Activity levels in the left hemisphere caudate–fusiform circuit predict how well a second language will be learned

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How second language (L2) learning is achieved in the human brain remains one of the fundamental questions of neuroscience and linguistics. Previous neuroimaging studies with bilinguals have consistently shown overlapping cortical organization of the native language (L1) and L2, leading to a prediction that a common neurobiological marker may be responsible for the development of the two languages. Here, by using functional MRI, we show that later skills to read in L2 are predicted by the activity level of the fusiform–caudate circuit in the left hemisphere, which nonetheless is not predictive of the ability to read in the native language. We scanned 10-y-old children while they performed a lexical decision task on L2 (and L1) stimuli. The subjects' written language (reading) skills were behaviorally assessed twice, the first time just before we performed the fMRI scan (time 1 reading) and the second time 1 y later (time 2 reading). A whole-brain based analysis revealed that activity levels in left caudate and left fusiform gyrus correlated with L2 literacy skills at time 1. After controlling for the effects of time 1 reading and nonverbal IQ, or the effect of in-scanner lexical performance, the development in L2 literacy skills (time 2 reading) was also predicted by activity in left caudate and fusiform regions that are thought to mediate language control functions and resolve competition arising from L1 during L2 learning. Our findings suggest that the activity level of left caudate and fusiform regions serves as an important neurobiological marker for predicting accomplishment in reading skills in a new language.

basal ganglia | biomarker | extrastriate cortex | visual system

A key characteristic of a typical language user in today's world is his or her bilinguality (1). For people who learn to read in a second language (L2), acquiring tens of thousands of words is an exceptional accomplishment of their neuroanatomical systems. Considerable evidence links the central mechanisms achieving this remarkable feat to one general brain system subserving different languages in bilingual learners (2–9), yet little is known about the neural circuit specific to nonnative language learning and processing that is characterized by the successful monitoring and control of the interaction and interference of the native language (L1) that competes for representation and selection (10–19). Hypothetically, this neural circuit may serve as important neurobiological determinants that are associated with accomplishment in reading skills in a new language.

In this study, we sought to identify neurobiological markers associated with learners' L2 literacy skills. We adapted a lexical decision paradigm developed to investigate reading skills and dyslexia (20, 21) for use in a blocked functional magnetic resonance imaging (fMRI) design. Twenty-six children (average age = 10 y and 3 mo), who were Chinese native speakers and started to learn English as L2 at age 6 and had not acquired high level of proficiency at the time of study (Table 1), were shown either real English words (e.g., *panda*) or artificial words (e.g., *yall*). Their task was to judge whether or not a viewed stimulus was a real English word. This paradigm is very simple, even to beginning learners of a language, but it measures the rudimentary processing of lexical items that is known to be a crucial indicator of language representation quality (22, 23). In the control task, subjects were asked to judge the direction of exposed arrows. This task controlled for activation owing to decision making involved in lexical judgment.

Results and Discussion

In examining the neural systems mediating the processing of words in the second language, we contrasted brain activation during lexical decision and arrow judgment (Fig. 1 and Table S1). Significantly activated brain regions comprised bilateral mid-inferior frontal gyrus, fusiform gyrus, midinferior occipital cortex, lingual gyrus, caudate nucleus, right inferior parietal lobule, left putamen, and left parahippocampal gyrus.

To determine whether any of the activity measures from lexical judgment was related to reading performance in L2, we constructed a second map based on a whole-brain voxel-wise regression of the intensity of activation during lexical decision and the reading skills measured right before fMRI scan [time 1 reading; $P < 0.05$ false discovery rate (FDR) corrected]. This map revealed regions where brain activity, evoked by using the simple lexical judgment on L2 stimuli, correlated positively with reading performance in that language (Fig. 2). We found that the activity level of two brain regions reliably correlated with how well L2 reading was achieved, specifically the left caudate nucleus ($x = -8, y = 16, z = 8$) and the left middle fusiform gyrus (BA 37; $x = -46, y = -57, z = -11$).

To better visualize the relationship between individual variability in activation levels of the two regions and reading performance, we followed a recent suggestion (24) and used nonindependent regions of interest (ROI) analysis as a quality control step, and then conducted correlation analyses for the ROIs. The results are reported in Fig. S1.

