Raichle, & Petersen, 1998).

The four word judgment tasks produced a similar pattern of activation in the visual and in the auditory modality. There are several possible reasons for this. First, the tasks were carefully constructed to be similar in terms of stimulus characteristics (e.g., word frequency, part of speech) and response characteristics (i.e., determine relation of last word with previous two words). These experimental tasks were also similar by involving word recognition, and in addition, the control tasks were matched in difficulty and behavioral response requirements. Thus, differences in brain activation across tasks must be due to differences in the degree to which orthographic, phonologic, semantic, or syntactic processes are accessed, which may be reflected in subtle differences in brain activation. The sample size of subjects here is too small to be confident that the subtle differences in activation between tasks are real and meaningful, although we note an obvious trend for the semantic task to produce more activation in the inferior frontal gyrus in both the visual and auditory modality. This is consistent with other findings that suggest the involvement of the left prefrontal area with semantic search (Petersen, Fox, Posner, Mintun, & Raichle, 1988; Petersen, Fox, Snyder, & Raichle, 1990).

Maturation Differences

The developmental differences reported in this paper are likely due in part to maturational differences and not just differences in skill level, consistent with previous studies that show non-linear patterns of maturation into adolescence. There is an early proliferation of dendrites, axons and synapses until about 1 to 4 years and this is followed by a gradual decline in the number of synapses through adolescence (Huttenlocher, 1990; Huttenlocher & de Courten, 1987). There is also a rapid increase in glucose metabolism until about 4 years and then the gradual decrease in glucose metabolism from about 10 to 18 years (Chugani, 1998) and the decrease in gray matter from 4 years (Pfefferbaum et al., 1994). However, both the synaptogenesis and glucose metabolism data clearly show that the developmental changes are not uniform across cortical or subcortical structures (Chugani, Phelps, & Mazziotta, 1987; Huttenlocher & Dabholkar, 1997) and developmental changes in volume for cytoarchitecturally defined regions differ between the hemispheres (Uylings, Malofeeva, Bogolepova, Amunts, & Zilles, 1999). For example, the peak in synaptogenesis tends to occur earlier in primary brain areas (e.g., visual and auditory) than in heteromodal brain areas (e.g., prefrontal). The reduction in the number of synapses and reduced metabolism through adolescence is consistent with the hypothesis that cognitive functions are represented in more focal neural regions as development proceeds (Casey et al., 1997; Gaillard et al., 2000; Hertz-Pannier et al., 1997). However, this focalization will likely depend on the cognitive process examined and the region of the brain investigated.

Research also shows that cortical white matter increases until 20 years (Pfefferbaum et al., 1994) and myelination occurs throughout late childhood (Yakolev & Lecours, 1967). Interestingly, recent research has suggested that fronto-temporal white matter tracks in the left hemisphere show a prolonged maturation through adolescence and this may be associated with the development of sophisticated linguistic abilities (Paus et al., 1999). In sum, the development of neural systems may involve increasing specialization and a simultaneous improvement in the efficient trans-

mission of neural signals between regions through axon tracts. These hypotheses are consistent with computational models of language which suggest that early in learning there are weak and widespread connections between units and with development these connections become stronger and more specific (Harm & Seidenberg, 1999; Plaut & Booth, 2000). Taken together, the computational models are consistent with the biological work in suggesting that developing systems become more specialized but also more strongly interconnected.

Implications for Research on Reading Disorders

Most of the research that has examined individual or population differences in linguistic processing has been conducted on adults with reading disorders (Booth & Burman, 2001). Our developmental data provide some interesting contrasts with the results of this research. The most robust and consistent finding is that reading disability in adults is associated with decreased activity in the temporo-parietal area, a finding which has been interpreted to reflect an underdeveloped or inefficient posterior reading network (Rumsey et al., 1992, 1997). If reading disability reflects a developmental delay, one might predict that children, who are less skilled readers, should show less activation than adults in the temporo-parietal area. However, we found that children activate the heteromodal area of the superior temporal gyrus more than adults in the visual word judgment tasks. Children may require integrative processing in Wernicke's area to form specialized orthographic processing mechanisms in the unimodal visual areas of fusiform gyrus and specialized phonologic processes in the unimodal auditory areas of superior temporal gyrus. Adults with reading disorders may have failed at forming these systems because they did not have early integrative processing necessary to form specialized systems. The brain activation differences between children and adults in our study suggest that adult reading disorders do *not* simply reflect an arrested state of early development. This is consistent with recent research that suggests a genetic component to dyslexia (Fagerheim et al., 1999; Morris et al., 2000; Noethen et al., 1999), although there may be a larger genetic component

