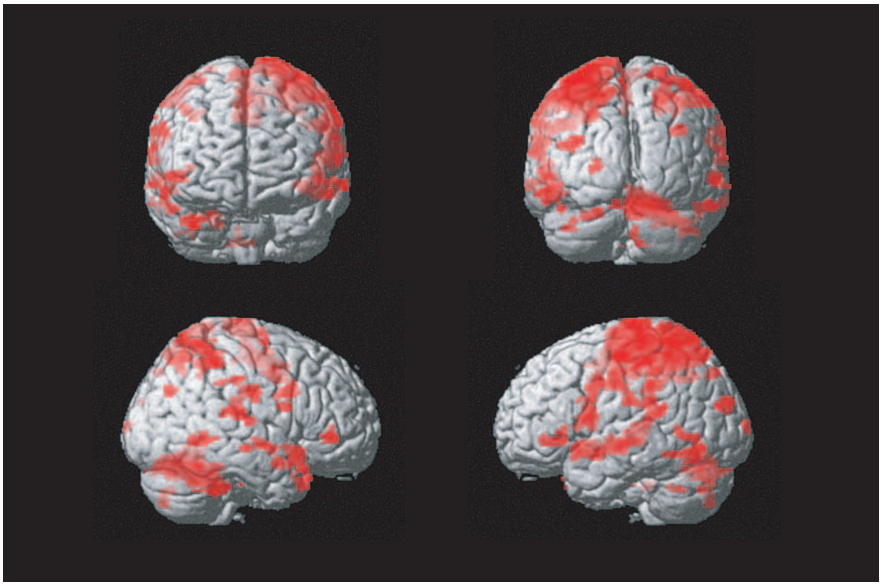

Plate 4. Activated brain areas while a healthy right-handed subject was engaged in a writing-to-dictation task relative to a resting baseline. Detail of this fMRI experiment was described elsewhere (Nakamura et al., 2001).

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Functional neuroanatomy of Japanese writing systems

Kimihiro Nakamura and Sid Kouider
Laboratoire des Sciences Cognitives et Psycholinguistique, France

Background: Most of the brain imaging studies to date have addressed the skill of writing as a paradigm to examine the neural correlates for complex limb movements. Although these data have enriched our view of the functional organization of the brain for motor aspects of writing, there have been few attempts to discuss their relevance to aphasiology research.
Aims: The aim of the present article is two-fold. First, we examined neuroimaging data on writing to provide an overview of the neurophysiological basis subserving the motor aspects of the skill. Second, while taking into consideration the framework provided by these data, we reviewed lesion and functional imaging studies of Japanese to discuss the possible difference in neural correlates that has been assumed for its two orthographic systems, kanji (logogram) and kana (syllabogram).
Main Contributions: The fronto-parietal cortical circuit linking the premotor with posterior parietal areas in the left hemisphere seems to constitute a basic neural substrate for the motor act of writing. Lesion and imaging data with Japanese suggest that writing of kana utilises these structures in conjunction with the left perisylvian area for spoken language. In contrast, writing of kanji shares this network for the later phase of motor execution, but recruits the left basal temporal area as an additional device for the generation of motor output.
Conclusions: The execution of writing, irrespective of the script type, is achieved by common brain structures used for a wide range of limb movements. Writing of kanji seems to differ from that of kana only in that the former needs the retrieval of visuospatial information of characters as an additional cognitive operation. This difference does not necessarily imply that the two kinds of script have distinct neural substrates.

As a modality of language production, the skill of writing is achieved by highly complex psychophysiological mechanisms which may be comparable to those for speaking. However, the use of visualised verbal symbols has been, and can be, thought a ‘‘non-natural’’ skill in the sense that it needs to be taught systematically and it might be merely an external device optionally implanted on the innate language systems (Bloomfield, 1933). This seems more or less the case, given that several different writing systems, ranging from pictographs to alphabetic scripts, evolved independently of each other in different parts of the world through not more than a few thousand years and that there still exist many illiterate communities that do not utilise written languages routinely (Crystal, 1997). The production of written language is therefore unlikely to be a biological or genetically driven ability in its own right as may be the case with spoken language. This specificity of writing as a late-learned, artificial skill may be consistent with

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Address correspondence to: Kimihiro Nakamura, Speech Physiology, Graduate School of Medicine, University of Tokyo, 7-3-1, Hongo, Tokyo 113–33, Japan. E-mail: kimihiro@m.u-tokyo.ac.jp

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neuropsychological data that disorders of the skill can occur separately from those of spoken language and that the former tend to be more vulnerable to brain insult (Friedland, 1990). In turn, however, it may not be very surprising that the human brain acts differently in the perception and generation of different writing systems if they each are linked with pronunciation and meaning to variously different degrees. This issue, as discussed later, has long been a central theme for many neurolinguistic studies of the Japanese language, which uses simultaneously two different orthographic systems, kanji (logogram) and kana (syllabogram).