Next, we examined brain regions where fMRI activations were predictive of later L2 reading performance. We reassessed the

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Table 1. Demographic characteristics and behavioral results

Variable	Result
Age, mo	123 (5.5)
Nonverbal IQ, %	78 (9.5)
Beginning age of L2 acquisition, y	6.35 (1.13)
Self rating of fluency in L1 and L2	
L1 (Chinese) speaking	4.92 (0.27)
L1 (Chinese) reading	3.77 (0.76)
L1 (Chinese) understanding	4.92 (0.27)
L2 (English) speaking	2.23 (0.43)
L2 (English) reading	2.50 (0.51)
L2 (English) understanding	2.42 (0.5)
Lexical decision accuracy in L1, %	90.5 (6.4)
Lexical decision accuracy in L2, %	58.7 (13.0)
Arrow decision accuracy, %	91.2 (4.6)
Reading scores before fMRI scanning (time 1)	
L1 reading (max = 110)	76.3 (4.6)
L2 reading (max = 110)	74.6 (15.1)
Reading scores one year after fMRI scanning (time 2)	
L1 (Chinese) reading (max = 400)	207.0 (18.5)
L2 (English) reading (max = 400)	78.1 (60.3)

SDs are given in parentheses.

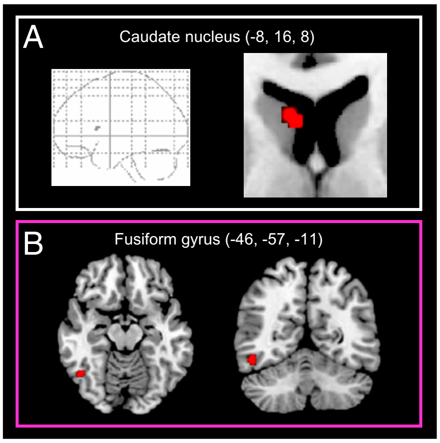

Fig. 2. Brain regions showing significant correlations between brain activity and time 1 reading skills in L2. The data are based on whole-brain multiple regression analysis correlating contrast images of lexical decision minus arrow judgment and time 1 reading scores. The voxelwise threshold was set at $P <$ 0.05 FDR corrected for multiple comparisons. All of the correlational maps (in color) are overlaid on the corresponding T1 images (in gray scale). Planes are axial sections in *A* and *B Left* and coronal views in *B Right*.

subjects' L2 reading skills 1 y after the fMRI scan (time 2 reading), and then performed another whole-brain-based regression analysis by correlating fMRI activation level during lexical decision with time 2 reading scores ($P < 0.05$ FDR corrected).

We found that the activity level of the two regions associated with time 1 reading was also significantly predictive of later reading skills in L2 (Fig. 3). Partial correlation analyses were conducted by extracting the average blood-oxygen-level-dependent (BOLD) contrast estimates of the two regions for each subject and then correlating the BOLD information with time 2 reading skills, controlling for the effects of reading performance at time 1 and nonverbal IQ. The partial correlation coefficient was 0.68 ($P <$ 0.005) for the left caudate nucleus and 0.49 ($P < 0.005$) for the left fusiform gyrus (Fig. S2).

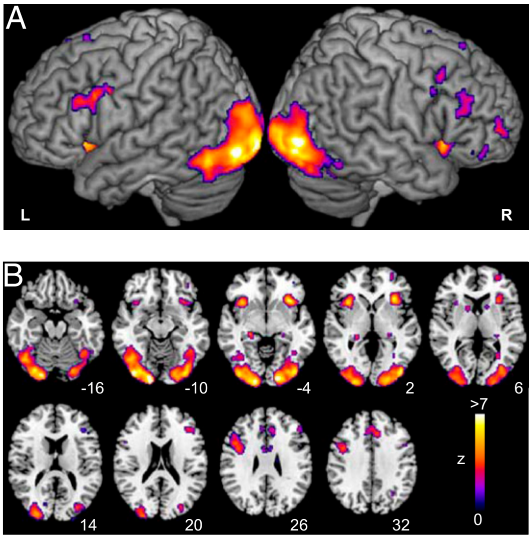

Fig. 1. Brain regions with significant activity during lexical decision in second language (L2). (*A*) Lateral view. (*B*) Axial sections. The significance threshold is $P < 0.001$ FDR corrected. All of the functional maps (in color) are overlaid on the corresponding T1 images (in gray scale). Planes are axial sections, labeled with the height (mm) relative to the bicommissural line. L, left hemisphere; R, right hemisphere.