to certain forms of reading disorder (Castles, Datta, Gayan, & Olson, 1999). It may be that certain genes code for development of brain regions responsible for orthographic (visual) processing and other genes code for brain regions responsible for phonologic (auditory) processing.

Future Research on Brain Function

Future studies should examine how different brain regions are functionally correlated. Computational models, like distributed attractor network models, show us that information is represented in the strength of the connections within and between systems (Plaut & Booth, 2000), so a greater emphasis should be placed on examining functional as well as effective connectivity in neural systems. Structural equation modeling seems to be a potentially useful tool for testing anatomical models of the effective connectivity in fMRI data (Buechel, Coull, & Friston, 1999; Fletcher, Buechel, Josephs, Friston, & Dolan, 1999; Friston, Phillips, Chawla, & Buechel, 1999). Future studies should also examine the relationship of multiple behavioral measures (accuracy as well as reaction time) to patterns of brain activation. By establishing a relation between behavioral performance on the cognitive task and brain activation, we can distinguish between those areas that are critical for performing a task and those that are activated incidentally. Some research shows that, in certain tasks, differences in accuracy levels may reflect unique processing strategies and may be associated with alternative activation patterns for normal children (Booth et al., 2001) and children with autism (Ring et al., 1999). Parametric manipulations of task difficulty may be especially helpful in determining how neural activation is related to cognitive processing (Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Just, Carpenter, Keller, Eddy, & Thulborn, 1996). Finally, research should measure the same process in multiple ways and in different modalities in order to determine the generality of activation patterns.

CONCLUSION

The goal of this study was to examine the general hypothesis that development of reading and oral-

language is characterized by increasing specialization. Our specialization hypothesis was supported by developmental changes between children and adults in the intensity of activation and in the overlap of brain regions during word processing. Future studies should address developmental differences in the components of reading and oral-language and determine when patterns of activation in children approximate adult patterns.

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APPENDIX A

Significant activation for adults and children in the four tasks (orthographic, phonologic, semantic, syntactic) in the visual modality. H: left (L) or right (R) hemisphere. BA: Brodmann's areas. z -score: only greater than 4.5 presented. Voxels: number of voxels in significant area as determined by z -score. 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. Areas of activation within each task are sorted by Z coordinate.