Cognitive models of writing are characterised by a modular architecture of multiple processing components, typically ranging from auditory analysis of speech input to motor execution, which may have separate neuroanatomical substrates and interact with each other (Margolin, 1981; Roeltgen, 1993). However, despite the diversity of the cognitive and sensorimotor processes involved in writing, most of the previous neuroimaging research has dealt with the skill only as a model to explore the central mechanisms for the control of complex limb movements (Braun, Heinz, Schweizer, Wiech, Birbaumer, & Topka, 2001; Scholz et al., 2000; Seitz et al., 1997; Siebner, Limmer, Peinemann, Bartenstein, Drzezga, & Conrad, 2001). The skill as a motor paradigm has been also employed for many electrophysiological and neuroimaging studies on neurological disorders of writing, such as writer's cramp (Berg, Preibisch, Hofmann, & Naumann, 2000; Deuschl, Toro, Matsumoto, & Hallett, 1995; Ibanez, Sadato, Karp, Deiber, & Hallett, 1999; Odergren, Stone-Elander, & Ingvar, 1998; Preibisch, Berg, Hofmann, Solymosi, & Naumann, 2001). Although these studies indeed provide important data concerning the neural substrate for motor aspects of writing, it is of note that few functional imaging studies have addressed the linguistic processes of the skill, or more specifically, the psychophysiological processes that may link the language system with motor action.

Accordingly, the limited set of neuroimaging data currently available, obtained from different experimental designs adapted for different purposes, does not automatically give us a more comprehensive view about the functional neuroanatomy of writing. The present article attempts to interpret the recent neuroimaging data relating to the skill and relevant lesion data by reference to the conventional neuropsychological models (Margolin, 1981; Roeltgen, 1993). The first section of the article is assigned to cast a look at neuroimaging studies of handwriting and consider the cerebral mechanisms for more peripheral aspects of the skill. In the second section, we review recent lesion and imaging data on Japanese to discuss the commonality and specificity for the phonographic and logographic scripts in terms of their neural substrate for writing.

HANDWRITING AS A MOTOR SKILL

Brain activation during writing

Brain activation experiments in normal subjects differ from lesion studies in that they are designed to reveal a whole set of brain regions active in a given task relative to another while some of these activation sites may not be specifically relevant to task requirements (e.g., Price, 1998). This ''inclusive'' nature of the technique may allow us to delineate a set of brain regions active in normal writing, including those structures whose implicit contribution during the execution of the task is not always predictable from lesion data. For example, a handwriting task usually yields strong activation in the anterior cingulate cortex and prefrontal cortex, while damage to these areas is not thought to entail a direct impact on the motoric or linguistic functions, which suggests that the skill is subserved by a distributed neural network for attention and motor execution. Indeed, functional magnetic resonance imaging (fMRI) allows us to visualize the extensive bilateral activation while a healthy right-handed subject is engaged in a writing-to-dictation task in comparison to a resting condition (Plate 4, situated between pages 656 and 657). The largest cluster of activation in the left frontoparietal region extends from the premotor areas to the left posterior parietal cortex. There are bilateral activations in the cingulate gyrus, basal ganglia, thalamus, and cerebellum. Overall pattern of activation is largely consistent with another study with positron emission tomography (PET) (Seitz et al., 1997), and can be thought to represent a basic set of brain regions active in the execution of writing.

Fronto-parietal network for handwriting as a motor skill

A central issue addressed by behavioural and neurophysiological studies of writing concerns how patterns of complex limb movements are coded independently of effector organs such as fingers and hands, as formulated by the concept of ''motor equivalence'' (Lashley, 1951). That is, the fact that we can write out a word not only by hand but also with a pen held between the toes suggests the existence of an abstract representation of the form of the letter or word, independent of the specific effectors. In this respect, several different lines of evidence point to the crucial role of the reciprocal connection between the premotor cortex and posterior parietal area, including the superior and inferior parietal lobules. A PET study by Seitz et al. (1997) showed that fast handwriting of an overlearned letter, as well as motor imagery of writing a nonsense letter, increases the activity of these posterior parietal areas, and suggested that the kinematic representations of graphomotor trajectories are represented in these regions. In another PET study (Van Mier, Tempel, Perlmutter, Raichle, & Petersen, 1998), a unimanual drawing task activated bilateral fronto-parietal regions, including the supplementary motor area (Brodmann [BA] 6) and posterior parietal cortex (BA 7 and 40), irrespective of whether left or right hand was used for the task. A recent PET study by Siebner et al. (2001) showed that fast and slow handwriting tasks both increase the regional cerebral flow in the lateral premotor cortex (BA 6) and inferior parietal areas (BA 40) in the left hemisphere regardless of the task condition. Notably, the slower writing condition, which requires continuous monitoring of sensory input to adjust the subsequent motor act, activated these structures more greatly, suggesting the importance of the areas for integrating the sensory feedback.

