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Activation of writing-specific brain regions when reading Chinese as a second language. Effects of training modality and transfer to novel characters

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ABSTRACT

We examined the implication of training modality on the cortical representation of Chinese words in adult second language learners of Chinese. In particular, we tested the implication of the neural substrates of writing in a reading task. The brain network sustaining finger writing was defined neuroanatomically based on an independent functional localizer. We examined the brain activations elicited by Chinese words learned via writing vs. pronunciation, and by novel untrained words, within regions of interest (ROIs) defined according to the position of the activation peaks in the localizer, and at the whole brain level. We revealed activations in the reading task that overlapped with several parts of the finger writing network. In addition, our results provide evidence that the neural substrates of writing are differentially involved in reading depending on the stored knowledge for words, as revealed by the fine-grained response of several regions including the left superior parietal lobule and left precentral gyrus / superior frontal sulcus to the experimental manipulations. Training modality and the linguistic properties of the characters also impacted the response of the left mid-fusiform gyrus, confirming its involvement as the brain region where linguistic, visual and sensorimotor information converge during orthographic processing. At the behavioral level, global handwriting quality during the training sessions was positively correlated to the final translation performance. Our results demonstrate substantial overlap in the neural substrates of reading and writing, and indicate that some regions sustaining handwriting are differentially involved in reading depending on the type of knowledge associated with words.

1. Introduction

Reading and writing are highly related skills, which are nonetheless most often studied independently in neuroscience. There are, however, a handful of studies that have examined the links between the two and whether knowledge of writing movements impacts upon reading. Results from these studies show a close relationship between cortical activation in regions related to handwriting and the visual perception of known single letters (Anderson et al., 1990; James and Gauthier, 2006, 2009; Longcamp et al., 2008, 2003, 2011, 2005). In one of the earliest fMRI investigations involving alphabetic languages, Longcamp et al. (2003) showed, in right-handed French adults, that passively viewing letters of the Roman alphabet elicited activation in the left premotor cortex (Brodmann Area 6, BA6) whereas passively viewing pseudo-letters, for which the participants had no stored motor programs, did not. Moreover, passively viewing letters activated areas of the left premotor cortex in common with those activated by the actual writing of letters. The fact that the activation of premotor areas during letter perception was linked to the retrieval of stored information about writing versus other possible motor activities such as sub-vocalization was demonstrated in a subsequent study (Longcamp et al., 2005). Using the same paradigm but with left-handed adults Longcamp et al. (2005) found activation in the homologous right hemisphere of the pre-motor cortex. The finding of overlapping cortical activation during passive viewing and actual writing of known letters has since been replicated in adults (James and Gauthier, 2006) as well as in children (James and Engelhardt, 2012).

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In like fashion to what has been found for alphabetic languages, there is a strong link between writing knowledge and stored visual representations of Chinese characters as well as Japanese kanji. In a seminal study, Flores d'Arcais (1994) showed that priming Chinese characters with a partial character facilitated subsequent recognition when the prime was consistent with the sequence of strokes normally used to write the character. This suggests that the specific motor schema for a given character may be an essential component of its representation. In line with this hypothesis, two imaging studies in Japanese, where participants had to recall the number of strokes of a kanji character when shown its syllabic transcription (Hirigana script) without performing finger movements, showed activation of sensorimotor areas activated during writing. Notably, BA6/9 was activated as was the rostral part of the supplementary motor area and the intraparietal sulcus (IPS) (Kato et al., 1999; Matsuo et al., 2003). The activation of a left premotor area during the visual processing of characters, whether alphabetic or morpho-syllabic, has been attributed to the neural representation of known letters, which is hypothesized to be distributed and to involve not only visual representations but motor patterns specific to their production as well (James and Engelhardt, 2012; James and Gauthier, 2006, 2009; Longcamp et al., 2003, 2005, 2011). This may occur, in part, due to the coupled learning of reading and handwriting during childhood.

To examine how visual and motor representations of characters may interact, various studies have manipulated learning modality. These studies have opposed producing new characters by hand to typing or simply viewing them and have shown that handwriting strongly impacts the later recognition of learned characters (Cao et al., 2013b; James & Atwood, 2009; James and Engelhardt, 2012; Kersey and James, 2013; Longcamp et al., 2008, 2005, 2006). In adults, learning new characters by actually writing them versus typing on a keyboard improves both recognition and retrieval, as shown in a behavioral study (Longcamp et al., 2006) and replicated both behaviorally and in an fMRI protocol (Longcamp et al., 2008). Training characters by hand as opposed to on a keyboard led to stronger activation in several cortical regions known to be involved in motor preparation and execution. Both Longcamp et al. (2008) and James and Atwood (2009) showed that following writing practice, neural activation patterns to newly trained characters resembled patterns observed for known letters. In addition, both studies identified a dorsal premotor region that was more strongly activated when participants viewed characters trained by hand. James and Atwood (2009) also identified increased neural activation in the left fusiform gyrus.

