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Cortical Plasticity for Language Processing in the Human Brain

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Abstract

A second language (L2) can be mastered at any time in life, though the L2 ability becomes rarely comparable to first language (L1) if it is acquired beyond the hypothesized critical period around puberty. The neural substrates of plasticity for acquiring languages are largely unknown. We used functional imaging to examine whether training in the conjugation of English verbs from present to past tense alters brain activations in 13-year-old twins. A novel experimental design contrasted past tense verb identification and verb matching, which were tested in either English (L2) or Japanese (L1). After two-month classroom training in the past tense, the left dorsal inferior frontal gyrus (IFG) exhibited significantly correlated activation increases for L2 within each pair of twins, and the increases were positively correlated with individual performance improvements. Moreover, the cortical plasticity for L2 acquisition was guided toward the L1 specialization of the left dorsal IFG, in spite of notable differences between L1 and L2 in the students' linguistic knowledge and in their performance in making past tense forms. These findings suggest a cortical mechanism underlying L2 acquisition of grammatical knowledge, which critically depends on shared genetic and

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environmental factors for each twin in a surprisingly predictive manner. Accumulating evidence from recent imaging and stimulation studies has suggested that the left IFG is specialized in grammatical processing, which is thus referred to as the "grammar center".

On the other hand, reading skills of letters and words are usually acquired at school age but can still be mastered in adulthood. To identify which brain regions in adults show plasticity for learning letters, Hangul letters were experimentally associated with either speech sounds (HS condition) or non-speech sounds (HN condition) in imaging sessions over two consecutive days. Selective activations under the HS condition were found in regions including the left posterior inferior temporal gyrus (PITG) and the parieto-occipital cortex (PO), as compared with activations under a condition for familiar letters and speech sounds, and with those under the HN condition. The left PITG showed a selective activation increase under the HS condition over two days, the degree of which predicted individual performance improvement. Therefore, the left PITG can be referred to as the "letter center". Furthermore, functional connectivity between the left PITG and the left PO was selectively enhanced under the HS condition. These results demonstrate that a new link between orthography and phonology is formed by the plasticity of a functional system involving the left PITG in association with the left PO. Our approach to evaluate learning procedures in terms of not only indirect behavioral changes but direct functional changes takes a first step toward a new era in the brain science of education.

Keywords: Language acquisition; Syntax; Universal grammar (UG); Letter learning; Functional magnetic resonance imaging (fMRI)

1. The Plasticity of the "Grammar Center"

The specialization of language processing in human cognitive systems is one of the central issues in neuroscience, and it has been highly debated from a number of perspectives based on lesion studies of Broca's aphasia and functional imaging studies of the prefrontal cortex (Caplan et al., 1999; Friederici, 2002; Sakai et al., 2003). The narrowest definition of Broca's area is the left pars opercularis [F3op, Brodmann's area (BA) 44] and the left pars triangularis (F3t, BA 45), a part of the third frontal convolution (F3) or the left inferior frontal gyrus (IFG). However, the syndrome referred to as permanent Broca's aphasia arises from a considerably larger brain lesion that includes the insula and subjacent white matter (Mohr, 1976), and the region medial to Broca's area (the left precentral gyrus of the insula) has been implicated in the motor planning of speech (Dronkers, 1996). Recent functional magnetic resonance imaging (fMRI) studies have provided accumulating evidence that the lateral surrounding region of Broca's area, including the left IFG and the left lateral premotor cortex (LPMC), is selectively related to grammatical processing (Stromswold et al., 1996; Dapretto and Bookheimer, 1999; Kang et al., 1999; Embick et al., 2000; Friederici et al., 2000; Suzuki and Sakai, 2003), independent of domain-general factors such as task difficulty and short-term memory (Hashimoto and Sakai, 2002), and of unreal language rule usage (Musso et al., 2003). Furthermore, the causal link between the activation of the left IFG and grammatical decisions has been recently proved by a transcranial magnetic stimulation (TMS) study (Sakai et al., 2002). Therefore, the left prefrontal regions can be suggested as the most likely candidate of the "grammar center" (Figure 1).