These results suggest that, although many regions are recruited during lexical decisions in L2, reflecting the multifaceted cognitive processes engaged in a word reading task, activity levels in a subset of areas correlate reliably with reading achievement. Particularly, both time 1 and time 2 reading in L2 were associated with the functions of the left caudate nucleus and the left fusiform gyrus. Because the reading performance at time 1 was partialled out in our correlation analysis, the activity level in the two brain regions reflects reading performance gain (i.e., learning potential).

To exclude the possibility that activation in the caudate–fusiform regions is not a reflection of learning ability but is determined by in-scanner lexical decision performance at time 1 (which is also cor-

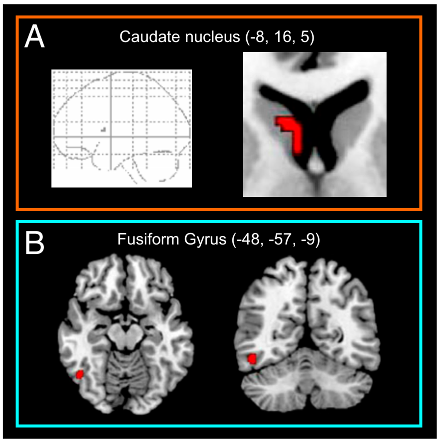

Fig. 3. Areas showing significant correlations between brain activity and later (time 2) reading skills in L2. A whole-brain multiple regression analysis was first conducted to examine the correlations between contrast images of lexical decision minus arrow judgment and time 2 reading scores ($P < 0.05$ FDR corrected for multiple comparisons). Within each significant cluster, the average BOLD contrast estimates were extracted for each subject, and partial correlation analyses were performed to evaluate the predictive power of brain activation in these regions and time 2 reading skills, controlling for the effects of reading performance at time 1 and nonverbal IQ. Thus, the activity level in the two brain regions reflects reading performance gain (i.e., learning potential), rather than lexical decision performance per se. The correlation maps (in color) are overlaid on the corresponding T1 images (in gray scale). Planes are axial sections in *A* and *B Left* and coronal views in *B Right*.

related with L2 reading behavior at both time 1 and time 2), we performed additional analyses correlating the BOLD information with time 2 reading skills in L2, partialing out the effect of in-scanner L2 lexical performance. The partial correlation coefficient was 0.713 ($P < 0.001$) for left caudate and 0.578 ($P < 0.005$) for left fusiform gyrus. These data provide direct evidence to date for contributions of the left hemisphere caudate-fusiform circuit to the growth in L2 literacy skills.

Because the reading tests used in time 1 and time 2 contained different items, and their sensitivity was not matched, we converted L2 reading ability at time 1, L2 reading ability at time 2, and in-scanner L2 lexical-decision performance to percentages and then conducted statistical analyses to compare how brain activation in the caudate and fusiform regions correlated with each of the three behavioral performances (Fig. 4). A higher correlation between brain activation and reading skills at time 2 was seen in the caudate nucleus ($r = 0.79$ vs. $r = 0.53$) as well as in the fusiform region ($r = 0.66$ vs. $r = 0.53$) than at time 1. Thus, the activation in the caudate–fusiform circuit seems to indeed reflect L2 learning ability.

How might the activation level of the left caudate and extrastriate cortex serve as the neurobiological markers of future L2 reading skills? One possible explanation is that effective learning and processing of L2 requires voluntary control of language in use (10–18) and even suppression of the production of words in the untargeted language (i.e., the native language; ref. 15), and the left caudate–fusiform circuit is required to serve this important function (14, 25). As shown by previous studies, the left caudate nucleus is heavily involved in the processing of L2 words in French (26) and German (27). It plays a critical role in monitoring and controlling the bilingual's language in use (14), and damage to the caudate causes a trilingual patient to involuntarily switch from one language to another (28). On the other hand, the left fusiform gyrus mediating the growth in L2 literacy in this study (coordinate: −46, −57, −11) is just anterior to areas V4 and TEO, which are known to efficiently filter out irrelevant information through biased competition among multiple objects competing for neural representation in selective visual attention, as demonstrated by recent single-cell physiology and neuroimaging studies (29–32). This competition mechanism

