How Are Icons Processed by the Brain? Neuroimaging Measures of Four Types of Visual Stimuli Used in Information Systems

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We sought to understand how users interpret meanings of symbols commonly used in information systems, especially how icons are processed by the brain. We investigated Chinese and English speakers' processing of 4 types of visual stimuli: icons, pictures, Chinese characters, and English words. The goal was to examine, via functional magnetic resonance imaging (fMRI) data, the hypothesis that people cognitively process icons as logographic words and to provide neurological evidence related to human–computer interaction (HCI), which has been rare in traditional information system studies. According to the neuroimaging data of 19 participants, we conclude that icons are not cognitively processed as logographical words like Chinese characters, although they both stimulate the semantic system in the brain that is needed for language processing. Instead, more similar to images and pictures, icons are not as efficient as words in conveying meanings, and brains (people) make more effort to process icons than words. We use this study to demonstrate that it is practicable to test information system constructs such as elements of graphical user interfaces (GUIs) with neuroscience data and that, with such data, we can better understand individual or group differences related to system usage and user–computer interactions.

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Introduction

Icons (symbolic signs of objects and concepts) are important visual representations of information in modern graphical user interfaces (GUIs) and traffic signs. By the definition of Horton (1994), icons are small images that represent objects or commands in modern GUIs. Abdullah and Hübner (2006) assert that, unlike pictures such as generic photographs that are open to various interpretations, icons are designed to have an unmistakable meaning that they are supposed to convey. Icons are often designed with the purpose of associating a symbol with a certain meaning, such as ancient iconography conveying semantics of objects and concepts in the formal development of logographic languages (Proctor & Vu, 2008). Although an icon is a small image, it represents a single object or concept like a word rather than "being worth a thousand words" like a picture.

Because icons are graphic representations like pictures and are often used to supplement texts, such relations create a challenge for researchers to clarify how people recognize and comprehend an icon. A common question asked by researchers is "How do people read icons?" For example, Horton (1994) suggested that reading symbolic information such as an icon demanded more of people's visual perception to understand its graphic elements. On the other hand, Haramundanis (1996) suggested that icons were like logographical words (e.g., Egyptian hieroglyphs, Mayan glyphs, or Chinese characters) and that learning the meaning of an icon was like learning to read a single logographical word. It is plausible that people read icons as symbolic words because they are designed with a certain graphic style to econvey a certain meaning just as the writing system of logographic language used a single graphical symbol as a word in ancient times.

Although Haramundanis (1996) objected to the idea that icons immediately convey meanings via visual representations of information, Pedell (1996) indicated that, through learning and retention, icons could stand alone and provide visual shorthand for meanings without referring to their labels or text definitions. Deriving from Haramundanis and Pedell's arguments about icon independence, a hypothesis can be proposed: Icons can stand alone as logographical words after learning and retention, and people read icons as they read single logographical words. Our study investigates this hypothesis by seeking the answer to a fundamental research question: Are icons pictures or logographical words in terms of how people interpret them? In addition, by addressing this question with functional magnetic resonance imaging (fMRI) data, we hope to expand the methods employed to answer information science questions.

To make logical contrasts and determine whether icons are interpreted as pictures or logographical words, our study examines how English and Chinese speakers deduce semantic meanings from four different types of visual stimuli: icons, Chinese characters (logographical words), pictures, and English words (alphabetical words), with the hypothesis that people cognitively process icons as logographical words instead of as pictures. We decided to address a specific research question concerning relations between symbols and the meanings to which they refer by neuroscience principles; how does the brain process icons cognitively to understand their meanings in contrast to other types of visual information? Therefore, our study employed a neuroscience research methodology, specifically, fMRI, because it is a noninvasive neuroimaging method and can directly provide observed physiological data to explore activities in the brain that are related to behaviors in reading symbols.

Thus, our goal is not only to understand how people cognitively process icons but also to demonstrate that such a neuroimaging tool is practical in information systems research. We want to contribute to a better understanding of human factors in human–computer interaction (HCI) and the role of graphic and textual information used in information systems that facilitate behaviors of users and developers such as decision making, judgment, and various economic and psychological issues. The findings of our study also have the potential to illuminate research on neuroergonomics (Parasuraman, 2003) and the development of neuroadaptive interfaces (Hettinger, Branco, Encarnacao, & Bonato, 2003) that are information systems that can dynamically adapt different users' variations in behavioral and cognitive states according to corresponding neural sources of the user in the future. It is our hope and belief that this study will afford a new and valuable window into human processing of icons and lead ultimately to the development of new theories of how to use symbols more effectively in information systems.

Theoretical Background

Relationship Between GUI Icons and Logographical Words

The relationship between icons and logographical words lies in the history and development of iconography. Recognizing and comprehending a single symbol is the simplest processing of reading in terms of iconographic communication. Iconographic communication (e.g., using signs, symbols, or icons to record and communicate information) is an important stage in the early development of a formal writing system. For example, Egyptian hieroglyphics use small and symbolic images to represent words, and similar developments were also found for ancient Aztec, Chinese, and Mayan cultures (Sassoon & Gaur, 1997). It is in the later stages that the relationship between writing and speech is tightened by the "phonetization" that allows symbolic expressions of objects and concepts to correspond to exact categories of speaking sounds by the grapheme–phoneme correspondence (GPC) rules (Gelb, 1963). Because of this combination of visual and auditory input, a word was born.

Just as ancient logographic words are used, modern GUIs use icons to provide visual representations of a certain concept, object, activity, place, or event by symbolic illustrations in the computing environment (Sassoon & Gaur, 1997). Iconic representations have become popular since the first GUI was developed at Xerox Palo Alto Research Center in 1979 and later embraced by mainstream software development companies such as Microsoft and Apple (Caplin, 2001). The common ground of icons and logographic words is the purpose of creating systematic symbols for reliable communication. According to Horton (1994, p. 3), "you can use an icon anywhere you would use a word label," which suggests the interchangeability in function between icons and words.

Reading an icon or a word requires complex processes of decoding components of the presented stimulus for the purpose of deriving or constructing meaning in the brain. Such processes involve visual representations of information being perceived by the retina, processed by the visual cortex, and interpreted by various brain areas (e.g., Broca's and Wernicke's areas) that form a network related to language processing and semantic cognition. "In the broadest sense, reading presumably entails basic sensory and motor components, as well as more central components, such as the analysis of visual word forms, the analysis of word sounds, and the analysis of word meaning" (Fiez & Petersen, 1998, p. 914). Presumably, reading symbolic information such as an icon demands more of our visual perception in the analysis of its graphics (Horton, 1994) and lacks the GPC rules to associate a sound with its visual forms. Superficially speaking, in spite of this difference

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in the analysis of phonology, both reading a word and reading an icon require semantic cognition of the brain in order to analyze the meaning associated with the visual representation.

Because iconography has historical connections to written words, it is plausible to argue that single-icon reading may share the same semantic system of language processing in the brain as single-word reading. However, understanding how human cognition works to interpret icons is not easy. Although there are studies such as McDougall and Curry's (2004) framework of icon interpretation from a cognitive psychological perspective and Yu and He's (2010) analysis of users' cognitive factors with icons, most similar articles lack empirical evidence to support their theoretical discussions about the mechanism of cognition in human icon processing.

HCI research into human icon processing follows most commonly the paradigm of behavioral methods in cognitive psychology (cf. Isherwood, McDougall, & Curry, 2007; McDougall & Curry, 2004; McDougall, Curry, & de Bruijn, 1999, 2001; McDougall, de Bruijn, & Curry, 2000; McDougall, Forsythe, & Stares, 2005). Using the paradigm of behavioral methods in HCI research has a long tradition. Early approaches such as the GOMS (Goals, Operators, Methods, and Selection rules) model and the human information processor model (or model human processor [MHP]) are examples of modeling human abilities and cognitive processes in HCI, which allow for different aspects of an interface and user responses to be studied and accurately predicted (Card, Moran, & Newell, 1983). However, behavioral methods have limitations in understanding the mechanisms of human cognition underlying physical responses. Beyond behavioral modeling of the efficiency and accuracy of end users' physical responses, HCI researchers recently have been adapting new methods to study how human cognition works to process different stimuli provided by machine interfaces in various computing environments. For instance, studies applying analyses of event-related potentials (ERPs) to HCI have shown the potential of using neuroimaging methods to understand human factors such as fatigue, depletion, and attention of cognitive resources during HCI tasks (e.g., Trimmel & Huber, 1998). These findings have demonstrated great potential for using neuroimaging methods to evaluate aspects of HCI that conventional behavioral testing tools cannot probe.

Application of cognitive neuroscience to HCI has been advocated under the heading of "neuroergonomics." According to Parasuraman (2003), "neuroergonomics focuses on investigations of the neural bases of mental functions and physical performance in relation to technology, work, leisure, transportation, health care and other settings in the real world" (p. 5). The goal of neuroergonomics is to use knowledge of the relation between brain function and human performance to design interfaces and computerized systems that are sensitive to brain function, with the intent of increasing the efficiency and safety of human–machine systems (Proctor & Vu, 2008). With this neuroergonomics approach, a better understanding of how humans establish connections between representations of the information system and their contextual meanings seems more promising.

Some might question why it is necessary to investigate brain functions to understand how people produce semantics (meanings) of perceived stimuli. A distinct reason is that human brains have the unique capability of creating contextual meanings during interactions with information perceived in a given environment. Even with all of our advances in technology, this special ability is still exclusive to humans and cannot be duplicated by current artificial devices (Freeman, 2000, 2002). The question of how humans create meanings remains mostly unexplored territory. Moreover, an objective and accurate measure of meanings has been shown to be an improbable application of mathematic precision (Klir & Wierman, 1999). It is seemingly impossible to explain the origin of semantic production except via probing into the neural mechanisms of the brain with neuroimaging methods.

