ARTICLE IN PRESS

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Acta Psychologica xxx (2005) xxx–xxx

acta psychologica

www.elsevier.com/locate/actpsy

Development of letter-specific processing: The effect of reading ability

E. Darcy Burgund [a,*], Bradley L. Schlaggar [b], Steven E. Petersen [b]

[a] *Department of Psychology—MS 25, Rice University, P.O. Box 1892, Houston, TX 77251, United States*
[b] *Washington University School of Medicine, St. Louis, MO 63110, United States*

Received 6 September 2005; received in revised form 22 November 2005; accepted 26 November 2005

Abstract

During development, perceptual processing is tuned to inputs in the environment such that certain frequently encountered classes of stimuli are processed more effectively than similar comparison stimuli. Letters represent a class of stimuli that are encountered frequently in the environment, at least in literate cultures. Thus, the present study examined the development of letter-specific processing in children 6–19 years old by comparing the difference between performance on a letter-matching task and an unfamiliar non-letter-matching task in different subject groups. Results revealed an increase in letter-specific processing with development. Moreover, comparisons of letter-specific processing in groups of subjects matched either in age or reading ability indicate that the emergence of letter-specific processing is linked to increased reading skill, rather than increased age per se. Findings support theories of perceptual expertise, which suggest that skilled processing drives the specialization of perceptual mechanisms for certain classes of stimuli.

PsycINFO classification: 2323; 2340; 2820

Keywords: Development; Visual perception; Reading

---

[*] Corresponding author. Tel.: +1 713 348 3413; fax: +1 713 348 5221.
E-mail address: dburgund@rice.edu (E.D. Burgund).

0001-6918/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.actpsy.2005.11.005

1. Introduction

During development perceptual processing is tuned to inputs encountered most frequently in the environment. For example, speech perception is tuned during the first year of life to discriminate phonemes from the native language more effectively than phonemes from an unfamiliar language (Cheour et al., 1998; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992). Similarly, face perception is tuned to discriminate individual human faces better than individual monkey faces by 9 months of age (Pascalis, de Haan, & Nelson, 2002). Both speech and face processings are fundamentally important abilities for effective interaction with others in the environment. Even though reading is a relatively new cultural invention, it is an extremely important skill, both socially and economically, in the present day. In addition, as with faces, letters represent a 'special' class of visual objects with which (literate) humans have extensive experience (Cohen & Dehaene, 2004; McCandliss, Cohen, & Dehaene, 2003). Thus, it is possible that perceptual narrowing occurs in the domain of letter processing.

Perceptual specificity in letter processing may be observed behaviorally by comparing performance on tasks with letters to performance on tasks with non-letters (i.e., unfamiliar visual forms that are similar to letters). Not surprisingly, when adult readers are tested, these comparisons reveal improved performance on letter tasks compared to non-letter tasks (Ambler & Proctor, 1976; Jackson, 1980; Kim, 1996; LaBerge, 1973; van Leeuwen & Lachmann, 2004). Findings of this sort indicate that adult readers have achieved a certain degree of perceptual specificity, such that letters are processed more effectively than other similar visual forms. Developmental work on letter processing has demonstrated that children become faster (more accurate) at processing both letters (Henderson, 1974; Reitsma, 1978) and non-letters (Gibson, Gibson, Pick, & Osser, 1962) with age. In addition, some studies have observed improved performance for letters compared to non-letters in children as young as six (Miller & Wood, 1995; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). However, previous studies have not compared letter and non-letter processings at different ages directly; thus it is unclear whether children of different ages exhibit the same advantage for letters over non-letters as adults, or whether this perceptual specificity emerges with development.

Letter-specific processing could emerge with development for several reasons. Most obvious, perhaps, are experiental and neural changes that occur as children age. For one, the amount of exposure to letters relative to non-letters increases with age, at least in literate cultures, producing a greater difference in the number of exposures to letters compared to non-letters in older individuals than in younger individuals. In addition, general neurobiological changes that continue well into adulthood, such as increased myelination, widespread synaptic pruning, and elaboration (Courchesne et al., 2000; Giedd et al., 1999; Klingberg, Vaidya, Gabrieli, Moseley, & Hedehus, 1999; Pfefferbaum et al., 1994; Sowell et al., 1999), may lead to fundamental differences in the efficacy and quality of processing in older and younger individuals. Critically, if letter-specific processing emerges due to maturational factors, older individuals should exhibit a greater advantage for letters over non-letters than younger individuals.