On the other hand, a few other neuroimaging studies used ''motor imagery'' of writing as a paradigm to examine the brain substrate for the planning of limb movements (Katanoda, Yoshikawa, & Sugishita, 2001; Kato, Isoda, Takehara, Matsuo, Moriya, & Nakai, 1999; Seitz et al., 1997; Sugishita, Takayama, Shiono, Yoshikawa, & Takahashi, 1996; Tokunaga et al., 1999). In accordance with the results on actual writing, these studies consistently reported activation of the left posterior parietal area and lateral premotor cortex despite the considerable variation in experimental settings, which may support the notion that motor imagery employs nearly the same set of brain structures as does overt movement (Crammond, 1997). For this issue, converging evidence was provided by a neuropsychological study by Sirigu, Duhamel, Cohen, Pillon, Dubois, & Agid (1996) which demonstrated that damage to the parietal cortex affects the ability to generate mental representations of limb movements. The authors suggested that the area constitutes the neural substrate for the storage of visual and kinesthetic limb postures and for mapping these representations to the premotor and motor regions which may contain the corresponding motor programs. Lastly, all these findings are compatible with neurophysiological data in monkeys that the fronto-parietal network linking the premotor cortex with posterior parietal regions works as a visuomotor controller which transforms proprioceptive, visual, gaze, attentional, and other information to produce the signals required for the selection, preparation, and execution of movements (Wise, Boussaoud, Johnson, & Caminiti, 1997). It is interesting to note that the left lateral premotor cortex (BA 6) active in the execution and imagery of writing represents the arm movements (Rizzolatti, 1998), and that the area partially overlaps the second frontal convolution corresponding to the so-called Exner's writing centre, damage to which is known to produce pure agraphia. Also, the role of the parietal cortex in motor control may be relevant to the fact that the superior parietal lobule (BA 7) in the left hemisphere is correlated with the motor execution of writing, as suggested by studies of apraxic agraphia (Alexander, Fisher, & Friedman, 1992; Otsuki, Soma, Arai, Otsuka, & Tsuji, 1999).

Moreover, the parietal lobe is thought to play an important role in the integration of sensory feedback during complex limb movements. It has been proposed that two different coordinate systems, a world-centred frame and a more intrinsic, body-centred one based on proprioceptive information, are concurrently available for encoding the sequence of limb movements (Lacquaniti, 1989). Indeed, behavioural studies of normal subjects showed that visual sensory feedback improves the speed and accuracy of writing (Kalmus, Fry, & Denes, 1960; Smith, McCrary, & Smith, 1960), whereas other studies suggested that proprioceptive information from the limbs contributes in the execution of drawing (Teasdale, Forget, Bard, Paillard, Fleury, & Lamarre, 1993; Verschueren, Swinnen, Cordo, & Dounskaia, 1999). Physiological studies in monkeys suggest that posterior parietal areas constitute the neural substrate for processing visual and somatosensory feedback during hand movements (Rizzolatti, 1998; Wise et al., 1997).

Obviously, other brain structures, especially the basal ganglia and cerebellum, are also thought to play a certain role in motor control of writing. The involvement of these areas in writing may be best illustrated by observations of basal ganglia disorders, such as writer's cramp and Parkinson's disease. Apart from the subcortical contribution, however, the set of recent data mentioned above concordantly highlights the importance of the fronto-parietal circuit as a neurophysiological basis for the execution of writing.

NEUROPSYCHOLOGICAL STUDIES OF JAPANESE WRITING SYSTEMS

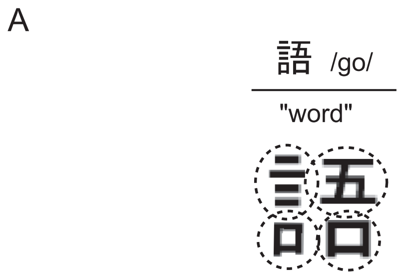
Kanji agraphia in posterior temporal lesions

The idea that orthographic representations of words may play a role in spelling was systematically put forward by descriptions of lexical (or orthographic) agraphia that selectively affects the ability to spell phonologically irregular words (Beauvois & Dérouesné, 1981; Roeltgen & Heilman, 1984). The disorder, which was originally attributed to impaired access to visual word images, seems to constitute a fairly distinct neuropsychological syndrome, for which critical lesions largely converge in the left parieto-occipital junction (Roeltgen, 1993). Although more recent work has raised doubt about whether such orthographic codes are indeed formatted as visual images (Del Grosso Destreri, Farina, Alberoni, Pomati, Nichelli, & Mariani, 2000; Margolin, 1981; Rapp & Caramazza, 1997), the conventional account for this form of agraphia provided a basic framework to describe neuropsychological mechanisms for writing in a more universal perspective. In Japanese, for example, a disorder equivalent to lexical agraphia has been described as ''kanji-selective'' agraphia (Soma, Sugishita, Kitamura, Maruyama, & Imanaga, 1989).

Kanji characters, originally imported from China in the fifth century, are used mainly for nouns and for the roots of verbs, adjectives, and adverbs (see Wydell & Butterworth, 1999, for detail). Most of them have rather complex graphic forms (Figure 1A) and several different readings. It is generally thought that normal Japanese adults need to know more than 3000 kanji characters for their everyday life. Most kanji characters are pronounced in several different ways, depending on the semantic or morphological context, e.g., 神 /*ka-mi*/ ‘‘god’’; 神経 /*shiN*-ke-i/‘‘nerve’’; 神社 /*jiN*-ja/‘‘shrine’’; 神主 /*kaN*-nu-shi/‘‘priest (shintoist)’’; 神戸 /ko-u-be/‘‘Kobe (city)’’. This close ‘‘visual-semantic’’ link between characters and their meaning is no less important for writing of kanji, for there are so many homophone words in Japanese that in writing-to-dictation people often need information other than phonology, especially the semantics, to select a lexical item matching the context among several homophone candidates stored in orthographic memory (Figure 1B).