Interpreting the meaning of stimuli is essentially a cognitive process of the brain. It is practical to take the neuroergonomics approach to investigate how human icon processing works and whether people do read icons as logographic words because of their epistemological connections. Consequently, the following section is devoted to reviewing the brain's neural mechanisms of language processing and the brain's semantic system to understand semantic productions of icons and texts.

The Semantic System in the Brain

Semantic cognition research seeks to understand cognitive processes that access stored knowledge about the world. Such semantic knowledge "is about objects and their properties, and of relationships between and among them, including knowledge of word meanings" (McClelland & Rogers, 2003, p. 311). It is generally believed that neural representations of semantic processing are widely distributed in the brain.

Object recognition and word recognition are two major categories of semantic cognition research. However, there is a clear dichotomy between using scenery pictures (representations of objects) and using words as stimuli in neuroimaging studies of semantic cognition. For example, in Binder, Desai, Graves, and Conant's (2009) review of 120 studies regarding cortical representation of the semantic system of language processing in the brain, the authors applied selective criteria that excluded studies emphasizing use of object pictures to elicit knowledge retrieval. Their inclusive criteria were based on the argument that object recognition and word recognition elicit semantic access routes that are not identical.

Binder et al. (2009, p. 2768) suggested that (a) "object recognition engages a complex, hierarchical perceptual stream that encodes progressively more abstract representations of object features and their spatial relationships," and

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(b) comprehension of a word did not entail activation of a detailed perceptual representation of the object to which it referred—literate people do not need to see a picture of a cup to understand the meaning of the word "cup." Evidence enlisted by Binder et al. included neuroimaging studies regarding (a) different activation patterns during matched word and picture recognition tasks, and (b) patients who had selective impairments between visual object recognition and word comprehension. Such evidence argued against a complete overlap between the knowledge systems underlying object and word recognition.

Although there is a clear dichotomy between using object pictures and using words as stimuli in semantic cognition research, icons are in a somewhat ambiguous place between these two types of stimuli. The main purpose of our study is to test the hypothesis that people read icons as logographic words instead of as pictures. We suggest that the same semantic system of language processing is also involved in icon recognition. Thus, Binder et al.'s (2009) review of the semantic system that processes word stimuli and correspondent tasks can provide fundamental knowledge about possible semantic contrasts that might be activated by iconic stimuli.

Binder et al.'s (2009) meta-analysis of 120 functional neuroimaging studies on semantic contrasts included (a) words versus pseudowords, (b) semantic task versus phonological task, and (c) high versus low meaningfulness. According to these studies, about 68% of the activation foci are in the left hemisphere and 32% in the right hemisphere. This indicates that the semantic system is widely distributed in the brain and has moderate lateralization in the left hemisphere. Binder et al. identified seven principal regions of the large-scale semantic network of the human brain (Figure 1). These cortical areas are (a) the angular gyrus (AG) and adjacent supramarginalgyrus (SMG), (b) the entire length of the middle temporal gyrus (MTG) and posterior portions of the inferior temporal gyrus (ITG), (c) a ventromedial region of the temporal lobe centered on the midfusiform gyrus and adjacent parahippocampus, (d) dorsomedial prefrontal cortex (DMPFC) in the superior frontal gyrus and adjacent middle frontal gyrus (MFG), (e) the inferior frontal gyrus (IFG), especially the pars orbitalis, (f) ventromedial prefrontal cortex (VMPFC) and orbital prefrontal cortex, and (g) the posterior cingulate gyrus and adjacent ventral precuneus.

Binder et al. (2009) proposed underlying functions of these seven principle regions that manifest essential roles in semantic cognition. The next few paragraphs are a summary of the empirical data from their meta-analysis.

The AG is anatomically connected almost entirely with other association regions and receives little or no direct input from primary sensory areas. The AG likely plays a role in complex information integration and knowledge retrieval such as sentence comprehension, discourse, problem solving, and planning.

The MTG, the ITG, the fusiform gyrus, and the parahippocampus in lateral and ventral temporal cortices are likely heteromodal cortices involved in supramodal integration and concept retrieval. The MTG and the ITG of the temporal lobe may be principal sites for storage of perceptual information about objects and their attributes (e.g., tools and their action concepts), whereas the superior temporal gyrus's (STG) role in language comprehension relates primarily to speech perception and phonological processing rather than to retrieval of word meaning. Most studies of the fusiform and parahippocampal gyri use object pictures as stimuli instead of words. However, these two areas are also important to language processing. The midfusiform gyrus plays a particular role in retrieving knowledge about the visual attributes of concrete objects. The parahippocampal component acts as an interface between lateral semantic memory and medial episodic memory networks.

The left DMPFC is adjacent to motivation and sustained attention networks (e.g., anterior cingulated gyrus, premotor cortex, and supplementary motor area). If the left DMPFC is

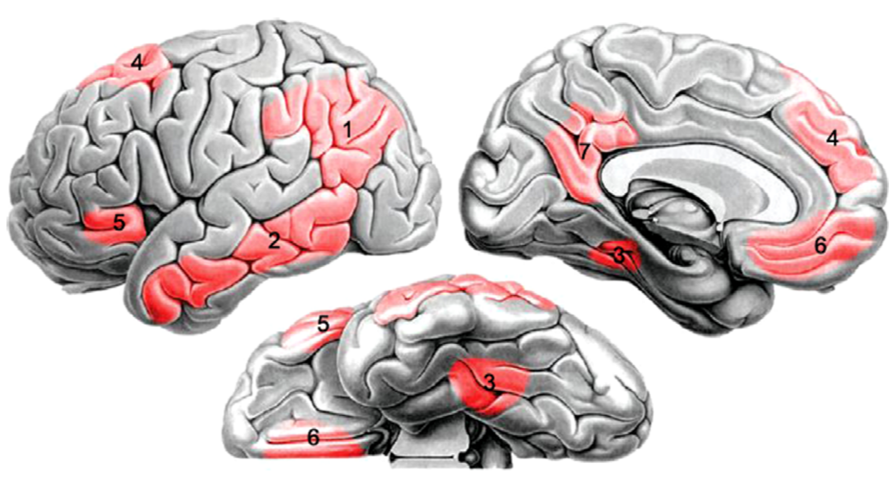

FIG. 1. Principal regions of the semantic network in the human brain (Binder et al., 2009). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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damaged, this will affect self-guided, goal-directed retrieval of semantic information. For example, patients having such a lesion can repeat words and name objects normally but cannot invent responses that are not formulaic according to preset procedures or instructions. The left IFG may affect the "efficiency" of semantic processing, but its functions are more related to phonological, working memory, and syntactic processes. The left VMPFC is implicated in many studies of motivation, emotion, and reward processing, and it probably plays a central role in processing the affective significance of concepts (e.g., the emotional attributes of words). The posterior cingulated gyrus has been linked with episodic and visuospatial memory functions, emotion processing, spatial attention, and visual imagery. By virtue of its strong connections with the hippocampus, the posterior cingulated gyrus acts as an interface between the semantic retrieval and the episodic encoding systems.

Binder et al.'s (2009) review of the semantic system in the brain provides great insight into the specific cortical regions underlying the semantic processing of word-related stimuli. This semantic system provides references that can be used in the comparison of single-icon versus single-word processing. This study hypothesizes that icons are processed by the brain as logographic words, so fMRI data should show the same or similar patterns of activated cortical regions in the semantic system during icon- and word-recognition tasks. For this reason, we focus on the contrasts within the semantic system to determine whether reading of icons is using the same language network that deals with words and logographic words.

Related fMRI Studies

Because Chinese characters evolved from visual symbols, several neuroimaging studies have explored the connections between Chinese character reading and picture naming (e.g., Chee et al., 2000; Lee et al., 2004; Yoon, Chung, Kim, Song, & Park, 2006). It has been proposed that the logographic nature of Chinese characters has greater predictability in mapping the word form to its meaning, whereas the semantic mapping of English words is based on the process of phonology. Although it is a rational hypothesis that there is a relatively large cognitive overlap between Chinese character identification and picture identification, many researchers argue that a great number of Chinese characters are discrete linguistic units including arbitrary symbols (radicals) that are neither pictographic nor alphabetic. This suggests that processing a character still will be more like language processing than picture processing for Chinese speakers. However, there are contradictory discourses in findings of neuroimaging studies about the relation between Chinese character reading and picture processing. For example, character–picture comparisons revealed dependent differences in blood-oxygenation-level dependent (BOLD) contrasts between logographic words and pictures in fMRI data (Chee et al., 2000).

Findings of Chee et al. (2000) and Lee et al. (2004) on character -naming relative to control conditions (i.e., picture naming or English word reading) argue that (a) semantic processing of Chinese characters shares greater similarities with English words than with pictures; (b) BOLD contrasts from effects of Chinese characters are more strongly related to the phonological pathway than the ventral or visual object-recognition pathway, and (c) Chinese logogram-to-phonology transformations (as seen in brain activation patterns) are similar to orthography-to-phonology transformations of English word reading, which suggests that the neural mechanisms for language processing are universal across different writing systems. On the other hand, Yoon et al. (2006) argued that "more right hemispheric regions, except for the inferior frontal cortex, are involved in the reading of Chinese characters compared with English words" and that there is "a right hemispheric dominance within the occipitotemporal and the left middle/medial frontal area for both reading Chinese characters and naming pictures" (p. 95). Yoon et al. suggested that such overlapping regions in the right hemisphere should not be overlooked and that the data "should reflect the specific visual processing of reading Chinese characters" (p. 90).

