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The representation of category typicality in the frontal cortex and its cross-linguistic variations

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ABSTRACT

When asked to judge the membership of typical (e.g., car) vs. atypical (e.g., train) pictures of a category (e.g., vehicle), native English ($N = 18$) and native Chinese speakers ($N = 18$) showed distinctive patterns of brain activity despite showing similar behavioral responses. Moreover, these differences were mainly due to the *amount* and *pervasiveness* of category information linguistically embedded in the everyday names of the items in the respective languages, with important differences across languages in how pervasive category labels are embedded in item-level terms. Nonetheless, the left inferior frontal gyrus and the bilateral medial frontal gyrus are the most consistent neural correlates of category typicality that persist across languages and linguistic cues. These data together suggest that both cross- and within-language differences in the explicitness of category information have strong effects on the nature of categorization processes performed by the brain.

1. Introduction

One of the fundamental insights into semantic memory is the role of typicality in both structuring and providing access to members of a category (Mervis, Catlin, & Rosch, 1976). When asked questions such as "*Is an ostrich a bird?*" or "*Is a robin a bird?*," the general behavioral finding (Mervis & Rosch, 1981) is that people respond more quickly and more accurately to "robin" than "ostrich" (i.e., demonstrate a "typicality effect") simply because "robin" is a more *typical* example of the category "bird" than "ostrich."

As one of the most consistent indexes of categorization processes in behavioral studies (Mervis & Rosch, 1981), the typicality effect has also been investigated with neuroimaging techniques such as the Event-Related Potential (ERP). ERP studies have found that typicality effects in linguistic stimuli are marked by a N400 component, such that atypical items of a category elicit a larger N400 than typical items, regardless of the frequency of the item labels (Fujihara, Nageishi, Koyama, & Nakajima, 1998; Heinze, Muente, & Kutas, 1998; Stuss, Picton, & Cerri, 1988). In addition to the N400 component found in the frontal, temporal, and parietal areas of the brain, studies with pictorial stimuli have found additional components at 160 ms (P160) in occipital areas and 280–300 ms (N300) in other posterior areas, representing additional perceptual and semantic processing of pictorial atypical vs. typical stimuli (Barrett & Rugg, 1990; Hauk et al., 2007; McPherson & Holcomb, 1999).

However, to the best of our knowledge, this classic "typicality effect" has not yet been directly investigated using neuroimaging techniques with high spatial resolution such as functional Magnet Reasoning Imaging (fMRI) (Patterson, 2007). Nonetheless, there have been some studies that have begun to shed light on what one might expect for such an effect. Studies investigating the orthographic typicality (e.g., CHEESE is a typical English word but SEIZE is an atypical one) or phonetic typicality (e.g., sounds belong to normal human voicing continuum or not) of word stimuli, for example, showed that atypical items elicited greater activation than typical items in language processing areas such as the left inferior frontal region and bilateral superior temporal regions (Myers, 2007; Woollams, Silani, Okada, Patterson, & Price, 2011). Moreover, fMRI studies using other categorization processing paradigms with English-speaking adults including both healthy controls and patients with semantic dementia have identified three qualitatively different categorization systems in the brain (Smith & Grossman, 2008). The first is a rule-based categorization process associated with a working memory system and selective attention in the frontal and parietal areas, especially the left inferior frontal gyrus. The second is a similarity-based categorization associated with explicit long-term memory and integration of perceptual

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features in the parietal-temporal areas. For the third, other sorts of implicit categorization processes associated with implicit long term memory in the temporal-occipital areas have also been identified. However, which of these three categorization systems might be involved in the typicality effect is still unknown. This question is particularly interesting for semantic typicality processing. Compared with other typicality processing such as orthographic typicality or phonetic typicality, semantic typicality processing is characterized by a more complicated connectionist representation where concepts correspond to distributed representations occupying positions in a multidimensional semantic space (Patterson, 2007). Studies on the brain mechanism of related semantic processing have found that categorization of both word and pictorial stimuli show activation in the bilateral middle and inferior frontal gyrus, the bilateral inferior parietal lobule, bilateral temporal-occipital conjunctions, anterior cingulate cortex and caudate (Adams & Janata, 2002; Ganis, Schendan, & Kosslyn, 2007; Grossman et al., 2002; Jiang et al., 2007; Koenig et al., 2005; Myers, 2007; Reber, Gitelman, Parrish, & Mesulam, 2003). The left inferior frontal gyrus, in particular, has been identified as a region which contributes greatly to semantic and lexical access (Bookheimer, 2002; Hagoort, Hald, Bastiaansen, & Petersson, 2004; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996). Thus, our first aim of the present study is to investigate the neural correlates of the semantic typicality effect by recording an MRI signal when participants perform a classic category verification task with pictorial stimuli. We would expect to identify a brain network involved in semantic processing, particularly in the inferior frontal cortex.