On the other hand, *the kana writing system, developed by simplifying the graphic forms of kanji, consists of two parallel phonetic syllabaries, hiragana and katakana, each composed of 46 basic characters. Hiragana is usually used for function words and grammatical endings of verbs, nouns, and adjectives, whereas katakana is used for writing foreign words*. (Note that this is a rough principle and that either kanji or hiragana can be used rather arbitrarily for writing many words, especially nouns.) With few exceptions, kana characters each have a one-to-one correspondence with their spoken forms, irrespective of their position within a word (e.g., さくら /*sa*-ku-ra/ ‘‘cherry-blossom’’; うさぎ /u-*sa*-gi/ ‘‘rabbit’’; うるさい /u-ru-*sa*-i/ ‘‘noisy’’; ささや /*sa*-*sa*-ya-ku/ ‘‘whisper’’). As illustrated in Figure 1B, any Japanese word can be spelled out in kana through a procedure comparable to phonology-to-orthography conversion, apart from the fact that such transcription in kana often causes some ambiguity because homophones are always homographs when written in kana (by contrast, there is no such ambiguity when spoken words are transcribed in kanji). While writing of kanji is generally thought to involve a stored representation of their orthographic forms, one may often need other information, such as the semantic context and lexical frequency of words to be written, to select the appropriate lexical items among many homophone words. To a certain degree, one may reasonably suppose a parallelism between kanji-selective agraphia and lexical agraphia, because words written in kanji and kana each are comparable to phonologically irregular and regular words in alphabetical languages. That is, the relationship between letter and sound is transparent for kana whereas it is extremely opaque for kanji.

A body of neuropsychological studies on Japanese suggests that different neural mechanisms work for processing the two orthographic systems. More specifically, Iwata (1984) proposed that writing of kana characters may be realised though fronto-parietal cortical connections, including the inferolateral frontal area and motor association cortex, whereas more posterior, temporo-occipital regions are important for writing kanji. In particular, kanji-selective agraphia has been well correlated with damage to the left postero-inferior temporal cortex (PITC) (Kawamura, Hirayama, Hasegawa, Takahashi, & Yamaura, 1987; Kawahata, Nagata, & Shishido, 1988; Soma et al., 1989; Yokota, Ishiai, Furukawa, & Tsukagoshi, 1990). A multiple case study by Soma et al. (1989) reported that focal lesions in the left PITC, largely corresponding to the inferolateral surface of BA 37, consistently produces a writing disorder selective for kanji. Typically, these patients complain of forgetting forms of characters to be written, but have no difficulty in copying kanji characters upon visual presentation of exemplars. Soma et al. (1989) further suggested that the symptom arises from impaired access to visual graphic forms of kanji characters and that it represents a writing disorder analogous to lexical agraphia in terms of the neuropsychological feature and lesion sites. Although none of these studies has systematically evaluated patients’ abilities for visual imagery of letter forms, they have provided empirical data suggesting that the mental visualisation of graphic forms plays a



B

/si-ko-u/

Kana	しこう	(hiragana)
	シコウ	(katakana)
Kanji	思考	"thinking"
	施行	"enforcement"
	志向	"intention"
	至高	"sublime"
	歯垢	"tartar"
	嗜好	"taste"
	試行	"trial"

Figure 1. **A:** Physical features of kanji characters. Most kanji characters are composed of two or more separate constituents. These elements are thought to serve as a basic subunit for learning and recognition of the whole graphic form, which might be achieved by computing the patterns of their combination.

B: Examples of homophones in Japanese. There are several different words which are pronounced as a same trisyllabic sound /si-ko-u /. Normal Japanese readers can readily understand the meaning of each exemplar when they are written in kanji, while it is highly ambiguous when transcribed in kana.

role as a reference for generating the intended motor sequence. This interpretation, compatible with the subjective impression that a normal Japanese person commonly feels in the act of writing of kanji, seems in good accordance with the neurophysiological data that the inferior temporal area works as a storehouse of visual long-term memory in primates (Miyashita, 1993). Accordingly, we assume here that it is visuospatial representations of graphic forms that play an important role in writing of many, if not all, kanji characters (Figure 2).

