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The impact of inverted text on visual word processing: An fMRI study

Bethany L. Sussman, Samir Reddigari, Sharlene D. Newman*

Indiana University, Department of Psychological and Brain Sciences, Bloomington, IN, USA

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ABSTRACT

Visual word recognition has been studied for decades. One question that has received limited attention is how different text presentation orientations disrupt word recognition. By examining how word recognition processes may be disrupted by different text orientations it is hoped that new insights can be gained concerning the process. Here, we examined the impact of rotating and inverting text on the neural network responsible for visual word recognition focusing primarily on a region of the occipto-temporal cortex referred to as the visual word form area (VWFA). A lexical decision task was employed in which words and pseudowords were presented in one of three orientations (upright, rotated or inverted). The results demonstrate that inversion caused the greatest disruption of visual word recognition processes. Both rotated and inverted text elicited increased activation in spatial attention regions within the right parietal cortex. However, inverted text recruited phonological and articulatory processing regions within the left inferior frontal and left inferior parietal cortices. Finally, the VWFA was found to not behave similarly to the fusiform face area in that unusual text orientations resulted in increased activation and not decreased activation. It is hypothesized here that the VWFA activation is modulated by feedback from linguistic processes.

1. Introduction

Reading is a complex cognitive process that, for most, becomes automatic. The relative ease with which we read, however, is dependent on viewing text in ways we are accustomed to seeing it and, like with the recognition of objects, presenting text in unusual orientations can significantly disrupt word recognition. Previous behavioral and neuroimaging studies have established that the specific manner in which text is transformed has an impact on the automaticity of reading (Cai, Paulignan, Brysbaert, Ibarrola, & Nazir, 2010; Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Goebel, Linden, Lanfermann, Zanella, & Singer, 1998; Ilg et al., 2010; Kao, Chen, & Chen, 2010; Kolers, 1968; Koriat & Norman, 1985; Poldrack, Desmond, Glover, & Gabrieli, 1998). For example, there is evidence that rotating words more than 60 degrees disrupts holistic word processing, forcing a serial processing strategy (Cohen et al., 2008; Koriat & Norman, 1985). Koriat and Norman (1985) showed that as the degree of rotation increases, word processing was increasingly slowed until 120 degrees (60 degrees from 180) where processing time asymptotes. Additionally, behavioral data consistently show that rotated whole words are easier to read than vertically inverted words (e.g. Kolers, 1968; Smith, Cambria, & Steffan, 1964; Sussman, 2014), indicating that not all word transformations lead to the same level of disruption. Additionally, it has been shown that rotation does not necessarily lead to a loss of mirror invariance in letter and word perception. Navon and Raveh (2004) demonstrated that, like with upright words, a reflected letter in words that were rotated 180° caused a disruption in lexical decision. Participants also found it easier to detect horizontally reflected letters when they were in the context of a word (compared to nonword) in both upright and rotated orientations. This suggests that the influences between linguistic (lexical) and visuo-spatial processing are not unidirectional. This also suggests that rotation, at least, preserves information about reading direction in the context of the reference frame for the written text. Other sources have shown that it is more difficult to detect upright letters when presented in an inverted word with upright letters, unless most of the letters are presented upright, similar to the Thatcher illusion seen in faces (see Erlikhman, Strother, Barzakov, & Caplovitz, 2017 for review).

This disruption of the automaticity of word recognition due to presentation orientation is reminiscent of what is found in the face processing literature – inverted faces are difficult to process and this unusual orientation disrupts holistic processing (see Bartlett & Searcy, 1993; Valentine, 1988 for review). In the face literature there are numerous studies suggesting that the inversion effect is localized to what is referred to as the fusiform face area (FFA; Kanwisher, McDermott, & Chun, 1997). The FFA is a category-specific (in this case faces) object recognition region located in the right fusiform gyrus. A region somewhat analogous to the FFA has been theorized for visual word

* Corresponding author at: 1101 E Tenth Street, Bloomington, IN 47405, USA.
E-mail address: sdnewman@indiana.edu (S.D. Newman).

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processing, the visual word form area (VWFA; Cohen et al., 2000).

The VWFA is located in the left occipito-temporal cortex and is associated with orthographic processing (Cohen et al., 2000, 2002; McCandliss, Cohen, & Dehaene, 2003). While the VWFA is equally sensitive to high and low frequency words (Fiebach, Friederici, Muller, & Cramon, 2002) and legal non-words (Cohen et al., 2000; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002), and case (Dehaene et al., 2001; Dehaene et al., 2004), it shows less activation to consonant strings (Cohen et al., 2002; Price, Wise, & Frackowiak, 1996) and scrambled words (Dehaene & Cohen, 2011). The reduced activation to scrambled words is similar to findings that the FFA responds less to inverted faces. This has led some to argue that the region is involved in sub-lexical processing (e.g. Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002) but is sensitive to the statistical likelihood of letter combinations and orthographic similarity (Nestor, Behrmann, & Plaut, 2012). Lexical effects in the region, however, have not been consistently observed with some studies showing greater activation for pseudowords (see Mechelli, Gorno-Tempini, & Price, 2003), and greater activation for low frequency words in nearby regions (Keller, Carpenter, & Just, 2001; Kronbichler et al., 2004). The VWFA also shows greater activity to non-words with higher bigram frequencies than those with lower bigram frequencies (Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006), supporting the hypothesis that it is sensitive to orthographic regularity.