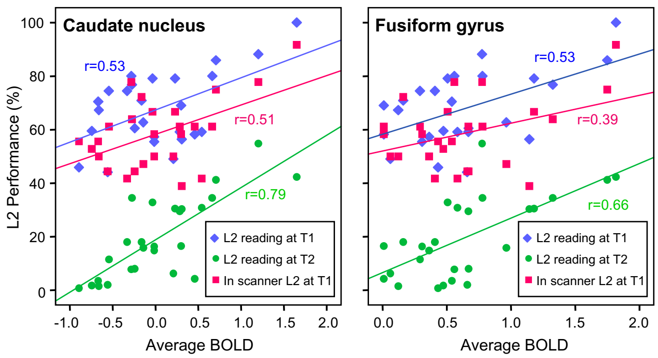

Fig. 4. Correlations between brain activity in the caudate nucleus and the left fusiform gyrus and L2 reading performance at time 1 and time 2. We converted L2 reading ability at time 1 and time 2 to percentages and then conducted statistical analyses to illustrate how brain activation in the two regions correlated with the results of two reading tests. Also shown is a correlation between brain activation and L2 lexical performance, which was converted to a percentage. A higher correlation between brain activation and reading skills at time 2 was obtained in left caudate ($r = 0.79$, $P < 0.001$ vs. $r = 0.53$, $P < 0.005$) as well as in the fusiform region ($r = 0.66$, $P < 0.001$ vs. $r = 0.53$, $P < 0.005$) than at time 1. The correlation between brain activity and in-scanner lexical performance was 0.51 ($P < 0.01$) at caudate and 0.39 ($P < 0.05$) at fusiform gyrus.

is also engaged during the acquisition of knowledge of a second language: For children who learn to become bilingual starting at about age 6, L1 as a dominant language is interactively competing with L2, and thus, to speak or read L2, individuals must inhibit lexical processing in L1 (10–18). Drawing on the language-control theory of the left caudate and the suppressive interaction theory of the extrastriate cortex in visual attention, we infer that the activity level of the left caudate and the left fusiform gyrus near V4 and TEO is predictive of learning potential in L2, not L1, reading acquisition.

To test this prediction, we performed fMRI scans when these subjects performed a lexical decision on L1 stimuli. We also tested the subjects' L1 reading skills twice, as we did for the L2 reading. Although the caudate nucleus and the left extrastriate cortex were strongly activated during lexical decision with L1 words/nonwords (Fig. S3), we found no reliable correlation between the activity level in either of the two regions and reading scores in the native language assessed in time 1 reading (Fig. S4). Activation in the left fusiform gyrus modestly correlated with L1 reading but failed to reach significance ($r = 0.32$, $P = 0.11$). We also found no reliable correlation between the activity level of the two regions and L1 reading performances measured in time 2 after time 1 reading scores and nonverbal IQ were controlled for ($r = 0.10$, $P = 0.63$ for left caudate; $r = 0.20$, $P = 0.34$ for left fusiform gyrus). The lack of significant correlations was even from statistics from a ROI analysis that inflates type 1 error (24), rather than from whole-brain-based computation.

The results thus indicate that the fusiform–caudate circuit functions as a critical neural determinant of L2, rather than L1, reading achievement. Our results of L1 reading are consistent with the findings of neuromarkers of English reading in native speakers that indicate no predictive effects of this circuit (33, 34).

Conclusion

Reading in L2 is a complex task that entails an interaction of two languages (35, 36). Contrary to previous clinical reports that suggest selective impairments in one of the two languages in bilingual patients (37–41), a number of brain-mapping studies showed a language-universal neuroanatomical system in the bilingual brain, and they have led to one critical prediction that a common neurobiological marker may be predictive of the growth of the literacy skills in the two languages. The results presented here suggest a surprising conclusion: The later skills to read in L2 are predicted by the activity level of the fusiform–caudate circuit in the left hemisphere, which is not associated with the ability to read in the native language. L2 literacy in the bilingual brain appears to develop along a path differing from that for the native language.