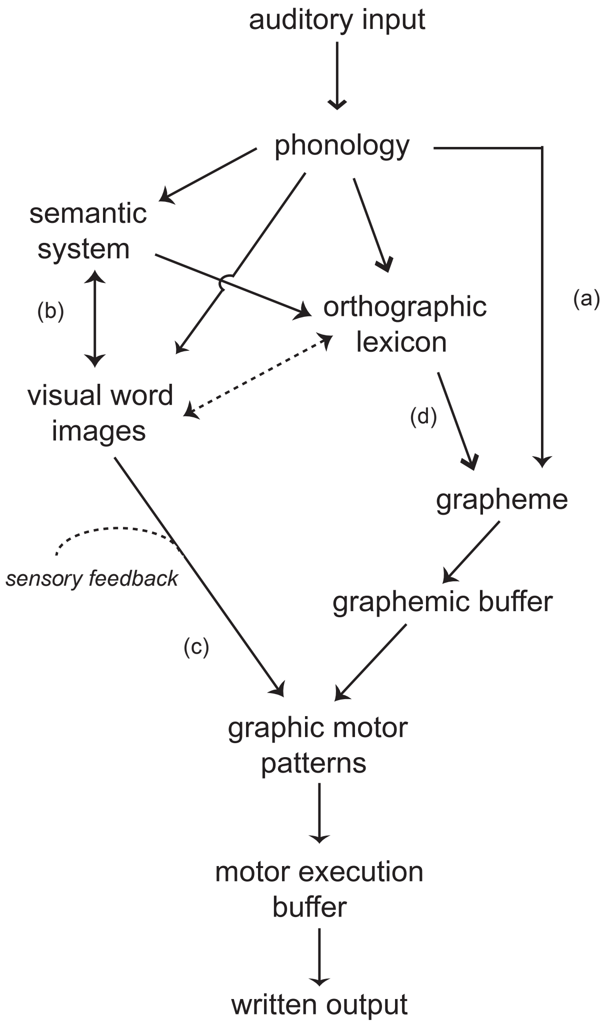


Figure 2. Cognitive processes involved in writing Japanese (Broken lines indicate rather hypothetical links). Since kana characters each have one-to-one correspondence with their spoken forms, any Japanese word can be spelled out in kana through a procedure comparable to the phonology-to-orthography conversion (a). In contrast, writing of kanji requires a stored representation of their orthographic forms. It is assumed here that visuospatial representations of orthographic word forms, or visual word images, play an important role in writing of most kanji characters. Such representations may act on several different stages in the execution of writing, including the semantic processing of the spoken input (b) and monitoring of the motor execution (c). On the other hand, it is possible for words of very high frequency or simpler graphic forms (either in kanji or kana) to be written directly by way of more abstract orthographic representations (d).

At the same time, it is possible that activation of visual representations of graphic forms occurs at several different stages involved in writing. First, such visual representations may be activated independently of the writing process *per se*. Probably because of the strong associative link between kanji and their meaning, visualisation of kanji graphic forms is thought an effective strategy commonly used by normal Japanese adults for understanding of spoken language, particularly in case of homonymy (Morton & Sasanuma, 1984). Second, as suggested by the observations that agraphic patients with PITC lesions can quickly copy kanji characters without difficulty, such visual word images may be important for activating stored graphic motor patterns required for the execution of writing. Third, given the complex visuospatial structure of kanji, such representations may help guide, monitor, and modify the ongoing motor execution of writing.

On the other hand, it also seems plausible to assume that different, motorically based representations of graphic forms play an important role in writing kanji. For example, Ihori, Kashiwagi, Kashiwagi, & Tanabe (1994) argued that graphic constituents of kanji as shown in Figure 1A have separate motor representations which might constitute a basic ‘‘motor unit’’ for writing out a complex graphic form of kanji. Moreover, it is possible that some kanji characters, such as those of very high frequency and simpler graphic forms, are written out directly without the mediation of the visuospatial representations. In this context, the modality of orthographic representations involved in writing kanji might be rather heterogeneous and include visuospatial as well as graphomotor representations. Whether words are represented in one or both formats may be determined by other psycholinguistic factors, such as their frequency, graphic complexity, and familiarity. However, the possibility of an amodal level of orthographic representation such as that involved in alphabetic writing systems (Rapp & Caramazza, 1997) remains an open question for logographic scripts due to the lack of empirical or experimental evidence regarding this matter. (By contrast, we may reasonably assume the presence of such amodal graphemic representation for the phonographic kana script [Figure 2], given the fact that the two forms of kana (hiragana and katakana), which are parallel phonetic transcriptions of same sound but are radically different from each other in their physical features, are comparable, to a certain degree, to allographic letters in alphabetic systems.)

The absence of amodal representations for kanji may account for the fact that lesion sites of lexical agraphia are typically located in left inferior parietal area (e.g., Roeltgen, 1993), which does not overlap those of kanji agraphia in PITC damage, despite the useful parallel that can be drawn between the two neuropsychological disorders. As discussed above, if we suppose that modalities of representations involved in writing are more or less different between alphabetic letters and kanji, i.e., abstract letter-forms for the former and more visuospatial ones for the latter, it may not be surprising if the distribution of lesion sites also differs between lexical agraphia and kanji agraphia.

Fronto-parietal network for writing of kana

There are several reports on the complementary dissociation in writing ability, that is, agraphia selective for kana (see Table 1). The patient reported by Tanaka, Yamadori, and Murata (1987) had two lesions involving the left angular gyrus and adjacent postero-superior temporal gyrus. Two other patients with kana agraphia also had left parietal lesions (Kimura, Matsuda, Kuroiwa, & Tohgi, 1986; Fujii, Motoyama, Shimizu, & Kurachi, 1995). In contrast, Abe, Yokoyama, Yorihuji, & Yanagihara (1993) described a

TABLE 1
Lesion sites and writing performance of patients with kana-selective agraphia

		% Correct (No. of test items)				
	Lesion site	*Kanji*	*Kana*	*Type of errors*[a]	*Effect of word length*	*Effect of lexicality*
Kimura et al. (1986)	L parietal lobe	—	—	No response Substitution	—	—
Tanaka et al. (1987)	L parietotemporal area	92% (50)*	50% (50)*	Substitution	Yes	—
Abe et al. (1993)	L mid frontal gyrus	100% (50)	75% (50)	Substitution ?	—	—
Fujii et al. (1995)	L supramarginal/angular gyri	90% (10)	45% (47)	Substitution Deletion/Intrusion	—	—
Sakurai et al. (1997)	L mid/inf frontal gyri	86% (100)	73% (100)	Deletion/No response Substitution	—	—
Hashimoto et al. (1998)	R frontoparietal area	96% (50)*	28% (50)*	Substitution Deletion	Yes	No
Kokubo et al. (2001)	R putamen	100% (20)	60% (20)	Substitution	Yes	No

* Error rates were calculated by the authors using the data presented in the original article.