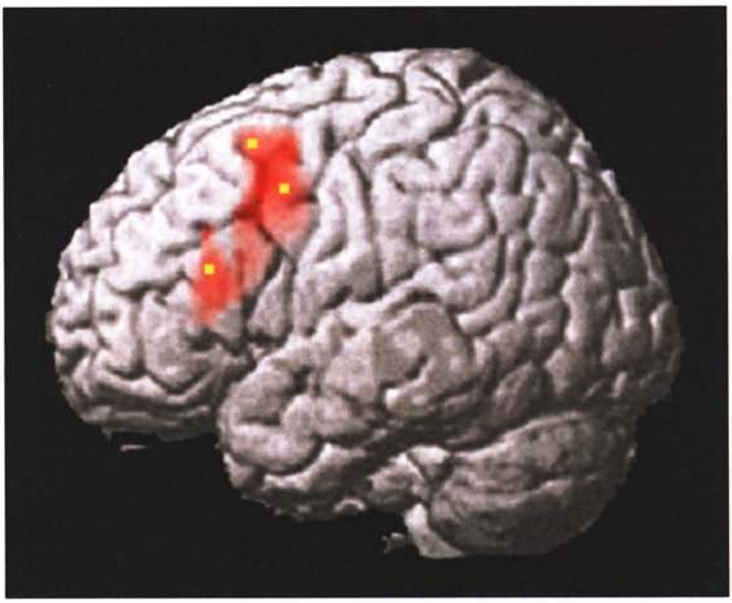

Figure 1. The grammar center in the left prefrontal cortex. Regions (red) identified by directly comparing syntactic decision tasks and a short-term memory task for words are projected together onto the left hemisphere of a surface-rendered standard brain.

The next primary challenge is how the function of the grammar center can be modified during the course of acquiring new languages. The native or first language (L1) is normally acquired in the first several years of life, during which children rapidly expand their linguistic knowledge (Gopnik et al., 1999; Boysson-

Bardies, 1999). In contrast, a second language (L2) can be mastered at any time in life, though the L2 ability becomes rarely comparable to L1 if it is acquired beyond the hypothesized critical period around puberty (Lenneberg, 1967; Johnson and Newport, 1989). Whether L2 relies on the same dedicated mechanism of L1, which may critically involve the maturation of the grammar center, is thus a matter of debate (Epstein et al., 1996). It has been recently reported that L1 and L2 are represented differentially in cortical areas during discourse production or listening tasks (Kim et al., 1997; Dehaene et al., 1997). However, other imaging studies have reported common neural substrates of L1 and L2 during word generation tasks (Klein et al., 1995; Chee et al., 1999). The critical experiments thus would be to clarify brain plasticity that represents new acquisition of L2, i.e., the dynamic processes of L2 acquisition and associated cortical changes, rather than static states that reflect a certain level of L2 performance.

We have examined whether the learning of English past tense verbs as L2 knowledge alters brain activations for the 13-year-old students (native Japanese speakers) studying English for the first time at a secondary education school in Japan (Sakai et al., 2004). We targeted twins as subjects (six monozygotic and one dizygotic twin pairs), because it is intriguing to ask whether shared factors of twins actually influence their language abilities and neural substrates for Japanese (L1) and English (L2). For two months, the students participated in intensive training in English verbs as part of their standard classroom education. To directly evaluate the brain's changes in activation due to this training, the twins completed two sets of fMRI sessions, one before the training (Day 1) and one after the training (Day 2). Figure 2A illustrates the experimental paradigm with four tasks used in fMRI sessions: an English verb-matching (EM) task, an English past tense (EP) task, a Japanese verb-matching (JM) task, and a Japanese past tense (JP) task. General cognitive factors such as word recognition and response selection were controlled by the EM and JM tasks, which were directly compared with the EP and JP tasks, respectively. A particular challenge in this study was to assess the effect of an educational method used in classroom lessons directly in terms of brain activation.