Alternatively, it is possible that letter-specific processing is specifically related to increased reading ability, rather than increased age per se (McCandliss et al., 2003). In line with theories of perceptual expertise (Gauthier, Skudlarski, Gore, & Anderson, 2000; Tanaka & Curran, 2001; Tarr & Gauthier, 2000), this alternative suggests that mere exposure to letters is not enough to produce letter specialization; rather letters must be processed meaningfully, in the context of words and sentences for specialization to emerge. According to this hypothesis, individuals with more advanced reading abilities should exhibit a greater advantage for letters over non-letters than individuals with less advanced reading abilities, regardless of their age.

Of course, in the natural world increased reading ability is difficult to dissociate from increased age, given the two variables' extremely high correlation. In the laboratory, however, the effects of age and ability on letter-specific processing may be examined independently by comparing groups of subjects that differ on only one of the two dimensions. That is, the effect of age on letter-specific processing may be examined by comparing groups of subjects that differ in age but not reading ability. Similarly, the effect of reading ability on letter-specific processing may be examined by comparing groups of subjects that differ in ability but not age. Thus, the present study had two goals: (1) to assess the development of letter-specific processing in children of different ages, and (2) to examine the relative contributions of age and reading ability to the emergence of such perceptual specificity.

2. Method

2.1. Subjects

Sixty-seven volunteers between the ages of 6- and 19-year old from the Rice University community and surrounding area participated (see Table 1 and Appendix A). Except for a few of the oldest participants who received credit towards psychology courses taken at Rice, all subjects were compensated $10 for their participation. Subjects were native speakers of English, had normal or corrected-to-normal vision, and no known psychological or neurological deficits. Adult subjects and parents of child subjects gave informed consent, and child subjects gave assent, in accordance with the guidelines and approval of the Rice University Institutional Review Board.

2.2. Materials

Stimuli were pairs of letters and pairs of unfamiliar non-letters. Letters were taken from the entire Roman alphabet, excluding the letters 'm' and 'h', which were used for practice. The similarity of the letters within each pair was determined using measurements provided by Boles and Clifford (1989), and letter pairs were balanced in terms of these similarity

Table 1
Mean age, ability, and performance for 4 age groups

Group (*N*)	Male	Age	Ability	Response times (ms)		Error rates (%)	
				Letters	Non-letters	Letters	Non-letters
6–8 years (17)	10	7.8 ± 0.6	483 ± 20.6	1251 ± 155	1230 ± 197	11.6 ± 6.3	12.9 ± 9.9
9–12 years (16)	8	10.5 ± 1.1	497 ± 15.9	1056 ± 250	1079 ± 168	6.7 ± 5.6	8.0 ± 6.0
13–16 years (16)	8	14.4 ± 1.0	522 ± 8.8	865 ± 122	933 ± 152	3.9 ± 5.0	5.6 ± 5.5
17–19 years (18)	7	18.7 ± 0.8	535 ± 6.9	639 ± 84	705 ± 122	4.1 ± 3.1	5.6 ± 5.4

Note: *N* = total number of subjects in each group; male = number of male subjects in each group. Age values are in years; ability values reflect performance on the Woodcock Reading Mastery Test—Revised. ± = standard deviation.

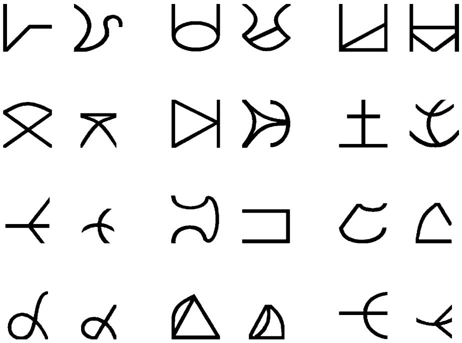

Fig. 1. Non-letters used in the present experiment.

measurements across the "same" and "different" response conditions. Unfamiliar non-letters were modeled after Gibson et al. (1962) and were similar to real letters in terms of size, number of lines (curved and straight; vertical and horizontal), and number of enclosed spaces (see Fig. 1). Twelve prototypes, plus a three-line variation of each prototype (Gibson et al., 1962) were used in the present study. Thus, unfamiliar pairs were created from a set of 24 letter-like forms (two versions of each of 12 prototypes). Half of the three-line variations were reduced in size, relative to their prototype, in order to approximate pairings of upper and lower case letters, which occurred in the letter-matching condition.