[a] The type of errors indicates predominant patterns of writing errors for each patient.

patient with kana-selective agraphia after damage to the left middle frontal region. Another patient had a lesion in the middle and inferior frontal gyri, although a PET scan of the patient showed more widespread hypoperfusion of the left frontal region and basal ganglia (Sakurai, Matsumura, Iwatsubo, & Momose, 1997). Furthermore, Kokubo, Suzuki, Yamadori, and Satou (2001) recently reported a left-handed patient with kana agraphia associated with right putaminal damage, whereas Hashimoto, Tanaka, and Yoshida (1998) described a case of kana agraphia associated with a right hemisphere lesion. Except for the last two cases, therefore, kana-selective agraphia seems correlated with lesions in either ventrolateral frontal area or inferior parietal cortex in the left hemisphere. It is of note that no single case of kana agraphia has been known to have lesions in left postero-inferior temporal area. Accordingly, overall distribution of the lesion sites described in these reports seems to point to the importance of the fronto-parietal network for writing of kana. This is in agreement with the neuroimaging studies on normal subjects which demonstrated the activation of the lateral premotor cortex to the posterior parietal area in the execution of an overlearned skill as writing letters (Seitz et al., 1997; Siebner et al., 2001).

Moreover, despite the variability in lesion sites distributed in the frontoparietal cortex and other brain regions, it appears a rather consistent feature common to these patients that their spelling errors, most of which are classified as literal paragraphia characterised by substitution, tend to increase with the number of kana characters to be written while their ability to copy remains unaffected (Fujii et al., 1995; Hashimoto et al., 1998; Kimura et al., 1986; Kokubo et al., 2001; Tanaka et al., 1987). Notably, Hashimoto et al. (1998) and Kokubo et al. (2001) claimed that the symptom can be interpreted as reflecting dysfunction of the graphemic buffer for storing temporally graphemic representations of words to be written. Concerning the dissociation in writing performance between the two scripts, Kokubo et al. (2001) raised two possible accounts; (i) there are two separate graphemic buffers for kanji and kana words, or (ii) the read-out process from the graphemic buffer is more efficient for kanji words, possibly because of their closer link with semantics. However, if we assume such a ‘‘kana-specific’’ graphemic buffer to be modality-independent and hence utilised for both hiragana and katakana, the former interpretation may fail to explain the finding that the patient’s writing performance differed between the two forms of kana. In contrast, the close ‘‘visual-semantic’’ and ‘‘visual-motoric’’ links for kanji, plausibly related to their ideographic nature, might allow the patients to access their visual graphic images, which in turn may help activate the malfunctioning graphic motor plans more effectively. Such interaction among representations of different modalities has been suggested by several neuropsychological studies. For example, Yaguchi, Bando, Kubo, Ohi, & Suzuki (1998) reported that a visual cue improved the writing performance of kanji in an agraphic patient with parietal damage, suggesting that visual representation of character forms activates the motor plans for writing them. In contrast, a recent study by Bartolomeo, Bachoud-Lévi, Chokron, & Degos (2002) reported that such facilitation works in a bi-directional way, i.e., visual images of letter forms can also be activated by motor-based knowledge. Another example of such cross-modal activation of dysfunctioning representations is ‘‘kinesthetic reading’’ of kana observed in Japanese alexic patients (Iwata, 1984). These patients can read aloud kana characters only when they are allowed to trace the forms of characters with their fingers. Interestingly, Iwata (1984) stated that the same manoeuvre does not improve the performance in reading kanji. These findings suggest that motor representations of kanji characters are more closely associated with their visual images while they are not interconnected with phonology as effectively.

On the other hand, despite the parallelism that can be postulated between kanji agraphia and lexical agraphia, it remains rather unknown whether these cases of kana-selective agraphia represent a disorder equivalent to phonological agraphia in the alphabetic writing systems. That is, none of these patients was shown to have typical clinical features of phonological agraphia, such as impaired ability to spell nonwords in contrast to preserved ability to spell familiar words and visual-related writing errors In fact, only two studies (Hashimoto et al., 1998; Kokubo et al., 2001) evaluated the effect of lexicality and/or familiarity on writing performance, while none of the others examined the issue systematically (see Table 1). Moreover, both of the former studies showed that the patients' writing ability was affected similarly for words and nonwords. Therefore, it seems hard to conclude that the writing disorder in these patients arose from phonlogical impairment (rather, as discussed before, it may reflect more peripheral or motoric deficit). Indeed, the fronto-parietal lesions found in these patients do not overlap the perisylvian lesions that are generally thought responsible for phonological agraphia (Roeltgen, 1993).

However, it may sound reasonable to predict that certain forms of phonological impairment should result in kana agraphias, especially as a parallel to deep alexia that can be caused by left perisylvian damage in Japanese as well (Sasanuma, 1987). While there have been a few descriptions of kana-selective agraphia associated with left fronto-temporal lesions (Paradis, Hagiwara, & Hildebrandt, 1985), no detailed case study seems available to date for this issue. Although it is plausible to assume that such process should play an important role in writing of kana, it seems unclear whether (or to what extent) dysfunction of the phonological system can leave writing of kanji unaffected, for there are a few reasons to believe that the phonological system needs to work properly for the production of kanji as well. This is because kanji characters each code not only semantic information but also several different phonetic values. Moreover, under the condition where two or more homophone words co-exist, people can select an optimal item among the ''competitors'' only by reference to other information, i.e., through the computation of either their frequency or the semantic context of spoken input. For the latter, the phonology-to-semantics link should be operating properly. These might partially explain why writing of kanji is not consistently preserved in perisylvian lesions.

