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Developmental changes in the neural influence of sublexical information on semantic processing

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ABSTRACT

Functional magnetic resonance imaging (fMRI) was used to examine the developmental changes in a group of normally developing children (aged 8–12) and adolescents (aged 13–16) during semantic processing. We manipulated association strength (i.e. a global reading unit) and semantic radical (i.e. a local reading unit) to explore the interaction of lexical and sublexical semantic information in making semantic judgments. In the semantic judgment task, two types of stimuli were used: visually-similar (i.e. shared a semantic radical) versus visually-dissimilar (i.e. did not share a semantic radical) character pairs. Participants were asked to indicate if two Chinese characters, arranged according to association strength, were related in meaning. The results showed greater developmental increases in activation in left angular gyrus (BA 39) in the visually-similar compared to the visually-dissimilar pairs for the strong association. There were also greater age-related increases in angular gyrus for the strong compared to weak association in the visually-similar pairs. Both of these results suggest that shared semantics at the sublexical level facilitates the integration of overlapping features at the lexical level in older children. In addition, there was a larger developmental increase in left posterior middle temporal gyrus (BA 21) for the weak compared to strong association in the visually-dissimilar pairs, suggesting conflicting sublexical information placed greater demands on access to lexical representations in the older children. All together, these results suggest that older children are more sensitive to sublexical information when processing lexical representations.

1. Introduction

The most prominent characteristic in Chinese is probably its use of a logographic script. Therefore, the recognition of distinctive orthographic units (i.e. characters) is widely studied (Tsang and Chen, 2009). Emerging evidence of developmental changes in semantic processing mainly focuses on the lexical level (i.e. the whole character), such as semantic association (Chou et al., 2009; Lee et al., 2011) and semantic priming (Wang et al., 2009; Zhou et al., 1998). However, the interactive process between lexical and sublexical (i.e. radicals, which are components of a character) semantic information in Chinese is not understood at a neural level. We aimed to explore developmental changes in how the semantic radical interacts with semantic association.

Previous morphological studies in English have investigated the mapping from orthography to semantics in word recognition (Morris et al., 2007; Pastizzo and Feldman, 2009; Rastle et al., 2000). The abovementioned studies suggest a convergent contribution of both orthographical similarity and semantic relatedness in visual word recognition. However, the relation between form and meaning in English is only partly consistent and admits many exceptions (e.g. *–or* in traitor and anchor), reflecting the lack of reliability of semantic information at the sublexical level (Seidenberg and Gonnerman, 2000). In contrast, Chinese includes greater semantic information at the sublexical level, showing a more direct mapping between orthography and semantics (Ho et al., 2000). In terms of the orthographic characteristics of Chinese characters, about 80% of Chinese characters are phonetic compound (phonograms) that consist of a semantic radical and a phonetic radical (Zhou, 1978). These semantic radicals may provide a reliable cue to the semantic category of the character. For instance, all characters that contain the semantic radical金 (/jin1/, metal), such as 銅 (/tong2/, copper), 鐵 (/tie3/, iron), indicate that the characters are related to the category of metal. In addition, many semantic radicals may not stand alone as a character in

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Chinese. An example is湖 (/hwu2/, lake) which is composed of a semantic radical of three dots arranged vertically on the left with an associated meaning of 'water'. The semantic radical in this example does not correspond to a real character.

Regarding the direct mapping between orthography and semantics in alphabetical languages such as English and French, when primes and targets share the same root (i.e. suffix: *viewers-view*), the activation of the root in the prime facilitates processing of the target via excitatory connections between morphemic representations and the whole word (Diependaele et al., 2011; Giraudo and Grainger, 2000, 2001). In addition, previous behavioral studies in Chinese have shown faster reaction time for visually-similar character pairs (i.e., sharing semantic radicals) compared to visually-dissimilar character pairs (i.e., not sharing semantic radicals) in semantic tasks for adult readers (Chen and Allport, 1995; Fang and Zhang, 2009; Leck, Weekes, and Chen, 1995; Williams and Bever, 2010). Aforementioned studies proposed that characters are automatically decomposed into radicals during recognition. Furthermore, interactive models suggested that the semantic radicals access semantic representations independently of and in parallel to the whole characters (Taft et al., 1999; Zhou and Marslen-Wilson, 1999, 2000). While there is evidence for interconnections between semantic radicals and whole characters from normal adults, relevant developmental data are not yet available. In particular, it is not clear how the brain constructs both lexical and sublexical level semantic information into an organized system over age. In order to explore the interaction between both levels of semantic information in Chinese, we systematically manipulated the degree of semantic association between character pairs at the lexical level and orthographic similarity at the sublexical level. In this study, orthographic similarity was defined as characters having the same orthographic component (i.e. semantic radicals) (Zhou and Marslen-Wilson, 1999). In the semantic association task, two types of stimuli were used: visually-similar versus visually-dissimilar character pairs. Based on the mapping from orthography to semantics in Chinese, this experimental design allowed us to examine the interactive process between lexical (i.e. semantic association) and sublexical (i.e. semantic radical) information.