Letters were presented in 36-point, Times font. All stimuli were presented centrally, in white against a black background, and subtended approximately 0.5° of the widest (horizontal or vertical) visual angle individually. Pairs of letters (and non-letters) subtended approximately 2° in the horizontal dimension. A chin rest was employed to keep subjects' eyes approximately 32 cm from the monitor. Stimuli were presented on the video monitor of an iMac computer (Apple Computer, Inc., Cupertino, CA). Presentation rate and response-time measurement were controlled by the PsyScope software package (Cohen, MacWhinney, Flatt, & Provost, 1993).

Each matching task was comprised of 96 stimulus pairs, half of which were exactly the same and half of which were different. Particular pairings of letters or non-letters and their left–right positioning were counterbalanced across subjects.

2.3. Procedure

Subjects were tested individually in sessions that lasted approximately 45 min. At the beginning of the session, a measure of the subject's reading ability was obtained using the word identification, word attack, and passage comprehension subtests of the Woodcock Reading Mastery Test—Revised. The average of the scores from the three subtests was used as the measure of each subject's reading ability.

Immediately after the reading assessment, subjects performed the letter and non-letter-matching tasks, administered in different counterbalanced orders. In both tasks, pairs were presented for 500 ms each at intervals of 2.5 s, 5 s, and 7.5 s (average rate of 1 pair per 5 s). Irregular timing was used in order to reduce the predictability of stimulus onsets. A fixation cross (+) preceded each presentation and remained on the screen between stimulus trials. For each stimulus pair, subjects were instructed to decide whether items were exactly the same or different, and to indicate their response as quickly as possible by pushing a key on the keyboard. Subjects pushed one key with the index finger of their right (or left) hand to indicate a "same" response, and another key with the index finger of their left (or right) hand, to indicate a "different" response. The hand (left vs. right) used to indicate a "same" response was counterbalanced across subjects. Before each task, subjects were engaged in 12 practice trials to ensure that they understood the instructions.

3. Results

For each subject, a measure of "letter-specific processing" was computed by subtracting the letter from the non-letter score and dividing by the non-letter score ([non-letter score – letter score]/non-letter score), for both response times and error rates. The difference between letter and non-letter scores was proportionalized by non-letter scores in this manner to reduce spurious distortions of within-subject differences due to overall group differences (see Chapman & Chapman, 1973; Chapman, Chapman, Curran, & Miller, 1994). This difference score was the dependent measure used in all analyses. In addition, all analyses were performed using difference scores based on response times and on error rates. However, as none of the analyses of error rates produced significant results (all $ps > .114$), only results from the analyses of response-time difference scores are reported.

3.1. Development of letter-specific processing

The effect of age on letter-specific processing was assessed through two analyses—a one-way analysis of variance (ANOVA), in which age was treated as a categorical variable, and a correlation analysis, in which age was treated as a continuous variable. For the ANOVA, subjects were divided into four groups of roughly equivalent size based on age (see Table 1 and Appendix A). As shown in Fig. 2 (left panel), this analysis revealed a significant effect of age, $F(3,63) = 3.56$, $p = .019$, in which difference scores were greater in the 17–19 and the 13–16 years old groups than in the 6–8 years old group, $t(33) = 3.08$, $p = .004$ and $t(31) = 2.60$, $p = .014$, respectively, for the simple effect contrasts. Similar results were revealed by the correlation analysis (see right panel of Fig. 2). A positive relationship was observed between age and difference score, such that increases in age lead to a greater difference in the processing of letters compared to non-letters, $r = .36, p = .003$.