In fact, it is not clear whether there is any brain region specifically required for writing of kana but not for kanji, although the former may place a greater demand on the phonological system, and the latter on the posterior temporal system. As illustrated by Iwata (1984), writing of kanji needs to incorporate the left temporo-occipital region as an additional device with the more basic frontoparietal system necessary for writing the phonographic letters. The fact that lesion sites for kana-selective agraphia tend to converge on frontoparietal areas and that such lesions most commonly affect writing of both kanji and kana rather suggests that these patients' symptom actually arises from a more generalised decay of the motor representation for writing stored in these areas. In other words, the fact that kana agraphia occurs only rarely can be explained by the possibility that the degradation of the system might be incidentally compensated for in the writing of kanji through a kind of facilitation mediated by the visual-motoric associative link as mentioned above. If so, these cases may not represent ''true'' kana-specific agraphia in its own right, in the sense that kanji-selective agraphia in left PITC damage is a ''true'' deficit of a normal function required for writing kanji. Anatomically, such alternative, visual-motoric associations subserving kanji might be mediated by some complementary input to the frontal cortex from the inferior temporal area. At least in primates, the inferior temporal cortex is known to have such projections to the frontal cortex (Hasegawa, Fukushima, Ihara, & Miyashita, 1998; Miyashita, 1993).

Neuroimaging studies on writing, however, have provided apparently conflicting results, for a PET study by Tokunaga et al. (1999) reported greater activation in the left angular gyrus during mental writing of kana relative to an equivalent task for kanji, whereas an fMRI study by Nakamura et al. (2001) did not detect any brain area specifically activated by the writing of kana.

Functional brain imaging of the writing of kanji

An fMRI study by Nakamura et al. (2000) demonstrated that the same posterior temporal region is indeed active not only in actual writing of kanji but also in visual mental recall of its character forms, suggesting that both writing of kanji and visual imagery of its graphic forms share common brain structures, including the left PITC. This finding complements the conventional view from lesion data that the area participates in the process of writing of kanji through the retrieval of its visual graphic forms. A subsequent fMRI study demonstrated similar activation of the left PITC in visual imagery of kana characters whereas activation of the same area tended to vary among individual subjects in writing of kana (Nakamura et al., 2001). The result that visual imagery of the graphic forms activated the left PITC similarly for both kanji and kana suggests that the visual orthographic forms *per se* are represented in this region regardless of the script type. The finding is compatible with the observation that damage to the left temporo-occipital region often causes disorders of visual imagery, including that of letter forms (Farah, 1995). In contrast, the result that writing of kana activates the left PITC to a varied degree among subjects, although apparently conflicting with lesion data that this particular skill is not affected by damage to the area, can be interpreted as reflecting varied cognitive strategies adopted by each subject for executing the task.

The set of neuroimaging data, coupled with many lesion studies mentioned before, suggests that normal Japanese subjects write kanji characters with some recourse to visual imagery of graphic forms. This stands in contrast to the view that physical letter codes for writing are not necessarily visually formatted in the alphabetical systems (Del Grosso Destreri et al., 2000; Margolin, 1981). Rapp and Caramazza (1997) stated that the abstract set of stroke features and motor plans might be available only for the writing of highly practised forms such as letters and digits, and not for all written output. Given the large set of kanji characters currently used and their complex graphic structures, the argument above does not conflict with the idea that normal Japanese writers exploit imagery-based information as a reference to control a complex stroke sequence of kanji.

This does not imply that people write kanji as they ‘‘draw’’ objects. On the contrary, the observation that patients with PITC lesion can quickly copy kanji characters without difficulty (Soma et al., 1989) suggests that writing of kanji also heavily depends on stored graphic motor patterns, which need to be incorporated with visual graphic images in motor execution of writing. Possibly relevant to the issue is the fact that most kanji characters are composed of several discrete constituents and that each character has built-in visuospatial information determined by the spatial distribution of the constituents (Figure 1A). Since these spatially discrete clusters are thought to constitute a basic unit for the visual recognition of kanji (Kaiho & Nomura, 1983; Saito, 1997), visual representations of each kanji may be constituted similarly as a sum of such components. On the other hand, as suggested by the fact that children usually learn to write a kanji character by repeated practice in writing each of its constituents separately, each of such elements is written out rather automatically in normal writing based on their motor representation acquired through the practice, whereas their spatial distribution needs to be organised based on a kind of visuospatial memory. In this sense, both visual- and motor-based knowledge is likely to operate in an interactive fashion in the process of writing kanji (e.g., Ihori et al., 1994). Since the retrieval of visuospatial information and execution of graphic motor patterns are likely to proceed in tandem and interact with each other through the process of normal writing, it is possible that dysfunction of one system results in a failure to activate another. Thus, this issue needs to be addressed more systematically with brain-damaged patients.