If the VWFA behaves similarly to words as the FFA does to faces (Kanwisher, Tong, & Nakayama, 1998), we would expect that unusual orientations of words will elicit less activation than upright words. However, it is unclear whether this is the case given that inverted faces are generally not recognized but inverted words, while more difficult to process, can be recognized and read. This behavioral difference may suggest that the FFA and VWFA respond differently to inversion. Kao et al. (2010) found activity decreases in VWFA in response to inverted Chinese characters in a same/different task. Other previous studies investigating reading mirrored and upside-down words, however, tend to show the opposite effect in occipito-temporal regions (Cohen et al., 2008; Dong et al., 2000; Goebel et al., 1998). The first fMRI investigation into the neural correlates of reading inverted text sought to identify changes in activation associated with the acquisition of mirror reading skills (Poldrack et al., 1998). They found that before training, mirror reading (of horizontally inverted text) elicited activity in occipito-temporal cortex (in the VWFA), the superior parietal lobule, the intraparietal sulcus, and the cerebellum, all bilaterally. As subjects became more proficient in mirror reading, activation in the right superior parietal cortex decreased while activity in a region analogous to the VWFA increased. The authors interpreted the initial activation patterns and differential changes following training to mean that subjects gained expertise and began to use similar word recognition processes as upright stimuli, no longer requiring as much use of spatial transformation mechanisms. This evidence suggests that increased parietal recruitment for spatial rotation is modulated by familiarity with the presented orientation.

At roughly the same time, Goebel et al. (1998) published an fMRI study that utilized separate tasks requiring lexical decisions on rotated and inverted text, as well as controlled eye movements. Somewhat similarly to Poldrack et al. (1998), they found increased activity in the VWFA in the left hemisphere and the intraparietal sulcus bilaterally when reading inverted text. Importantly, the activation in these areas was dissociable from oculomotor activation. They therefore concluded that these regions (in particular the intraparietal sulci) contributed to the spatial transformation needed to read inverted text. But importantly the activation of the VWFA did not behave similarly to the FFA, that is, it did not have reduced activation for transformed words compared to upright words.

In addition to inverted text impacting processing in the VWFA, both the Poldrack et al. (1998) and the Goebel et al. (1998) studies as well as more recent studies (Cai et al., 2010; Ilg et al., 2010) reported modulation of parietal activation. The role of the parietal cortices in processing inverted words was more directly addressed by both Ilg et al. (2010) and Dong et al. (2000). The stimuli used in the Dong et al. study consisted of Japanese kana, which are phonograms representing individual syllables. The authors claimed that unlike the horizontal inversion used by Poldrack et al. (1998), which required readers of English to process the text right-to-left, horizontal inversion of kana, which is oriented vertically, prevents any activation caused by oculomotion differences between the normal and inverted conditions. Relative to canonically presented words and pseudowords, the inverted text elicited greater activation in bilateral occipito-temporal cortex, right posterior parietal cortex, right cerebellum, and left inferior frontal cortex. Critically, they found that the magnitude of the BOLD signal change in the right superior parietal cortex was significantly correlated with the error index of the lexical decision task. No such correlation was found for any other brain region. This finding, taken with the decrease in right parietal activation following training found by Poldrack et al. (1998), was sufficient for the authors to conclude that the right parietal cortex is responsible for the mental transformation necessary to read inverted kana. Additionally, they attributed the inferior frontal activation to the phonological rehearsal necessary to read the mirrored symbols phonogram-by-phonogram, showing an interaction between the orthographic processing for text transformation and phonology.

The findings of Kao et al. (2010) differ in important ways to the other studies discussed above. In their comprehensive study of how character inversion alters activity in the visual word form area, Kao et al. (2010) found no differential activity in the parietal cortices in either hemisphere when subjects performed a same/different task on upright and inverted Chinese characters. They did find differential activation in bilateral occipito-temporal areas, however, it was reduced activation. There are two key differences between Kao et al.'s investigation and those previously discussed. First, the stimuli used in this experiment were logographic Chinese characters, each containing one semantic and one phonologic component. While there was an element of phonological information incorporated into each stimulus, the stimuli were not composed of serial phonological symbols in the way alphabetic words or kana are designed. The stimuli were therefore processed as one symbol corresponding to one word. Second, this experiment employed a task requiring the participant to make a same/different decision on two stimuli in the same orientation, and did not require lexical decision. This suggests that a linguistic task associated with transformed text stimuli increases the need for spatial manipulation reflected by parietal activation. However, the 40 lexical stimuli were taken from a list of the most commonly used 1500 Chinese characters, and the authors assumed all subjects would be familiar with all the logograms used.

The absence of differential parietal activation for inversion of Chinese characters is a surprising finding given the consistency of the neuroimaging results seen for alphabetic or phonographic orthographies. It is likely this stark difference is due to the task; all of the previous studies utilized a lexical decision task and thus required the subject to read every stimulus, while Kao and colleagues used a same/different task. There are several aspects of Kao et al. (2010)'s design that may explain the lack of parietal activity. First, the two stimuli were always presented in the same orientation, and thus did not require a mental transformation to compare an inverted character to an upright one. If superior parietal cortex is indeed implicated in the spatial transformation of visual stimuli, as has been previously assumed, the absence of parietal activation in Kao et al. (2010)'s study would be anticipated. Second, a same/different judgment does not necessitate explicit linguistic processing of the stimulus. However, the authors reported stronger behavioral and neurophysiological effects of inversion for real characters than for non-characters, suggesting that the subjects were at least somewhat influenced by the lexicality of the stimuli. Additionally, the authors chose characters with which all subjects were