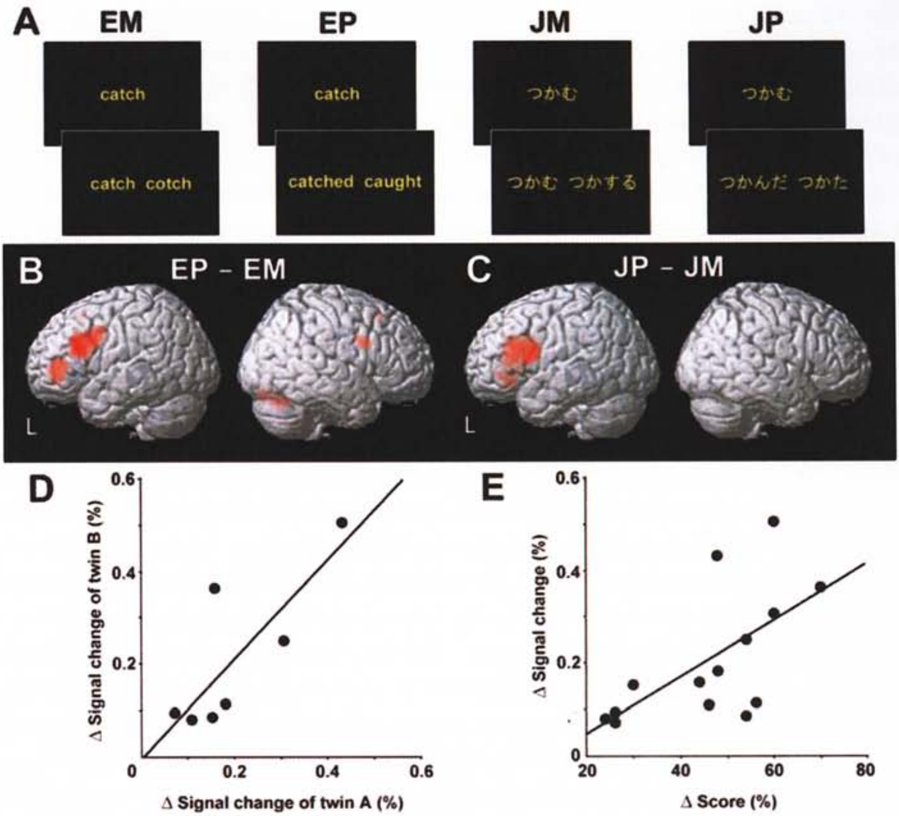

Figure 2. Correlated functional changes of the grammar center in twins induced by classroom education of second language. (A) The four language tasks used to test the plasticity of the grammar center. (*Left to right:* English verb-matching (EM) task, English past tense (EP) task, Japanese verb-matching (JM) task, and Japanese past tense (JP) task. For JP, one example (*tsukamu*; gross: catch) is shown, and the one on the left (*tsukannda*; gross: caught) is correct. Japanese stimuli were presented in both the *hiragana* and *kanji* writing systems and were matched with English words of the same meaning. (B) EP – EM for Day 2. The most prominent activation change was observed in the left (L) inferior frontal gyrus (IFG). (C) JP – JM for Day 2. Note the consistent activation in the left IFG. (D) The activation increases (ΔSignal change: Day 2 – Day 1) of the left dorsal IFG in EP – EM, plotted for each pair of twins (identified as twin A and twin B). (E) Significant correlation between L2 performance improvements and activation increases in the left dorsal IFG. For all individual participants, the activation increases (ΔSignal change: Day 2 – Day 1) of the left IFG in EP – EM are plotted against improvements in examination scores (ΔScore: Day 2 – Day 1). A regression line is shown.