Materials and Methods

Subjects. We scanned 26 children (14 boys and 12 girls, average age 10 y and 3 mo, range from 9 y 5 mo to 11 y 5 mo) from the Beijing Yongtai Primary School who were native Chinese speakers and spent more time studying Chinese (L1) than English (L2) at school. They were physically healthy and free of neurological disease, head injury, and psychiatric disorder. The study was approved by the ethical committee of the Beijing MRI Center for Brain Research, Chinese Academy of Sciences, and informed consent was obtained from all subjects and their parents. The subjects' demographic characteristics are shown in Table 1. A language-experience questionnaire was used to obtain measures of subjects' current level of fluency in L1 and L2 as reported by the subjects, teachers, and parents. The first section of the questionnaire was concerned with subjects' language history. On average, the children participating in the study began learning L2 at age 6.35. In the second section, the questionnaire contained three rating scales for L1 and L2 fluency, one for each of the three language skills including speaking, reading, and understanding. The endpoints of the rating scale were 1 and 5 (1 = *not fluent*; 5 = *very fluent*). The average rating scores are reported in Table 1.

The standardized Chinese version of Raven's Standard Progressive Matrices was used as an index of nonverbal intelligence. The mean nonverbal

Raven IQ fell in the 78th percentile (ranged from the 50th to the 95th percentile, SD = 9.5).

Design and Materials. The functional activation task used in this study was a lexical decision in which subjects were instructed to decide whether or not a visually-exposed stimulus was an English word (or a Chinese character). The English nonwords (or noncharacters) in "no" trials were orthographically legal but without meanings. To perform the lexical decision successfully, subjects must rely on visuo-orthographic familiarity and semantic accessibility of a viewed stimulus. All English words and Chinese characters were selected from grade 1 textbooks of English and Chinese and, therefore, were commonly encountered.

A blocked design was used, with six blocks of the lexical decision task (three for each language) alternated with six blocks of the baseline task (arrow judgment). Presentation of the L1 and L2 blocks was counterbalanced for each subject. Each experimental block consisted of a 2-s instruction and 12 trials (24 s), whereas each baseline block consisted of a 2-s instruction and 8 trials (16 s). On each trial, a stimulus was displayed for 1,500 ms, followed by a 500-ms blank interval. For the lexical decision tasks, subjects indicated a positive response by pressing the key corresponding to their right (dominant) hand and a negative response by pressing the key corresponding to their left (nondominant) hand. For the arrow judgment task, they pressed the key corresponding to their left hand if an arrow pointed upward and the key corresponding to their right hand if an arrow pointed downward. They were asked to perform the tasks as quickly and accurately as possible.

Before we conducted the fMRI study, subjects' performance in L1 and L2 was assessed by a formal and regular language examination. The examination consisted of a number of questions ranging from lexical to sentence levels, and the full mark was 110. Subjects' language scores in L1 and L2 from this examination are shown in Table 1. One year after the fMRI experiment, we evaluated subjects' reading ability in the two languages again, this time by asking them to read aloud 400 Chinese characters and 400 English words. These characters/words were selected from textbooks used in primary schools in Beijing for first to sixth graders, 40 from each. The remaining 160 were selected from low-frequency characters/words in a linguistic corpus that was not covered in primary school textbooks. Characters and words were arranged in a sequence of increasing difficulty (as determined by grade level and visual complexity or stroke number). Subjects were asked to read the characters/words aloud as quickly and accurately as possible within 3 min. Their reading scores are illustrated in Table 1.

MRI Acquisition. Whole-brain imaging data were acquired on a 3 T Siemens MRI scanner at the Beijing MRI Center for Brain Research of the Chinese Academy of Sciences using T2*-weighted gradient-echo echo planar imaging (EPI) sequence (echo time = 30 ms, repetition time = 2 s, flip angle = 90°, field of view = 22 cm). Thirty-two contiguous axial slices were acquired parallel to the AC-PC line. High-resolution ($2 \times 2 \times 2$ mm^3) anatomical images were acquired using a T1-weighted, 3D gradient-echo sequence. Visual stimuli were presented to subjects through a projector onto a translucent screen. Subjects viewed the stimuli through a mirror attached to the head coil.