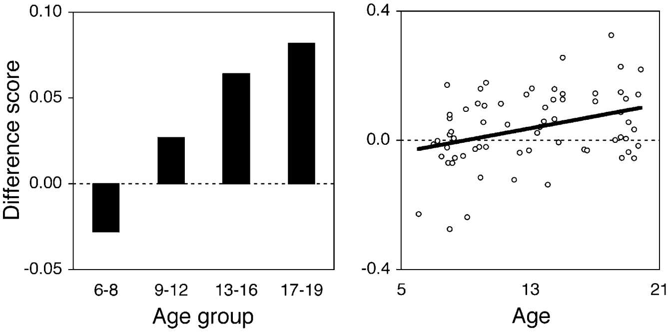

Fig. 2. Difference scores as a function of age. Scores represent the difference between response times during letter and non-letter trials (see text for further details).

4. Relative contributions of age and reading ability

To assess the relative contributions of age and reading ability to letter-specific processing, subjects were organized into "ability-matched" groups and "age-matched" groups (see Table 2 and Appendix A). Groups were created by a research assistant who was blind to the purpose of the study and did not have access to the performance data. Ability-matched groups were equated for reading ability, $t(30) = .21$, $p = .838$, yet differed significantly in age, $t(30) = 3.62$, $p < .0005$; age-matched groups were equated in age, $t(30) = .77$, $p = .446$, yet differed significantly in reading ability, $t(30) = 6.04$, $p < .0001$. For each of the two types

Table 2
Mean age, ability, and performance for ability-matched and age-matched groups

Group (*N*)	Male	Age	Ability	Response times (ms)		Error rates (%)	
				Letters	Non-letters	Letters	Non-letters
Ability matched							
Young (16)	8	9.5 ± 2.4	504 ± 18.9	1143 ± 224	1189 ± 184	7.9 ± 6.6	8.7 ± 6.7
Old (16)	9	13.1 ± 2.8	506 ± 17.1	871 ± 197	920 ± 177	5.4 ± 4.7	7.4 ± 3.8
Age matched							
Low ability (16)	9	10.7 ± 2.6	488 ± 17.2	1109 ± 246	1072 ± 185	8.7 ± 6.6	11.1 ± 10.1
High ability (16)	7	11.5 ± 3.0	519 ± 10.4	950 ± 221	1029 ± 233	5.9 ± 6.8	7.0 ± 6.4

Note: See note for Table 1.

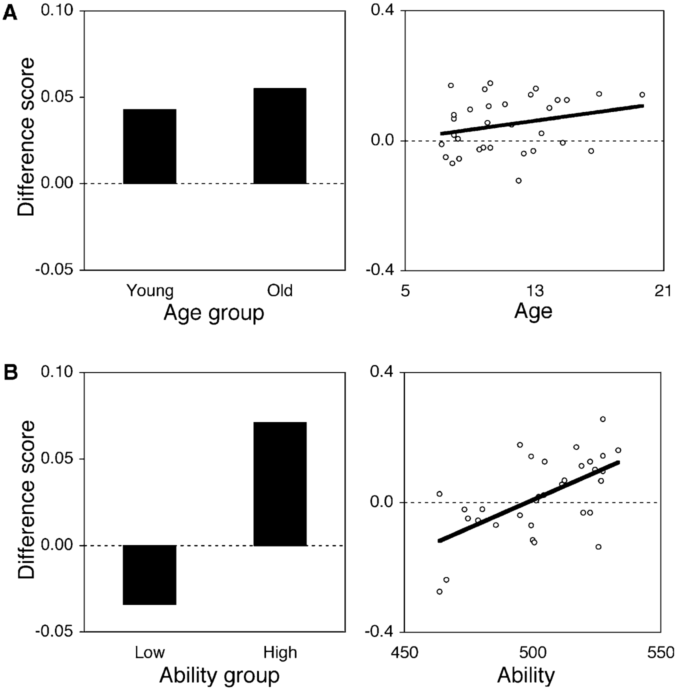

Fig. 3. Difference scores in ability-matched subjects as a function of age (A), and in age-matched subjects as a function of ability (B).