	Location			Magnitude		Coordinates		
	Area	H	BA	z -score	Voxels	X	Y	Z
Adults								
<i>Orthographic</i>	Inferior frontal gyrus	L	9	5.44	35	-42	6	30
	Middle frontal gyrus	L	46	5.14	20	-48	39	15
	Fusiform gyrus	L	39	7.66	266	-45	-60	-12
	Fusiform gyrus	R	19	7.01	196	27	-81	-12
<i>Phonologic</i>	Middle frontal gyrus	L	9	6.11	156	-45	9	33
	Middle temporal gyrus	L	22	5.30	22	-54	-42	3
	Inferior frontal gyrus	L	45	5.10	47	-54	33	3
	Inferior temporal gyrus	L	37	7.54	353	-45	-60	-9
	Middle occipital gyrus	R	18	6.64	317	39	-81	-9
<i>Semantic</i>	Cuneus	R	18	5.59	33	21	-93	9
	Inferior frontal gyrus	L	46	6.49	366	-51	42	3
	Middle temporal gyrus	L	22	6.33	58	-54	-42	3
	Fusiform gyrus	L	37	7.14	273	-45	-60	-9
	Fusiform gyrus	R	37	6.14	176	45	-63	-15
<i>Syntactic</i>	Inferior frontal gyrus	L	46	4.86	70	-48	36	9
	Middle temporal gyrus	L	22	4.68	40	-54	-45	3
	Cuneus	L	18	5.29	18	-21	-96	0
	Inferior occipital gyrus	L	18	5.99	125	-30	-87	-3
Children								
<i>Orthographic</i>	Inferior frontal gyrus	L	44	5.58	278	-45	9	18
	Superior temporal gyrus	L	21	5.58	29	-48	-33	6
	Fusiform gyrus	L	18	5.93	308	-18	-87	-15
	Cerebellum	R	-	5.63	83	33	-81	-21
<i>Phonologic</i>	Superior frontal gyrus	-	6	6.41	64	0	-6	69
	Inferior frontal gyrus	L	9	6.49	114	-45	12	27
	Middle temporal gyrus	L	22	6.40	62	-51	-36	3
	Cerebellum	R	-	5.69	131	36	-78	-21
	Cerebellum	L	-	6.64	345	-33	-60	-30
<i>Semantic</i>	Inferior frontal gyrus	L	9	7.16	592	-39	12	24
	Middle temporal gyrus	L	22	7.44	146	-48	-36	3
	Fusiform gyrus	L	18	5.13	134	-18	-87	-15
	Cerebellum	R	-	6.14	77	36	-75	-21
	Cerebellum	L	-	7.17	103	-42	-51	-33
<i>Syntactic</i>	Middle temporal gyrus	L	22	7.13	129	-48	-36	0
	Middle frontal gyrus	L	10	5.14	46	-54	33	0
	Cerebellum	L	-	7.17	192	-39	-75	-24
	Cerebellum	R	-	6.75	53	36	-81	-24

APPENDIX B

Significant activation for adults and children in the four tasks (orthographic, phonologic, semantic, syntactic) in the auditory modality. See Appendix A for description.

	Location			Magnitude		Coordinates		
	Area	H	BA	z-score	Voxels	X	Y	Z
Adults								
<i>Orthographic</i>	Inferior frontal gyrus	L	9	6.72	97	-42	6	30
	Superior temporal gyrus	L	21	7.47	299	-63	-15	9
	Superior temporal gyrus	R	21	5.43	22	66	-15	0
	Cerebellum	L	-	5.46	24	-51	-57	-24
<i>Phonologic</i>	Superior temporal gyrus	L	21	8.04	382	-63	-15	9
	Superior temporal gyrus	R	21	5.07	91	66	-15	0
<i>Semantic</i>	Middle frontal gyrus	L	46	4.67	116	-45	24	24
	Superior temporal gyrus	L	21	7.76	457	-63	-15	9
	Superior temporal gyrus	R	21	5.54	71	66	-15	0
	Fusiform gyrus	L	37	5.07	34	-48	-63	-18
<i>Syntactic</i>	Middle frontal gyrus	L	46	5.70	52	-45	21	24
	Superior temporal gyrus	L	21	8.18	443	-63	-15	9
	Superior temporal gyrus	R	21	6.77	161	66	-15	0
Children								
<i>Orthographic</i>	Middle temporal gyrus	L	22	7.32	357	-60	-18	-3
	Middle temporal gyrus	R	22	5.87	52	63	-21	-9
	Middle occipital gyrus	L	37	5.73	47	-45	-69	-9
	Cerebellum	R	-	4.70	38	15	-72	-15
<i>Phonologic</i>	Middle temporal gyrus	L	22	7.14	367	-60	-21	-3
	Middle temporal gyrus	R	22	5.89	92	60	-21	-6
<i>Semantic</i>	Superior temporal gyrus	R	21	5.50	100	60	-30	9
	Inferior frontal gyrus	L	45	4.50	153	-54	33	3
	Middle temporal gyrus	L	22	7.60	536	-60	-21	-3
	Cerebellum	L	-	6.25	33	-42	-48	-33
<i>Syntactic</i>	Middle temporal gyrus	L	22	7.64	396	-60	-21	-3
	Middle temporal gyrus	R	22	5.59	96	63	-21	-3