Some studies have tried to explore the differences between modulated neural activations of pictographic/ideographic logographical words and phonetic logographic words. For instance, studies by Sugishita, Otomo, Kabe, and Yunoki (1992); Nakamura et al. (2002); and Nakamura, Dehaene, Jobert, Le Bihan, and Kouider (2005) on distinctions between Japanese Kanji (adapted Chinese characters) and Kana (Japanese alphabets) showed that (a) the processing routes for these two types of words were not clearly separated and used largely the same cortical regions, (b) writing and subliminal priming of Kanji (presumed to be ideographic) and Kana (presumed to be phonographic) scripts modulated the visual occipitotemporal activations according to their graphic features, and (c) Kanji had slightly more mesial and right-predominant activation, whereas Kana had greater occipital activation.

Chen, Fu, Iversen, Smith, and Matthews (2002) conducted a similar test for dual processing routes in reading by directly contrasting Chinese character and Pinyin (Chinese alphabetic sound symbols based on the Romanization system) reading, and suggested that (a) reading Chinese characters and Pinyin activated a common brain network including the inferior frontal, middle, and inferior temporal gyri, the inferior and superior parietal lobules, and the extrastriate area; (b) reading Pinyin led to a greater activation in the inferior parietal cortex bilaterally, the precuneus, and the anterior middle temporal gyrus; and (c) reading Chinese led to greater activation in the left fusiform gyrus, the bilateral cuneus, the posterior middle temporal, the right inferior frontal gyrus, and the bilateral superior frontal gyrus.

The findings of Chen et al. (2002) and Yoon et al. (2006) seemed to suggest that reading Chinese was different from reading English because single-word processing

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in Chinese involved more modulated activations in bilateral and right hemispheric regions and required a greater extent of the semantic system in the brain. Their findings concurred with Binder et al.'s (2009) review indicating that the activation foci of language processing were widely distributed in both hemispheres. In addition, reading Chinese activated regions that were more associated with the ventral pathway of visual word processing in the left hemisphere, whereas reading English modulated greater activation in the dorsal pathway of phonological processing in the language network. On the other hand, the relation between Chinese character reading and picture naming is opposite to the relation between Chinese character reading and English word reading. Chee et al. (2000) argued that access to meaning for Chinese characters involved obligatory phonological processing in the left middle and superior temporal gyri as in English words, whereas picture naming happened after semantic accessing and had a predominantly right occipital effect that was not specifically related to reading words. Therefore, Chinese characters were processed more like English words and not processed as pictures.

As previous studies indicated, the processing of Chinese characters, English words, and pictures shared the same semantic system that covered both hemispheres, and their differences in the perceptual processing were identified by contrasting each condition's modulated activations of fMRI data. This study uses the same contrasting method to determine whether the brain processes icons as logographic words instead of pictures.

Challenges of Comparing Different Visual Stimuli in fMRI Studies

The cultural differences among language groups might influence the cognitive processes of different languages. Although it is assumed that language processing is a universal mechanism in human cognition across cultures, results of language-related neuroimaging experiments might be biased by factors that are subject specific (e.g., gender, age, handedness, and literacy) and language specific (e.g., phonemes, metaphors, lexicality, categorization, and frequency; Démonet, Thierry, & Cardebat, 2005). These factors have to be controlled in the experimental design. In addition, past studies have often failed to address differences between native and nonnative speakers of a logographic language. For instance, Chee et al. (2000), Lee et al. (2004), and Yoon et al. (2006) did not recruit native English speakers (except for Chinese–English bilinguals) to participate in experimental conditions that could be used as a control/referential comparison for Chinese and English processing. Other factors such as insufficient number of subjects, variations of stimuli duration, task difficulty, handedness, gender, age, and literacy could also contribute to produce false-positive results of observed BOLD activations in word-reading conditions (Démonet et al., 2005). These issues again suggest the necessity of refining the details of experimental design.

Research Question and Hypothesis Development

We established two theses in preparation for our empirical investigations. First, because of the etymological and functional connections between modern icons and logographic words, it is plausible that people read icons as logographic words. Second, new approaches such as neuroimaging methods have emerged by which to investigate the connection between brain functions and semantic productions of human information processing. Such neuroimaging methods have potential for addressing this study's research question of whether icons are cognitively processed as pictures or logographic words. Thus, we follow in the footsteps of studies in neuroimaging studies of symbol interpretations in contrast to other visual stimuli and describe our neuroimaging research design.

We operationalized our research question as, "are people's fMRI data of reading icons different from those of reading pictures or of reading logographic words such as Chinese characters?" We proposed that predicted patterns of fMRI data modulated by icons would not be significantly different from those of Chinese characters and would be significantly different from those of pictures. In other words, no significant contrasts in brain regions would be found between conditions of interpreting icons and Chinese characters, whereas significant contrasts should be identifiable between conditions of interpreting icons and interpreting pictures. Factors of represented semantics and native language literacy would also have effects on the dependent variables. Their interactions with other factors could also pertain. For example, concrete stimuli were expected to be processed more efficiently than abstract stimuli and to have different fMRI contrasts (cf. Fiebach & Friederici, 2004; Kiehl et al., 1999). Finally, we expected that Chinese native speakers might engage different brain regions in the logographic word condition in contrast to native English speakers' brain regions in the word condition (cf. Kim, Relkin, Lee, & Hirsch, 1997; Yoon et al., 2006).

Methods

We employed fMRI methods to identify brain regions that were employed to read icons in contrast to neural correlates of reading pictures, English words, and Chinese characters in order to determine whether the same or different neural networks were required to process these four types of stimuli. The objective of this study was to establish premises regarding whether icons and Chinese characters stimulated the same language representations in the brain and had distinct patterns of responses that were different from the perception of pictures.

Independent and Dependent Variables

Table 1 lists the independent and dependent variables of this study. Four factors were chosen as independent

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TABLE 1. Independent and dependent variables.

Within-subject variables																																
F1	Chinese characters								English words								Icons								Pictures							
F2	Concrete				Abstract				Concrete				Abstract				Concrete				Abstract				Concrete				Abstract			
F3	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

Note. Between-subject variables (F4): Native English speakers and native Chinese speakers. Measures: fMRI imaging data including structural scans and BOLD signals.

variables (IVs): F1, types of stimuli (icons, pictures, Chinese characters, and English words); F2, types of semantics (concrete and abstract); F3, experimental runs (run 1, run 2, run 3, and run 4); and F4, native language literacy (English speakers "EN" and Chinese speakers "CH"). F1, F2, and F3 were within-subject variables, and F4 is a between-subject variable. The dependent variables (DVs) of this study are fMRI imaging data including structural magnetic resonance imaging scans and BOLD signals of hemodynamic responses of the test participant's brain that determine modulated activations of brain regions associated with the experimental conditions. BOLD signals were collected while the test participant was performing a semantic-judgment task of sorting stimuli into two categories, concrete and abstract. A semantic-judgment task was employed simply to ensure that the subjects were actually processing the visual stimuli. Details of the task and methods of fMRI data acquisition are described in a later section.

Selection of Test Materials

We selected 200 stimuli for this study. These 200 stimuli consisted of 50 icons, 50 pictures, 50 single English nouns, and 50 single Chinese characters (also nouns). Each type of stimulus had 25 highly comprehensible stimuli that represented concrete objects and 25 highly comprehensible stimuli that represented abstract concepts.

The criterion for selecting these 200 stimuli was based on the statistical analysis performed on the rating scores collected from the web-based questionnaire of a previous study that surveyed 500 visual stimuli with 211 participants (Huang, 2011a, 2011b). These surveyed 500 stimuli included (a) 135 icons designed by Gerd Arntz (1900–1988), Manual on Uniform Traffic Control Devices (MUTCD) 2003 Edition With Revision No. 1, and the Professional Association for Design (AIGA).[1] (b) 125 high-frequency single English nouns; (c) 127 high-frequency single Chinese characters (also nouns); and (d) 113 pictures including object pictures in the ETH-80 database (Kunnath, Cornell, Kysilka, & Witta, 2005) and pictures selected from Google Images (http://images.google.com/) by using high-frequency nouns of objects and concepts as key words for search. Each of these 500 stimuli was assigned rating scores (i.e., very concrete = 1; concrete = 2; abstract = 3; very abstract = 4; N/A = 0) by earlier test participants. The zero scores "N/A" were excluded in the analysis so that they would not influence sample means of each type of stimuli.

In the earlier (Huang, 2011a, 2011b) study, each participant was given a general definition of what concrete and abstract stimuli were. The general definition suggested that, if the stimulus represented a physically existing object, such as a cup, it would be concrete; if the stimulus represented a concept, such as love, it would be abstract. The participant was asked to choose the best category that fitted the presented stimulus based on his or her interpretations of its meaning. Under these circumstances, a stimulus was considered concrete if its mean score was lower than the sample mean (as 1 represented "very concrete" and 2 represented "concrete") and abstract if its mean score was higher than the sample mean (with 3 and 4 representing "abstract" and "very abstract," respectively).

We wanted to use stimuli that were maximally representative of the "concrete" and "abstract" categories so that they could be highly comprehensible for our test participants to sort into these two categories in a behavioral task with minimized risk of ambiguity. Thus, those stimuli with means most below or above the sample mean were marked as highly comprehensible stimuli. In our case, the 25 lowest-rated icons were selected as highly comprehensible concrete icons ($z < -1.00$); the 25 highest-rated icons were chosen as highly comprehensible abstract icons ($z > 1.04$), and the same approach was applied to the rest of the stimuli types. In other words, we selected 200 highly comprehensible stimuli in two distinctive categories according to the survey ratings and expected test participants to judge easily whether a stimulus from these 200 stimuli was concrete or abstract as long as our test participants in this study were from the same population as that from whom we established the statistical norms in the previous study. All stimuli had the same displaying format as bitmap images that were in the same size (470×470 pixels) and color (black-and-white images with gray-scale contrasts). Table 2 shows 8 examples of these 200 selected stimuli.