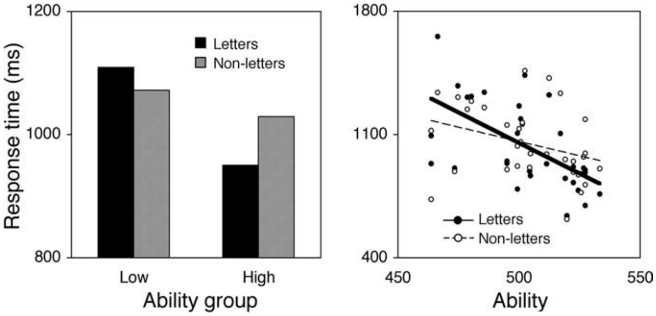

Fig. 4. Response times during letter and non-letter-matching tasks in age-matched subjects as a function of ability.

of groupings, a subset of the 67 subjects was selected independently; thus some subjects were included in both the ability and the age-matched groups (e.g., low ability and young age), while other subjects were not included in either (see Appendix A).

The effect of age on difference scores was tested in the ability-matched groups, and the effect of ability on difference scores was tested in the age-matched groups, using group-based and correlation analyses. Results are depicted in Fig. 3. Analyses of the ability-matched subjects did not reveal effects of age. Difference scores did not differ between the young and old age groups, $t(30) = .39$, $p = .699$ (left panel of Fig. 3A), nor were they significantly related to age, $r = .26$, $p = .156$ (right panel of Fig. 3A). In contrast, analyses of the age-matched subjects revealed effects of ability. Difference scores were greater in the high-ability group than in the low-ability group, $t(30) = 2.68$, $p = .012$ (left panel of Fig. 3B), and increased linearly with increased ability, $r = .60$, $p < .001$ (right panel of Fig. 3B).

Although statistics were not calculated for the raw letter and non-letter scores, Fig. 4 illustrates that the increase in difference scores for high compared to low-ability readers was due to a greater decrease in response times with ability for letters than for non-letters. This rules out the possibility that changes in difference scores with ability were due to changes in the processing of non-letters rather than changes in the processing of letters.

5. Discussion

The goal of the present experiment was to examine the emergence of letter-specific processing with development, and to assess the relative contributions of age and reading ability to this specificity. Results indicate that letter-specific processing emerges gradually with development, with the largest increases in specificity occurring between the ages of 8 and 13 years old. Moreover, results indicate that increased reading ability is a better predictor of increased letter-specific processing than increased age. Indeed, when subjects were equated in terms of reading ability, no difference in letter-specific processing between older and younger groups was observed. When subjects were equated in terms of age, however, high-ability readers exhibited greater letter-specificity than low-ability readers. Thus, results are in line with theories of perceptual expertise, which suggest that skilled processing, rather than maturation, drives the specialization of perceptual mechanisms for certain classes of stimuli (Gauthier et al., 2000; McCandliss et al., 2003; Tanaka & Curran, 2001; Tarr & Gauthier, 2000).

That perceptual narrowing for letters should involve skilled processing, rather than maturation, is not surprising given that letter recognition demands arbitrary mappings between symbols and meanings that are defined culturally (Cohen & Dehaene, 2004; McCandliss, Posner, & Givon, 1997; Polk & Farah, 1995, 1998). For example, efficient readers must map dissimilar looking inputs to the same output in order to generalize across different letter cases and fonts (e.g., A a ɑ). At the same time, however, efficient readers must map similar looking inputs to different outputs in order to discriminate between certain letters (e.g., O Q C). These contradictory goals cannot be achieved without explicit training of the system; thus the emergence of letter-specific processing should be closely linked to reading skill.

The particular computational problems posed by reading to the visual system have lead some researchers to argue for a neural region, located within the left occipital-temporal lobe, that is specialized for the processing of visual word forms (Cohen & Dehaene, 2004; Cohen et al., 2002; McCandliss et al., 2003; but see Price & Devlin, 2003). Critically, this 'visual word form area' is tuned preferentially to the shapes of letters compared to other similar shapes. Indeed, neuroimaging studies of skilled readers have revealed greater activity in this region for strings of letters compared to strings of digits (Polk et al., 2002) and strings of non-letters (Petersen, Fox, Snyder, & Raichle, 1990; Price, Wise, & Frackowiak, 1996). Moreover, studies observing less activity in the left occipital-temporal region in dyslexic subjects than in normally reading controls provide a link between activity in this region and reading ability (Shaywitz et al., 2002; Simos, Breier, Fletcher, Bergman, & Papanicolaou, 2000).