When the EP task was contrasted with the EM task (EP – EM) in a random effects analysis for Day 2, activations were found primarily in the left IFG (Figure

2B), which were absent in EP - EM for Day 1. Moreover, the JP – JM contrast for Day 2 revealed the left IFG activation (Figure 2C), which was stable and remained unchanged between Days 1 and 2. It is thus striking to note that the left IFG activated for the English past tense verbs exactly match the regions activated for the Japanese past tense verbs, which is in agreement with the universal nature of grammatical processing. These results suggest that the cortical plasticity for L2 acquisition is guided toward the L1 specialization of the left dorsal IFG, at least at the age of 13, in spite of notable differences between L1 and L2 in the students' linguistic knowledge and in their performance in making past tense forms.

We next examined whether or not shared factors of twins influence the functional changes observed here. The activation increases at one local maximum (coordinates in the standard brain: –45, 21, 30) of the left dorsal IFG across Days 1 and 2 showed a highly significant correlation within each pair of twins ($r = 0.80$) (Figure 2D). The permutation procedure of randomly assigning each individual to a new pair resulted in the normal distribution with mean $r = 0.0$ and $SD = 0.39$, confirming this statistical significance at $P = 0.02$. The activation changes of the same region in JP – JM showed no positive correlation within each pair of twins ($r = -0.46$), indicating that the significant correlation is selective to L2 acquisition. These results suggest that the functional changes specifically observed in the left IFG are susceptible to shared genetic and environmental factors for each twin in a surprisingly predictive manner. Furthermore, the activation increases in the left IFG predicted the extent to which each individual subject improved his/her knowledge of the past tense, as shown by a significant positive correlation ($r = 0.63$) between the improvements in examination scores and the activation increases in EP – EM across Days 1 and 2 (Figure 1E). Therefore, we conclude that the amount by which activation increases in the left dorsal IFG is a good indicator of individual improvement in acquiring L2 past tense knowledge. The present fMRI study thus successfully elucidates one type of cerebral mechanisms involving the grammar center, indicating how new linguistic knowledge is acquired and represented in individual brains. To our knowledge, the present study is the first direct demonstration that classroom education, if properly executed, can change the function of the prefrontal cortex.

2. The Plasticity of the "Letter Center"

Reading letters and words consists of multiple steps including orthographic, phonological, and lexico-semantic processing, which are usually acquired at school age but can still be mastered in adulthood. Previous imaging studies for adult subjects have reported that the left fusiform gyrus (FG) showed more activation for visually presented consonant letter strings than for pseudofonts or faces (Price et al., 1996; Puce et al., 1996; Tarkiainen et al., 2002), indicating that this region is selectively involved in letter recognition. Moreover, recent functional imaging studies have clarified that the left FG showed larger activation for both pronounceable words and pseudowords than for unpronounceable consonant letter strings (Fiez et al., 1999; Brunswick et al., 1999; Cohen et al., 2002), suggesting that the left FG discriminates, on the basis of orthographic regularities, between legal and illegal strings. Several studies have also reported that the activation for letter strings extended into the left posterior inferior temporal gyrus (PITG) (Paulesu et al., 2000; Xu et al., 2001; Mechelli et al., 2003). While the left FG/PITG is thus referred to as the "visual word form area" (McCandliss et al., 2003), other researchers have clarified that this region is also activated during various multimodal tasks that do not engage visual word form processing (Price and Devlin, 2003). It is thus crucial to determine which cognitive factors are responsible for activating the left FG/PITG. In this paper, we tentatively call the left FG/PITG the "letter center".