[1]Because there are various design styles of icons, we selected symbols that comply with AIGA design guidelines and MUTCD standards and modified them based on Arntz's style. Wang et al. (2007) assert that most modern HCI icons are combination symbols best described as a fusion of a concrete symbol and an abstract symbol in that it depicts both items that exist in the real world and arbitrary elements, and choosing such combination symbols as our representative icons would have introduced confounds in the process of determining the concrete versus abstract dichotomy of our stimuli.

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TABLE 2. Samples of stimuli and their normative ratings.

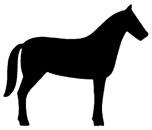		car	山
Z-score = −1.46 Concrete icon	Z-score = −1.90 Concrete picture	Z-score = −1.40 Concrete word	Z-score = –0.82 Concrete character
		hope	愛
Z-score = 2.05 Abstract icon	Z-score = 2.03 Abstract picture	Z-score = 1.67 Abstract word	Z-score = 1.88 Abstract character

TABLE 3. Content of stimuli presentation.

		220 Seconds					
	8 Seconds		Chinese characters	English words	Icons	Pictures	Null
Run 1	Fixation (+)	Stimuli set 1	16 concrete	13 concrete	11 concrete	16 concrete	10
		Sequence 1	9 abstract	12 abstract	14 abstract	9 abstract	
Run 2	Fixation (+)	Stimuli set 2	9 concrete	12 concrete	15 concrete	9 concrete	10
		Sequence 2	16 abstract	13 abstract	10 abstract	16 abstract	
Run 3	Fixation (+)	Stimuli set 1	16 concrete	13 concrete	11 concrete	16 concrete	10
		Sequence 3	9 abstract	12 abstract	14 abstract	9 abstract	
Run 4	Fixation (+)	Stimuli set 2	9 concrete	12 concrete	15 concrete	9 concrete	10
		Sequence 4	16 abstract	13 abstract	10 abstract	16 abstract	

Experimental Design of Event-Related fMRI Paradigm

The stimuli were presented by the DMDX (Display-Master DX) software[2] on a laptop computer with a monitor having a 640 × 480 resolution and projected to an overhead mirror in the MR scanner. The presentation contained four runs. Each run had 110 trials consisting of 25 icons, 25 pictures, 25 single Chinese characters, 25 words, and 10 null conditions. Each run contained both concrete and abstract stimuli. The null condition was a small black cross that served as a visual fixation point at the center of the screen, offered to inhibit the test participant from getting into a response rhythm. All stimuli were presented with a white background. The first and the third runs had the same set of 100 stimuli in two different orders, and the second and the fourth runs had a second shared set of another 100 stimuli also in two different orders. Therefore, the participant would see each stimulus twice during the whole experiment.

Every run started with a null condition for 8 seconds and then playing the first stimulus. The interstimulus interval (ISI) was 2 seconds. Each stimulus was presented for 2 seconds before the next stimulus appeared on the screen. The presentation showed stimuli continuously until all 110 trials for each run had been played. Therefore, each run lasted for exactly 228 seconds. All four runs had different sequences of displaying the stimuli. Such sequences were designed according to the principles of event-related design.[3] The optimal sequence for each run to play the stimuli was generated by optseq2.[4] Another reason of choosing the event-related design was to reduce practice and

[2]DMDX is a Win 32-based display system used in psychological laboratories around the world to measure reaction times to visual and auditory stimuli. It was programmed by Jonathan Forster at the University of Arizona. The software is available to download at http://www.u.arizona.edu/~kforster/dmdx/dmdx.htm.

[3]"In most event-related designs, different conditions of the IV are associated with different events. . . . Each event is separated in time from the previous event, with an interstimulus interval, or ISI, that can range from about 2 s to 20 s depending on the goals of the experiment. This differs from typical blocked designs, which may present many stimuli consecutively within a task block. Also unlike blocked designs, the different conditions are usually presented in a random order rather than an alternating pattern. Event-related designs . . . emphasize that [different conditions of] stimuli are presented one at a time rather than within a block of trials (that has the same condition of stimuli)" (Huettel et al., 2003, p. 303).

[4]Optseq2 is a software tool for automatically scheduling the order and timing of events for rapid-presentation event-related experiments (http://surfer.nmr.mgh.harvard.edu/optseq/).

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fatigue effects that could affect the accuracy and efficiency of subjects' performance (Huettel, Song, & McCarthy, 2003). Table 3 summarizes the content of the presentation.

Behavioral Task

Test participants were asked to perform a semantic decision-making task, which was to sort a presented stimulus into a concrete or abstract category by determining whether it represented a concrete object or an abstract concept. The reason for asking the participants to interpret presented stimuli in terms of concrete and abstract categories was to correspond to previous studies on classifications of icon taxonomy (Wang, Hung, & Liao, 2007), types of pictorial learning (Kunnath et al., 2005), and classification of concrete and abstract nouns in English and Chinese. This task was chosen to ensure that test participants would try to process the meanings of the presented stimuli similarly to the process of judging concrete and abstract nouns in language tests by understanding the meanings of words.

The participant was given a general guideline on how to sort the stimuli. The general guideline suggested that, if the stimulus represented a physically existing object such as a cup, it should be sorted into the concrete category; if the stimulus represented a concept such as love, it should be sorted into the abstract category. The participant was asked to choose the best category that fit the presented stimulus based on his or her interpretations of its meaning.

Test participants were asked to respond behaviorally to stimuli by pressing one of two different buttons on a response box with the index and middle fingers of their right hand. The participant was to use the right index finger to press button 1 when a concrete stimulus that represented an object appeared on the screen and to use the right middle finger to press button 2 when an abstract stimulus that represented a concept appeared on the screen. In addition, the participant was instructed to do nothing when he saw the null condition. All participants performed this task to every presented stimulus, except that English speakers were instructed to treat all Chinese characters as abstract because they did not and were not expected to understand the meaning of these stimuli.

Participants were instructed to perform the task based on their semantic interpretations of the presented stimuli without being informed that there were statistical consensuses on the semantics of each stimulus according to the earlier study's data (Huang, 2011a, 2011b). The presentation did not provide feedback to the test participants to inform them whether their response to each stimulus was "correct" or not (i.e., sorting a presented stimulus into a category that was consistent with the statistical norms in the previous study) and would keep playing consecutive stimuli. Participants were instructed not to linger on a previous trial once they had made a response and should focus on the next one even if they thought that they had made a mistake sorting the presented stimulus into a wrong category. In addition, the test participant had to administer a response to each stimulus within the first 1.8-second period of the 2-second ISI. If the test participant failed to respond in this allotted 1.8-second during each trial, the trial was counted as a slip. (This 1.8-second constraint on participants' reaction time was to avoid mismatching the current reaction time to the next stimulus presentation. This control allowed DMDX to have a 0.2-second interval to switch the display from the current stimulus to the next one so that the onset time of each stimulus could be precisely maintained between the 2-second ISIs.) All test participants repeated the same task for all four runs in the MR scanner and could take a short break between runs per request.

Participants' reaction times (msec) and numbers of errors were recorded by DMDX. Reaction time was defined as the period of time starting at the moment when the stimulus was shown on the screen and ending at the moment when the participant administered a response. Every valid measure of a participant's reaction time for each trial had to be shorter than 1.8 seconds. Errors were counted when the participant either exceeded the 1.8-second constraint to respond to the trial or responded incorrectly (i.e., responses that were different from the statistical norms established in the previous study and slips). Such errors would be excluded from our fMRI data analyses to ensure the integrity of neural correlates of experimental conditions.

Selection of Participants

From a pool of 78 participants who had participated in a previous behavioral study that tested the reliability of the fMRI paradigm, 20 subjects who had better performance (i.e., making faster responses and fewer mistakes) in responding to the fMRI paradigm were selected to participate in this study. These participants included 10 Chinese and 10 English speakers to form two language groups. The number of subjects met the minimum statistical requirement of sample size for an event-related design in experiment and group analysis of fMRI studies (cf. Desmond & Glover, 2002; Murphy & Garavan, 2004). Each group had five males and five females to control the gender factor that was related to language processing (cf. Kaiser, Haller, Schmitz, & Nitsch, 2009). All 20 participants had to be right-handed and within the age range of 18–35 years. Such screening was to control the factors of handedness and age (cf. Fridriksson, Morrow, Moser, & Baylis, 2006; Knecht et al., 2000). These 20 participants were also screened to make sure that they had normal or corrected-to-normal vision and did not have histories of mental illnesses, neurological diseases, or head injuries.

FMRI Acquisition Method

Functional imaging was acquired with a General Electric 3.0 Tesla magnetic resonance imaging (MRI) scanner using a parallel-acquisitions echo-planar imaging (EPI) sequence (GeneRalized Autocalibrating Partially Parallel Acquisitions, GRAPPA). Functional images were collected by utilizing whole-head coverage with slice orientation to reduce artifact (approximately 20° off the AC-PC plane [referring to the anterior and posterior commissures], TR = 2 seconds, echo time [TE] = 30 msec, 35 axial slices oriented for best whole-head coverage, acquisition voxel size = 3.125 × 3.125 × 3 mm with a 0.3-mm interslice gap). The first four EPI volumes were discarded to allow scans to reach equilibrium. In all cases, the presentation of stimuli was viewed utilizing a back-projection screen and a mirror mounted on the top of the head coil. Responses were collected using a MR-compatible, two-button response pad that was held in the right hand. In addition to obtaining EPI images during task performance, one or two high-resolution T1 spoiled gradient recalled (SPGR) scans were acquired for the purpose of orienting individual participants in standard MNI (Montreal Neurological Institute) coordinate space. These images were acquired in the sagittal plane using a 1.3-mm slice thickness with 1-mm in-plane resolution.