Results from the present study are in line with theories suggesting that preferential tuning for letters and words compared to less familiar stimuli within the left occipital-temporal 'visual word form area' is related to increased reading ability. It is important to note, however, that other brain regions related to perceptual processing have been implicated in the development of reading skill as well. In particular, the left temporal-parietal cortex exhibits less activity in dyslexic subjects than in normal-reading subjects during phonological decoding tasks (tasks at which dyslexic subjects are particularly impaired; Paulesu et al., 2001; Temple et al., 2001). Furthermore, activity in this region increases to normal levels in dyslexic subjects after extensive training and improved performance on phonological decoding tasks (Temple et al., 2003). These findings indicate a clear role for phonological decoding and the left temporal-parietal cortex in the development of reading skill. Thus, it is possible that results from the present study reflect changes in this region, in addition to changes in the putative 'visual word form area.' Indeed, mastery of the concept that written symbols are associated with phonemes is necessary for the development of skilled reading (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001).

In sum, results from the present study provide converging evidence for the role of reading skill in the progressive development of system(s) specialized for the processing of letters. In addition, results underscore the importance of separating increases in skill from maturational change when possible. Finally, results provide an example of perceptual tuning during development in response to culturally determined processing demands.

Acknowledgements

Support for this research was provided by the Social Sciences Division at Rice University. Thanks are owed to Sapphira Goradia and Rebecca Villarreal for assistance with data collection and analysis, and to David Balota for helpful discussions that lead to this work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.actpsy.2005.11.005.

References

Ambler, B. A., & Proctor, J. D. (1976). The familiarity effect for single-letter pairs. *Journal of Experimental Psychology. Human Perception and Performance, 2*, 222–234.

Boles, D. B., & Clifford, J. E. (1989). An upper- and lowercase alphabetic similarity matrix, with derived generation similarity values. *Behavior Research Methods, Instruments, and Computers, 21*, 579–583.

Chapman, L. J., & Chapman, J. P. (1973). Problems in the measurement of cognitive deficit. *Psychological Bulletin, 79*, 380–385.

Chapman, L. J., Chapman, J. P., Curran, T. E., & Miller, M. B. (1994). Do children and the elderly show heightened semantic priming. How to answer the question. *Developmental Review, 14*, 159–185.

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., et al. (1998). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience, 1*, 351–353.

Cohen, J. D., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: a new graphic interactive environment for designing psychology experiments. *Behavioral Research Methods, Instruments, and Computers, 25*, 257–271.

Cohen, L., & Dehaene, S. (2004). Specialization within the ventral stream: the case for the visual word form area. *NeuroImage, 22*, 466–476.

Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex. Functional properties of the visual word form area. *Brain, 125*, 1054–1069.

Courchesne, E., Chisum, H. J., Townsend, J., Cowles, A., Covington, J., Egaas, B., et al. (2000). Normal brain development and aging: quantitative analysis at in vivo MR imaging in healthy volunteers. *Neuroradiology, 216*, 672–682.

Gauthier, I., Skudlarski, P., Gore, J. C., & Anderson, A. W. (2000). Expertise for cars and birds recruits brain areas involved in face recognition. *Nature Neuroscience, 3*, 191–197.

Gibson, E. J., Gibson, J. J., Pick, A. D., & Osser, H. (1962). A developmental study of the discrimination of letter-like forms. *Journal of Comparative and Physiological Psychology, 55*, 897–906.

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., et al. (1999). Brain development during childhood and adolescence: a longitudinal MRI study. *Nature Neuroscience, 2*, 861–863.

Henderson, S. E. (1974). Speed of letter cancellation on the basis of visual and name identity in young children. *Journal of Experimental Child Psychology, 17*, 347–352.

Jackson, M. D. (1980). Further evidence for a relationship between memory access and reading ability. *Journal of Verbal Learning and Verbal Behavior, 19*, 683–694.

Kim, H. (1996). Qualitative hemispheric differences for processing trigrams. *Brain and Cognition, 30*, 205–214.

Klingberg, T., Vaidya, C. J., Gabrieli, J. D., Moseley, M. E., & Hedehus, M. (1999). Myelination and organization of the frontal white matter in children: a diffusion tensor MRI study. *NeuroReport, 10*, 2817–2821.

Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., & Lindblom, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science, 255*, 606–608.

LaBerge, D. (1973). Attention and the measurement of perceptual learning. *Memory and Cognition, 1*, 268–276.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Science, 7*, 293–299.

McCandliss, B. D., Posner, M. I., & Givon, T. (1997). Brain plasticity in learning visual words. *Cognitive Psychology, 33*, 88–110.

Miller, S. L., & Wood, F. B. (1995). Electrophysiological indicants of black–white discrimination performance for letter and non-letter patterns. *The International Journal of Neuroscience, 80*, 299–316.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science, 296*, 1321–1323.

Paulesu, E., Demonet, J. F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N., et al. (2001). Dyslexia: cultural diversity and biological unity. *Science, 291*, 2165–2167.

Petersen, S. E., Fox, P. T., Snyder, A. Z., & Raichle, M. E. (1990). Activation of extrastriate and frontal cortical areas by visual words and word-like stimuli. *Science, 249*, 1041–1044.

Pfefferbaum, A., Mathalon, D. H., Sullivan, E. V., Rawles, J. M., Zipursky, R. B., & Lim, K. O. (1994). A quantitative magnetic resonance imaging study of changes in brain morphology from infancy to late adulthood. *Archives of Neurology, 51*, 874–887.

Polk, T. A., & Farah, M. J. (1995). Brain localization for arbitrary stimulus categories: a simple account based on Hebbian learning. *Proceedings of the National Academy of Sciences (USA), 92*, 12370–12373.

Polk, T. A., & Farah, M. J. (1998). The neural development and organization of letter recognition: evidence from functional neuroimaging, computational modeling, and behavioral studies. *Proceedings of the National Academy of Sciences (USA), 95*, 847–852.

Polk, T. A., Stallcup, M., Aguirre, G. K., Alsop, D. C., D'Esposito, M., Detre, J. A., et al. (2002). Neural specialization for letter recognition. *Journal of Cognitive Neuroscience, 14*, 145–159.

Price, C. J., & Devlin, J. T. (2003). The myth of the visual word form area. *NeuroImage, 19*, 473–481.

Price, C. J., Wise, R. J. S., & Frackowiak, R. S. J. (1996). Demonstrating the implicit processing of visually presented words and pseudowords. *Cerebral Cortex, 6*, 62–70.

Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science in the Public Interest, 2*, 31–74.

Reitsma, P. (1978). Changes in letter processing in beginning readers. *Child Psychology, 25*, 315–325.

Shaywitz, B. A., Shaywitz, S. E., Pugh, K. R., Mencl, W. E., Fulbright, R. K., Skudlarski, P., et al. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry, 52*, 101–110.

Simos, P. G., Breier, J. I., Fletcher, J. M., Bergman, E., & Papanicolaou, A. C. (2000). Cerebral mechanisms involved in word reading in dyslexic children: a magnetic source imaging approach. *Cerebral Cortex, 10*, 809–816.

Sowell, E. R., Thompson, P. M., Holmes, C. J., Batth, R., Jernigan, T. L., & Toga, A. W. (1999). Localizing age-related changes in brain structure between childhood and adolescence using statistical parametric mapping. *NeuroImage, 9*, 587–597.

Tanaka, J. W., & Curran, T. (2001). A neural basis for expert object recognition. *Psychological Science, 12*, 43–47.

Tarr, M. J., & Gauthier, I. (2000). FFA: a flexible fusiform area for subordinate-level visual processing automatized by expertise. *Nature Neuroscience, 3*, 764–769.

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenish, M. M., et al. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. *Proceedings of the National Academy of Sciences—USA, 100*, 2860–2865.

Temple, E., Poldrack, R. A., Salidis, J., Deutsch, G. K., Tallal, P., Merzenich, M. M., et al. (2001). Disrupted neural responses to phonological and orthographic processing in dyslexic children: an fMRI study. *NeuroReport, 12*, 299–307.

Turkeltaub, P. E., Gareau, L., Flowers, D. L., Zeffiro, T. A., & Eden, G. F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience, 6*, 767–773.

van Leeuwen, C., & Lachmann, T. (2004). Negative and positive congruence effects in letters and shapes. *Perception and Psychophysics, 66*, 908–925.