Previous research using a semantic judgment task at the lexical level has identified brain regions for processing distantly related pairs (i.e. weak association) in left inferior frontal gyrus (IFG. BA 45, 47) and left middle temporal gyrus (MTG, BA 21) (Booth et al., 2002; Chou et al., 2006a,b, 2009). One of functional roles of the left inferior frontal gyrus has been suggested to result from the difficulty of retrieving/selecting appropriate features and/or inhibiting irrelevant features (Lee et al., 2011; Badre and Wagner, 2007). In support of this, many studies have identified greater inferior frontal activation in semantic tasks with greater retrieval and/or selection demands (Bedny et al., 2008; Kuperberg et al., 2008; Pexman et al., 2007; Snyder et al., 2007; Thompson-Schill et al., 1997, 1999). Distantly related pairs also produced greater activation in the left MTG (Chou et al., 2009). There is extensive evidence demonstrating that semantic content is represented in this region (Blumenfeld et al., 2006; Davis et al., 2004; Gourovitch et al., 2000; Kable et al., 2005; Noppeney et al., 2003). A review article also proposed that the MTG is a principal site for the storage of representations (Binder et al., 2009). For weak association, participants may need extensive access to semantic representations in order to identify overlapping features for distant relationships (Booth et al., 2007; Huang et al., 2012). In terms of the present study, we wished to determine whether lack of congruent sublexical information for the visually-dissimilar pairs may place greater processing demands on the access to lexical representations and greater engagement of selecting appropriate representations, reflecting greater activation in the MTG and IFG as compared to the visually-similar pairs.

In contrast, processing closely related pairs (i.e. strong association) elicited greater activation in left angular gyrus (AG, BA 39), suggesting greater integration of features to determine the semantic relationship between words, as closely related pairs share more overlapping features (Grossman et al., 2003; Koenig et al., 2005). Recent studies have suggested that the AG is related to manipulating semantic knowledge within the current context (Corbett et al., 2009; Jefferies and Lambon Ralph, 2006; Whitney et al., 2011). In addition, Binder and Desai (2011) propose that this region is related to capturing similarity structures to define conceptual categories. Researchers suggest the role of this region as "combinatorial semantic processing", integrating incoming semantic information into a current lexical level, sentential or narrative context (Humphries et al., 2006, 2007; Lau et al., 2008). In the context of the present study, we propose that AG, as a high level convergence zone, may use the shared radical to categorize the semantic knowledge into an organized structure, allowing the overlapping features to be integrated at the lexical level. This integration in visually-similar pairs with shared semantic radicals may be especially pronounced for strong association pairs because of the large number of shared features.

Evidence from both functional and structural imaging studies is consistent with the notion that a developmental increase of processing conceptual knowledge continues into adolescence and is associated with changes in left IFG, left MTG, and left AG. Adolescents (aged 13–16) are better than children (aged 8–12) at selecting/retrieving relevant features (Adleman et al., 2002; Lamm et al., 2006), accessing lexical representations (Lee et al., 2011), and integrating conceptual relations (Crone et al., 2006; Thibaut et al., 2010). The age-related changes in processing conceptual knowledge are thought to be related to semantic selection/retrieval in the IFG, access of lexical representations in MTG, and the integration of semantic information in the angular gyrus (Chou et al., 2009). The changes during adolescence suggest that teenagers are more capable of maintaining conceptual knowledge in an organized state, using a flexible mechanism to retrieve/select relevant information and integrate relationships between these concepts (Blakemore and Choudhury, 2006; Crone et al., 2009).

Previous studies have shown developmental increases in the MTG when making semantic judgments are particularly pronounced for the weaker association, whereas these studies have shown developmental increases in the AG are pronounced for the stronger association (Chou et al., 2009; Lee et al., 2011). We extend this work by directly examining the neural correlates of processing lexical and sublexical semantic information for children. In particular, we aimed to determine whether the semantic radicals at the sublexical level would interact with the semantic association at the lexical level, supporting the shared features between two characters to be detected and integrated at the lexical level. We expected that character pairs that shared a semantic radical (i.e. visually-similar pairs) would modulate AG activation because this shared information would allow for greater integration of semantic features at the level of the radical. In addition, the effect of the shared semantic radicals in the AG should increase with age. In contrast, we expected that pairs that did not share a semantic radical (i.e. visually-dissimilar pairs) would modulate developmental differences in the MTG and IFG because the lack of shared information would place greater demands on access to semantic representations and engage greater effort to select the appropriate features and/or inhibiting irrelevant features during judgment.