A fundamental question is whether the left FG/PITG or other regions show plasticity for learning to associate letters with speech sounds, which is one critical subprocess of reading. In a recent fMRI study, we examined whether forming a new link between orthography and other linguistic information is necessary for the cortical plasticity in those regions (Hashimoto and Sakai, 2004). Cortical activations were monitored while the adult subjects were trained with Hangul letters for the first time. The subjects were Japanese who had learned kana letters by the age of seven, but they had no knowledge about Hangul letters before the experiments. Kana and Hangul letters are exclusively used in the Japanese and Korean languages, respectively. For both kana and Hangul letters used in the present study, there was a one-to-one correspondence between each letter and a speech sound. Here we focused on prelexical processing and used nonsense words for all the linguistic stimuli. The subjects participated in fMRI sessions over two consecutive days (Days 1 and 2, approximately 24 hours apart). The scanning sessions served as both testing and repeated exposures to the Hangul letters, and there was no separate training session except the initial exposure to the letters.

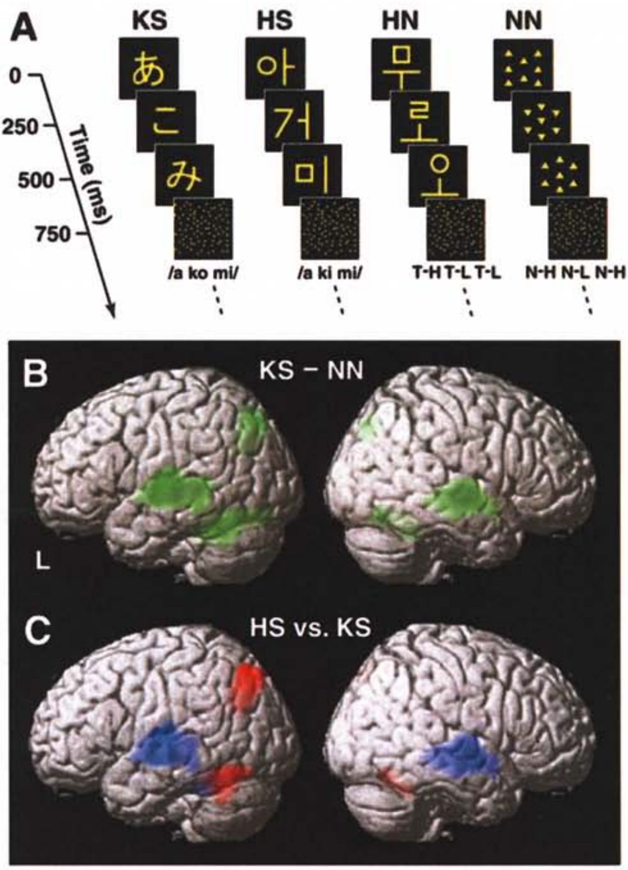

Figure 3. An audiovisual matching paradigm for testing a new link between orthography and phonology. (A) The four experimental conditions: kana and speech (KS), Hangul and speech (HS), Hangul and non-speech (HN), and non-letter and non-speech (NN). Under one of these conditions, a string of three visual stimuli (250 ms each) was presented at the center of the screen for each trial of 4 s. The subjects were asked to judge whether or not the visual string matched a string of auditory stimuli (total of 550 ms) that were presented either before or after the visual stimuli. A random dot pattern was presented between visual strings. A red cross for fixation was always shown at the center of the screen, but it was omitted from the figure. For the KS and NN examples the visual and auditory strings matched, and they did not match for the HS and HN examples. (B) Regions identified by the contrast KS – NN (green), using the data in Days 1 and 2. Activations of the superior and middle temporal gyri (STG/MTG) are bilateral, while left-dominant activation is observed over the fusiform gyrus (FG), the posterior inferior temporal gyrus (PITG), and the parieto-occipital cortex (PO). (C) Regions identified by HS – KS (red) and KS – HS (blue). Whereas the bilateral STG/MTG and the left FG are selectively activated under the KS condition, the left PITG and the left PO show selective activations under the HS condition.