Posterior temporal activation in writing

A few more words may be needed regarding the fact that the activation of the left PITC in the writing process seems rather inconsistent among previous functional imaging studies. For example, a PET study by Petrides, Alivisatos, & Evans (1995) described bilateral activation of the posterior temporal regions in a comparison between writing-to-dictation and delayed recall of learned words, but both activation sites were located more dorsally than Brodmann area 37 as mentioned above. A PET study by Seitz et al. (1997) used three kinds of behavioural tasks, i.e., learning, performance, and imagery of writing a letter ''r'', while none of the three tasks exhibited activation of the left posterior temporal areas. A recent fMRI study by Katanoda et al. (2001) described extensive occipito-temporal activation in writing minus finger-tapping comparison, but reported no activation of that area in either writing minus silent naming or in writing minus word retrieval. Moreover, a PET study (Tokunaga et al., 1999) compared brain activity during mental writing between kanji and kana and reported that the area was significantly more active for kanji.

Most of the discrepancies, however, may be attributed to the considerable variation of experimental designs. Namely, both Petrides et al. (1995) and Katanoda et al. (2001) used a kind of word retrieval task as a control condition. Since lesion and neuroimaging data indicate that the left basal temporal region (BA 37) plays an important role in word retrieval (Price, 1998), it is likely that the possible activation of the area during both activation and control tasks was cancelled out by comparing the two conditions. On the other hand, writing of a single letter as used by Seitz et al. (1997) may not recruit the area consistently, as is the case with the varied activation patterns during writing of kana (Nakamura et al., 2000). Such variability of activation patterns associated with differences in the experimental design is not surprising, because subtle changes in these factors during cognitive tasks can seriously influence the brain response as observed in functional brain imaging (Price, Wise, Watson, Patterson, Howard, & Frackowiak, 1994).

CONCLUSIONS

Neuroimaging studies of writing, as well as several other lines of evidence, indicate that the fronto-parietal circuit constitutes a basic cortical substrate for motor aspect of the skill. As summarised in Figure 3, the present review of neuropsychological and imaging studies of Japanese suggests that the writing of the two kinds of script commonly utilises the same brain structure in the left hemisphere, i.e., the perisylvian area for earlier auditory-verbal processing and the frontoparietal network for motor execution. The retrieval of visuospatial information of graphic forms needs to be incorporated as an

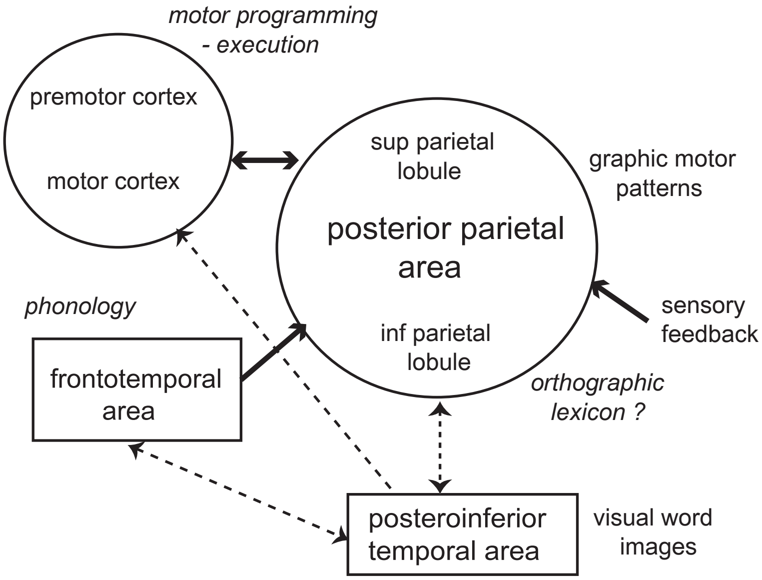


Figure 3. Schematic illustration of cognitive processes involved in writing and their neural correlates. Spoken input needs to be converted to phonology in the left perisylvian cortex. For writing of kana, the phonology is translated to graphic motor patterns represented in the left posterior parietal lobe, which in turn are executed in the motor cortex by way of the premotor area. This reciprocal connection between the posterior parietal area and the premotor cortex constitutes a basic neural substrate for motor aspect of writing. The posterior parietal area also receives sensory feedback from the visual and somatosensory cortices and modulates the activity of the frontal areas on-line. The retrieval of visuospatial information of graphic forms needs to be incorporated as an additional cognitive component rather specifically in the process of writing kanji that is subserved by the left posteroinferior temporal area.

additional cognitive component rather specifically in the process of writing kanji, which is subserved by the left postero-inferior temporal area. However, this does not imply that visual orthographic representations of kana are not stored in the area, but rather suggest that such representations, which do exist in the same area, do not play a vital role in writing of kana. This might argue against the conventional view that these two script systems have separate neural representations.

One of the key issues in functional neuroanatomy of writing concerns how the frontoparietal system for motor action interacts with cortical language areas as revealed by lesion and imaging studies. Functional connectivity among these areas is another important aspect which may be addressed by the complementary use of other techniques, such as electrophysiology and transcranial magnetic stimulation. At the same time, however, the extent to which we can plausibly localise a given cognitive function in particular brain regions is an open question. While the execution of writing is achieved by a complex of many processing components modularly organised in the brain, it remains rather unknown to what extent brain representations for such cognitive modules vary across individuals. For instance, Galaburda, Rosen, & Sherman (1990) suggest considerable individual variability in the cytoarchitecture of the cortical language area, which may be determined through developmental or genetic processes. Also, on the behavioural side, mental strategies used for writing may vary across individuals and across items. This seems especially the case when we consider the large set of characters used by the cognitive processes involved in the writing of kanji.

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