Data Analysis and Results

FMRI data were acquired at the Imaging Research Center at the University of Texas at Austin with the selected participants from November 12 to December 2, 2010. Data of one female Chinese participant were not included in the final analysis because of her excessive head movements in the scanner during the experimental process.

Behavioral Data Analysis: Method

Analysis of variance (ANOVA) for repeated measures was employed to analyze collected data. F values with Greenhouse-Geisser-corrected degrees of freedom (df) were used to determine significant mean differences between factors unless such contrasts had passed Mauchly's test of sphericity (cf. Geisser & Greenhouse, 1958; Mauchly, 1940). The statistical analysis tested the effects of IVs and interactions among IVs to determine whether they had influences resulting in significant differences of estimated means of each condition's reaction times and error counts of participants' behavioral performance.

Behavioral Data on Errors

There were significant contrasts in numbers of errors in within-subject factors including different experimental runs, $F(3, 54) = 102.363$, $p < 0.01$; represented semantics, $F(1, 18) = 8.214$, $p < 0.05$; and types of stimuli, $F(3, 54) = 148.043$, $p < 0.01$. Pairwise comparisons of different experimental runs indicated that participants made significantly more errors in the first run (mean = 2.194, significant mean differences in contrast to all other runs at $p = 0.01$) and significantly fewer errors in the fourth run (mean = 0.544, significant mean differences in contrast to all other runs at $p = 0.01$). The difference between the second and third run's mean error was not significant at $p = 0.05$, but their mean errors were both significantly lower than in the first run and significantly higher than in the fourth run ($p < 0.01$). Pairwise comparisons of different represented semantics indicated that participants made significantly more errors with abstract stimuli (significant mean difference = 0.559 at $p = 0.05$). Pairwise comparisons of different types of stimuli indicated that people made significantly more errors with icons (mean = 2.752, significant mean differences in contrast to all other runs: 1.944 more than Chinese characters, 1.750 more than English words, and 0.475 more than pictures at $p = 0.01$) and pictures (mean = 2.681, significant mean differences in contrast to all other runs: 1.469 more than Chinese characters, 1.275 more than English words, and 475 fewer than icons at $p = 0.01$). The mean difference between errors made with Chinese characters and English words was not significant at $p = 0.05$.

There were significant interactions in runs × semantics, $F(3, 54) = 12.952$, $p < 0.01$; runs × stimuli, Greenhouse-Geisser $F(2.839, 51.107) = 99.262$, $p < 0.01$; and runs × semantics × stimuli, Greenhouse-Geisser $F(4.176, 78.166) = 24.695$, $p < 0.01$. These significant interactions indicated that participants made significantly more errors with abstract stimuli in earlier runs. Participants made more errors in earlier runs with influences from different types of stimuli. For example, participants made significantly more errors with icons in the first run, and, in later runs, errors with pictures were significantly more frequent than the rest. Participants also made significantly more errors with concrete/abstract pictures and icons and significantly fewer errors with concrete/abstract English words and Chinese characters, especially in the earlier runs.

The main effect between subject groups was significant, $F(1, 18) = 6.385$, $p < 0.05$, and there were significant interaction effects between subjects regarding different types of stimuli. In this case, significant interactions were found in stimuli × subjects, $F(3, 54) = 8.008$, $p < 0.01$. Chinese speakers made significantly more errors with Chinese characters than English speakers. This significant difference was not critical, because English speakers did not interpret meanings of Chinese characters.

In conclusion, participants' behavioral data for errors were consistent with findings of our pilot behavioral study. Because the data on errors would be excluded and not reflected in the fMRI analyses, the purpose of this analysis of participants' behavioral data was mainly to show that participants' behavioral responses did not change significantly from our pilot study with 78 subjects.

Behavioral Data about Reaction Times

There were significant contrasts of reaction times in all within-subject factors including different experimental runs, $F(3, 54) = 67.385$, $p < 0.01$; represented semantics, $F(1, 18) = 9.509$, $p < 0.01$; and types of stimuli, $F(3, 54) = 110.073$, $p < 0.01$. Pairwise comparisons of different experimental runs indicated that participants were significantly slower in the first run (mean = 1,004.136 msec, significant mean differences in contrast to all other runs at $p = 0.01$) and significantly faster in later runs, reaching their maximum speed in the third and fourth runs (mean = 871.667 msec and 863.903 msec, significant mean differences in contrast to runs 1 and 2 at $p = 0.01$). Pairwise comparisons of different represented semantics indicated that participants responded significantly slower with abstract stimuli (significant mean difference = 44.164 msec at $p = 0.01$). Pairwise comparisons of different types of stimuli indicated that participants spent a significantly longer time interpreting pictures (mean = 1,016.980 msec) than all other types of stimuli at $p = 0.01$. Interpreting icons (mean = 948.801 msec) was significantly faster than interpreting pictures and significantly slower than interpreting Chinese characters at $p = 0.01$. Interpreting English words (mean = 933.317 msec) was also significantly faster than interpreting pictures and significantly slower than interpreting Chinese characters at $p = 0.01$. Interpreting Chinese characters (mean = 801.603 msec) was significantly faster than all other types of stimuli at $p = 0.01$.

There were significant interactions in runs × semantics, $F(3, 54) = 3.888$, $p < 0.05$; runs × stimuli, $F(9, 162) = 11.578$, $p < 0.01$; semantics × stimuli, $F(3, 54) = 5.170$, $p < 0.01$; and runs × semantics × stimuli, $F(9, 162) = 4.938$, $p < 0.01$. These effects of significant interactions indicated that participants were significantly slower with abstract stimuli in earlier runs, and such a pattern persisted even though they had improved performance in later runs. Participants were also slower in earlier runs with influences from different types of stimuli in a pattern of spending more time interpreting pictures than icons, English words, and Chinese characters. Participants also needed significantly more time with abstract pictures and abstract icons and significantly less time with concrete English words and Chinese characters.

The main effect between subject groups was significant, $F(1, 18) = 11.283$, $p < 0.01$, and there was a significant interaction in stimuli × subjects, $F(3, 54) = 15.924$, $p < 0.01$. This indicated that English speakers responded significantly faster with Chinese characters than Chinese speakers regardless of different conditions of runs and/or semantics. This significant efficiency was because Chinese characters served as meaningless stimuli to English speakers, who were not required to perform semantic interpretations between concrete and abstract conditions. English speakers' responses to Chinese characters thus needed less cognitive load and were behaviorally faster. In conclusion, participants' behavioral data on reaction times were also consistent with findings of our pilot study with 78 subjects.

FMRI Analysis: Method

FMRI data analysis was carried out using FMRI Expert Analysis Tool (FEAT) version 5.98, part of FSL (FMRIB's Software Library, http://www.fmrib.ox.ac.uk/fsl). Z (Gaussianized T/F) statistic images were thresholded using a cluster-corrected significance threshold of $p < 0.01$. Locations of significant activations in brain regions are identified according to (a) the Harvard–Oxford Cortical Structural Atlas and (b) Talairach Daemon Labels provided by fslview. In agreement with the experimental design of the fMRI paradigm, each participant's functional imaging data consisted of four runs. Excluding all error and null trials, these four runs were combined and normalized as one participant's data. Ten English speakers' data were then combined to reflect the English group's data, and the same process was applied to the nine Chinese speakers' data. These normalized imaging data were analyzed to determine critical BOLD contrasts within and between these two language groups to determine whether fMRI data modulated by the experimental condition of interpreting icons shared greater similarities with logographic words than with pictures within the same semantic system of the brain.

FMRI Analysis: Utilization of the Language-Based Semantic System

The overall utilization of the language-based semantic system in the brain was observed in both English and Chinese speakers under conditions of sorting these four different types of stimuli into concrete and abstract categories. For example, brain regions suggested by Binder et al. (2009) could be identified by contrasting English words and icons in Chinese participants (Figure 2). Figure 2A–C reflects sagittal, coronal, and axial planes, respectively. For Figure 2B,C, the right side corresponds to the left side of the brain. The same is true for Figures 3 and 4.

FMRI contrasts of within- and between-group analyses under conditions of processing these four types of visual stimuli revealed significant proportions of activated brain regions including the AG in both hemispheres; bilateral posterior division of the SMG; both bilateral posterior division and temporo-occipital part of the MTG; right posterior division of the cingulate gyrus; interhemisphere areas of the DMPFC and the VMPFC; right parietal operculum cortex; both pars triangularis and pars opercularis of the IFG and its surrounding areas such as the MFG and the frontal pole in both hemispheres; the temporal occipital fusiform cortext and the posterior division of the temperoal fusiform cortex in both hemispheres; and Brodmann areas 2, 3, 4, 6, 7, 8, 9, 10, 13, 17, 18 19, 20, 21, 22, 23, 30, 31, 32, 37, 38, 39, 40, 43, 45, 46, and 47. These observed areas were in agreement with the activation of foci of semantic contrasts in the meta-analysis of Binder et al. (2009) and the proposed brain regions involved in language processing according to Démonet et al. (2005). Such findings imply that participants were in general utilizing the language-based semantic system in the brain to complete the experimental task successfully.