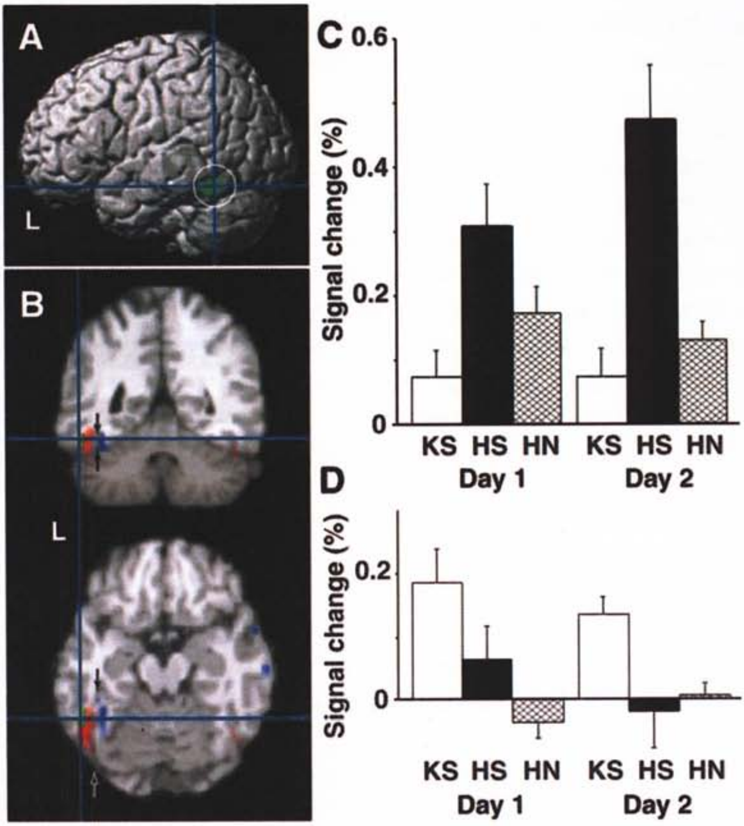

Figure 4. Direct visualization of cortical plasticity of the letter center for forming a new link between orthography and phonology. (A) A region exhibiting an activation increase induced by learning Hangul letters with speech sounds. The interaction of task by day in HS – NN for Day 2 – Day 1 resulted in significant activation in the left PITG (green), projected onto a surface-rendered standard brain. The location of its local maximum is shown by blue crosshairs (y = –51, z = –18). (B) The separation within the left FG/PITG. On the coronal (y = –51) and axial (z = –18) slices of a standard brain, the regions identified by KS – HS and HS – KS are shown in blue and red, respectively. Arrows indicate the lateral occipitotemporal sulcus that corresponds to the border between the PITG (lateral) and the FG (medial). Note that the region (green) with the interaction of task by day shown in (A) is localized within the left PITG. (C) Averaged activation data among subjects at the local maximum (–54, –51, –18) of the left PITG. Mean percent signal changes for KS (open bars), HS (filled bars), and HN_1 (crosshatched bars) on Days 1 and 2 are shown with reference to the corresponding NN condition. Error bars denote standard errors among the subjects. Note the selective activation increase under the HS condition from Day 1 to Day 2. (D) Averaged activation data at the local maximum (–36, –42, –24) of the left FG. In contrast to the left PITG, the left FG shows larger activation for KS than for HS or HN, with no significant activation change between Days 1 and 2.