Data Analysis. SPM2 and in-house software were used for image preprocessing and statistical analyses. The functional images were realigned and unwarped to remove movement-by-susceptibility induced variance. They were then spatially normalized to an EPI template based on the ICBM152 stereotactic space, an approximation of canonical space and spatially smoothed by an isotropic Gaussian kernel (6-mm full width at half-maximum). Individual subject's activation *t* map was generated by using the general linear model in which time series were convolved with the canonical hemodynamic response function and were high-pass-filtered at 128 s. Individual lexical decision versus arrow judgment contrast images were then used in a random effects model to create a group-level statistical map, with the voxelwise threshold set at $P < 0.001$, FDR corrected for multiple comparisons, and an extent threshold of 10 contiguous voxels. To identify the important neural determinants in predicting learning achievement in L2, we performed whole-brain multiple regression analyses correlating time 1 contrast images of lexical decision minus arrow judgment and time 1 reading scores, controlling for the effect of nonverbal intelligence. The voxelwise threshold was set at $P < 0.05$ FDR corrected for multiple comparisons, with an extent threshold of 3 contiguous voxels. We next conducted a whole-brain multiple regression analysis to examine the correlations between contrast images of lexical decision minus arrow judgment and time 2 reading scores, with the voxelwise threshold set at $P < 0.05$ FDR corrected for multiple comparisons and an extent threshold of 3 contiguous voxels. Within each activated region, the average BOLD contrast estimates of the voxels were extracted for each subject, and partial correlation analyses were performed to evaluate the predictive power of brain activation in these regions for time 2 reading skills, controlling for the effects of reading performance at time 1 and nonverbal IQ. Functional MRI data analysis for L1 followed the same procedure. Brain regions are estimated from Talairach and Tournoux (42), after adjustments for differences between MNI and Talairach coordinates.

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NEUROSCIENCE

1. Li Wei (2007) A user-friendly linguistics. *Int J Appl Linguist* 17:1–3.
2. Illes J, et al. (1999) Convergent cortical representation of semantic processing in bilinguals. *Brain Lang* 70:347–363.
3. Gandour J, et al. (2007) Neural basis of first and second language processing of sentence-level linguistic prosody. *Hum Brain Mapp* 28:94–108.
4. Tan LH, et al. (2003) Neural systems of second language reading are shaped by native language. *Hum Brain Mapp* 18:158–166.
5. Chan AH, et al. (2008) Neural correlates of nouns and verbs in early bilinguals. *Ann N Y Acad Sci* 1145:30–40.
6. Chee MWL, et al. (2000) Overlap and dissociation of semantic processing of Chinese characters, English words, and pictures: evidence from fMRI. *Neuroimage* 12:392–403.
7. Sheng L, McGregor KK, Marian V (2006) Lexical-semantic organization in bilingual children: evidence from a repeated word association task. *J Speech Lang Hear Res* 49: 572–587.
8. Pu Y, et al. (2001) Cerebral hemodynamic response in Chinese (first) and English (second) language processing revealed by event-related functional MRI. *Magn Reson Imaging* 19:643–647.
9. Frenck-Mestre C, Anton JL, Roth M, Vaid J, Viallet F (2005) Articulation in early and late bilinguals' two languages: evidence from functional magnetic resonance imaging. *Neuroreport* 16:761–765.
10. Li Wei (2009) *Bilingualism and Multilingualism: Critical Concepts in Linguistics* (Routledge, London).
11. Green DW (1998) Mental control of the bilingual lexico-semantic system. *Biling Lang Cogn* 1:67–81.
12. Green DW, Crinion J, Price CJ (2006) Convergence, degeneracy and control. *Lang Learn* 56(S1):99–125.
13. Price CJ, Green DW, von Studnitz R (1999) A functional imaging study of translation and language switching. *Brain* 122:2221–2235.
14. Crinion J, et al. (2006) Language control in the bilingual brain. *Science* 312:1537–1540.
15. Ullman MT, A cognitive neuroscience perspective on second language acquisition: the declarative/procedural model. *Mind and Context in Adult Second Language Acquisition: Methods, Theory, and Practice*, ed Sanz C (Georgetown University Press, Washington, DC), pp 141–178.
16. Hernandez A, Li P, MacWhinney B (2005) The emergence of competing modules in bilingualism. *Trends Cogn Sci* 9:220–225.
17. Kroll JF, de Groot AMB (2005) *Handbook of Bilingualism: Psycholinguistic approaches* (Oxford Univ Press, New York).
18. Thierry G, Wu YJ (2007) Brain potentials reveal unconscious translation during foreign-language comprehension. *Proc Natl Acad Sci USA* 104:12530–12535.
19. Kovelman I, Baker SA, Petitto LA (2008) Bilingual and monolingual brains compared: a functional magnetic resonance imaging investigation of syntactic processing and a possible "neural signature" of bilingualism. *J Cogn Neurosci* 20:153–169.
20. Siok WT, Perfetti CA, Jin Z, Tan LH (2004) Biological abnormality of impaired reading is constrained by culture. *Nature* 431:71–76.
21. Rumsey JM, et al. (1997) A positron emission tomographic study of impaired word recognition and phonological processing in dyslexic men. *Arch Neurol* 54:562–573.
22. Perfetti CA (1992) The representation problem in reading acquisition. *Reading Acquisition*, eds Gough PB, Ehri LC, Treiman R (Lawrence Erlbaum Associates, Hillsdale, NJ), pp 145–174.
23. Perfetti CA (2007) Reading ability: Lexical quality to comprehension. *Sci Stud Read* 11: 357–383.
24. Poldrack RA, Mumford JA (2009) Independence in ROI analysis: where is the voodoo? *Soc Cogn Affect Neurosci* 4:208–213.
25. Ali N, Green DW, Kherif F, Devlin JT, Price CJ (2010) The role of the left head of caudate in suppressing irrelevant words. *J Cogn Neurosci* 22:2369–2386.
26. Klein D, Watkins KE, Zatorre RJ, Milner B (2006) Word and nonword repetition in bilingual subjects: a PET study. *Hum Brain Mapp* 27:153–161.
27. Rüschemeyer SA, Fiebach CJ, Kempe V, Friederici AD (2005) Processing lexical semantic and syntactic information in first and second language: fMRI evidence from German and Russian. *Hum Brain Mapp* 25:266–286.
28. Abutalebi J, Miozzo A, Cappa SF (2000) Do subcortical structures control "language selection" in polyglots? Evidence from pathological language mixing. *Neurocase* 6: 51–56.