FMRI Analysis: Comparisons Between English and Chinese Speakers

Within-group analyses revealed that a certain brain region was critical to participants to sort these stimuli into concrete and abstract categories: left IFG for English speak-

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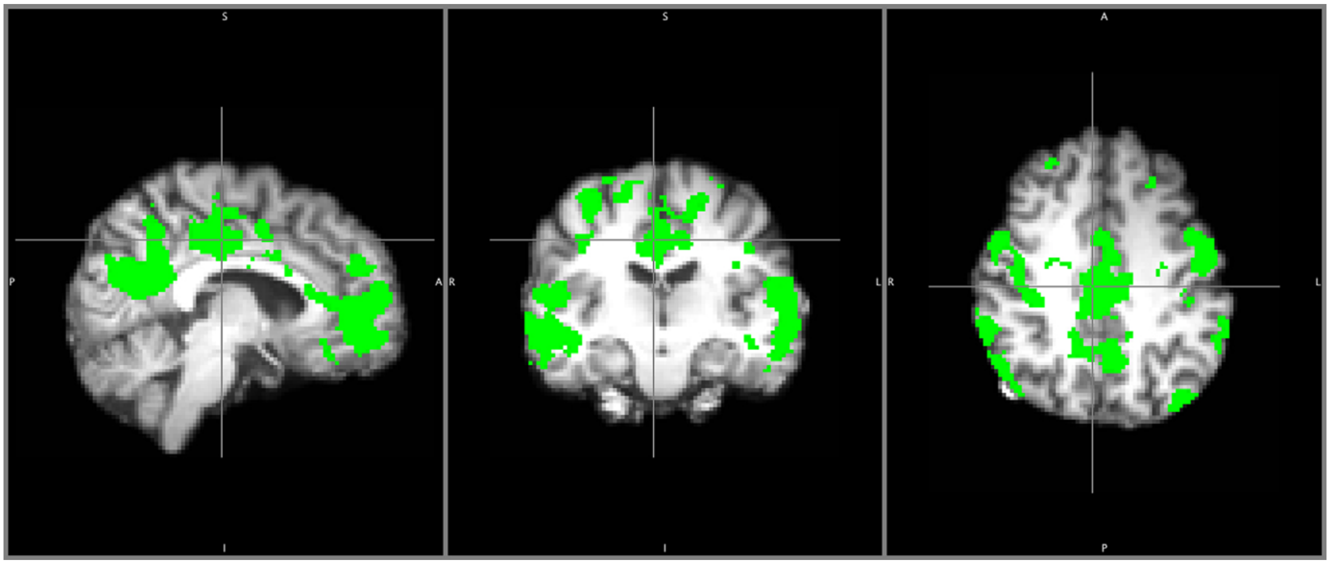

FIG. 2. Overall modulated activations of the language-based semantic system. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

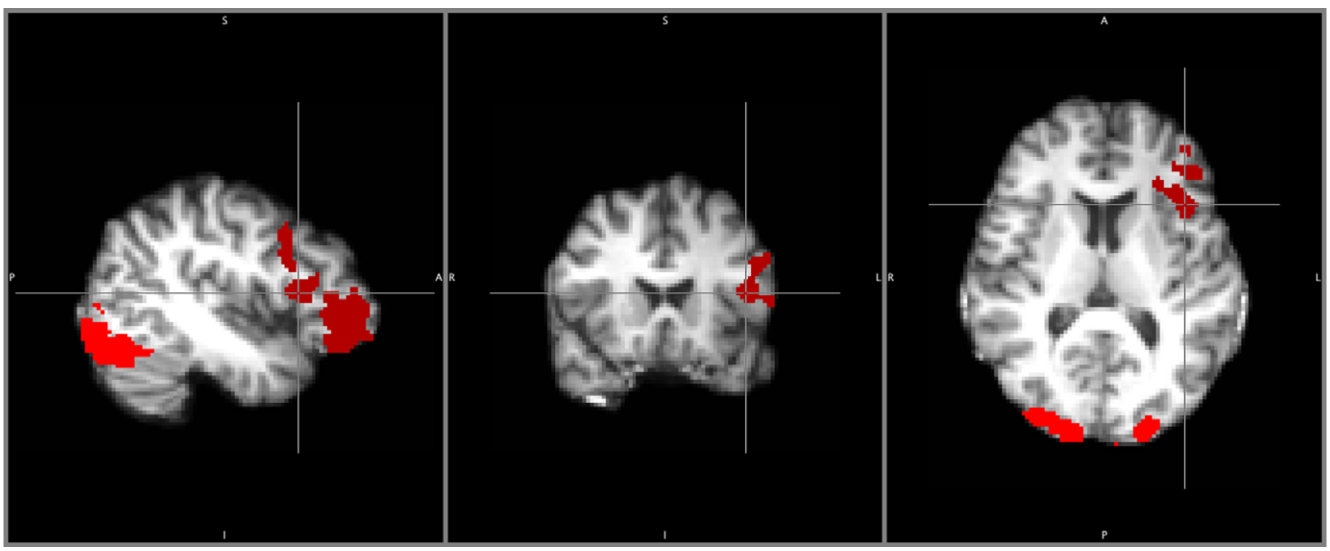

FIG. 3. Modulated activations in the left IFG of English speakers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

ers and left SMG for Chinese speakers. Figure 3 shows modulated activations in the left IFG of English speakers under the condition of interpreting icons, and Figure 4 shows modulated activations in the left SMG of Chinese speakers under the same experimental condition.

Similar modulated activations could also be observed in other within-subject analyses across all analyses, with some variances of other, accompanying brain regions that were significantly activated in fMRI contrasts. English speakers would often have accompanying activations in the left MFG and the left frontal pole in addition to the left IFG, whereas Chinese speakers would have accompanying activations in the bilateral IFG in addition to the left SMG. The left IFG and the left SMG are two brain areas critical to human language processing that have been discussed in both the classic model and the modern framework of language representations in the brain (Kandel, Schwartz, & Jessell, 2000). The significant contrasts in these two regions could imply that participants might be generating words in order to complete the experimental task successfully.

Despite an apparently different pattern of excitations in the brain between the left IFG and the left SMG, between-group analyses did not find significant differences in fMRI contrasts between English and Chinese speakers that were

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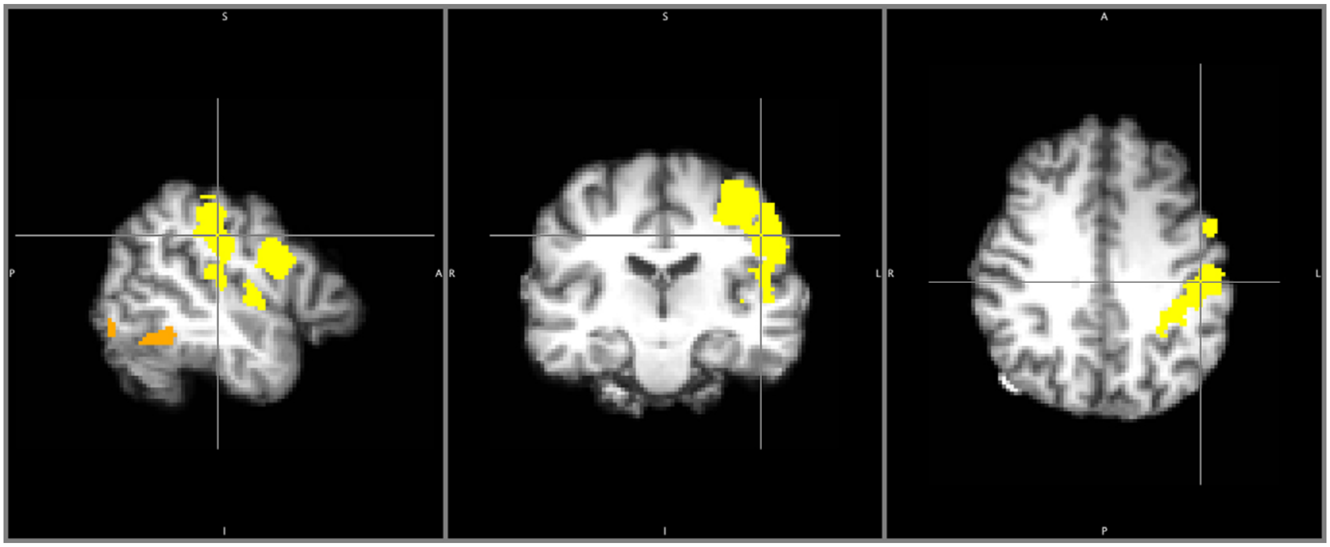

FIG. 4. Modulated activations in the left SMG of Chinese speakers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

critical to the semantic processes of sorting these four types of stimuli into concrete and abstract categories. Most significant differences in fMRI contrasts in between-group analyses were found in the primary visual and motor cortexes that were responsible for the perceptual and behavioral processes of the experimental task. However, there was one exception: when contrasting fMRI data under icons versus Chinese characters or vice versa, there were significant fMRI contrasts between Chinese and English speakers in the right hemisphere that involved modulated activations in the AG, the temporo-occipical part of the MTG, the MFG, and the IFG. This might imply that these brain areas in the right hemisphere were critical to the visual processing of Chinese characters regardless of whether the test participants understood the meanings of Chinese characters or not. Such findings were in agreement with Yoon et al. (2006) about the possibility of a right hemispheric dominance within the occipitotemporal and the left middle/medial frontal area for both reading Chinese characters and naming pictures.

FMRI Analysis: Comparisons Among Icons, Pictures, and Chinese Characters

FMRI contrasts among conditions of interpreting icons, pictures, and Chinese characters indicated that there were significant differences between icons and Chinese characters, whereas there was no significant difference between icons and pictures in BOLD signals at $p < 0.01$. Figures 5 and 6 show Chinese and English speakers' fMRI contrasts under these experimental conditions. Figures 5 and 6 show axially oriented slices from the bottom of the brain (top-left corner) to the top of the brain (bottom-right corner), and the left side of each head is the right side of the brain. In both Figures 5 and 6, the colored areas indicate significant contrasts in brain excitations as both Chinese (in Figure 5) and English (in Figure 6) speakers processed icons versus Chinese characters. The absence of the color in the right-side images of Figures 5 and 6 reflect no significant differences in the processing of icons versus pictures.