The second aim of the present study is to investigate how the neural correlates of the typicality effect might be similar or differ across languages. The idea that language plays an important role in categorization is not new in cognitive psychology. As Whorf suggested in the linguistic relativity hypothesis, "We dissect nature along lines laid down by our native language."(Whorf, 1956). Developmental studies have shown that language shapes the way that object categories are organized and structured in children's minds (Martinez & Shatz, 1996; Yoshida & Smith, 2003). In addition, cross-linguistic studies have found that different languages differ greatly in providing linguistic cues to a word's semantic category. For example, in English, basic level object nouns usually do not share any obvious relationships to their superordinate category labels (e.g., nouns for wheeled vehicles are bicycle, truck, car, taxi, bus, train, etc.), although some do (e.g., cuttlefish, catfish). In contrast, most basic level object nouns in Mandarin Chinese contain superordinate category information in some way, either by sharing a common root morpheme (Tardif, 2006) (e.g., all wheeled vehicles share the common morpheme *che1* (车) that means "vehicle", such as bicycle – *zi4xing2che1*自行车, truck – *ka3che1*卡车, car – *jiao4che1*轿车, taxi – *chu1zu1che1*出租车, bus – *gong1gong4qi4che1*公共汽车, train – *huo3che1*火车), or by including a unpronounceable orthographic "radical" that cues either the basic or superordinate category in the written character (Zhou, Marslen-Wilson, Taft, & Shu, 1999; Zhou, 1978) (e.g., the noun "fish" (*yu2*鱼)) is not only a simple character in its own right, but is also an orthographic component (also known as a "semantic radical") in the written character for different fish names, such as carp – *li3*鲤, bass – *lu2*鲈, catfish – *nian2*鲇, and shark – *sha*鲨). Over 80% of Chinese characters provide semantic radicals (Zhou et al., 1999; Zhou, 1978), and these can be traced back to the oracle bone characters used 3500 years ago (e.g., the radical of "water" *shui3*水 in the characters of river – *he2* 河 and wine – *jiu3* 酒), thus creating a fascinating and long-standing tradition of cueing category information that is pervasive in basic level terms in Chinese.

In summary, in English, nouns tend to have opaque or "non-transparent" cues to categories, whereas Chinese nouns have a highly productive and pervasive morphological and orthographic compounding system which provides explicit cues to category membership. How could these language differences then influence categorization processes and the typicality effect? Since both typical and atypical nouns in Chinese contain exactly the same linguistic cue (whether morphological or orthographic), it is possible that this pervasive system of cues might be used to aid Chinese speakers in making category judgments and thus obviate the need for typicality as a cue. This hypothesis was supported in a series of cross-cultural ERP studies comparing English and Chinese speaking adults with a category verification task. In these studies, Chinese speaking adults showed no N300 or N400 components revealing no apparent differences in the processing of typical vs. atypical items (Liu et al., 2010) despite clear differences with the identical stimuli for English-speaking adults and strong similarities in the N300 and N400 effects shown across languages for within vs. out of category items. These studies led to the suggestion that the linguistic cues in Chinese nouns facilitated the semantic access of category information in Chinese speaking adults and eliminated the left frontal N300 and N400 typicality effects. However, the locus of these cross-linguistic similarities and differences are still not clear.

In the current study, we investigated the neural correlates of the typicality effect and its cross-linguistic variations with native US English and native Chinese speakers using event-related fMRI. We conducted a category verification task with pictorial stimuli that differ in both typicality and linguistic cues to category membership and demonstrate that these linguistic cues are responsible for differing levels of brain activation in the same brain areas identified by others as responsible for semantic categorization, despite overall similarities in behavioral responses.

2. Methods

2.1. Participants

Twenty native Mandarin Chinese speakers and 19 native US English speakers (from US or Canada) in Beijing, all right-handed with normal vision, participated in this study and were each paid RMB100 (approximately US$12). Considering previous studies have demonstrated differences between bilinguals and monolinguals in naming task (Ameel, Malt, Storms, & Van Assche, 2009; Ameel, Storms, Malt, & Sloman, 2005), we also controlled the Language 2 (L2) level in participants recruiting. To minimize the proficiency of English, all native Chinese speakers were college students who had not yet passed College English Test (CET). To minimize the proficiency of Chinese for native English speakers, they were required to have lived in Beijing for less than three years and have learned Chinese for less than one year. Three participants were excluded from further analysis, two Chinese speakers for poor behavioral performance and one English speaker for uncorrectable head movement (>4 mm) during fMRI acquisition. The final sample consisted of 18 Chinese speakers (10 females, *M* age = 22.33 years) and 18 English speakers (10 females, *M* age = 25.38 years) in the behavioral and fMRI data analysis. The recruitment of participants in Beijing was approved by IRBs at Beijing Normal University and the University of Michigan (B04-00001580-M1).

2.2. Stimuli

Twenty-eight grayscale object pictures of 14 categories were selected from previous ERP studies (Liu et al., 2010) (Fig. 1), for which two pilot studies were conducted to refine and ensure the cross-linguistic comparability of the pictorial stimuli and their judged typicality. In Pilot Study one, 25 English and 25 Chinese