29. Desimone R, Duncan J (1995) Neural mechanisms of selective visual attention. *Annu Rev Neurosci* 18:193–222.
30. Reynolds JH, Chelazzi L, Desimone R (1999) Competitive mechanisms subserve attention in macaque areas V2 and V4. *J Neurosci* 19:1736–1753.
31. Kastner S, De Weerd P, Desimone R, Ungerleider LG (1998) Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. *Science* 282: 108–111.
32. Beck DM, Kastner S (2005) Stimulus context modulates competition in human extrastriate cortex. *Nat Neurosci* 8:1110–1116.
33. Hoeft F, et al. (2007) Prediction of children's reading skills using behavioral, functional, and structural neuroimaging measures. *Behav Neurosci* 121:602–613.
34. Gabrieli JDE (2009) Dyslexia: a new synergy between education and cognitive neuroscience. *Science* 325:280–283.
35. Yip V, Matthews S (2007) *The Bilingual Child* (Cambridge University Press, Cambridge, UK).
36. Diamond J (2010) Social science. The benefits of multilingualism. *Science* 330: 332–333.
37. Gomez-Tortosa E, Martin EM, Gaviria M, Charbel F, Ausman JI (1995) Selective deficit of one language in a bilingual patient following surgery in the left perisylvian area. *Brain Lang* 48:320–325.
38. Schwartz MS (1994) Ictal language shift in a polyglot. *J Neurol Neurosurg Psychiatry* 57:121.
39. Ojemann GA (1983) Brain organization for language from the perspective of electrical stimulation mapping. *Behav Brain Sci* 6:189–230.
40. Lorch M (2007) Bilingualism and memory: early 19th century ideas about the significance of polyglot aphasia. *Cortex* 43:658–666.
41. Ozkaya G, et al. (2006) Aphasic status epilepticus with periodic lateralized epileptiform discharges in a bilingual patient as a presenting sign of "AIDS-toxoplasmosis complex". *Epilepsy Behav* 9:193–196.
42. Talairach J, Tournoux P (1988) *Co-Planar Stereotactic Atlas of the Human Brain* (Theime Medical, New York).