Despite the fact that English speakers could not understand the meaning of Chinese characters, their fMRI contrast showed patterns similar to those of the Chinese speakers under the condition of icons versus Chinese characters. Modulated activations in the IFG and the frontal pole in both hemispheres were identified in both English and Chinese speakers, with additional activations in the left DMPFC and VMPFC of Chinese speakers. Such modulated activations might imply that the phonological processing was an essential mechanism to compare icons and Chinese characters in the experimental task, and Chinese speakers might be more motivated and have better sustained attention than English speakers during this comparison. In addition, as mentioned in the previous section, between-group analysis under icons versus Chinese characters revealed that the IFG, the MFG, the AG, and the MTG in the right hemisphere were critical to the visual processing of Chinese characters. These significant fMRI contrasts between icons and Chinese characters imply that the cognitive mechanism for interpreting icons was different from that for interpreting Chinese characters in the task of sorting them into concrete and abstract categories, even for native Chinese speakers.

On the other hand, there was no significant difference in BOLD signals under the condition of icons versus pictures in either Chinese or English speakers' fMRI contrasts at $p < 0.01$. There was also no significant difference in between-group analysis under this condition. Such results implied that the cognitive mechanism for interpreting icons is similar to that for interpreting pictures in the experimental task.

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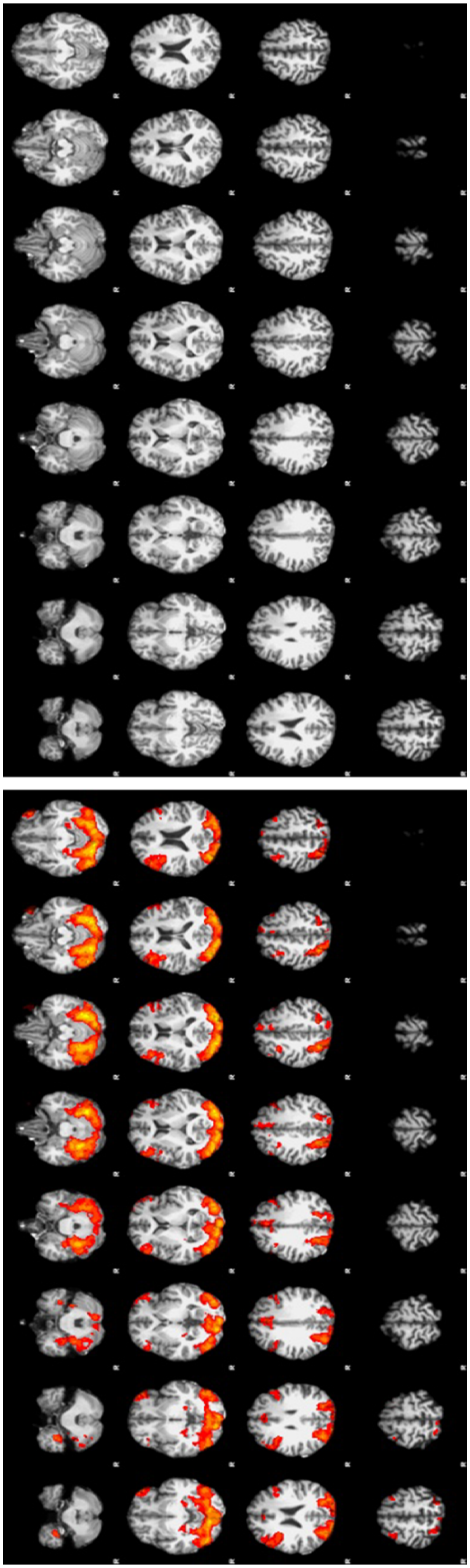

FIG. 5. Left: Chinese speakers and icons versus Chinese characters. Right: Icons versus pictures. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

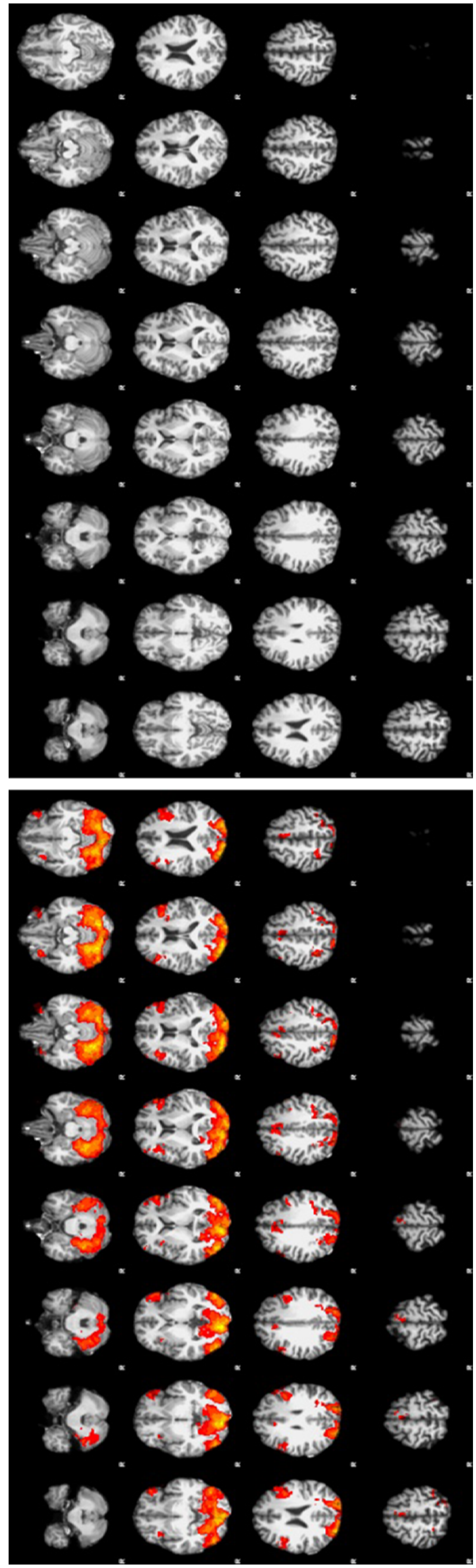

FIG. 6. Left: English speakers and icons versus Chinese characters. Right: Icons versus pictures. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Discussion

Key Findings

Key findings of this study can be categorized into three results.

1. There were modulated activations in the left IFG and the left SMG suggesting that participants were generating words while performing the cognitive task of concrete versus abstract judgment regardless of the types of visual information.
2. There were also modulated activations in the brain that were associated with the left-lateralized (but not restricted to such a lateralization) network of language-based semantic processing while participants were interpreting all four types of visual information.
3. In the within-subject analysis, the modulated activations were found in the left IFG of English speakers and in the left SMG of Chinese speakers, but there were no modulated contrasts in the between-subject analysis. These analyses suggested that English and Chinese speakers use the language-based semantic system in the same way but with different emphases in these two brain regions. In addition, such modulated activations were also influenced by the types of visual information, indicating that the process of interpreting meanings of icons was less complicated than interpreting pictures and significantly different from single English word or Chinese character processing.

When contrasting concrete and abstract stimuli in a task of semantic judgment, the left IFG plays a critical role according to the fMRI data collected from the participants. The modulated activation of the left IFG was observed in both English and Chinese speakers when they were under conditions of interpreting concrete stimuli, interpreting abstract stimuli, and differentiating abstract stimuli from concrete stimuli. The left IFG (traditionally labeled as Broca's area or Brodmann area 45) is associated with the efficiency of language processing, especially of the phonological and syntactic processes of words. This implies that the participants in this experiment rely on such language processes to make concrete versus abstract judgments regardless of the types of stimuli that are presented to them. Therefore, it is plausible that participants were generating words when they were interpreting meanings of icons and pictures.

Another finding is that interpreting the meanings of abstract stimuli requires a broader network in the brain than with concrete stimuli. This is concluded from two subtractions of fMRI data under conditions of (a) contrasting concrete stimuli from abstract stimuli and (b) contrasting abstract stimuli from concrete stimuli. In the former contrast, there were no additional modulated activations in brain areas within or between Chinese and English speakers, whereas, in the later contrast, although there were no significant activations between English and Chinese speakers, Chinese speakers require additional resources in the right IFG, the right MFG, the left SFG, and the left frontal pole, and English speakers require additional resources in the IFG, the SFG, the frontal pole, the temporal pole in the left hemisphere, and the DMPFC and the VMPFC in both hemispheres. This finding suggests that abstract stimuli were harder than concrete stimuli for the brain to process in terms of requiring more resources in the neocortex.

While participants were interpreting all four types of visual information, there were modulated activations in the brain that were associated with the left-lateralized network of language-based semantic processing and several additional areas in the right hemisphere that are symmetrical to those in the left hemisphere. These modulated activations include the STG, the MTG, the parietal operculum, the AG, the SMG, the midfusiform gyrus, the IFG, the frontal pole, the DMPFC, the VMPFC, and the posterior cingulate gyrus. While participants were interpreting all four types of visual information, the left SMG of the Chinese speaker was specifically active, whereas the left IFG of the English speakers was specifically active. Contrasts in the overall condition between Chinese and English participants showed no modulated activations, which suggests that Chinese and English participants were probably using the same network but with different weights in using the left SMG and the left IFG. This implies that Chinese speakers favor information integration, whereas English speakers favor phonological processing in the processes of interpreting all four types of visual information.

Contrasts in imaging data in conditions of different types of visual information revealed that interpreting meanings of icons was different from interpreting English words and Chinese characters and was similar to interpreting pictures. While interpreting icons, Chinese participants had modulated activations in the left SMG, whereas English participants had modulated activations in the left IFG and the left MFG. Contrasts between Chinese and English speakers while they were interpreting icons showed no modulated activations, which suggested that they might again be using a same network with different emphases on information integration and phonological processing.