The fMRI sessions consisted of four audiovisual matching tasks characterized as the following conditions: kana and speech (KS), Hangul and speech (HS), Hangul and non-speech (HN), and non-letter and non-speech (NN) (Figure 3A). Under the KS condition, the subjects were presented with a string of three kana letters for each trial of 4 s, and they were asked to judge whether or not it matched a string of three-syllable speech sounds. Individual letters were serially presented to ensure that the subjects attended equally to each letter. Because each letter was immediately masked by the next letter or a masking stimulus for the last letter, the subjects had to recognize each individual letter within the brief presentation time (250 ms). Under the HS condition, the subjects were asked to judge whether a string of three Hangul letters matched a string of three-syllable speech sounds. Under the HN condition, we used another set of eight Hangul letters, and the subjects were trained to associate these complex Hangul letters with non-speech sounds. This condition lacks phonology; thus, no link between orthography and phonology is trained throughout the experiments. Under the NN condition, in order to control for general cognitive factors related to low-level cross-modal matching and association, we further replaced letters with geometric patterns that are associated with non-speech sounds. We targeted HS as a major learning condition of interest for matching speech sounds with newly learned letters, whereas KS and HN served as control conditions for speech sounds and Hangul letters, respectively.

By employing this novel audiovisual matching paradigm to examine cross-modal learning effects on cortical plasticity, we obtained three striking results. First, we found that the regions recruited for integrating newly learned orthographic and phonological information, the left PITG and the parieto-occipital cortex (PO), are indeed separable from the specific regions of the superior and middle temporal gyri (STG/MTG), necessary for processing associative information including already acquired orthography (Figs. 3B & 3C). Moreover, the left PITG and the left PO activations, which are selectively enhanced under the HS condition in comparison with those under the KS and HN conditions, are not due to auditory factors alone, because the same set of speech sounds were presented under the KS and HS conditions. We also excluded the possibility that they reflect visual exposure to new and complex letters alone, given that the complexity of the visual stimuli used under the HS and HN conditions was basically equivalent. Therefore, we conclude that the left PITG and the left PO subserve the formation of a new link between letter and speech representations. Second, the left PITG, but not the left FG, showed a selective activation increase under the HS condition over two days (Figure 4), the degree of which was predictive of individual performance improvement. Behavioral results also indicate that learning effects of HS and HN on Day 1 were clearly manifested on Day 2. Moreover, it is intriguing that the functional separation between the two adjacent regions of the left PITG and the left FG followed the anatomical boundary of the lateral occipitotemporal sulcus (Figure 4B). These results suggest that the left PITG plays a primary and critical role in the cortical plasticity involved in learning new letters. Third, we demonstrated that functional connectivity between the left PITG and the left PO was selectively enhanced under the HS condition, but not under the KS or HN condition. The present fMRI study thus establishes that the human adult brain is still adaptable to new associations between orthographic and phonological stimuli, and that this type of learning is achieved in only two days by the rapid plasticity of a functional system critically involving the left PITG in association with the left PO.

The ability of learning to read is selectively impaired in patients diagnosed with developmental dyslexia (Shaywitz, 1996; Habib, 2000). With regard to the neurological basis of this impairment, previous imaging studies have revealed reduced activation in the left FG/PITG of dyslexic adults relative to that in normal controls when reading words or pseudowords (Shaywitz et al., 1998; Brunswick et al., 1999; Paulesu et al., 2001). A magnetoencephalography (MEG) study revealed cortical responses selective to letter strings in the left inferior occipitotemporal cortex in normal adults; these responses were not detectable in dyslexics (Helenius et al., 1999). The findings in the present study are consistent with those in these studies, in that they suggest that the lesions in the left FG/PITG may impair linking orthography to phonology. Furthermore, we have clearly established differential roles for the left FG and the left PITG; the left FG processes information about already acquired orthography, whereas the left PITG integrates newly learned orthography and phonology. We suggest that in the case of the literate adult reader, a selective lesion of the left FG or the left PITG might lead to double dissociation of deficits in reading letters, such that a left FG lesion selectively impairs already acquired orthography, whereas a left PITG impairment selectively impairs the formation of a new link between orthography and phonology. Taken together, the present results provide the initial step towards understanding the neural mechanisms that underlie the scope and limits of learning in school-age children and adulthood. Research in this direction could contribute to the neuroscience of education, and be utilized to develop effective training programs for language learners and for patients with language disabilities.

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