In pre-literate children, writing but not visual-only training produced increased activation in bilateral anterior fusiform gyri from pre- to post-training scans in a letter recognition task (James, 2010). Moreover, activation in the left fusiform gyrus was specific to writing training, which calls into question the specificity of this area for visual word processing (see also Devlin et al., 2006). These findings were corroborated in a subsequent study, which compared the effect of freely producing letters to tracing or typing them on the cortical network activated during letter perception (James and Engelhardt, 2012). Only letters that were freely written during training elicited activation in areas related to letter recognition in a subsequent passive viewing task. Hence, even early in learning, when motor programs are not yet highly automated, writing training leads to the subsequent activation of cortical areas related to letter perception. To account for these results, James and Engelhardt (2012) have suggested that the production of numerous "noisy" outputs, i.e. semi-accurate productions of the intended character, enables the extraction of invariant features and hence the creation of an abstract exemplar (see also, Li and James, 2016).

While the above mentioned studies showed clear effects of writing on both the learning of the visuospatial features of characters and their cortical representation, they were not designed to examine the effect of handwriting on linguistic processing per se. That is, they all looked at processing at the sublexical level, whether letters in alphabetic languages or strokes in morpho-syllabic languages. Neither isolated letters nor stroke information generally convey lexical or semantic information. While one study on alphabetic languages (James and Gauthier, 2009) showed that writing letters interfered more with letter perception than did drawing shapes, and that this motor effect was indeed specific to linguistic stimuli (i.e., drawing shapes did not interfere with perceiving shapes), the results remain at the pre-lexical level. The question thus remains open as to whether the same type of motor reactivation will occur during the processing of stored higher level units, i.e. during lexical processing.

To examine how writing may impact the learning and subsequent retrieval of higher level linguistic units, several studies have looked at whole character processing in Chinese. This question has been approached both behaviorally (Guan et al., 2011, 2015; Tan et al., 2005a; for a recent review, see Perfetti and Tan, 2013) and using electrophysiology to track the time course of cortical processing (Cao et al., 2013a). In an fMRI study, Cao et al. (2013b) used a training protocol based on that of Guan et al. (2011) to examine the effect of training modality on brain activation for learned characters in adult L2 learners of Chinese. They found that handwriting led to stronger activation of the bilateral superior parietal lobule (SPL) and right postcentral gyrus than did pinyin typing. In addition, for characters learned by hand, the amount of activation in the left sensorimotor cortex was correlated with accuracy in lexical processing. Cao et al. (2013b) argued that writing is an active encoding mechanism that accelerates the establishment of stable orthographic patterns, and therefore impacts higher-level linguistic processing in reading.

A limitation of all the above mentioned studies, which partially motivated the present study, is the absence of a direct comparison between the spatial location of the brain regions activated in either the visual perception of characters or in reading and the actual network sustaining handwriting. Apart from Longcamp et al. (2003) and James and Gauthier (2006) who used a functional localizer to evaluate the overlap of premotor activations, other studies have inferred that the gestural representations of handwriting are reactivated based on observed premotor or sensorimotor activation triggered by the visual presentation of characters. Direct mapping of the brain regions involved in writing is essential because other motor functions, especially those involved in the retrieval of phonological codes and articulation in speech production, could also be mobilized in reading and explain possible premotor, parietal or subcortical activations that would therefore incorrectly be attributed to writing knowledge reactivation.

The aim of the present experiment was to investigate the implication of the neural substrates of writing in a reading task that required lexical processing of single words in an ecological situation. In this aim, the brain network sustaining writing was defined neuroanatomically based on an independent functional localizer, and brain activations observed during reading were referred to the position of the activation peaks in the finger writing localizer. Producing a writing gesture involves specific brain regions, as revealed by neuropsychological data from brain-damaged patients with agraphia or dysgraphia (Alexander et al., 1992; Anderson et al., 1990; Han and Bi, 2009; Ishihara et al., 2010) as well as brain imaging experiments (James and Gauthier, 2006; Longcamp et al., 2014; Planton et al., 2013; Purcell et al., 2011b; Sugihara et al., 2006). In a meta-analysis of 18 neuroimaging studies, Planton et al. (2013) highlighted several cortical regions of the left hemisphere that are crucially implicated in the control of handwriting, in the superior parietal cortex at the level of the SPL/IPS, and the premotor cortex at the level of the superior frontal sulcus (SFS), the ventral premotor cortex, the right cerebellum and the left thalamus.

The protocol used in the current study was partially based on that by Cao et al. (2013b) in which English speaking adults learned Chinese characters either by writing them or typing their pinyin equivalent. In the present study, French students of Chinese learned new characters