Contrasts between conditions of interpreting icons and pictures revealed that (a) Chinese participants required additional resources in the IFG, the MFG, the AG, the SMG, and the MTG in the right hemisphere, and English participants needed additional resources in the primary visual cortex to contrast pictures from icons and (b) both Chinese and English participants had no significantly modulated activations when contrasting icons from pictures. This suggests that interpreting icons was not really different from interpreting pictures and that icons were processed within the same but a smaller network of brain areas as used to process pictures. This is in direct opposition to our original hypothesis, assuming that icons are not processed as pictures.

When contrasting icons with Chinese characters, interpreting icons required more resources in the IFG and the frontal pole bilaterally of both Chinese and English speakers. The Chinese participants seemed to be more motivated, because the modulated activations of the left DMPFC and

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VMPFC were also observed in this contrast. Moreover, in contrast to English speakers, Chinese speakers required more resources in the right hemisphere, including areas of the AG, the MTG, the MFG, and the IFG. When contrasting Chinese characters from icons, interpreting Chinese characters required more resources in the AG, the SMG, the DMPFC, the VMPFC in the right hemisphere, the left posterior cingulate gyrus of Chinese participants, and in the same bilateral areas of English participants. In contrast to English participants, Chinese participants, needed no extra resources in the brain for this contrast, whereas English participants required more resources in the AG, the MTG, the MFG, and the IFG in the right hemisphere to contrast Chinese characters from icons. From these two contrasts, we conclude that interpreting icons is different from interpreting Chinese characters in terms of how the brain processes these two types of visual information.

When contrasting icons from English words, interpreting icons required more resources in the IFG, the MFG and the frontal pole in the right hemisphere of both Chinese and English speakers. There were no major differences between Chinese and English speakers in this contrast, in which Chinese participants were on average more active in the primary visual cortex and English participants were on average more active in the primary motor cortex. When contrasting English words from icons, interpreting English words required more resources in the bilateral activations of the MTG, the AG, the SMG, the left DMPFC, the right posterior cingulate gyrus of Chinese participants and in the bilateral activations of the MTG, the AG, the SMG, the posterior cingulate gyrus of English participants. There were again no major differences between Chinese and English speakers in this contrast, in which both Chinese and English participants were on average more active in the primary visual cortex. By these two contrasts, interpreting icons is different from interpreting English words in terms of how the brain processes these two types of visual information.

Limitations and Controls

The fMRI contrasts are based on subtractive methods to identify significant activations of brain areas that are modulated by different experimental conditions. Such subtractive methods can identify critical brain areas only after contrasting fMRI data modulated by experimental conditions and cannot directly show the functional connections among these critical brain areas. The purpose of our analyses of fMRI data is not to understand the neural mechanisms of these identified critical areas that are used to interpreting icons, pictures, Chinese characters, and English words, but rather to use established references in fMRI studies regarding semantic-language processing to see whether processing icons is significantly different from processing other types of stimuli with collected neuroimaging data. In addition, it should be noted that the "no differences" findings in the fMRI contrasts does not necessarily mean that there were no differences in the states of participants' neural mechanisms at all. Such findings are based on statistical principles of choosing a threshold that determines Z scores of the BOLD signals to decide whether a cluster of the fMRI contrast was statistically significant to be considered as a modulated activation according to the comparison of two experimental conditions. The threshold level ($p < 0.01$) used in this study is a well-accepted standard in fMRI research.

One of the greatest challenges of this study was to recruit enough numbers of fluent bilingual English/Chinese participants after two screening processes. With $N = 19$, the sample size of our fMRI study meets commonly accepted practice in the neuroscience community, as discussed by Desmond and Glover (2002) and Murphy and Garavan (2004), and we have met the minimum statistical requirement for an event-related design in experiment and group analysis of fMRI studies. We also used a very conservative statistical threshold, cluster-corrected $p < 0.01$ at the very least, so we have controlled well for false positives. A large sample may reveal some more subtle effects, but we are currently not overinterpreting what data we have.

Implications for Information System Design and Conclusions

During the cognitive task of sorting stimuli into concrete and abstract categories, English and Chinese speakers used the same language-based semantic systems with slightly different emphases in the IFG and the SMG that were responsible for phonological processing, syntactic processing, and complex information integration to interpret meanings of icons, pictures, single English words, and Chinese characters. The pattern of brain activities while processing icons was more similar to the processing of pictures than to the processing of logographic words.

The participants were using language-based semantic processing, especially phonological and syntactic processing, when performing the concrete versus abstract judgment regardless of the types of visual information presented. The seven areas of the language-based semantic system in the left hemisphere proposed by Binder et al. (2009) and corresponding symmetrical areas in the right hemisphere were significantly active while the participants were interpreting these four types of visual information in the concrete versus abstract judgment task.

As for correctly interpreting icons, modulated activations of brain areas share great similarities in the condition of interpreting pictures using a smaller network that is more focused in the left hemisphere. On the other hand, in contrast to interpreting texts such as single English words and Chinese characters, even though interpreting icons required brain areas that were essential for language processing, the pattern of modulated activations of these areas was significantly different from the pattern of interpreting these two types of texts in the contrast analyses.

To summarize, BOLD contrasts of neuroimaging data revealed that (a) there were modulated activations in the left IFG and the left SMG indicating that participants were

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generating words during the cognitive task of concrete versus abstract judgment regardless of the types of visual information; (b) modulated activations in the brain were associated with the left-lateralized (but not restricted to such a lateralization) network of language-based semantic processing while participants were interpreting all four types of visual information; and (c) specific contrasts of modulated activations in our participants' brains suggested that, although the modulated activations might be more weighted in the left IFG of English speakers and in the left SMG of Chinese speakers for the task, how these two groups used the language-based semantic system in the brain was not significantly different. Such modulated activations were also influenced by the types of visual information, indicating that the process of interpreting meanings of icons was less complicated than interpreting pictures and significantly different from single English word or Chinese character processing.

Findings of this study refute our hypothesis that icons are cognitively processed as logographic words, although they share the neural network that is essential for semantic interpretation in the brain. In other words, icons are not processed as logographic words when people are interpreting their meanings despite the fact that the language-based semantic system in the brain is used; rather, they are processed more like pictures.

This study has provided empirical fMRI evidence of how human icon processing works in the brain, and here we advance the use of neuroimaging as a method to for information scientists. However, human icon processing and icon interpretation in fact occur in a wider and much more complex context. Watzman and Re (2008) and Freeman (2000, 2002) suggested that meanings of symbols were sociocultural and cognitive products of end users' mental activities, so we have endeavored to create a window for seeing how such products were generated with respect to neuroscience. Symbols such as icons, pictures, and texts are major visual elements in information systems. Every day we spend a significant amount of time interacting with these three types of visual information on our cell phones, computers, and other electronic devices that have GUIs. Therefore, it is important to study how people read and interpret meanings of symbols, and this understanding of human information processing and human factors will allow us to design better interactive information and systems that will not waste users' time.

This study demonstrates that there are fundamental differences in the utilization of brain resources to process graphic and textual information. We believe that these neurological findings that are not seen in traditional information system studies provide profound insights for information systems designers about the use of graphic symbols. For example, designers should avoid using abstract symbols, because they are harder for people to understand; people respond more slowly to them, and the brain requires more resources to process them. In addition, we have demonstrated that it is practicable to test design elements of GUIs with neuroscience data, and, with such neuroscience data, we can better understand individual or group behavior related to system usage and user–computer interactions.

One implication for information system design is that icons are not as efficient as words in conveying semantics because it takes more brain resources to process them and requires a vaster neural network, and the behavioral data (errors and reaction time) collected in our fMRI scanning sessions supports the idea that such vast activation is effortful; our subjects consistently and statistically responded significantly more slowly and made more errors with pictures and icons than with words in both concrete and abstract categories. This finding is coherent throughout our pilot behavioral study with 78 participants, and it was the same in the 19 fMRI participants. Our taxonomic and behavioral studies (Huang, 2011a, 2011b) before this fMRI investigation also provided evidence suggesting that people rated icons more as ambiguous than words and behaviorally responded to icons more slowly than to words. In user interface design, there is still a common belief since Wiedenbeck's study in 1999 (e.g., Caplin, 2001) that icons are more effective and efficient than text labels despite the fact that research findings have repeatedly shown that stand-alone icons have no superiority over texts in terms of usability. We believe that adding new evidence from our fMRI data can add to our knowledge on this topic.

Our findings might not yet steer changes in the design of icons, but, as fMRI studies follow on from the one presented here and our understanding of processing differences becomes more detailed, such data might guide icon design. Imaging data also allow some alteration of theories with a new "physical" constraint. The promise is the same as it has been for cognitive science: no more endless model tweaking if we now potentially have a physical constraint. That the processing of icons is more similar to neural processing of images and pictures implies that interpreting meanings of icons requires a larger semantic network and more resources in the brain, which suggests that icons are not as efficient as words in conveying meanings.

We hope that this study will provide researchers in information systems with a better understanding of the role of graphic and textual of information in information systems and social media that use symbols and text; icons are not words, and people need additional context and brain resources to help them learn the meanings of symbols. In other words, brains (people) make more effort to process icons than words. In addition, evidence has shown that people rated icons more ambiguous than words and behaviorally responded to icons more slowly than to words (Huang, 2011a, 2011b); it is likely that people would stumble upon ambiguous symbols on GUIs that cause them to slow their tasks of finding things. We suggest that developers of system interfaces and interactive information should consider such knowledge revealed by the empirical evidence of this study when they are implementing elements of graphic and textual cues in their designs. Finally, we are enthusiastic about the promise of adding fMRI to the information science researcher's tool belt.

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